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*Energy and Environment*

# Transportation Environmental Issues: Air, Noise, Water, Mitigation Processes, and Alternative Fuels

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# Transportation Research Record 1444

# Contents

# Foreword

The papers in this volume cover a variety of environmental and transportation energy topics. They are divided into five topical areas:

- Energy and alternative fuels,
- Environmental analysis,
- Air quality,
- Noise, and
- Enhancements.

The papers on energy and alternative fuels address electric vehicles, alternative fuels, and fuel consumption models. The papers on electric vehicles provide evaluations of electric bus operations, regulatory impediments (including safety and zero-emission vehicles rules), and the prospects for neighborhood electric vehicles.

The first set of environment-related papers contains a paper on the on-site treatment of contaminated soils and another paper on wastes and sludge transportation and landfill selection. The next set of papers reflects TRB's new activities that address the interrelationships between transportation and the protection of natural resources. This set includes a paper on state department of transportation policies on endangered species and a paper on wetlands mitigation.

On the important issue of transportation-related air quality, several topics are considered, including improving transportation air quality models through better road link speed estimates, the trip-based approach to estimating emissions, and the impacts of programs such as intelligent vehicle-highway systems and automobile retirement programs on potential emissions and air quality. Other papers discuss the relationship between transportation-related air quality and economic development, travel forecasting guidelines under the clean air acts, modeling for a regional transportation emissions inventory, the effects of power enrichment on carbon monoxide emissions, and a framework for evaluating transportation control measures.

Three papers address transportation-related noise. Two papers on aircraft noise consider ground-noise abatement of aircraft at a metropolitan airport and the effects of helicopter noise on rural communities. A third paper proposes procedures for prioritizing noise-barrier locations.

Under the Intermodal Surface Transportation Efficiency Act of 1991, federal aid funds are set aside for a special transportation enhancements program. The last paper in this Record describes the enhancements program for the San Francisco Bay Area.

# PART 1

# Energy and Alternative Fuels

# Electric Buses in Operation: The Chattanooga Experience

THOMAS W. DUGAN

In the early 1990s the City of Chattanooga, Tennessee, and the Chattanooga Area Regional Transportation Authority (CARTA) were looking for an innovative approach to the need for a downtown shuttle. As a result of finding a solution to this problem, the transit system has embarked on the most extensive electric transit vehicle program in the United States. The program now uses electric buses made with existing technology and actively participates in developing new electric vehicle technologies, testing vehicles and components, manufacturing electric transit vehicles, and formating the Electric Transit Vehicle Institute. The history of the program, the policy and operational issues that were addressed by the CARTA governing board and management staff, and the areas of consideration for transit systems considering the use of electric transit vehicles are provided, as are the author's thoughts concerning the future of electric transit vehicles. Emphasis is given to the policy and organizational concerns that face a transit system seeking to implement a new technology from the perspective of an agency whose focus is on the actual real-life operation of electric buses rather than short-term demonstration programs.

Chattanooga, Tennessee, unlike many other southern urban centers, became a manufacturing center after the Civil War. The availability of inexpensive, low-grade iron ore led to the development of many foundries and related manufacturing industries. At one time in the 1950s Chattanooga had the highest number of manufacturing employees per capita of any city in the United States. Chattanooga's location, in a valley surrounded by ridges and mountains, inevitably led to one of the worse air pollution problems in the country. By the mid-1960s Chattanooga was consistently being rated among the worse three urban areas of the country in terms of air pollution.

Government and private-sector leaders came together in the early 1970s to develop plans to change the air quality of the region. Some regulations were already in place, and local leaders wanted to get ahead of the air quality requirements that were sure to come in the future. Local industries made large investments in equipment to clean the air, and today Chattanooga is in full compliance with all clean air regulations. As such it is one of the few urban areas in the country not facing onerous regulations concerning air quality and mitigation measures.

Chattanooga continues to have some environmental problems. Parts of the creek tributary system off the Tennessee River are heavily polluted. Mobile air pollution (from automobiles, etc.) is beginning to become a concern just as the stationary pollution sources were in the 1960s. But these issues are now seen not as an impediment to economic development but rather as a source of future economic development. The solving of environmental problems is seen as a process that leads to the development of new industry and to the identification of Chattanooga as a center for innovation and change.

Chattanooga Area Regional Transportation Authority, 1617 Wilcox Boulevard, Chattanooga, Tenn. 37406.

In the 1980s two additional developments that would have a major impact on the development of electric transit vehicles in Chattanooga took place. First, the form of government changed. As a result of a civil rights suit, the old commissioner form of government was replaced by a strong mayor-city council form of government. The commissioner form of government had five commissioners, elected at-large, who functioned as the legislative branch of local government but who also had executive branch responsibilities over their individual departments—finance, police and fire, recreation, education, and public works. The new form of government has an elected mayor and nine council members elected from districts.

There have been several positive aspects to the new council form of government. One aspect of the council that has had a profound effect on the issues of environment and electric bus development was the election of citizen-representatives who brought to the council a view that the issues of environment and quality of life were better handled on a local rather than a regional, state, or federal level. In addition these council members believed that Chattanooga could become a leader in the development of solutions to traditional urban problems, solutions that emphasized new thoughts, new technologies, and new policies, and that such solutions could provide the foundation for future economic development in the city and the region.

A second development was the active participation in community affairs by members of the economic elite. Historically, in Chattanooga, the wealthy families had always participated in support of the arts, private education, and charities. In the mid-1980s, however, funding and leadership began to appear in the areas of education, downtown development, housing, and economic development. Chattanooga Venture, a private nonprofit corporation, was organized to develop a broad, community-based process of developing lists of community priorities and then to function as a facilitator of new programs to address these issues. Chattanooga Neighborhood Enterprises was created with the visionary goal of securing adequate housing for every family in Chattanooga. The Chattanooga Education Foundation was formed to provide additional resources and new perspectives to the public education system. Each of these agencies has received strong financial support from private foundations.

The RiverCity Corporation was also formed during this time period. A private, nonprofit organization, the RiverCity Corporation has a Board of Directors that represents the private and the public sectors. The purpose for the organization is the planning and development of the central business district, with particular emphasis on the north area adjacent to the Tennessee River. For the first time an organization was in place with all the key players on board to focus on downtown and riverfront development. Through the provision of private and public financial support a

core group of professionals was hired and an urban design studio was established. In addition the most progressive experts in the country were brought in to participate in the development of the downtown plan. Through this effort the creation of the downtown shuttle and parking system, proposed by the Chattanooga Area Regional Transportation Authority, was planned, fine-tuned, and placed in a position of prominence.

## CHATTANOOGA'S TRANSIT SYSTEM

The Chattanooga Area Regional Transportation Authority (CARTA) is a traditional provider of public transportation services to the Chattanooga area. It operates a 60-bus fleet, employs about 120 persons, and is governed by an 11-member Board of Directors appointed by the political subdivisions that provide its funding. As the downtown planning process was under way CARTA was requested to develop a transportation plan to tie the elements of the downtown plan together.

Downtown Chattanooga is a long, narrow geographic area stretching from the Tennessee River in the north to the I-24 Interstate highway in the south. East and west it ranges from approximately 6 to 10 blocks wide, with a freeway bordering the western edge and a ridge bordering the eastern boundary. Development in the downtown gravitates to three areas: the riverfront to the north, the Miller Park district in the center, and the Choo-Choo resort area in the south. This distance extends about 2 mi. The distance involved caused a problem to planners in that it was beyond walking distance, and yet the plan would not work if it depended on the automobile.

The north end of the downtown has seen major development in the past 3 years. The Tennessee Aquarium, a $45 million, privately financed facility, opened in 1992 and recorded 1.5 million visitors in its first year. A new visitors' center has opened within the $6 million Ross' Landing plaza that surrounds the aquarium. Within 2 blocks the first downtown housing built in 30 years opened in 1992, a new children's museum was to have broken ground in early 1994, and new restaurants have been opening at a rate of one every 6 months.

The central area of downtown is anchored by the Miller Park and Miller Plaza developments and the office complex of the Tennessee Valley Authority and continues to be the commercial and retail center of the downtown. To the south the area around the Choo-Choo resort is under current planning to expand the Warehouse Row development, a very successful retail-office complex specializing in direct, upscale outlets.

The transportation solution to the problem of tying together these development centers was developed by CARTA in 1991 and was composed of two parts. The first part was the location of parking garages at the key entrances to downtown to act as intercepts for the automobile traffic. The second part was a high-quality, high-frequency shuttle system that would connect the intercept garages with downtown destinations. This system would permit local workers and out-of-town visitors to leave their automobiles at one location and use the shuttle to move about town. In addition the revenues from the parking facilities would provide the funding necessary for the operation of the shuttle.

To this end CARTA applied for and received approval of a $19.6 million grant from FTA for the parking facilities, vehicles, and construction of passenger stations. Of the total, $15.7 million will come from FTA and about $2 million each will come from the Tennessee Department of Transportation and the City of Chattanooga.

The issue then confronting CARTA and the community was the choice of vehicles for the shuttle.

## POLICY ISSUES AND ELECTRIC VEHICLES

### Community Requirements

As CARTA began the process of selecting a vehicle type for the shuttle it was provided with a set of criteria by community leaders through the downtown planning process. The shuttle had to be of equal quality to the developments in the downtown, it had to be something more than just a ride—it had to be an experience in and of itself, it had to serve as a connector to the developments, and it had to have a positive impact on the environment.

The word *quality* is used extensively in the literature body. In terms of development that Chattanooga has experienced in the last 3 to 5 years, however, the meaning was obvious to CARTA planners. The Tennessee Aquarium is considered among the top three aquariums in the United States. The plaza that surrounds the aquarium was designed by some of the leading urban designers in the country and has become an attraction on its own. The community was not interested in its downtown transportation system being something other than a unique, innovative form that would become another part of the statement that the city was making about its future.

To make certain that the shuttle attracted people from their automobiles, the system had to be more than just a ride—it had to be an experience. Local workers and visitors should be interested in using the shuttle because of its identity and not just as a method of getting from one place to another.

The shuttle system had to be designed in a way to connect the many locations in the downtown area. The connection not only had to be made by locating the routing near the various locations but it also had to be through well-defined passenger boarding areas, distinct graphics, and an effective informational system. The system design also had to have the ability to be expanded and modified as new developments were opened. And, finally, given the city's recent commitment to environmental issues, the shuttle had to be environmentally acceptable.

### CARTA Board Policy Concerns

For CARTA the issues separated into both board-level policy issues and staff-level operational issues. The board was concerned with community needs, environmental issues, community support for the CARTA program, financial resources, and broader community issues such as economic development and environmental impacts. The CARTA staff focused on operational issues such as vehicle dependability, functionality of the technology, organizational resources in terms of skills, and the ability to deal with change, labor relations, and vehicle maintenance.

The CARTA Board of Directors is unique within the transit industry. It is both active in its participation in transit activities and is also visionary within an industry that is more known for its conservatism than its willingness to take risks. Taking its cue from a community dedicated to innovation and new approaches to old problems, the board set about for a vehicle that would be

unique and environmentally beneficial and that would provide for the opportunity for economic development expansion.

The CARTA staff found it difficult to keep up with the visions of the board. CARTA, as noted before, is a traditional, fixed-route, diesel fuel–using bus system. The existing buses were very dependable, no new skills or training were required, the service fit with existing labor and management agreements, and of greatest import, no change was necessary. Initial thoughts from the staff focused on buses that were designed to look like vintage trolleys rather than a new technology.

After an initial investigation into a vintage rail trolley system, CARTA turned its attention to electric, battery-operated buses on the basis of a series of articles that chronicled the use of such vehicles in Santa Barbara, California. After a series of visits to Santa Barbara by CARTA board members and top management, the decision was made to pursue this type of vehicle. At this point CARTA retained the services of a local person who had broad and successful manufacturing experience and who was looking for a new business opportunity. His mission was to answer the following questions: Does electric technology that would result in a vehicle that CARTA could use in the downtown shuttle exist today, is anyone making such a vehicle, and if not, could the vehicle be made in Chattanooga?

Thus in late summer 1991 CARTA made a decision to pursue a technology and a vehicle that had not yet been demonstrated to be able to match the rigors of regular use in an urban setting. Even the Santa Barbara experience was in a very moderate climate, with little topographical diversity and ridership levels below what was expected in Chattanooga. The opening of the Tennessee Aquarium in May 1992 required that CARTA place a shuttle in operation using 35-ft diesel fuel–using buses. What had been expected to be a shuttle operation that would carry 10,000 to 20,000 passengers per month became a critical component of the downtown experience, transporting between 50,000 and 100,000 passengers per month. The Santa Barbara vehicle had a seating capacity of 22 passengers, whereas the diesel bus in Chattanooga sat 37 and was already being overwhelmed during peak periods.

The Chattanooga consultant hired by CARTA investigated electric vehicle technology in the United States and Europe and returned with the following results: (a) the existing technology was sufficient to support an electric shuttle bus for use in the CARTA downtown project, (b) no company was currently manufacturing a vehicle that would meet CARTA's needs, and (c) it was feasible to develop a manufacturing organization in Chattanooga to design and build an electric, battery-powered bus for use in Chattanooga and for export to other cities in the United States. What followed was the creation of Advanced Vehicle Systems (AVS), a start-up company in Chattanooga formed to produce electric transit vehicles.

Another outcome of this investigative phase of the program was the development of a relationship between CARTA and Electrotek Concepts, a private company that operates the Electric Vehicle Test Facility in Chattanooga. This facility, originally built by the Tennessee Valley Authority and leased to the private sector, is the only facility in the world that is exclusively dedicated to the testing of electric vehicles and electric vehicle components. The staff at the facility has over 70 years of combined experience with electric vehicles and has done testing for some of the largest companies in the world. Electrotek Concepts functions as an independent testing laboratory for the electric vehicle industry. Both CARTA and AVS developed relationships with Electrotek to provide testing and technical assistance in the development of their electric buses.

Thus the CARTA Board of Directors had met and exceeded their goals. CARTA would be using a new technology, they had the complete support of the political and business communities, the vehicle would be environmentally positive, and the decision had resulted in the creation of a new manufacturing enterprise in the city. Up to this point little attention had been paid to the issues that confronted the CARTA staff in terms of actually operating this new type of vehicle. The positive attention that attached itself to this new vehicle overshadowed any operational concerns that might have been in the minds of the CARTA staff. In fact the can-do attitude of the Board was contagious and permeated through top management.

**Creation of Electric Transit Vehicle Institute**

CARTA and Chattanooga, as a result of plans to implement what would become the largest electric transit vehicle fleet in the world, began to receive calls from various concerns interested in the program. Electric vehicle component manufacturers, other transit systems, electric utility companies, and representatives of state and federal agencies made contact with CARTA to be briefed on the Chattanooga program. As a result of this interest the CARTA board formed the Electric Transit Vehicle Institute (ETVI), a private, nonprofit organization whose mission is to further the development and use of electric transit vehicles. ETVI was provided a grant by CARTA to initiate its work.

The CARTA Board of Directors also granted funding to ETVI to be used to buy two electric buses. Knowing the lengthy process of receiving grant approval and not wanting to lose momentum created by the decision to use electric buses and the resulting positive response, CARTA leadership wanted to use ETVI as a method of getting electric buses on the streets of Chattanooga as soon as possible. Thus the first two electric buses were ordered from Specialty Vehicle Manufacturing Corporation of Downey, California, and were dedicated into service by the Administrator of FTA in June 1992.

The first electric buses received by CARTA were 6.71 m (22 ft) long, were 2.34 m (92 in.) wide, and had an overall height of 2.51 m (99 in.). The vehicle seated 22 passengers or 19 passengers with one wheelchair. Wheelchair accessibility was provided through a ramp built into the ramp at the entrance of the vehicle. The nominal curb weight was 5,488 kg (12,100 lb), with a gross vehicle weight of 7,711 kg (17,000 lb). The top speed was rated at 64.5 km/hr (40 mph), with an acceleration of 23 sec from 0 to 40 km/hr.

The unit was powered by a direct-current motor rated at 32 kW (continuous) with separate armature and field connections. Nominal input was 216 V. The motor was manufactured by Nelco. The vehicle included a transistorized controller to control power to the motor armature and the motor field separately using independent chopper circuits. This chloride controller had a nominal input of 216 V, with a maximum armature current of 390 A, a maximum field current of 20 A, and a maximum regeneration current of 200 A.

The traction battery was configured by using 108 cells with a nominal voltage of 2.0. The cells were series connected in four batteries of 27 cells with a nominal battery voltage of 54. The 54-V batteries were series connected to provide a nominal traction

battery of 216 V. The cells were capable of delivering 500 A intermittently for periods of up to 90 sec and 200 A continuously without damage to the cell.

The cells were lead acid that used flooded electrolyte. Cells had a nominal weight of 20.4 kg (45 lb) each and a nominal capacity of 375 A-hr. Nominal energy was 73 kWhr at a 5-hr rate at 25°C (77°F).

## CARTA Staff Policy Issues

In June 1992 CARTA thus entered the new world of electric buses. The vehicles had no air-conditioning or heating and had windows that were totally removable (thus either it had windows or it had no windows); there were no parts manuals, maintenance manuals, or operators' manuals; and no program for staff training had been developed. The ability of CARTA as an organization to accept change was now to be put to the test.

It was known that the political, business, and other community leaders were very supportive of the program. Adequate funding had been provided for the operation and maintenance of the vehicles. AVS was still in the start-up stage but had entered into a joint development agreement with Specialty Vehicles and was available to provide a direct, local contact with the vehicle manufacturer. In addition public acceptance and support for the new vehicles was very strong from the first day. Many Chattanoogans expressed pride that CARTA took the lead in this area, and more than one visitor to the city requested information on the vehicles to take home to their transit system.

The positive political and community environment made the change easier for top CARTA management to accept. It did not initially, however, help at the line level in the CARTA organization. The maintenance department took an attitude of benign neglect in the hope that this fad would go away. The scheduling department had never before had to deal with a vehicle with a limited number of hours during which it could operate, and the impact of this fact on the scheduling of vehicles and routes was troublesome. The marketing department was concerned about the lack of interior and exterior advertising space on the vehicle, all of which had been completely sold on the diesel shuttle buses. The operations department was concerned about the training needed for drivers of the electric bus, because it had regenerative braking and the range of the vehicle would definitely be affected by the habits of the driver.

CARTA top management was faced with dealing simultaneously with a series of issues. First, management had to confront head-on the issue of technological change. Second, they had to deal with the immediate use in service of a new technology. Third, they had to deal with nonvehicle issues that would be affected by the new vehicle, such as scheduling, marketing, and support facilities.

### *Dealing with Change*

For all the talk about humans being bored, in a rut, or unhappy with repetitive tasks, the fact is that change is more stressful than the status quo. CARTA management embarked on an undefined and unplanned process to encourage change, and it was stressful to openly acknowledge that change. Meetings were held with drivers, mechanics, and staff in which the plans for the electric buses were discussed and questions answered. It was emphasized that this new program would help all phases of the CARTA operation as it pertained to local financial support for public transportation. Opportunities for career advancement and training were emphasized. Fears concerning possible obsolescence of existing skills were put to rest. And above all there was an honest empathy for the concerns, fears, and stress. The feelings of the members of the organization were treated as real.

In the area of drivers, special attention was given to training the shuttle drivers on the use of the electric bus. Information was provided to them so that they could respond to questions from riders. Printed materials that could be given to riders who wanted technical information were developed, and ETVI was identified as a source for further information. News stories that highlighted the drivers as well as the vehicles were prepared. AVS organized meetings for drivers so that they could receive input for future design changes with the next generation of electric buses.

Meetings were also held with the maintenance personnel. Assurances were provided that there would continue to be a steady workload for diesel mechanics. At the same time employees who had an interest in the electric buses were encouraged to let management know of their interest. Additional training was offered through the local technical college. AVS established a standing committee of maintenance employees to provide continuous input to the manufacturer, with the membership of the committee rotated so that all employees could be involved. One particular employee who had the electrical knowledge and demonstrated a keen interest in the new vehicles was promoted to a position of leadman—electric vehicles.

In retrospect a better job could have been done in preparing the organization for the change that occurred. However the key to successfully implementing the electric bus into the CARTA system was the acceptance and acknowledgment of the difficulties that would be faced by the individuals responsible for the vehicles and the service. Then the continuous participation by these individuals permitted them to help design the program rather than be forced by the program to change in response.

### *Immediate Use of New Technology*

The difficulties noted were exacerbated by the need to introduce the vehicles into service immediately. The first question to be answered was what range could the new vehicles provide? When delivered the vehicles came with 375-A-hr battery packs. However these were temporary batteries on loan until the new batteries could be delivered to CARTA. The vehicles were introduced into service in 4-hr blocks of time. This was expanded to 6 hr and then to 8 hr. The range for the buses appeared to be about 120 km (75 mi). Acceleration was good, and the top speed of 64.5 km/hr (40 mph) was above what was needed for the shuttle route, although it did pose a minor problem on the routing of the bus from the CARTA facility to downtown and back, which normally used a highway with an 80-km/hr (50 mph) limit.

When the new batteries were delivered it was found that the original 375-A-hr batteries were being replaced with 300-A-hr battery packs. Confusion on this issue centered on whether CARTA wanted to incorporate battery exchanges as a regular part of the daily service cycle. The 300-A-hr battery packs were smaller and much easier to get in and out of the bus. CARTA agreed to use the new battery packs and experiment with battery exchanges. The result was a reduction of range to about 97 km (60 mi) with an operating day of 6 to 7 hr. The difficulties in

scheduling battery exchanges led to a decision to adjust the vehicle schedule to match the expected range of 97 km.

The initial two vehicles had many problems, primarily with the steering and suspension. There was a great deal of contact between Chattanooga and Santa Barbara, California, for the first 3 to 4 months, and major modifications of the vehicle were undertaken. However the basic propulsion system (the batteries, motor, and controller) operated flawlessly.

The next issue was matching CARTA's staff resources to the new buses. CARTA has a professionally trained maintenance staff for diesel buses, and as part of that staff there are persons with significant knowledge in electrical systems and theory. However CARTA had to rely a great deal on the manufacturer's representatives and the technical personnel from the vehicle component manufacturers to get through the first few months. During that time AVS was beginning to develop its core staff and assisted CARTA in the maintenance troubleshooting. Also Georgia Power in Atlanta had purchased two similar vehicles right after CARTA, and there was constant communication between the two maintenance staffs. AVS arranged joint meetings of Georgia Power and CARTA staffs to discuss the good and bad points of the vehicles and the changes that each agency had made on their vehicles.

A series of related events required CARTA to reshape its policy on staffing for the electric bus fleet. In early fall 1992 CARTA went out for bid for 12 electric buses. Four of these were to be 22-ft models similar to the ones already received and eight were specified to be capable of carrying up to 30 passengers, a vehicle never before produced. AVS and Specialty Vehicle, in a joint arrangement, were awarded the contract. In summer 1993 ETVI participated in two consortia that were successful in securing funding from the Advanced Research Projects Administration (ARPA) of the U.S. Department of Defense that would result in two additional electric buses incorporating the leading technology for demonstration and use in Chattanooga. Thus CARTA had to plan for the receipt of 14 additional electric buses by the end of 1994.

The interest that developed in the Chattanooga program and that led to the creation of ETVI continued to accelerate. One or both of CARTA's electric buses were routinely being shipped to various cities for demonstrations. The buses went to Minneapolis, Miami, Memphis, Boston, Philadelphia, and on three separate occasions (including President Clinton's Inauguration), Washington, D.C. Although ETVI took care of much of the planning and supervision of these demonstrations, there was a great deal of CARTA staff and maintenance time dedicated to these projects.

CARTA continued to upgrade the existing vehicles. Propane heating systems were installed in late fall 1992. An experiment using cellular phones in place of traditional radios was completed (but it was not a success). And in summer 1993 CARTA planned service additions to the downtown shuttle that would place its spare vehicle ratio at a precariously low level.

With these additional strains on the staff, particularly in the maintenance area, it was decided to create a new electrical position and add two positions to the maintenance division. Even with the decision made, the lead time to get the staff to a level necessary in numbers and skills to deal with a small fleet of electric buses was estimated to be between 6 months and 1 year.

### *Nonvehicle Issues*

The process of scheduling transit buses and drivers is a technical skill in which the objective is to minimize the pay time required to operate the bus service. Huge numbers of variables and constraints must be factored into the equation, such as the hours and days of operation, guaranteed pay time, pay penalties for overtime and spread time, and the comparison of added cost for increased personnel versus increased built-in overtime. At CARTA one area in which the scheduler was not concerned was in the operating range of the bus. The traditional diesel bus could stay out all day and the scheduler had only to worry about assigning persons to drive the vehicle. The electric bus, in its current configuration, cannot stay out all day, so a new variable was added to the scheduler's equation. If CARTA decided to use battery exchange as a means of extending the vehicle range, additional variables were introduced concerning the pay time for the driver while the vehicle was being recharged.

For the marketing department, the electric vehicle created an uncertainty surrounding advertising revenues. The downtown shuttle with the diesel buses had been totally sold in terms of interior advertising. The new 22-ft vehicles had no interior advertising, and the plans for the 30-ft model were incomplete. The current buyers of the space wanted some assurance as to future advertising, and the marketing department wanted to be able to calculate potential revenue from this activity. Although this may appear to be a small issue, the buyers of the space were among the downtown merchants who had most strongly supported the development of the shuttle and the revenue from the space generated nearly $30,000 annually for CARTA.

The storage and recharging of the vehicles required further consideration. The round-trip distance between the CARTA facility and the downtown starting point for the shuttle is 6 mi. This meant that approximately 10 percent of the operating range of the electric bus was being used to get it to and from the route. Initially this led to a view that a downtown location for storage and recharging would be preferable. However the cost of building and staffing a satellite facility was unacceptable. Also the downtown location, if only used for storage and recharging, would still mean that cleaning and maintenance would have to be done at the main facility.

The storage and recharging of the original two vehicles is currently done in one bay of the CARTA maintenance facility. Plans are now under way for the modification of the existing storage facility or the construction of a new facility for the larger electric fleet. Experts in electric vehicle technology have been brought in to deal with issues of thermal management, hydrogen gas dispersion, and acid leaks. Issues involving safety and environmental protection are receiving priority treatment.

The handling of the issues that confronted the staff have primarily been accomplished on the run. Many were understood before the first vehicle arrived and were dealt with, others were known but waited for a solution until some operating experience was gained, and others were never anticipated. Finally there are those issues that have yet to be resolved.

## CURRENT STATUS OF CHATTANOOGA PROGRAM

As of September 1, 1993, CARTA owned and operated three electric buses. Four additional vehicles were expected to be delivered within 30 days, including one of the 31-ft buses that incorporates a radical design involving a second rear axle that supports the entire battery assemblage, which can be removed from the rest of the vehicle in less than 10 min. By the end of 1993 an additional

seven vehicles were expected. In mid-1994 two vehicles being developed under the ARPA program were to have begun operation in Chattanooga. Thus by the end of 1994 CARTA will own and operate between 10 and 16 electric buses, the largest known fleet of electric transit vehicles in the world.

ETVI has received financing from CARTA, the Tennessee Department of Transportation, the Tennessee Valley Authority, FTA, and the U.S. Department of Defense to underwrite its activities. Currently ETVI is working with CARTA to develop training programs for staff, drivers, and mechanics; supervising the ARPA demonstration projects in Chattanooga; developing a central data base for electric transit vehicles; and gathering transit and electric utility input on the design of future electric buses.

At this time the project would have to be credited as being a success. The vehicles are operating every day, are well received by the riders, and are supported by local leaders. Regional, national, and even international interest has continued to grow. At least one group representing utilities, transit, manufacturers, or government is making contact with CARTA and ETVI each week, with groups regularly visiting Chattanooga to meet with the manufacturer (AVS), the user (CARTA), the test facility (Electrotek), and ETVI, all in one geographic location. This living laboratory presents a unique opportunity to advance the state of the technology.

## DECISION TO IMPLEMENT ELECTRIC TRANSIT VEHICLE PROGRAM

The transit industry is a conservative industry. Very little funding has been committed to research and development. Vendors who serve the transit industry have little incentive to conduct such research given the relatively small market that transit represents. A significant number of people are employed in the industries that manufacture and service internal combustion engines and heavy-duty transmissions. Although such industries would not be significantly disrupted by changes from diesel and gasoline to natural gas and propane, there could be a significant economic displacement if there was a wholesale switch to electricity as the fuel of choice.

The technical expertise found within much of the transit industry is not attached to electrical theory and practice. On the other hand the utility industry is not experienced, for the most part, in the transportation area, particularly electric buses. The battery technology being used by CARTA and Santa Barbara is not new. In fact the same systems were being tested in the early 1970s as a result of the first energy crisis.

Thus any transit system wanting to begin on the path toward electric buses will be faced with some obstacles. But there are rewards also. Federal environmental and energy regulations are making the continued use of diesel fuel and, in the future, internal combustion engines much more difficult, if not impossible. The public's awareness of environmental protection has been enlarged and the "old, smelly bus" will increasingly be under attack, whereas those systems that select environmentally beneficial options will have strong public support.

The author has had the opportunity to discuss the electric transit vehicle issue with several in the transit industry and representatives of the utility and private manufacturing industries, and it appears that there are six issues that a community needs to address before deciding to enter the field of electric buses.

First, the local political and business community must support the program. There must be a positive environment within which the transit agency or utility may operate. There must be a recognition by the local leaders that this is still a new territory in which temporary setbacks are the norm.

Second, the leadership of the transit system must have a vision. This unusual foresight must look past the initial difficulties and grasp the long-term benefits and potential. It is very easy for a board of directors, a city council, or top management to initially accept the concept only to reverse course when difficulties arise. Transit systems are normally judged by being dependable, not innovative. The introduction of a new technology requires a long-term commitment, not just a short-term demonstration period.

Third, there must be a commitment of resources necessary to get the job done. Preliminary data at CARTA indicate that electric buses will be less expensive to operate over the long term. But the initial implementation of the program requires added investment in training, facilities, tools, and staff time. Fuel costs in terms of cents per mile are about 50 percent of the fuel cost per mile of the diesel bus. Normal maintenance costs (preventative, minor repairs, component replacement) are also about half for electrics compared with those for diesels. Record-keeping at CARTA during the initial months of operation of the electrics has not been exact, but Santa Barbara numbers are nearly identical in terms of fuel and basic maintenance costs, being about one-half for electrics. However until electric fleets are operated long enough to incorporate life cycle costs such as battery replacement, structural degradation, and motor repair and replacement, it cannot be asserted (without condition) that the long-term costs of electrics will compare favorably to those of diesels. At this point it is known only that the operating costs to date have been lower.

Fourth, acceptance of change must be integrated throughout the organization. U.S. public transportation has long been mired in a philosophy of continuing to do things that it knows will not work with the hope that they will. Traditional fixed-route services, old-fashioned labor and management relations, and continued use of big, aesthetically displeasing urban buses are examples of this philosophy. For example many labor contracts do not envision a day when bus drivers would pull their vehicle into a rapid recharging station and connect the vehicle for a short battery charge, requiring instead that an additional maintenance employee be used to do the recharging. Whether or not electric buses are the way of the future, transit organizations must become welcomers of change, not entrenched opponents.

Fifth, there must be a partnership relationship between the transit system and the vehicle and component manufacturers. Normal procurement procedures involving the writing of voluminous specifications and the selection of the product on a price basis will not work in the electric vehicle industry. The technological changes occurring daily require the relationship to be fluid to take advantage of new developments. The normal hostile relationship between vendor and buyer must be replaced with a collaborative effort in which both parties realize that their success is directly tied to the success of the other party.

Sixth, the transit system must go into the project understanding that an electric vehicle will not satisfy the same requirements as a diesel bus. Developments are now under way in air-conditioning and heating systems, battery development, range extension through auxiliary power units, rapid recharging, and battery exchange systems. All are focused on trying to get the electric vehicle to act more like a diesel vehicle. But the fact is that the

industry has not yet reached that goal. Even so the existing electric transit vehicle can, conservatively stated, meet 25 percent of the needs of most urban public transportation systems. Most transit systems place vehicles in service for 2 to 4 hr during the morning peak and again in the afternoon peak. Thus electric buses could be used for this additional demand period and be recharged in between these periods and during the evening. For example CARTA needs 45 peak buses for its regular service, whereas only 25 are operated all day long.

## FUTURE OF ELECTRIC TRANSIT VEHICLES

It is not difficult to envision alternative scenarios for electric transit vehicles in the future. Technological developments that would solve problems dealing with range and horsepower very well may quickly appear. Another energy crisis could galvanize federal support for alternative fuels at a level necessary to move from the drawing board to the road. On the other hand the continued disproportional level of work being done in other alternative fuels may yield positive results before positive results are obtained for electric vehicles. Work on totally different propulsion systems, such as the fuel cell, may make current thinking about alternative fuels obsolete.

The recommendations that follow are those of the author, an operator of urban public transportation systems for the past 20 years. They are not technical in nature, because that is not his background. They are policy oriented and focused on the issues that will result in the best possible environment for the continued development and use of electric transit vehicles. In fact the recommendations could just as well be for alternative fuels. There are actions required by the national government, the private sector, and the transit community. These actions provide the minimum foundation necessary to sustain an effective program of introducing new technologies to the transit industry.

1. The federal government must continue and expand, when possible, programs such as the FTA challenge grant, the U.S. Department of Defense ARPA program, and the Technology Reinvestment Program. These programs all share a common requirement of local matching funds (normally in a one-to-one ratio), thereby ensuring a commitment from the local agency. In addition these programs are broadly defined to permit the maximum level of innovation and flexibility in project design and implementation.

2. The federal government should, within the programs noted, increase the emphasis on practical demonstrations of new vehicles and technologies. Basic research must continue to be funded, but there is far too little work being done in the demonstration of the new technology in real-life operating environments. There is a growing concern that a continuation of the current approach to electric vehicle research and development will lag behind the practical application of technology that is occurring in Europe and Japan. CARTA is placing new electric buses in regular service upon completion of their manufacture without waiting for the normal testing and evaluation process to be done by the manufacturer. Although this poses a risk to the operating organization, it accelerates the development of the technology by providing for the rapid feedback from the operator to the manufacturer.

3. The private sector, including vehicle manufacturers, component manufacturers, and utility companies, must develop knowledge of public transit operations. There has been a tendency for vehicle design and component development to come from the viewpoint of the technical staff of the provider rather than as a response to the needs of the transit system. This point of view may have resulted from the initial target being private automobiles and light-duty vehicles. But CARTA in 1 year will introduce more people to the concept of electric vehicles than the major automobile manufacturers may do in the next 10. Although the long-term focus will undoubtedly be on the much larger automobile, van, and small truck market, the short-term developments must be responsive to the needs of the transit community.

4. Process must replace product in the relationship between the transit operator and the vehicle manufacturer. Formalized, price-based procurement will need to be replaced with negotiated procurement that permits constant change through the construction process. The technology is changing so rapidly that a transit property will probably receive a vehicle much different from the original specifications. Indeed transit systems should demand the right to take advantage of improvements throughout the construction process.

This raises questions that will need to be addressed by the transit system, the manufacturer, and the funding agencies. How can price be determined given the fluid nature of the process? In the development of new technological approaches to electric buses, what level of risk should be borne by the transit system compared with that borne by the manufacturer? How will traditional warranty issues be handled? How will product improvements be provided to existing customers? How will the large development costs be distributed over a relatively small buying population?

5. For electric transit vehicles to succeed transit systems must take risks and accept change. This will require leadership from the community, the governing bodies, and top management. It will require a commitment to training and resource allocation sufficient to support the new vehicles. It will require changing practices that have been held sacred in the transit industry for nearly 50 years. And it will require a long-term view rather than the normal next-day perspective. CARTA could have purchased a few vehicles for use in its downtown shuttle, thereby receiving a snapshot of the electric vehicle technology. Instead the decision was to change the organization to be able to handle a changing technology, thereby buying a moving picture rather than a snapshot. This decision, critical to the overall success of the program, requires the organization to accept constant change and, in fact, to require constant change.

6. Ultimately the success of electric transit vehicles will come when one transit system makes the commitment to completely replace its fleet with electric buses—and then shows others that it can be done. When a person owns two automobiles, he or she becomes attached to one over the other and finds ways to limit the use of the less desirable vehicle. Transit systems that have more than one type of bus will find that one is preferred over another and inevitably is used more extensively. But when the fleet is of one type the entire organization must come together behind that vehicle and commit the resources necessary to maintaining the service to the community.

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# Regulatory Impediments to Neighborhood Electric Vehicles: Safety Standards and Zero-Emission Vehicle Rules

TIMOTHY E. LIPMAN, KENNETH S. KURANI, AND DANIEL SPERLING

The California Air Resources Board mandated the production of zero-emission vehicles (ZEVs) starting in 1998. Other states may follow. Among the types of vehicles that may satisfy the requirements of this mandate are small, neighborhood electric vehicles (NEVs) that would be used in urban areas and on collector and arterial streets for a wide range of short trips. Although NEVs hold the potential for large energy and environmental benefits, their introduction is hindered by two institutional barriers. The first of these is the federal safety standards designed for full-sized, gasoline-powered automobiles. The second is the California ZEV regulations that may not award ZEV credits to manufacturers for all vehicles certified as ZEVs, particularly very small NEVs. Also there are important inconsistencies in the vehicle definitions used in these and other regulations and vehicle codes. This has created confusion with regard to their applicability to various small vehicle designs. The history of legislative rule making as it relates to small vehicles is explored, and possible strategies for overcoming these regulatory barriers to the production and sale of NEVs are discussed.

Persistent nonattainment of ambient air quality standards in many U.S. cities and the continued almost 100 percent reliance of the transportation sector on petroleum have prompted new federal, state, and local initiatives to introduce alternative transportation fuels. One of the most far reaching of these requirements for new vehicle technology has been enacted by the California Air Resources Board (CARB). Section 1960.1 of Title 13 of the California Code of Regulations requires that 2 percent of new cars delivered for sale by major automakers in California in 1998 be zero-emission vehicles (ZEVs). These proportions increase to 5 percent in 2001 and 10 percent in 2003. On February 1, 1994, 12 states in the Northeast requested permission from the Environmental Protection Agency (EPA) to adopt similar rules.

Battery-powered electric vehicles (EVs) represent the only available technology that currently meets the ZEV definition. Because of their zero tailpipe emissions and flexibility of energy supply, EVs are promising prospects. But because of the high cost and relatively poor energy storage characteristics of batteries, many market analyses conclude that few consumers would buy EVs (*1–3*). Although other studies differ in the conclusion (*4,5*), this uncertainty about the market for full-size battery-powered EVs highlights the need to explore other applications and designs for EVs.

One new type of vehicle that could help meet environmental and energy goals is the neighborhood electric vehicle (NEV) (see paper by Sperling, this Record). These efficient, clean vehicles could play a valuable role in reducing air pollution, energy consumption, dependence on foreign oil supplies, and greenhouse gas emissions. They would be used primarily in urban areas and would not, in general, be intended or designed for freeway travel. Their operating environment would be urban and suburban arterials, collector streets, and alleys.

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Many of the policy issues confronting the introduction of NEVs can be grouped into the following broad categories:

- Modification of regulations and standards to eliminate institutional barriers to the sale and operation of NEVs,
- Development of incentives to stimulate manufacturers to produce NEVs and for consumers to purchase them, and
- Coordination between local, state, and federal agencies to develop the infrastructure and traffic control measures where necessary to provide an appropriate operating environment for NEVs.

This paper addresses two underlying institutional barriers in the first category: NHTSA federal motor vehicle safety standards (FMVSSs) and language in existing air quality and energy legislation (such as the definitions of ZEV promulgated by CARB), which may not formally recognize these vehicles as "passenger cars." This paper examines the recent history of rule making by NHTSA as it relates to small vehicles. The existing procedures under which vehicles that do not conform to the panoply of FMVSSs are sent to market and the potential for obtaining exemptions for or amending problematic standards are described. The paper then discusses the potential for the creation of a new vehicle category and proposes a vehicle definition scheme that would accommodate the specialized needs of NEVs. Finally the paper explores discrepancies in vehicle definitions in various codes and regulations, including the ZEV mandate, as they affect the regulatory treatment of NEVs.

## COMPLIANCE WITH FMVSSs

The National Traffic and Motor Vehicle Safety Act of 1966 empowered the U.S. Department of Transportation to set national safety standards for motor vehicles under the authority of the National Highway Safety Bureau, which later became NHTSA (*6*). NHTSA's primary mandate is to set safety standards that define the minimum level of safety performance for motor vehicles (*7*). The standards promulgated by NHTSA generally fall into three categories: crash avoidance (series 100), crashworthiness (series 200), and postcrash (series 300). Automakers are responsible for "self-certifying" their vehicles. A second section of the FMVSSs in 49 CFR addresses the administrative considerations that are

relevant to EVs, and this includes NHTSA enforcement (Part 554) and temporary exemption (Part 555) (*8*).

The FMVSSs were originally written for internal combustion engine vehicles, but the recent resurgence in interest in EVs, coupled with government regulations encouraging or mandating their use, has led NHTSA to reinvestigate the potential need for new or modified standards. The willingness of NHTSA to explore the development of specific standards for EVs suggests that there may also be potential for modifications in the rules that would allow NEVs to operate in specific environments. An examination of the recent history of NHTSA rule making with regard to both three-wheeled and lightweight vehicles sheds light on the potential to create new rules that would allow the production and use of NEVs.

### Safety Standards and Vehicle Classifications

To demonstrate the interplay between rule making and vehicle design and to introduce the history of rule making regarding small vehicles, consider the case of three-wheel vehicles. Under the current federal vehicle classification system, a small, three-wheel EV would be a "motorcycle," but a small four-wheel EV would be considered a "passenger car." As a result three-wheel designs would be subject only to the minimal safety standards that apply to motorcycles, whereas four-wheel designs would face the much more stringent standards applied to full size passenger cars. The long history behind these rules, particularly with regard to the motorcycle definition, provides some insight into the future potential of small EV classification strategies.

On May 16, 1973, NHTSA published a notice of proposed rule making that examined the vehicle classification system with regard to the apparent inequity in the treatment of lightweight vehicles with similar purposes but with a different number of wheels. In that proposal, which sought to revise the motorcycle definition, NHTSA said "Whatever the requirements for lightweight vehicles may be in the future, there is no evidence . . . at this time that a dividing line based on whether they have three or four wheels is rational" (*9*). NHTSA went on to propose a motorcycle definition that would exclude enclosed, three-wheel vehicles (*9*). The proposal was subsequently deemed ambiguous and revised several times, but the long history of proposals, comments, and revisions ultimately resulted in no change to the motorcycle definition. The clear inequity in the treatment of vehicles with three and four wheels was never resolved, despite NHTSA's original concern that:

> . . . the present [May 16, 1973] definitional dividing line between three and four wheels would create a major incentive for manufacturers of small vehicles, *such as those that may be developed in the future for urban transportation*, to choose a three-wheeled design and thereby escape the necessity to conform to many safety standards. (emphasis added) (*9*)

One dilemma posed by this classification system with regard to the three-wheel EV is the trade-off faced by both potential manufacturers and consumers between the cost of compliance with safety regulations (and thus vehicle price) and consumers' own desire for convenient and safe, but inexpensive vehicles. A small three-wheel vehicle that qualifies as a motorcycle offers the lowest cost of compliance because of the relatively few standards that would need to be met. But the fact that these vehicles, like motorcycles, may be viewed as unsafe, coupled with the inconvenience to consumers of being required to abide by helmet laws, would likely result in a reduced potential market share, despite the relatively low cost of the vehicle. A four-wheel design, classified as a passenger car, would have to meet much more rigorous standards, resulting in much higher costs (*10*).

One solution to the problem of NHTSA compliance for NEVs is to define a new vehicle category that defines standards that small, lightweight vehicles must meet. In fact in 1967 the NHTSA safety regulations included a general exemption from motor vehicle safety standards for four-wheel vehicles that weighed under 455 kg (1,000 lbs). The exemption was justified on the premise that it would be impossible for such "lightweight vehicles" to meet the standards imposed on full-size cars. The wisdom of this decision was quickly challenged by the Center for Auto Safety, which argued that the exemption should be revoked.

> . . . the energy exchange in a collision between two vehicles will result in more disastrous consequences for the lighter of the vehicles. . . . Further delay in (lightweight) vehicle compliance may create an unreasonable and intolerable risk of harm to the motoring public. (*11*)

On August 16, 1972, NHTSA issued a notice of proposed rule making to remove the general exemption, citing the growing interest in lightweight vehicles and declaring that the potential safety hazard was an issue that needed to be addressed. At that time NHTSA conceded that lightweight vehicles might not meet all the safety standards, but emphasized that exemptions from specific standards that could not be met might be possible. Standards pertaining to structural strength and crush distance were determined to be potentially problematic for small vehicles, but those pertaining to lighting, braking, and glazing would easily be met. Because of the different standards that might and might not be met and because such standard specific exemptions already applied to heavy vehicles, NHTSA concluded

> It thus appears in the public interest to consider the needs and problems of lightweight vehicles on a standard-by-standard basis *as is presently done in the case of heavy vehicles*, which receive differential treatment in several standards, rather than by an across the board exemption. (emphasis added) (*12*)

Thus, on May 16, 1973, NHTSA removed the general exemption for lightweight vehicles, but once again emphasized that potential manufacturers could petition for an amendment to any impractical standard or could petition for a temporary exemption on one of several potential bases (*13*). This policy toward lightweight vehicles remained unchallenged until 1979, when NHTSA received a petition for the creation of a lightweight vehicle category. NHTSA refused the petition in 1981, stating "As a general matter, cars of all sizes should comply with the same safety standards" (*14*). NHTSA argued that the lightweight vehicle exemption was unnecessary because it had found no evidence that the cost of meeting safety standards was preventing the manufacture of lightweight vehicles. Furthermore it argued that the technology was available to build "relatively" light passenger cars that could achieve a high degree of fuel economy while also complying with the standards. Finally NHTSA pointed out that although lightweight vehicles were in use in Europe and Japan, the vehicle mix in those countries was different from that in the United States and that the greater average vehicle weight in the United States would

result in a greater risk of severe injuries for occupants of lightweight vehicles if these vehicles were not able to meet the full range of safety standards. Thus the petition was denied and prospective manufacturers of lightweight vehicles were encouraged to develop designs that would comply with the standards to ensure the safety of the vehicle users (*14*).

This rule-making history suggests that in the short term it would be difficult to reinstate a general exemption for lightweight vehicles. A more feasible initial alternative would be to identify those safety standards that cannot be met for a given type of vehicle and to pursue exemptions or amendments for those standards to allow those vehicles to be licensed and operated on public roads.

### Temporary Exemption from FMVSSs

The design, certification, and testing of vehicle models can be an expensive process. For example the cost in 1989 and 1990 for Conceptor/EPRI to test the compliance of the electric G-Van with seven FMVSSs approached $1,000,000 (*8*). Clearly the costs of compliance with all the FMVSSs, as would be required for a new vehicle design, could easily reach millions of dollars, because the procedure would need to include the cost of the test facility, multiple vehicles, damage to test equipment, and redesigning and retesting of prototypes. Sensitive to the needs of small companies, NHTSA allows manufacturers of lightweight vehicles to seek temporary exemptions from one or more of the FMVSSs (*8*). Under 49 CFR Part 555, an exemption from one or more standards may be granted for up to 2,500 vehicles per year on one of the following bases: facilitation of the development of new low-emission vehicles, substantial economic hardship, or the existence of an equivalent overall level of safety.

The exemption procedure is available to any manufacturer selling fewer than 10,000 units per year and might prove very useful to a company interested in marketing NEVs. For a small company with low (or no) annual sales, the exemption procedure may be the only way to put vehicles on the market, at least in the short term. In fact as of 1994 existing converters and manufacturers of "full-size" EVs were selling their vehicles under one or more of these exemptions. The exemption period could be used to facilitate demonstration projects and assessments of vehicle safety, potential markets, requirements for new infrastructure, and the operational feasibility of NEVs. If the trial period indicates that NEVs would significantly and positively advance air quality, energy, and mobility goals, manufacturers and regulators may wish to pursue the more challenging option of creating a new vehicle classification. Such a classification would remove manufacturers' uncertainty regarding design and operational characteristics, provide consumers with an appropriate standard of safety, and clarify for regulators the role of such vehicles in improving air quality and advancing energy policy.

NEVs would likely qualify for the exemption as "low-emission motor vehicles." The primary challenge in obtaining such an exemption would be in convincing NHTSA that the failure of a vehicle to meet one or more standards would not constitute an unreasonable degradation in its safety. To the extent that this would require detailed crash test reports demonstrating the safety of the vehicle, the cost of this process might become a hindrance to the small manufacturers included in the regulation.

In the short term NEVs that are not able to meet all of the FMVSSs could be allowed to operate under temporary, low-emission vehicle exemptions from specific safety standards. The high cost of meeting the provisions of the FMVSSs is a strong argument for the temporary exemption procedure, but the ease of obtaining an exemption would likely depend on the type and number of standards that the vehicle does not meet and the perceived safety risk of allowing the vehicles to be licensed without conforming to the standards. In the longer term the number of exempted vehicles that could operate in this manner is very limited. If NEVs are to be one part of an integrated solution to the problem of improving air quality and energy efficiency, a new vehicle category must be defined along with modified or new standards that apply to the safety concepts employed in small vehicles.

### Permanent Amendment to FMVSSs

It is possible that a permanent amendment to one or more of the FMVSSs could be granted for NEVs on a standard-by-standard basis. Historically this has been attempted only for vehicles such as the motor-driven cycle and not for passenger vehicles. The process by which standards are added or amended is very time-consuming, particularly for those standards concerned with crash protection (T. Vinson, Office of Strategic Planning and Evaluation, NHTSA, unpublished information, March 15, 1993). A petition to alter a standard may be discussed and revised for 2 or 3 years before being accepted. Because of a lack of precedents, it is unclear exactly what argument would be necessary to convince NHTSA of the need for a standard to be amended, but this option is potentially less difficult than the creation of a completely new vehicle category and should be considered, particularly if only a few of the standards prove to be problematic.

Although the degree of difficulty in meeting these standards will differ by vehicle design, several standards were identified by NHTSA in 1978 as being potentially problematic for electric vehicles in general (*15*). Some other standards were not noted by NHTSA but have since been identified as presenting possible difficulties for small vehicles (*16*). A total of 15 standards have been identified to date, primarily in the level 200 (crashworthiness) category, which suggests that attempting to obtain separate amendments to each standard would be difficult and time consuming.

A careful examination of these standards suggests that gaining NHTSA approval for the operation of NEVs may be one of the greatest challenges facing those who wish to introduce these vehicles into the U.S. market. In its 1978 study NHTSA concluded that the CitiCar, a small EV that weighed less than 591 kg (1,300 lbs), would "no doubt have difficulty meeting existing safety standards (*15*). Given the number of standards with which compliance of NEVs is likely to be problematic or that are simply not applicable to the characteristics of the vehicles, potential manufacturers currently have few options: apply for temporary exemptions or attempt to operate under loopholes in the law, such as those that exist for three-wheel vehicles. Examples of vehicles that use each approach include two Danish designs: the Kewet El-Jet, a four-wheel vehicle that is operating under a temporary exemption, and the City-Com City-El, a three-wheel design that is classified as a motorcycle.

### Creating a New Vehicle Category

A final alternative is to develop a new category of vehicle with an accompanying set of fully relevant standards. At the time of

the 1978 NHTSA study the CitiCar was determined to be so dissimilar from conventional vehicles that the agency considered developing rules for "a special class of vehicles with restrictions on weight, operational performance, passenger capacity, and use" (*8*). This option was subsequently deemed infeasible, but perhaps it will be reexplored if a sizable market for small vehicles develops.

There are two primary justifications for the creation of a new lightweight vehicle category with an accompanying set of crashworthiness standards. The first of these is that safety concepts designed to minimize the hazards of vehicle collisions (i.e., composite materials, air bags, and rigid passenger compartments) have improved much in the past 20 years, making it potentially easier for lightweight vehicles to provide a level of safety comparable to that provided by heavier passenger vehicles. The current FMVSSs in some cases are highly prescriptive, specifying the means by which standards are to be met (i.e., crush zone distance, etc.), and this approach excludes other safety concepts that may be more appropriate for small vehicles. The second justification for a new category is that NEVs are the only small vehicles that will require substantially different standards. Not only will they operate in low-speed environments that will not be as hazardous as those of freeway-capable vehicles but their safety can be enhanced through specialized traffic control measures and infrastructure design concepts. These measures can be employed to restrict the commingling of NEVs with heavier, faster vehicles when necessary (see paper by Stein et al., this Record). In a larger sense safety must be considered in context. In the case of NEVs the context is slow-moving traffic, a restricted operating environment, and tailored traffic controls.

The development of a new vehicle category will require that consensus be reached among manufacturers and regulators as to the description of this new class of vehicle. This may be somewhat difficult, but in the long term it seems unavoidable given that the characteristics of NEVs essentially preclude them from complying (at a reasonable cost) with all of the safety standards currently imposed on passenger vehicles. The following new definitions are suggested as a starting point for discussion:

*Minivehicle* (MV): a motor vehicle having three or more wheels in contact with the ground, a fully enclosed passenger compartment, a vehicle curb weight of less than 910 kg (2,000 lbs), and a top operating speed of over 65 km/hr (40 mph) and that is designed and used for the transportation of people.

*Mini-electric vehicle* (MEV): a minivehicle that is powered by electrical energy.

*Neighborhood electric vehicle* (NEV): a motor vehicle having three or more wheels in contact with the ground, a fully enclosed passenger compartment, a vehicle curb weight of less than 910 kg (2,000 lbs), and a top operating speed of 65 km/hr (40 mph) or less and that is powered by electrical energy.

This scheme can be represented as shown in Figure 1.

This classification system is useful because it accomplishes three important tasks. First, it makes the basic distinction between small vehicles, with a vehicle curb weight of under 910 kg (2,000 lbs), and larger vehicles. This distinction is necessary because the current set of FMVSSs has been designed for full-size vehicles, and all small vehicles, regardless of their propulsion system, may benefit from standards specifically designed for them. Second, a useful distinction is made between the vehicles that employ electric propulsion (i.e., NEV, MEV, and EV) and those that do not. This is the most basic division needed for the purpose of applying different propulsion-related standards to various vehicle types and for accommodating current and future incentive policies that lower the price and increase the convenience of EVs to encourage their socially desirable emission and energy use characteristics. Other refinements can be added to this basic framework for full size and small hybrid vehicles and for other alternate-fuel vehicles. Third, this classification scheme distinguishes between MEVs, which will likely be freeway capable and should meet the intent of the FMVSSs (although possibly employing new safety concepts), and the slower and generally smaller NEVs, which are not freeway capable and thus have clearly distinct requirements for safety standards.

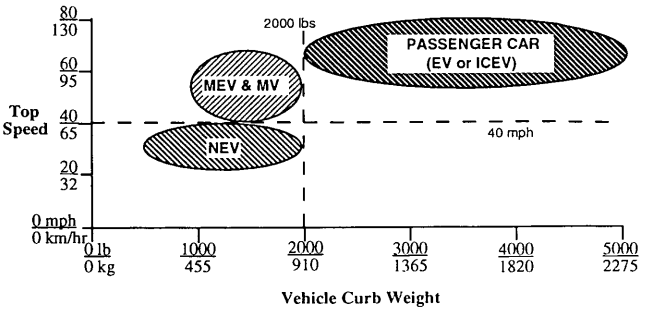


**FIGURE 1 Proposed vehicle classification scheme.**

Thus a new classification scheme would provide a simple framework that could be used for the dual purposes of developing incentive policies for the use of clean, efficient vehicles and of developing safety standards that address the specific needs of different vehicle types and sizes. It is important to note that the majority of the standards will be met without difficulty by small vehicles, but in the long term standards that are based on vehicle speed and size will need to be modified, particularly for NEVs, for these vehicles to be brought to market at a reasonable cost.

## INCONSISTENT REGULATIONS AND ZEV MANDATE

The primary motivation for manufacturers to introduce EVs in California is the ZEV mandate promulgated by CARB in Section 1960.1 of Title 13 of the California Code of Regulations. But the applicability of that mandate to NEVs is unclear because of the inconsistent and vague vehicle definitions in regulations and codes. The ZEV mandate applies only to passenger cars and light-duty trucks. Although the definition of a "passenger car" used by CARB is "any motor vehicle designed primarily for transportation of persons and having a design capacity of 12 persons or less," at this time some vehicles, particularly NEVs with three wheels, that would be certified as ZEVs (for purposes of tax credits and other incentives) would not be awarded ZEV credits (California Code of Regulations, Title 13, Section 1900). Manufacturers of four-wheel NEVs apparently would receive ZEV credits, but CARB has yet to make an official determination on the inclusion of various types of NEVs in the credit scheme. The fate of NEVs with regard to this critical mandate is therefore unclear.

In addition to the uncertainties surrounding the CARB ZEV regulations, NEVs face the problem of a lack of consistency among the vehicle definitions used by various regulations and vehicle codes. The EPA Clean Air Act Amendments (CAAA), the Corporate Average Fuel Economy (CAFE) standards, the federal Uniform Vehicle Code (UVC), and the California Vehicle Code (CVC) all use different motor vehicle definitions, adding greatly to the confusion surrounding policy and regulatory issues related to NEVs. To choose a particularly bewildering example, a three-wheel EV capable of 50-mph travel (an early prototype made by the Horlacher company would meet these criteria) would be considered a "passenger vehicle" by CVC, a "motorcycle" by UVC, a "passenger car" by CARB, a "light-duty vehicle" under CAAA, and possibly a "passenger automobile" and possibly not (depending on a determination by the Secretary of Transportation) for purposes of inclusion under the CAFE standards.

The definitions used in promulgating the CAFE standards and the regulations of CAAA are confusing in that the terms *passenger car*, *passenger automobile*, and *light-duty vehicle* are all used to mean essentially the same thing, but subtle differences do exist. A *passenger automobile* is defined, for the purposes of CAFE standards, as a vehicle designed to carry "no more than 10 individuals," and a *light-duty vehicle* is defined, for the purposes of CAAA, as being "capable of seating 12 passengers or less." Thus a vehicle seating 11 passengers is a "light-duty vehicle" but not a "passenger automobile" (40 CFR §600.002-85 and 40 CFR §86.082-2). Of greater relevance to the NEV is the language of the CAFE regulation defining an *automobile* as a "four-wheel vehicle." The exclusion of vehicles with fewer than four wheels would hold barring a determination by the Secretary of Transportation that such vehicles would be "substantially used for the same purposes" (40 CFR §600.002-85).

A first and obvious recommendation would be to combine the terms *passenger car*, *passenger automobile*, and *passenger vehicle* and give the resulting term a clear and consistent definition throughout the various codes and regulations. The authors suggest using the term *passenger car*, as used in UVC, because it is the most widely used and thus the easiest to standardize and also because it has a simple definition that clearly excludes motorcycles and could easily be modified to exclude other vehicle categories. Another recommendation would be to define the terms *light-duty vehicle*, *medium-duty vehicle*, and *heavy-duty vehicle* primarily in terms of the weight of the vehicle and to restrict the usage of these terms to situations in which the weight of the vehicle is important. In cases in which weight is not an issue, more general terminology should be used (i.e., *passenger car*, *neighborhood electric vehicle*, etc.).

In summary simplifying and reconciling the terms used to define vehicles would remove a considerable amount of confusion that currently exists. A consistent and precise definition scheme would allow manufacturers to know with certainty how various vehicle designs would be affected by laws and regulations and would aid them in their strategic planning in bringing their vehicles to market and in meeting the ZEV mandate. Given the potential importance of the mandate in California and elsewhere in promoting the sale of EVs, the success of the NEV concept may depend on it being included in the provisions of the rule. Such inclusion would likely have to be supported by analyses of how much pollution and gasoline vehicle use is reduced as a result of each NEV purchase. If analysis shows that NEVs are used much less than gasoline-powered vehicles (and full-sized EVs), fractional ZEV credits could be awarded.

## CONCLUSIONS

The introduction of small, limited-performance NEVs to consumers and cities confronts a rule-making system tied to full-size, gasoline-powered cars. Standards and rules need to be made more flexible to accommodate differences. A first step is to define appropriate classifications, definitions, and standards for NEVs and other small vehicles. Specifically the development of NHTSA safety regulations that are appropriate for small vehicles operating in restricted environments and the inclusion of all NEV designs in the credit scheme of the ZEV mandate are critically important for the success of the NEV concept. The second issue, qualification for ZEV credits, is of especially great importance because it creates a potential market for NEVs.

A research agenda designed to address the issues raised in this paper must include safety, emissions, and vehicle use studies. Development and testing of new safety concepts, new materials, and the interaction between vehicles in low-speed operating environments will clarify how safety standards can be modified to allow for the safe operation of NEVs. The potential for these vehicles to substitute for short, low-speed, urban trips suggests that their emissions reductions may be far greater than indicated by the number of trips or number of miles they travel. Thus the ability of NEVs to complement, rather than replace, gasoline-powered vehicles within a household stock of vehicles must be assessed.

With the cooperation of vehicle manufacturers and federal and state agencies, procedures and policies that will allow NEVs to meet the requirements of ZEV regulations in California and other states and to provide safe transportation can be implemented. If this is done the viability of the ZEV mandate will be strengthened and a new mode of safe, efficient, and environmentally benign transportation will become available.

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# Prospects for Neighborhood Electric Vehicles

DANIEL SPERLING

Neighborhood electric vehicles (NEVs) are a promising strategy for easing the growing tension between demands for greater automotive travel and calls for improved environmental quality. By reducing performance and driving range expectations, NEVs overcome the battery problem of larger electric vehicles while still serving the mobility demands of many travelers. The introduction of NEVs is likely to be slowed by a web of road and vehicle rules designed with the standard vehicle of the past in mind and by uniform vehicle size expectations on the part of consumers, government regulators, and highway suppliers. The energy and environmental benefits are potentially so large, however, and the opportunity to create more human-scale communities so promising that it would be irresponsible not to pursue NEVs in a more deliberate fashion.

As cars proliferated during the twentieth century people came to rely on them more, creating a spiraling dependency. Why go to the small local grocery and hardware stores when giant department and warehouse stores are only another 20 min away by car? As dependence on cars increased, cars began to dominate streets. Streets were made wider and sidewalks narrower or nonexistent. Now most people in suburban neighborhoods often do not consider walking, bicycling, or even riding public transit. Automobility has spiraled upward, creating, in an iterative fashion, an increasingly car-centric infrastructure and social behavior.

Some excesses of automobile dependence can be avoided, but at least for the United States and other affluent countries, private transportation is here to stay into the foreseeable future (*1*). The growing tension between demand for greater automobility and demand for better environmental quality can be eased, however, with more environmentally benign vehicles.

One strategy is to use very small electric vehicles (EVs), for now referred to as *neighborhood electric vehicles* (NEVs). Not only will they reduce environmental degradation but they also could be a catalyst in creating more environmentally benign, human-scale communities.

## THE CHALLENGE

Motor vehicles of today are capable of carrying four or more people, accelerating quickly to 100 km/hr (62 mph) and cruising comfortably at 120 km/hr. These attributes are desirable for some trips. As long as all vehicles are expected to serve all trips large powerful vehicles will be preferred. But this all-around capability comes at a cost not only in terms of the direct costs of vehicles, fuels, and road space but also external environmental costs and the indirect costs of maintaining a car-centric transportation system. Moreover for most trips and households, large, full-powered vehicles are not necessary. Almost 40 percent of households own two vehicles, and an additional 20 percent own three or more vehicles (for a total of 54 million households with two or more vehicles) (*2*). About half of all trips are less than 5 mi and are made by a single person traveling at relatively low speed (*3*).

The problem is a uniformity of expectations by consumers, government regulators, and highway suppliers. All vehicles are expected to satisfy all purposes, all roads are built to serve all vehicles, and all rules are designed for the standard vehicle of the past. The result is an inertia that discourages innovation and change by vehicle users and suppliers.

The time is ripe for change. Continued attachment to large cars is a dam holding back a sea of policy demands. This continued attachment frustrates efforts to reduce energy consumption (via more stringent Corporate Average Fuel Economy standards), adopt battery-powered zero-emission vehicles, and create more human-scale neighborhoods.

Small cars are one outlet for relieving these pressures. They provide the opportunity not only to greatly reduce energy and environmental impacts but also to catalyze the creation of more human-scale neighborhoods. Neighborhood cars are a compelling concept that deserves to be tested and nurtured. The potential drawbacks—principally safety of occupants—are few and can be mitigated, whereas the potential social, economic, and environmental benefits are positive. Realizing those benefits requires overcoming the hegemony of large vehicles, which is not an easy task.

The key to introducing small cars is dispensing with the one-size-fits-all mentality that pervades the transportation system (*4*). Changes must be made in rigid safety regulations that discourage innovation, automaker hostility to small cars, standardized infrastructure designs that discriminate against small vehicles, and traffic control rules that serve only large vehicles.

The one-size-fits-all philosophy of the automobile industry is, even apart from this new class of neighborhood and commuter cars, becoming increasingly anachronistic. The principal force for change is increasing affluence and car ownership. With the growing abundance of vehicles, no longer must each vehicle serve every purpose. Vehicles can be designed to respond to more specialized desires of consumers—as is already happening. Recent examples of this shift toward more specialized vehicles, albeit in a more modest fashion than proposed here, are small and large vans, two-seat sports cars, minivans, and sport utility (luxury four-wheel-drive) vehicles.

A new group of small vehicles that follow in this tradition can be envisioned: small specialized vehicles, smaller than a subcompact car and pickup truck, including narrow commuter cars that use less road and parking space and consume less energy; small shared "station" cars that are used for accessing transit stops and

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stations; small trucks used on large campuses, in office parks, on military bases, and in dense downtowns; and neighborhood cars used strictly for local travel. These niche applications could eventually constitute a large number of vehicles.

The focus of this paper is NEVs. Although this is only one of the market niches suggested and might take longer to evolve than some of the others, the long-term market potential and possible social benefits of NEVs dwarf those of other mini-EV market niches. Moreover most of the barriers facing the other small electric vehicles are common to NEVs.

## DEFINING NEVs

NEVs are defined to include those vehicles that are not capable of traveling on freeways. They would tend to be small and light, but their distinguishing feature is a top speed of about 70 km/hr or less. They are unique in requiring specialized road infrastructure and in contributing to local land use goals. The other small electric vehicles identified above, such as narrow or small commuter cars with limited range and that occupy limited space, might have features in common with NEVs but are less likely to influence land use changes.

One NEV variation mentioned above is the shared-use "station car." These vehicles are intended primarily for driving to and from transit stations. They are inspired by a desire of transit operators in large cities for riders to use less parking space at stations and stimulate patronage, and secondarily to reduce the travel costs of potential patrons. Costs are reduced by using smaller and therefore inherently cheaper vehicles and shared ownership. By sharing ownership a single vehicle might be used by several commuters each day. The vehicle might be dropped off at a station by a person arriving from a residence, picked up by an arriving transit rider traveling in the countercommute direction, returned by that same person to the station later, and perhaps used by still another transit user arriving at that station in the evening and needing a ride home. The station cars could also be used during the day for personal errands or as a fleet vehicle for business trips. This concept of station cars has been experimented with in Europe and Japan with bicycles and small cars, with limited success. A station car association was formed in the United States in 1993 by several pairs of transit operators and electric utilities, principally those in the San Francisco and Chicago areas.

A general defining characteristic of NEVs is their specialization for local travel. They will have low top speeds and low power needs. Most NEVs will be very small, accommodating one or two people plus storage space, but some may be larger to accommodate families with several children. NEVs range from top-end NEVs that are intended for travel on arterial streets at speeds of up to 70 km/hr to bottom-end NEVs with top speeds of about 30 km/hr. Bottom-end NEVs would have separate rights-of-way, mixing with other motor vehicles only in specialized circumstances, such as streets with stringent speed and vehicle size restrictions. The range of NEVs need not exceed 50 km or so, because they are driven only on short trips and can be readily recharged each night.

Even bottom-end NEVs would be significant upgrades from golf carts. Consider, for instance, a prototype vehicle made by Trans 2. Although it resembles a golf cart in top speed and carrying capacity, it has superior performance, safety, and comfort. Its lower center of gravity and frontwheel drive provide improved stability, cornering, and maneuverability; carlike suspension provides better responsiveness; the vehicles are outfitted with windshield wipers, horn, side-view mirrors, and three-point seat belts anchored to the frame; and the vehicle has a higher and more visible profile, a full array of gauges, and lockable storage areas. It has a range of 40 km, four wheels, and two seats. It is intended to be used on low-speed residential streets, separate lanes, or roads dedicated to low-speed vehicles, perhaps including bicycles. It was designed by a small company in Michigan that is currently negotiating with larger companies to assist in marketing and manufacturing. Targeted at mobility-impaired individuals, retirement communities, resorts, and new towns designed to accommodate such vehicles, it is designed to sell for about $5,000.

One step up is the City-El made in Denmark. It has a top speed of 55 km/hr, a range of about 50 km, three wheels, and one seat plus storage space. Several thousand were sold in the 1980s and early 1990s in Europe. The selling price, including batteries, in 1993 was about $7,000. The Sacramento Municipal Utility District imported over 100 of these vehicles in 1993 and 1994; they are leased and lent to individuals in the area.

The Kewet, another small EV produced in Denmark, was first sold in the United States in 1993. It has a top speed of 65 km/hr, four wheels, a range of 50 km, two seats, and four wheels and costs $12,800 (in 1994). The Kewet and City-El are essentially hand-built by using primitive technology. If the vehicles were mass-produced in a modern factory the cost would be reduced dramatically.

Neighborhood vehicles need not be electric. They could burn gasoline or other fossil fuel in an internal combustion engine, perhaps hybridized with batteries, and be competitive or even superior—on a private cost basis—to pure battery-powered neighborhood vehicles. But the zero-emission vehicle (ZEV) mandate (if fully implemented) overturns such a finding. Battery power will likely dominate because, as indicated below, automakers need to sell ZEVs, and NEVs may prove to be the easiest and least costly way to do so. Moreover as NEV technology is improved, neighborhood electric cars will likely be seen as superior to neighborhood gasoline-powered cars in terms of convenience and reliability, if not cost.

## CASE FOR NEVs

As indicated above the time is ripe for NEVs. Several trends and forces are converging to enhance the environmental, economic, and social attractiveness of NEVs. The potential benefits are large.

### Environmental Benefits

The environmental and energy benefits of NEVs are the most obvious. NEVs are far more attractive environmentally than either gasoline-powered or even general-purpose electric cars. They consume only a fraction of the energy that conventional-size EVs and gasoline-powered vehicles do and therefore emit only a fraction of the quantity of greenhouse gases and air pollutants. Even if the power plants that supply electricity to NEVs were to rely primarily on coal, NEVs would still contribute little pollution or greenhouse gases.

The environmental and energy benefits are even more impressive, however, because NEVs replace the most polluting and in-

efficient trips of gasoline-powered vehicles: short, slow urban trips. During short trips and the first few minutes of longer trips, gasoline-powered vehicles emit 10 times or more pollutants per kilometer than they do after the catalysts are warmed up. EVs have no catalyst and no cold-hot distinction. Emissions from the last mile are as low as those from the first.

For instance compare a Kewet (750 kg including batteries) with a subcompact gasoline-powered car. Assume that trips average 4 km, speeds vary between 0 and 55 km/hr, about 60 percent of the trips are from a cold start, and electricity for the NEV comes from an average mix of U.S. power plants (which will use 52 percent coal in 2000). In this case, relative to a subcompact gasoline-powered car, the NEV would reduce carbon monoxide emissions by 99 percent, hydrocarbon emissions by 99, and nitrogen oxide emissions by 92 percent (M. W. Wang, personal communication, based on work by Q. Wang et al. *5*). The already low emissions of EVs are reduced further by NEVs.

NEVs also reduce energy use and greenhouse gas emissions sharply. NEVs would use less than half the energy of a typical subcompact EV (on the basis of actual data from the Kewet as well as from simulation models) (M. W. Wang, personal communication, based on work by Q. Wang et al. *5*). This energy reduction is a more than 60 percent reduction in carbon dioxide emissions relative to those of a subcompact gasoline-powered car, even with today's coal-dominated mix of power plants (using the same assumptions as for the emissions estimate). The reductions would be even more dramatic in practice because EVs are relatively more energy efficient than gasoline-powered cars at the slow speeds typical of NEV driving (but relatively less efficient than gasoline-powered cars at high speeds).

NEVs are environmentally superior compared not only with all other personal vehicles but also with mass transit. The energy consumption and emissions of a transit bus or even fixed-rail electric transit system would be considerably higher per passenger kilometer than those of a single-occupant NEV.

In summary because NEVs use so little energy and operate almost exclusively under driving conditions in which electric propulsion is most attractive, the already large benefits of EVs become overwhelmingly positive with a NEV.

## Land Use and Mobility Benefits: NEVs as Catalyst

NEVs also address a variety of social ills associated with increased automobility: lack of mobility by poor, elderly, and physically disabled persons; consumption of large quantities of land; and marginalization of the most environmentally benign forms of travel: walking and bicycling.

Increased mobility for those precluded from driving because of physical disabilities is especially compelling in places where transit service is sparse, as is the case in most of the United States. The ease of driving a NEV makes it accessible to a broader range of individuals, including the expanding elderly population (the population of individuals over the age of 50 in the United States is expected to almost double between 1990 and 2020, from 63.5 million to 112 million). One option for making already easy-to-drive NEVs more accessible to mobility-impaired individuals is to substitute the driver's seat with a place for a wheelchair. Other options are to adapt the already simple driving controls to hand controls and to partially or fully automate the controls.

The use of NEVs, because of their smaller size, would provide another benefit: an opportunity to shrink lane widths and parking space and expand the capacity of existing road space.

The greatest contribution of NEVs, however, may ultimately be as a stand-in for nonmotorized travel. Over time automobiles have come to dominate the thinking and actions of local governments. Governments have focused attention on creating a safe and accommodating environment for cars—building abundant roads and parking spaces and imposing traffic controls to ensure speedy, safe travel. Many neighborhoods do not even have sidewalks. Mathematical travel demand models, used to prioritize new transportation investments, usually ignore bicycles and pedestrians. Pedestrians and bicyclists are usually afterthoughts. The most long-lasting effect of NEVs paradoxically might be to reverse the trend toward less nonmotorized travel.

The appearance of NEVs, even in small numbers, forces a rethinking of rules and investments preoccupied with the automobile. More important the use of NEVs, even in limited circumstances, provokes planners, politicians, zoning boards, and others who write building and street codes to rethink their car-centric rules and plans. NEVs would provide a justification for rewriting building and traffic rules and diverting road and land development investments toward the needs of pedestrians and bicyclists. Gradually bikeways and pedestrian paths might become more widespread and more intensively used. Walking and bicycles are not for everyone, but even a small shift from motorized vehicles would have positive effects on congestion, pollution, and energy use.

Although the details of integrating NEVs into each neighborhood would need to be worked out (as indicated later), the existence of NEVs provides an opportunity for more intimate and integrated neighborhoods, enhanced mobility, and the creation of a more hospitable environment for pedestrians and bicyclists. NEVs could be the key to easing tension between those who applaud the mobility benefits of the automobile and those who blame it for destroying the social fabric of modern communities (*6*).

## ZEV Mandate

Instrumental in aiding the introduction of neighborhood cars will be the ZEV mandate. As major automakers confront the high cost of meeting the ZEV mandate with full-size gasoline-like electric cars, they will undoubtedly become increasingly receptive to new approaches. Recognizing the relatively poor energy storage characteristics of batteries, they will undoubtedly conclude, for the reasons listed, that smaller EVs are economically and environmentally superior and technically more sensible than larger EVs.

NEVs are arguably the most compelling application of battery-powered electric propulsion. NEVs do not suffer from the shortcomings of batteries like larger EVs do simply because they require relatively little energy or power. Their low energy needs are due to their low weight, low top speed, short driving range, and because NEVs do not travel far on any one trip, less demanding interior heating and cooling demands. Innovative energy-efficient techniques such as compressed air- and solar-powered air circulation can readily be used. In addition the low weight of the battery pack allows for a lighter structural design and therefore still greater weight and energy reductions. Although based on simple designs and relatively unsophisticated engineering, the City-El described earlier carries only 110 kg of conventional lead-acid bat-

teries, costing \$250, the Kewet carries 270 kg of batteries, and the Trans 2 carries only 130 kg of batteries. In contrast a typical subcompact EV would need more than 450 kg of lead-acid batteries (the very energy-efficient Impact prototype EV of General Motors carries 410 kg of batteries). Under mass-produced conditions NEVs should be much cheaper to own and operate than a full-size gasoline-powered or electric car.

As major automakers begin to recognize the relative ease of building a cost-competitive NEV they will likely reconsider their historic disinterest in small EVs. The key question will be: Will there be a market for what is easiest and cheapest to build?

## INFRASTRUCTURE CHANGES

Inflexible safety standards and standardized roadway designs discourage efforts to introduce a neighborhood car. All roads are built to serve all vehicles, and all rules are designed for the standard vehicle of the past. Important changes are needed in government policy and practice.

A new paradigm of road design that does not revolve around conventional cars is needed. One might argue that the road system should be designed to serve pedestrians, bicycles, NEVs, conventional cars, and service trucks, in that order. Such a road system might look very different from that in most suburban communities.

Today's municipal engineers and planners rely on design standards and priorities that discourage and even preclude smaller vehicles and ignore pedestrians and bicyclists. They build wide neighborhood streets that are empty most of the time and consume large amounts of space. Professional guidelines call for a minimum street width of 6.7 m (22 ft), even though cars are less than 2 m wide. This design standard effectively disperses the neighborhoods, making car travel even more necessary. If developers prefer to build narrower roads, they must go through an arduous appeals process. This car-centric mentality discourages innovative designs, including the use of narrow roads suited to NEVs.

Some NEVs will be used on roads and in communities designed for such vehicles. Others will be used in established communities. Superimposing NEVs on an established road system is especially challenging, but not impossible. The city of Davis, California, provides a model of how such changes are possible. Through the late 1960s the city of Davis and the University of California campus adjacent to the city had a typical gridlike automobile-based road system. A few individuals started a campaign to promote bicycles. Through trial and error roads and traffic controls were gradually adapted to bicycle use. Some roads were closed to motorized vehicles, others required special permits for motorized vehicles, special bicycle lanes were created on still others, and eventually entirely new bicycle paths were built. There is now an entire network of connected bicycle paths and lanes, with traffic circles and other traffic control devices designed specifically for bicycles. Police traveling on bicycles enforce traffic rules, including stop signs, by issuing tickets.

The same process could be followed with NEVs. Although guidelines can and should be developed to assist local planners and officials, each community will need to grapple with the local circumstances (*7*) (see paper by Stein, this Record). Just as with bicycles in Davis, some roads can be closed to conventional vehicles permanently or for certain hours, narrower and cheaper roads can be built for NEVs (for instance through cul-de-sacs), lanes can be set aside for NEVs on wide roads, and special crossings of major arterials can be created. In communities with transit stations and park-and-ride lots for transit and carpools, special access and parking can be created for NEVs. Preferential parking can be created in shopping areas and at workplaces. Many inexpensive changes in infrastructure can be made to accommodate and even reward NEV use.

## SAFETY, LIABILITY, AND TRAFFIC CONTROL

Safety may be the most controversial aspect of small cars. Safety regulators in the United States are diligent, determined, and effective. Their mission is to increase the survivability of vehicle occupants in an accident. Safety debates are guided by this regulatory mission. But this regulatory approach is narrow; it misses the larger benefits that result from a safer system. Vehicle safety could be enhanced, for instance, by limiting the mixing of large and small vehicles, perhaps by banning trucks from roads designated for NEVs and by limiting the speed limit on NEV-designated roads by using speed bumps and other "calming" devices. Moreover local residents along speed-controlled and vehicle-restricted streets benefit by being liberated to bicycle and walk in relative safety. Unfortunately safety data do not exist for such a transportation system to determine how large and important these safety benefits might be.

The narrowed safety debate will therefore probably focus on the undeniable physical reality that an occupant of a small car is clearly more vulnerable to injury than an occupant of a larger car, all else being equal. But even at this level it is not evident that occupants of very small cars will be at greater risk, because all else need not be equal. The small car could be made safer through better design and use of safety devices inside the cabin. Race car drivers, for instance, survive crashes at 240 km/hr by using ultrastiff shells with internal restraints.

The U.S. government, through NHTSA, has created the most detailed and prescriptive vehicle safety standards in the world. Currently there are no safety regulations or laws specific to EVs of any size or type—although several proposed rules regarding recharging, crash avoidance, and crashworthiness were issued in the early 1990s—and there are none specifically targeted at small vehicles. They currently promulgate standards only for light-duty passenger cars and trucks, motorcycles, and golf carts. (These standards are not necessarily consistent or above reproach; safety standards for minivans, for instance, although they are used disproportionately for families and children, are less stringent than those for cars.)

The golf cart category is for vehicles weighing less than 590 kg, designed to operate at not greater than 25 km/hr, and designed to carry golf equipment and not more than two people. NEVs will not qualify for this lenient category, and thus they must meet the same standards as a full-size vehicle, even though they do not travel on freeways or at high speeds.

There are exceptions. In 1967 a broad exemption from the standards was granted for four-wheel vehicles weighing less than 450 kg on the grounds that it was impossible for such vehicles to meet the general standards; that exemption was subsequently removed in 1973. NHTSA subsequently rebuffed several efforts to reinstate a similar exemption, reflecting its insistence that all vehicles meet the same standards (*8*) (see paper by Lipman et al., this Record).

It is uncertain how difficult it would be to obtain an exemption or create a new category for NEVs.

Manufacturers are left with two options: they may petition for an amendment to any impractical standard and may apply for a temporary exemption. It is difficult to win amendments. Exemptions may be granted on the basis of substantial economic hardship for a manufacturer that produces 2,500 vehicles per year (for manufacturers of less than 10,000 vehicles per year), as an aid in the development of new vehicle safety or low-emission engine features, or for vehicles that provide a level of safety equivalent to that provided by conventional vehicles. A NEV would easily qualify on the low-emission criteria, and possibly on the other two grounds as well. The exemptions are renewable, but it is uncertain how many renewals would be granted.

The safety of NEVs is possibly the most critical issue in determining how and where to introduce NEVs. Unfortunately little evidence is available to make a reasonable determination, largely because the safety record is sensitive to the design of the vehicle and how it is used. Bolder thinking is needed. Safety regulators must consider safety in context: one context is slow and small cars and bikes in specially designed neighborhoods.

## LIABILITY

NEVs are smaller and therefore inherently less safe, all else being equal, than conventional vehicles, but this difference does not automatically imply that a manufacturer or anyone else is more vulnerable to legal action. Indeed legal precedent suggests that NEVs would not create extra liability risk (*9*).

Product liability falls into three categories: strict liability, negligence, and warranty. Negligence or warranty violations are not relevant because NEVs do not present new or unique negligence or warranty issues. Strict liability may be due to manufacturing, design, or warning defects. In determining liability risks for NEVs, one question is pivotal: Does the use of a NEV pose any unreasonable danger to the user?

A NEV clearly poses a danger: if the vehicle hits a truck, the occupants are likely to suffer more injury than if they had been in a 2-metric-ton luxury car. Is it, legally speaking, an unreasonable danger? Probably not. Legal precedent suggests that the danger is unreasonable only if the danger is not clear and obvious to the user of the vehicle. As long as a vehicle appears to be very different from a conventional vehicle, which by definition they will, then the liability risk is low.

This same reasoning protects manufacturers of bicycles and motorcycles from litigation. Clearly motorcycles are dangerous, but by being aware of this danger, the driver implicitly is accepting the risk. The danger is therefore not unreasonable.

An exception would be if a manufacturer could have significantly improved vehicle safety at a small cost—as Ford Motor Company could have done to eliminate the exploding gasoline tanks in its Pinto automobiles. NEV manufacturers might be vulnerable to this argument because there will be considerable experimentation initially in designing an inexpensive NEV. For instance even the apparently simple problem of installing an air bag is not simple; because the size and materials of the NEV might be different from those of a conventional car, the triggering and design of the detonator and bag must be unique to these vehicles. NEV manufacturers are protected somewhat if their designs are determined to be state of the art in manufacturing at the time of production, but this and most other liability determinations are highly subjective. In the opinion of one product liability expert speaking at a workshop on subcars, NEVs pose no greater liability than any other vehicle, as long as an appropriate effort is made to avoid risks (*9*). One exception to this conclusion may be three-wheel vehicles with the single wheel in front; this configuration is widely considered to be more dangerous than the single-wheel-in-back configuration.

The goal from both safety and liability perspectives may be to create designated areas for NEVs, for instance, "drive-slow" zones. A NEV involved in an accident while in such a zone would be assumed not to be at fault—just as is the case with pedestrians in crosswalks.

## TRAFFIC CONTROL RULES AND GOLF CART PRECEDENT

For a vehicle to be operated on a public road in the United States it must be registered with the state's department of motor vehicles and must be in compliance with federal safety standards for passenger vehicles or motorcycles or hold a special exemption. Three-wheel NEVs evade these restrictions because most states will probably allow them to be registered as motorcycles. In some states even four-wheel NEVs may be allowed (see paper by Lipman et al., this Record); Arizona, for instance, allows golf carts to be registered as recreational vehicles and to be licensed as motorcycles. The only regulation facing golf carts in Arizona, in addition to those related to licensing and registration, is that they must not impede the flow of traffic.

The most likely entry by NEVs into the urban community is suggested by recent urban experiences with golf carts. Until recently in California golf carts were only allowed on streets within 2.4 km of a golf course with speed limits of 40 km/hr or less. Under pressure from Palm Desert, California, a small affluent community where golf carts were becoming increasingly popular substitutes for cars, the state's Attorney General loosened the interpretation of state law to allow golf carts to operate on any street with a speed limit of 40 km/hr or less, as long as the vehicle was registered with the Department of Motor Vehicle, had license plates, and was equipped with certain minimal safety features (e.g., headlights and reflectors).

The Attorney General also allowed local authorities to designate certain streets for combined use by both golf carts and conventional vehicles. On those streets the golf cart does not have to be registered with the state or equipped in any particular way, as long as it is not operated after dark.

Accordingly in January 1993 Palm Desert designated many local streets for combined use, with the requirement that the golf carts be electric, registered with the city (but not the state), and be outfitted with headlights, turn signals, mirrors, a horn, and reflectors. Lanes have been painted on the streets to limit commingling with larger vehicles.

Palm Desert's treatment of golf carts illustrates how NEVs could be accommodated in local communities, even without the blessing of federal safety regulators; NEVs that cannot meet safety standards designed for conventional cars could be treated by local and state governments as special cases and accommodated accordingly. The challenge is to do so in a safe manner.

Ultimately federal safety regulators will have to address NEVs. The precedents being established in communities such as Palm

Desert will provide the evidence and motivation to design future rules and regulations that accommodate NEVs and protect the safety of NEV users.

## MARKETING OF NEVs

One important niche for NEVs is resort communities and facilities. These are generally located on mountains, at seashores, and in other environmentally fragile areas where clean and uncongested environments are highly valued. A subset of this market niche is owners of the approximately 3 million second homes in vacation areas of the United States. They could purchase a NEV and leave it at the vacation home for use on visits. Another subset of this market niche is park areas, such as Yosemite, where vehicle exhaust is damaging the natural environment. A plausible strategy is to ban gasoline- and diesel fuel-powered vehicles and replace them with electric buses, electric cars, and NEVs. According to an unpublished industry report, about 110 million people visit the 68 national parks and recreation areas in the United States annually, and many more visit national seashore parks and other federal, state, and local recreation and tourist areas. The potential for daily and hourly rental of small EVs at these sites is large.

A second niche is closed neighborhoods and communities where speeds are controlled and communities are receptive to NEVs. Palm Desert, California, is one such community.

A third market niche is mobility-impaired individuals, estimated to include about 10 million people in the United States. NEVs are easy to drive partly because they operate at slow speeds and are small and easy to maneuver. This ease of driving can be easily enhanced. Controls can be designed for hands only, similar to the thousands of motorized wheelchairs and many retrofitted gasoline-powered vehicles. Another enhancement is the use of partially or fully automated controls. Automated controls are much easier and cheaper to install on NEVs than on full-size vehicles because the speeds are much lower. Many service and delivery vehicles in factories are already fully automated, made possible by their slow speeds (and a relatively controlled environment). Partial controls could be installed on NEVs to aid with steering or braking and to avoid collisions. Automated vehicle control for conventional cars is already a primary focus of research in California and by the Intelligent Vehicle Highway Systems program of the U.S. Department of Transportation as well as many companies. With the expanding population of elderly people, many of whom are mobility impaired, neighborhood cars could become increasingly important as a means of transport.

A fourth market niche is those individuals who drive short distances to urban rail transit stations and bus park-and-ride lots. The vehicle for this niche is sometimes referred to as a *station car.* NEVs are well suited to this application. If the vehicle is owned by the rail operator or a third party and is used by multiple drivers and for other purposes during the day, the cost could be spread over a large number of people, thereby reducing the cost per trip and user.

A fifth market niche is large new developments that can be designed specifically for NEVs. In California alone neighborhood electric cars are being considered as integral elements in four new town developments covering over 40,000 ha. Several developers are considering providing a neighborhood electric car with some or all houses sold in the new towns. The potential market in these new towns is in the hundreds of thousands.

These five market niches could be just the beginning. Initially neighborhood electric cars will not be accepted in most locations because of safety problems in mixing with much larger vehicles and because road and parking infrastructure is not suited to their use. But as neighborhood cars gain acceptance in various niches, local governments and developers are likely to alter road and parking infrastructure to accommodate and even reward users of these vehicles. At the same time lobbying groups will emerge to push for changes in liability and traffic control rules that hinder the market penetration of NEVs.

Unfortunately credible quantitative estimates of market penetration have not and cannot be made at this time. Research into the potential market for NEVs is fragmentary and speculative. It appears, however, that the long-term market for NEVs could be millions per year in the United States. Even in the short term, with little change in consumer expectations and various government rules, the market might be sizable. According to unpublished industry marketing studies, about 140,000 golf carts and small electric industrial vehicles are sold annually in the United States; one such study estimates that about 20,000 golf carts are used in part for personal transportation. Market penetration will depend on a large number of factors related to ZEV and safety rule making, local initiatives to accommodate NEVs, liability rulings, rulings regarding traffic control, and the entrepreneurial initiative of manufacturers.

## CONCLUSIONS

NEVs are not a panacea for near-term problems, but they are energy efficient, emit low levels of pollutants, and are scaled for neighborhood use. NEVs would use less space than conventional vehicles, provide the premise for lowering vehicle speeds in neighborhoods, and help create a more pedestrian-friendly setting while still providing high levels of mobility. They also would be economical, in part because they are an ideal application of battery-powered electric propulsion. Indeed it is a fortunate coincidence that the market applications in which electric vehicles are best suited—short trips—are also the applications in which EVs provide the largest environmental benefits. NEVs clearly are an attractive option. They fit well into any vision of a sustainable transportation-energy future.

However, will this good idea ever be realized? NEVs confront large perceptual, physical, and regulatory barriers. There is a uniformity of expectations by consumers, government regulators, and highway suppliers that results in all vehicles being expected to satisfy all purposes, all roads serving all vehicles, and all rules being designed for the standard vehicle of the past. The result is an inertia that discourages innovation and change by vehicle suppliers and users. The success of NEVs will depend on an openness by regulators and highway suppliers to new types of vehicles and entrepreneurial initiative by vehicle manufacturers.

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# Roadway Infrastructure for Neighborhood Electric Vehicles

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The neighborhood electric vehicle (NEV) is a small, electric car designed for low-speed, local trips in neighborhoods and urban areas. The market potential for NEVs depends in part on the availability of a network of safe and accessible roads. The processes involved in developing new infrastructure are explored, and some design concepts are presented. To accommodate NEVs safely on existing roads designed for large vehicles and fast-moving traffic, infrastructure standards and designs will need to be modified; this will occur through a process of experimentation as the market for NEVs grows and planners and engineers discover which designs work and which do not. The results of local experiments will provide the evidence for modifying state and federal rules and guidelines codified in geometric and traffic control policy manuals. Ultimately the provision and management of road infrastructure must become more flexible to accommodate alternatives to the full-size, gasoline-powered automobile.

Pedestrians, bicycles, automobiles, trucks, and buses are part of a larger infrastructure system. At certain times and places these modes compete for scarce resources—notably road space and parking. Other times they complement one another: pedestrians and bicyclists may work together to lobby for new paths that neither could obtain alone, or auto and transit trips may be linked to provide suburban residents with access to downtown employment. And at still other times, a travel mode may operate in a constrained environment or serve a specialized purpose such that it faces little competition from any other mode. Travel modes may share common facilities or may travel on dedicated rights-of-way (ROWs). Motor vehicles have streets and freeways; bicyclists have streets, bike lanes, and paths; and pedestrians have crosswalks, sidewalks, and pedestrian malls.

Of all these modes, motor vehicles—automobiles and trucks—have shaped U.S. cities, in part through the demands for specific infrastructure designed to serve them. Energy-efficient and low-polluting alternatives such as walking, bicycling, and using small vehicles have been marginalized. Many suburban residents have nowhere to walk or cycle. Their shops, restaurants, theaters, schools, and workplaces are inaccessible except by car. Urban residents play a daily game, circling blocks in search of a parking space large enough for their automobile—one more low-speed, stop-and-go, inefficient, and highly polluting trip.

This paper explores infrastructure designs for small, less polluting vehicles suitable for nonfreeway travel. These vehicles are referred to as neighborhood electric vehicles (NEVs); others refer to these small cars, sometimes with slightly different applications in mind, as subcars (*1*), city cars, and station cars. [Note that these small cars could operate on other fuels or engines, but California's zero-emission vehicle mandate puts a premium on electric propulsion (see the papers by Lipman et al. and Sperling, this Record)]. NEVs are designed for short trips on surface streets, to carry small loads, and generally for one or two people, although they might be designed for additional passengers. They are not intended to be freeway capable, allowing for a dramatic reduction in energy and power needs. NEVs would serve those trips that consumers find too long for walking and bicycling but that do not require the use of full-size automobiles.

Existing competitive and complementary relationships among travel modes will be upset and reformulated when a new travel mode is introduced. The purposes of this paper are to identify the types of infrastructure needed to accommodate NEV transportation, to understand the underlying institutional processes involved in designing and implementing improvements, and to present some generalizable NEV-friendly infrastructure concepts.

## DIVERSIFYING TRANSPORTATION INFRASTRUCTURE

High levels of safety and accessibility have been attained by refining vehicle technology and driver capabilities for multipurpose roadways. NEVs are not always well served by this system, but that does not mean that NEVs are inherently less useful and less safe than full-size automobiles. With their own infrastructure and supportive design practices, NEVs can be far safer and more convenient than full-size cars. With their own lanes, paths, and parking, NEV users could attain high levels of safety, convenience, and accessibility. NEV-friendly infrastructures would take account of and exploit the NEV's reduced length and width, lower speed, lighter weight, and reduced noise.

The type and scale of NEV infrastructures would vary across communities, depending in part on which vehicle types prevail. The slower, open chassis "low-end" NEVs [with top speeds of about 35 km/hr (~20 mph)] may be too vulnerable on high-speed, high-volume streets and may require more extensive traffic separation than the quicker, fully enclosed "high-end" NEVs [with top speeds of up to 65 km/hr (~40 mph)]. High-end NEVs may require only limited changes to the existing networks.

Improvement in safety, however, is only one reason for enhancing and diversifying infrastructures. Regardless of safety features or speed capabilities, NEV users may prefer separate lanes and paths because of the enhanced driving experience or easier access to destinations. Demand for NEV-friendly infrastructure may depend on the traffic environment and driver preferences, as well as safety and performance attributes of NEVs.

Separate NEV lanes and paths might be provided where there are high speed limits, high truck volumes, multiple lanes, a history of reckless driving and car accidents, or congested traffic. Where separate NEV lanes and paths are in place, traffic control devices

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will be necessary to inform the public of proper facility use. Lane use signs would be needed to inform NEVs of upcoming lane separation and merging lanes, warning and ROW signs would have to be placed at the intersections of NEV paths and roadways, and route guidance signs similar to street signs and route guidance signs used for orienting motor vehicles on the larger network will be necessary to orient NEV traffic on NEV paths. Preferential parking might be provided in congested downtown areas or at transit stations.

NEV-centric infrastructure could be broadly introduced into new land use developments. New developments can be designed around NEV-centric design concepts. Land use designs can emphasize short trips; ROWs can be created for an internal network of NEV paths. NEVs are suited to pedestrian- and transit-oriented developments and mixed-use neighborhoods where many activities are within easy access of residences. NEVs represent a useful and possibly superior vehicle for residents of such communities. An expanded discussion of neotraditional land uses that may be amenable to NEV transportation can be found elsewhere (*2–4*).

## EVOLUTION OF TRANSPORTATION INFRASTRUCTURE

It will take time for NEV-friendly and NEV-centric infrastructures to evolve. Today's infrastructures did not appear spontaneously in their present forms. Many years were spent expanding and refining the networks and developing standard practices. Traffic lanes were quite narrow until vehicle speed capabilities increased and trucks began sharing the roads. When safety became an issue, streets were widened, speed limits lowered, or restrictions imposed on vehicle commingling. Eventually geometric standards for street widths, curves, and intersection designs were codified in state and federal rules and guidelines. Traffic control devices were created and modified to enhance safety not only for autos and trucks but also for bicycles and pedestrians.

Infrastructure design and management (and codified rules) evolve over time as a result of continuing experimentation. To evaluate which is the safest and most comfortable lane width, engineers experiment with a variety of lane sizes and vehicle speeds. They test driver responses to new traffic control concepts. They experiment with sign sizes, symbols, and locations. NEV-centric designs will evolve through this same process of experimentation, although modern computer simulation techniques are now available to expedite the process.

Infrastructure design does not evolve randomly; it evolves in response to shifting demand and organized interest groups. Throughout the history of civilization engineers have responded to changing transportation technologies, land use strategies, and demands for greater transportation safety and efficiency (*5*). The demand for automobiles and trucks over carts and carriages resulted in a dramatic shift in engineering design. Before the automobile made its debut, bicycle lobbies were a major voice in the design of transportation facilities (*6*). Today although small relative to automobile lobbies, bicycle lobbies still take an active role in engineering design. The construction and modification of road infrastructure to serve NEVs will depend on advocacy by NEV interest groups. These lobbies, like all the others, will include vehicle owners, vehicle manufacturers, and various public interest groups.

In the near term one would expect that NEVs will be purchased in small numbers by people who live in places amenable to their use. As the number of NEV owners grows, towns will begin incremental improvements to local infrastructures. Increased NEV-centric infrastructure will attract more people and vehicle manufacturers to the NEV concept, and as the market grows the NEV lobby will grow as well. Local lobbies will turn into regional and state lobbies, and eventually state and federal policies toward future community planning and roadway improvement projects will be influenced.

Consider the retirement community of Palm Desert, California. For years golf carts were used for recreation in Palm Desert, but they were not permitted on public streets except to travel to and from golf courses. Based in part on a survey of residents' desired golf cart use, Palm Desert and the South Coast Air Quality Management District lobbied the California state legislature to allow the city to conduct a golf cart pilot program. The state set conditions and required the local engineers to implement safety enhancements to the existing city streets. In response Palm Desert developed and implemented improvement strategies and created new design standards (*7*). The city now has golf cart lanes on higher-speed streets, separate ROWs, and new traffic control devices designed specifically for golf carts. In 1994 the city was evaluating the effectiveness of these infrastructures. This pilot program has stimulated interest in NEVs in several California cities including Davis, Sacramento, Berkeley, San Francisco, Santa Cruz, and Los Angeles.

## CODIFYING GUIDELINES

The deployment and modification of roads and traffic controls are overseen by state and federal agencies. To enhance safety FHWA and the National Committee of Uniform Traffic Control Devices specify application, design, and placement standards for traffic control devices. FHWA states that traffic control devices "on all streets and highways in each State shall be in substantial conformance with standards issued or endorsed by the Federal Highway Administrator" (*8*). AASHTO establishes standard practices for geometric design of streets and highways and for bicycle facilities.

Local governments follow these state and federal standards and procedures for three reasons. First, the standards have evolved from years of refinement. If they are followed properly the safety and efficiency of transportation facilities will likely be improved. Second, for any projects that use state or federal financing, local authorities are required to comply with those guidelines; rarely would they be able to forgo those funds. Finally, if localities follow the standards, they may be less vulnerable to lawsuits charging negligence. Courts have recognized the individual's right to collect damages when injuries result from an improperly designed facility. The state and federal standards provide a framework for this notion of "proper" design.

Because the NEV is a new class of vehicle, NEV infrastructure will ultimately require new design guidelines set forth by AASHTO and FHWA. Before NEV-centric designs can be codified and published in policy manuals, they must be widely examined by many organizations and individuals. AASHTO states "During the developmental process, comments [are] sought and considered from all the States, the Federal Highway Administration, and representatives of the American Public Works Associa-

tion, the National Association of County Engineers, the National League of Cities, and other interested parties'' (*9*).

The FHWA approval process for traffic control devices is also extensive. The city of Palm Desert, for example, spent 2 years petitioning FHWA to approve a golf cart symbol. It did finally succeed, but only after being forced to make numerous design revisions in accordance with conformity guidelines in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*8*).

## DESIGN AND IMPLEMENTATION

### Starting Point for New Designs

Although AASHTO and FHWA have not specified any dimensions of NEV lanes and curves or the placement and contents of NEV signs, they do provide design processes. Local planners and engineers can use these existing processes contained in AASHTO's manual on geometric design and FHWA's MUTCD to help develop NEV-centric design concepts.

The most critical factor in geometric design is the ''design vehicle.'' The physical characteristics of this vehicle determine lane widths, curve radii, sight distance, grading, and parking. The design vehicle is specified to have larger physical dimensions and a larger minimum turning radius than most vehicles in the design class (*9*). Vehicle speed, acceleration, and braking capabilities are also parameters used in facility design. It will be necessary to specify these for NEVs to determine maximum grades, minimum length of passing zones and merging lanes, signal timing, as well as where NEVs will be allowed and what types of traffic separation will be required.

Table 1 compares the critical dimensions of AASHTO's design passenger car with the dimensions of the authors' proposed NEV design vehicle. On the basis of the author's review of existing NEV models and prototype attributes the authors propose a vehicle design width of 1.5 m (5 ft), sufficient for a fully enclosed NEV with spacious side-by-side seating. The authors also propose that the design length, wheelbase, and minimum outside turning radius be 2.7 m (9 ft), 1.8 m (6 ft), and 4 m (13 ft), respectively. As Table 1 shows the acceleration of AASHTO's passenger car far exceeds the capabilities of the NEV. It takes the AASHTO design passenger car 69 m (225 ft) to accelerate from 0 to 30 mph, whereas the NEV of the proposed design needs twice that distance. For this reason NEVs may require greater sight distances, longer merging lanes, and longer minimum green times for traffic signals at wide intersections with actuated signals calibrated for higher-speed traffic.

In the area of traffic control the MUTCD provides a list of five basic requirements for any traffic control device. Devices must (a) fulfill a need, (b) command attention, (c) convey a clear and simple meaning, (d) command respect of road users, and (e) give adequate time for proper response (*8*). Design, placement, operation, maintenance, and uniformity characteristics must all be considered to meet these basic requirements. The most challenging requirement that must be satisfied is conveying clear and simple meanings. Because NEVs are an unfamiliar technology, it may be difficult to find familiar words and images to represent the NEV in a manner that is accurate and easy to interpret. NEV attributes easiest to represent in visual images may be the small wheel base, short overhang over the front and rear wheels, and single or double vehicle occupancy. Educational plaques might include words such as *small*, *mini*, *micro*, *slow*, *reduced-speed*, and *low-speed*. So not to be confused with larger, freeway-capable automobiles, terms such as *vehicle*, *car*, or *cart* are preferred to *auto* and *automobile*.

### Infrastructure Design Concepts

Figure 1 shows a simple network with a NEV path and lane and several traffic control devices. The path turns into a dedicated NEV lane when it joins a road for full-size motor vehicles. Suggested signage and geometric designs are presented in Figure 1 and are described below.

#### *Geometrics*

The NEV lane and one-way NEV path should be at least 2.1 m (7 ft) wide, providing at least a 0.3-m (1-ft) buffer zone to either

**TABLE 1 Comparison of AASHTO and NEV Design Vehicles**

| Physical Attribute | Design Vehicle Characteristics, by Vehicle Type: AASHTO Passenger Car | Neighborhood Electric Vehicle |
|---|---|---|
| Height (m)[a] | 1.30 | 1.37 |
| Width (m) | 2.14 | 1.53 |
| Length (m) | 5.80 | 2.75 |
| Wheelbase (m) | 3.36 | 1.83 |
| Minimum Turning Radius[b] | | |
| Outside (m)[c] | 7.32 | 3.97 |
| Inside (m)[d] | 4.21 | 2.14 |
| Acceleration ($m/s^2$)[e] | 1.31 | 0.67 |
| Distance required to accelerate from 0 to 30 mph (m) | 69 | 134 |

[a]Conversion: 1 meter = 3.28 feet
[b]Vehicle speed less than 10 mph.
[c]Track of the outer front overhang.
[d]Track of the inner rear wheel.
[e]From 0 to 30 mph on level surface.

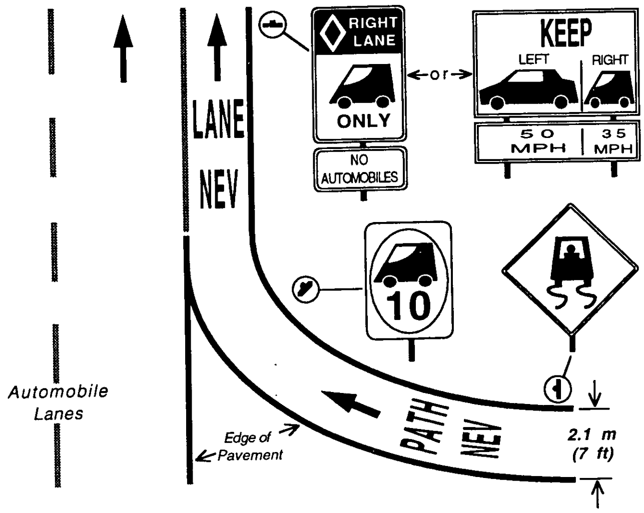


**FIGURE 1 Suggested signage and geometric standards for NEVs.**

side of the NEV. AASHTO specifies lane widths that provide at least this much space to either side of vehicles, even on facilities where speeds and traffic volumes are low. So not to be confused with an automobile lane, lane width should not exceed 2.4 m (8 ft). Clear lane markings, signs, and a preference toward lanes of minimum width will help reduce driver confusion. For purposes of drainage, clearance from roadside obstructions, and emergency stopping, NEV paths should have a 0.6-m (2-ft) graded area adjacent to the pavement. AASHTO specifies this minimum dimension for both motor vehicle and bicycle facilities (*9,10*). Where space permits, shoulders should be made wide enough for NEVs to completely pull off the traveled way. This becomes increasingly important as vehicle speeds and volumes increase.

The authors propose a wider lane and path standard than those developed for golf carts because the authors' design vehicle is wider than the golf cart and may operate above golf cart speeds on these facilities. In Peachtree City, Georgia, which has 97 km (60 mi) of golf cart paths (*11*), pavement widths for two-way paths are 2.4 m (8 ft), which is not wide enough to accommodate two NEV design vehicles passing each other. Before establishing extensive NEV networks, width criteria for lanes, paths, and curves should be matched carefully with the vehicle and its expected operating speed.

### *Traffic Controls*

NEVs will require traffic controls to provide notices of warning, regulation, and direction. Figure 1 shows two types of traffic partition signs in the upper right. The preferential lane sign provides NEVs with the option of using a NEV lane, but would not require it. Slower NEVs could use the separate lane, whereas faster NEVs could commingle with traffic. For peak-hour NEV lanes, such a sign could be accompanied by parking regulation information. The other travel path sign strictly regulates lane use. This sign would require NEVs to use the separate lane. These signs may be appropriate in areas deemed unfit for commingling at all times by all NEVs. Respective lane speed information can also be posted on these signs or speeds can be stenciled onto the street surface.

Route guidance and warning signs are also invaluable on NEV networks. On NEV paths routes should be marked with NEV-specific signs to orient drivers. Warning signs should inform drivers of potential hazards, such as the tight curve shown in the example in Figure 1.

## Implementation Strategies

Of the three types of surface streets—local, collector, and arterial—access to arterial streets is most problematic. Retrofitting of arterials will require creative solutions. Speed limits could be reduced, NEV lanes could use parking channels and road shoulders, and travel lanes may be narrowed to make space available for NEV lanes. NEVs may also use existing bicycle lanes, or ROWs can be expanded. Planners will see advantages and disadvantages in each strategy.

### *Modifying Street Parking*

Curbside parallel parking spaces along arterial streets are a perfect size for NEV lanes. Conversion of parking spaces to NEV lanes might face strong opposition, however, from businesses and residents who will lose their parking, local governments that will lose parking revenue, and pedestrians opposed to losing the parked-car buffer zone between sidewalks and moving vehicles. On the other hand in some cases parking removal may reduce traffic congestion by eliminating street-side activity or by forcing people to find alternatives to their automobiles.

Planners must be creative in appeasing those affected by parking removal. Compromises may include increasing parking capacity elsewhere or using the parking channel for only parts of the day.

### *Sharing Bicycle Facilities*

The use of bicycle lanes and paths as shared-use NEV facilities may be feasible in special circumstances, but it may not be acceptable for many bicyclists if it is adopted as a general policy. Just as automobiles and trucks threaten NEVs, NEVs threaten bicyclists. Commingling may not be appropriate when bicycle or NEV volumes are high or where bicycle lanes or paths are narrow. The California Department of Transportation restricts the use of bicycle paths by all motor vehicles with the exception of mopeds (*12*). A combination of legislation and development of appropriate traffic controls and geometrics may be needed before NEVs and bicycles share the same ROW.

The advantage of sharing the same facilities is that many bike lanes and paths are already in place in many cities and may be easily upgraded to serve NEV traffic. On streets that already have bike lanes, introduction of a third lane may cause confusion for facility users.

### *Selecting from Remaining Options*

Perhaps the most cost-effective way to retrofit an existing road for NEVs is to lower speed limits. Lower speeds may make a

facility safer for everyone. Some facilities will still be driven at speeds above the posted limit, so planners should be concerned with the actual speeds on a facility and not measure safety solely by what is posted. The lowering of speed limits may cause congestion and decrease facility throughput. Pretimed traffic signals may also need to be recalibrated for the reduced traffic speeds.

In some areas the use of street shoulders may be the only feasible option for introducing NEV lanes. Shoulders are the last uniform element of the roadway that has not been fully dominated by the automobile. The conversion of road shculders may be controversial, especially near state and federal highway facilities, because their use as through lanes is not part of AASHTO's definition of shoulders. Redefinition may require legislation. It may also be necessary to upgrade shoulders to achieve uniform lane width standards.

Automobile lane widths may also be reduced or ROWs may be expanded to make room for NEV facilities. Lane narrowing will be possible only where broad lanes are common. In the case of four-lane arterials, center lanes may need to be restriped, whereas two-lane arterials can be reduced by imposing a NEV lane along the edge. Side effects may result from lane narrowing. Speeds may drop when lanes are narrowed and capacity may be reduced (*9*). Lane narrowing may be attractive on some streets as a traffic-calming strategy for reducing speed differentials between vehicle types. However drivers may not feel as comfortable or safe on narrow lanes, especially when traffic or truck volumes are high. Expansion of the ROW may require substantial commitment in resources, depending on land costs and existing road border conditions. In urban, residential, and commercial areas additional ROWs may not be available because of existing sidewalks, front yards, storefronts, driveway curb cuts, and drainage channels.

Instead of retrofitting existing facilities a less costly strategy for providing NEV access may be to build new paths between abutting properties and cul-de-sacs, along storm channels, through fields and alleyways, beside train tracks, and inland to existing roadways. In the development of bicycle paths during the 1970s bicycle organizations were dismayed that bicycle trails did not contribute useful linkages for utility bicycling (*13*). The effectiveness of separate paths should be measured in part by their proximity to population centers and their ability to provide access to activities.

## CONCLUSION

Roadway infrastructure can be built and modified to enhance the safety and utility of NEVs. The challenge is most difficult when existing roads serve fast-moving traffic, but improvements are possible, as demonstrated time and again with other modes. New design concepts and practices will evolve through experimentation. Local planners will need to work with regulators to develop sensible guidelines and standards for both geometrics and traffic control devices. In some cases dedicated paths will prove to be attractive and effective. More commonly, especially initially, efforts will need to be focused on conversion and adaptation of existing facilities: removing street parking, narrowing lanes, lowering speed limits, and upgrading shoulders. The need for enhanced infrastructures will ultimately depend on the size of NEV markets, the performance capabilities and safety characteristics of NEVs, the expectations of NEV users, and the traffic environments where these vehicles will operate.

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# Fuel Emission Standards and Cost-Effective Use of Alternative Fuels in California

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Possible emission regulations on gasoline suppliers to encourage the use of alternative transportation fuels such as compressed natural gas, methanol, and electricity are examined. A theoretical model based on the concept of marketable emission permits is built for gasoline suppliers. This model shows that a fleet average emission standard on gasoline suppliers will encourage the sale of clean fuels that would otherwise not be profitable because clean fuels will generate valuable emission permits. Next a dynamic empirical model that determines the least-cost solution to meeting emission standards for new vehicles and fuels is built. The empirical model includes emission trading and banking of hydrocarbon, carbon monoxide, and nitrogen oxide permits. Under the assumption that individuals view all types of alternative-fuel and gasoline vehicles as perfect substitutes, the least-cost combination of fuels and vehicles consists mainly of methanol and compressed natural gas vehicles. If consumers favor gasoline vehicles over alternative-fuel vehicles by $350, then the least-cost combination of fuels and vehicles also includes significant numbers of gasoline vehicles.

To reduce pollution from mobile sources the Clean Air Act Amendments of 1990 (CAAA) encourage the use of clean fuels such as methanol, ethanol, and natural gas. Beginning in 1995 the CAAA require the sale of cleaner-burning reformulated gasoline in the nine cities with the worst ozone pollution. The CAAA also establish a clean-fueled-vehicle pilot program in California. This program requires the production, sale, and distribution in California of 150,000 clean-fueled vehicles each year beginning with model year 1996 and 300,000 such vehicles annually in model year 1999 and subsequent years. The CAAA also require the state of California to adopt a program to ensure the production, distribution, and availability of fuels for these vehicles.

Complementary regulations adopted by the California Air Resources Board (CARB) (*1,2*) require the production of low-emission vehicles (LEVs) and the availability of alternative fuels. The LEV regulations for vehicle emissions are based on the concept of marketable permits, whereby hydrocarbon standards are applied to automobile manufacturers, who are allowed to average, trade, and bank emission permits. The averaging, trading, and banking provisions are, however, subject to a number of restrictions (*1,2*). In addition, starting in 1998, 2 percent of all new vehicles sold each year in California must be electric vehicles. The required percentage of electric vehicles sold increases to 10 percent by 2003. In addition California has adopted Phase 2 reformulated gasoline standards for gasoline sold after January 1, 1996.

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CARB's answer to the chicken-or-egg problem of matching alternative-fuel vehicles (AFVs) and alternative fuels is to give vehicle manufacturers the right to certify vehicles by using any type of fuel they desire so long as they meet fleet average standards; gasoline suppliers must produce and offer for sale alternative fuels when demand for them reaches specified levels. Gasoline suppliers may produce and offer for sale the specified volumes of alternative fuels themselves, or they may contract out the responsibility to third parties.

The LEV and clean-fuel regulations are a significant improvement in mobile source regulation because they more fully recognize that vehicles and fuels should be treated as a system for cost-effective emission control. Nonetheless there are two serious flaws with CARB's approach. First, the regulations are structured to have gasoline suppliers produce, buy, and sell volumes of alternative fuels. Instead, as argued below, gasoline suppliers should face a volume-weighted *emission* standard.

Second, several factors weaken the link between fuels and vehicles for achieving the least-cost way to reduce emissions. This lack of coordination occurs because the regulations directly control the emissions of vehicles and the emissions of gasoline through its composition, but do not fully coordinate the economic decisions of vehicle manufacturers, fuel suppliers, and drivers. This paper's two main objectives are to describe a better way to introduce alternative fuels and AFVs through the use of emission standards on gasoline suppliers and to estimate the least-cost fuel-vehicle combinations for attaining emission standards.

## PREVIOUS RESEARCH

Growing interest in AFVs as a technological fix to urban pollution problems has spawned a large number of studies on the emission impacts and cost-effectiveness of various potential vehicle and fuel combinations (*3–6*). The study described here is the first to combine the environmental and engineering data within the framework of an economic cost-minimization approach that uses the regulatory mechanism of marketable pollution permits. The permit systems described below are also the first to explicitly model the transition of alternative fuels and vehicles through time by use of a dynamic model. A dynamic model for AFVs is important because it recognizes that fuel and vehicle choice decisions in one period are necessarily connected with fuel-vehicle choice decisions of other periods. The decisions must be made jointly and cannot be broken down into a series of period-by-period decisions.

Historically gasoline has been the primary transportation fuel. Hence the regulation of fuels has meant the regulation of the com-

ponents of gasoline. The design of market incentive mechanisms that incorporate gasoline and alternative transportation fuels requires that a number of additional considerations be taken into account. The permit systems proposed in this paper require that gasoline suppliers meet individual sales volume-weighted standards for the major pollutants emitted by vehicles: nonmethane organic gases (NMOGs) (reactivity adjusted), carbon monoxide (CO), and nitrogen oxides ($NO_x$).

Gasoline suppliers could meet the standards through any combination of fuel production and distribution or by any purchase of permits for emissions from producers or refiners who have generated excess emission reductions. These standards would be defined in terms of vehicle emissions and could be made greater, equal to, or less than those faced by vehicle manufacturers. This permit system is superior to CARB's rules because it is based on the emissions of the vehicle stock, not simply the number of vehicles that use the various fuels, and will therefore better tie emissions to fuel use. Moreover as shown below, it gives economic incentives to supply clean but expensive fuels.

CARB's rules (*1*) allow vehicle manufacturers to meet the fleet average standard by certifying vehicles to any combination of transitional LEVs (TLEVs), LEVs, ultra-LEVs (ULEVs), zero-emission vehicles (ZEVs; ZEVs are expected to be electric vehicles), or conventional vehicles so as long as their sales-weighted hydrocarbon emissions do not exceed the fleet average NMOG emissions standard. Under CARB's plan only NMOG standards are averaged; all vehicles must meet the standards for CO and $NO_x$ applicable to the emissions category to which they certify. The *implied* CO and $NO_x$ standards used in the present study are determined by combining the fleet average NMOG implementation schedule with the CO and $NO_x$ standards for the mix of vehicle classes that CARB believes to be "sensible" (*1*,p.23).

In setting up a fuel permit system the volumes of the different alternative fuels need to be adjusted to achieve gasoline equivalent gallons (GEGs), that is, fuel that provides the same amount of energy as a gallon of gasoline. In addition the average miles per GEG of each type of vehicle must be calculated, taking into consideration the vehicle fleet that uses each fuel. The units of the standards are in grams per GEG. Specifically the emissions of criterion pollutant $k$ ($k$ = NMOG, CO, $NO_x$) per GEG of each fuel $j$ [Phase 2 gasoline, CNG, M85, etc.) in each time period are calculated as:

$$E_{kjt} = \left(\frac{\text{grams}}{\text{GEG}}\right)_{kjt} = \left(\frac{\text{grams}}{\text{mile}}\right)_{kjt} * \left(\frac{\text{miles}}{\text{GEG}}\right)_{jt} \quad (1)$$

The first term on the right-hand side is the grams per mile for vehicle type $j$. The second term is the average miles per gallon of each type of vehicle running on fuel $j$.

Given that emissions for fuels are affected by the vehicle fleet that uses the fuels, permits are generated when a fuel supplier sells fuels with weighted-average emissions less than those of the fleet average standard. The permit system presented below also allows fuel suppliers to bank emission permits. That is if a fuel manufacturer more than meets its emission standards, it can store, or bank, the generated permits for later use. An examination of emission banking for manufacturers of light-duty vehicles has been presented previously (*7*).

Banking allows firms to reduce emissions for some initial period and then release them at a later time. The benefits of banking to firms are the cost savings from being able to smooth out emission rates. This trade-off may be desirable if there are not really thresholds at which environmental or human harm occurs, but rather less pollution is less harmful and more pollution produces greater harm. In addition if firms use banking to smooth emissions over time and if marginal damages from emissions are increasing, banking generates lower total damages. Given that vehicle emission standards are increasing in severity through time, firms will want to have the ability to bank emission permits.

The following equation expresses the number of sellable or bankable permits of emission $k$ in year $t$.

$$\text{Permits}_{kt} = \check{E}_{kt} * \sum_j \text{MPG}_{jt} * \text{GEG}_{jt} - \sum_j E_{kjt} * \text{MPG}_{jt} * \text{GEG}_{jt} \quad (2)$$

where $\check{E}_{kt}$ equals the fleet average standard of grams of pollutant $k$ per mile for vehicles in year $t$, and $E_{kjt}$ equals the certified emissions of pollutant $k$ in year $t$ for vehicle type $j$. Because selling an additional GEG increases a fuel supplier's effective standard, this form of standard encourages fuel suppliers to sell additional GEGs whose use in vehicles produces less pollution per mile than the fleet average standard. Collecting terms, it can be shown that

$$\text{permits}_{kt} = \sum_j \overline{E}_{jkt} * \text{MPG}_{jt} * \text{GEG}_{jt},$$

where $\overline{E}_{jkt}$ is the difference between the fleet average standard and the emissions of vehicles that use fuel $j$.

## PERMIT SYSTEM FOR FUEL SUPPLIERS GIVEN VEHICLE STOCK

In the scenario envisioned here each fuel supplier is assumed to maximize profits from selling various fuels and purchasing or selling permits over a $t = (1, \ldots T)$ period planning horizon, subject to an emission constraint on the fuels sold. For the individual fuel supplier the changes in the stock of vehicles can be taken as exogenous. This problem does not address the question of getting the right mix of vehicles and fuels on the road to minimize the social costs of meeting emission constraints. It has the more modest objective of easing the transition to alternative fuels by rewarding suppliers of clean fuels with valuable permits and penalizing the distribution of dirty fuels. For fuel supplier $i$ the problem can be mathematically expressed as

$$\max_{y^i_{kt}, \text{GEG}^i_{jt}, B^i_{kt}} \sum_t \delta_t \left[ \sum_j \pi^i_{jt}(\text{GEG}) + \sum_k Z_{kt} * y^i_{kt} \right] \quad (3)$$

subject to:

$$\sum_j E_{kjt} * \text{MPG}_{jt} * \text{GEG}^i_{jt} + y^i_{kt} \leq \overline{S}^i_k, \quad \forall\, k, t \quad (4)$$

$$B^i_{kt+1} = B^i_{kt} + y^i_{kt}, \quad \forall\, k, t \quad (5)$$

$$\text{GEG}^i_{jt}, \quad B^i_{kt} \geq 0, \quad y^i_{kt} \gtreqless 0 \quad (6)$$

where

$k$ = NMOG, CO, and $NO_x$;
$j$ = fuel type (phase 2 gasoline, methanol, etc.);

$\delta_t = 1/(1 + r)^t$, or the discount factor in year $t$;
$Z_{kt}$ = the per unit price of permits $y_{kt}$ of emission $k$ in year $t$, $y^i_{kt} > 0$ represents sales, $y^i_{kt} < 0$ are permit purchases;
$\pi(\text{GEG})^i_{jt}$ = the profit function of gasoline supplier $i$ from supplying fuel $j$ in year $t$;
$\text{MPG}_{jt}$ = average mile per GEG of vehicles using fuel $j$ at time $t$; and
$B^i_{kt}$ = $i$th firm's stock of banked emissions $k$ in year $t$ (in g).

The objective function (Equation 3) of this problem says that individual fuel suppliers will maximize the profits from selling the various fuels and selling (or purchasing) permits over the $T$ period time horizon. The first constraint, Equation 4, requires that emissions of each pollutant from all fuels sold by this fuel supplier plus the quantity of pollution permits bought or sold at time $t$ must be less than the standard for that pollutant at time $t$. Equation 5 defines the stock of the emission bank in each year as the total amount bought or sold in any year plus the level in the bank from the previous year. By setting the initial stock of the bank at zero ($B_{kt} = 0$) and requiring that the stock be nonnegative in each year ($B_{kt} \geq 0$), borrowing against the future is disallowed.

From the first-order conditions it can be shown that fuel suppliers should equate the present value of marginal profit from supplying each fuel to the weighted sum of the pollution cost of that fuel. The marginal profits of clean fuels can be negative, because clean fuels generate credits that can be sold. In contrast the marginal profits from the sale of dirty fuels must be positive or else (from the Kuhn-Tucker conditions) the quantity sold must be zero. Moreover for any two consecutive time periods when the stock of banked pollutants is positive, firms will equate the discounted value of permits with the marginal value of being able to pollute one more unit of pollutant $k$. This type of fuel permit system gives fuel suppliers an incentive to produce expensive, but clean fuels because they can sell pollution permits from the sale of the clean fuels.

## EMPIRICAL MODEL OF EMISSION TRADING FOR FUEL SUPPLIERS

Marketable emission permits derive their optimality properties from allocating abatement activities such that the marginal cost of abatement is equated across all sources. Savings are generated because of differences in the marginal costs of abatement between different suppliers. In the scenario described savings are generated when gasoline producers have different marginal production and distribution costs for the various fuels.

Except for reformulated gasoline, alternative fuels either are produced by only one supplier or are not currently produced in a way that is representative of wide-scale use. In the long run wide-scale use of alternative fuels can be expected to lead to multiple suppliers. For now, though, the cost savings from trading emission credits can be calculated by assuming only one supplier of each fuel, but allowing the quantity of each fuel chosen to be determined by a cost-minimizing model that allows fuel suppliers to use any combination of fuels so long as the resulting emissions meet given standards. Cost savings are determined by comparing this outcome with other outcomes, such as electric vehicle (EV) mandates or vehicle penetration scenarios expected by air quality management plans.

To fairly compare fuel-vehicle systems the model must incorporate differences in vehicle costs in the choice of fuels. This is done by determining the incremental cost differential between AFVs and gasoline vehicles, annualizing this incremental capital cost over an assumed vehicle lifetime, and adding this annualized vehicle cost to incremental operation and maintenance costs and to the respective fuel costs. This cost then represents the fuel cost to manufacturers; the cost of fuel $j$ to consumers is the production and transportation costs of fuel $j$ minus the annualized incremental vehicle costs of vehicles that use fuel $j$.

### Mathematical Representation of Empirical Model

The equilibrium model shown below determines the least-cost solution to meeting emission standards for new vehicles and fuels. Consistent with focusing on fuels it is written from the fuel suppliers' perspective. This model, though, explicitly makes vehicles a separate choice variable and takes vehicle vintages into account. Since fuel emission standards are based on the vehicle stock that uses the various fuels, the optimal solution is the same as if vehicle manufacturers took fuel costs into consideration and optimally chose fuels, but faced standards based on the whole fleet of vehicles from the time that the standards are set and into the future.

The empirical optimization model is mathematically represented as follows:

$$\min_{\text{GEG}_{jt}, V_{ajt}, B_{kt}, I_{kt}} \text{TC} = \sum_t \sum_j \delta_t P_{jt} * \text{GEG}_{jt} \tag{7}$$

subject to:

$$\sum_j E_{jt} * \text{MPG}_{ij} * \text{GEG}_{jkt} + I_{kt} \leq \bar{S}_{kt}, \quad \forall\, K, t \tag{8}$$

$$B_{kt+1} = B_{kt} + I_{kt}, \quad \forall\, k, t \tag{9}$$

$$Q_{jt} \sum_a V_{ajt} = \text{GEG}_{jt}, \quad \forall\, j, t \tag{10}$$

$$V_{ajt+1} = V_{ajt}, \quad \forall\, j, t \tag{11}$$

$$\sum_j \text{GEG}_{jt} = \text{tsale}_t, \quad \text{for } t = 1, \ldots T \tag{12}$$

$$B_{kl} = 0;\ 0 \leq B^t_k;\ \text{GEG}_{jt} \geq 0, \quad \forall\, j, k, t \tag{13}$$

$$V_{Ajt} = 0 \tag{14}$$

where

TC = total fuel and incremental vehicle costs;
$Q_{jt}$ = the per vehicle quantity of fuel $j$ used by vehicles in year $t$;
$P_{jt}$ = per unit of production, transportation, and distribution and incremental vehicle cost of fuel $j$ in year $t$;
$V_{ajt}$ = number of vehicles of vintage $a$ using fuel $j$ in year $t$, where $A$ is the terminal vintage for vehicles; and
$\text{tsale}_t$ = total quantity of fuel use (on a gasoline equivalent basis) in year $t$.

The other symbols are as defined previously.

The objective function (Equation 7) minimizes the total fuel and incremental vehicle costs of all vehicles introduced over the *T* period time horizon. Equation 8 requires that the sum of emissions of pollutant *k* from all fuels plus the net amount of pollution *k* banked at time period *t* must be less than the standard for pollutant *k* at time *t*. The standard is equal to the product of the fleetwide vehicle emission standards and the expected equivalent sales quantity of gasoline. Equation 9 defines the stock of the emission bank in each year as the total amount invested (positive or negative) in any year plus the level in the bank from the previous year. Equation 10 allocates the quantity of fuel *j* used in time period *t* to the vehicles of the various age classes that use it. Equation 11 specifies that vehicles grow in age each year with no mortality until the end of their expected lifetimes. Constraint Equation 12 requires that the sum of all efficiency-weighted GEGs equals the predicted volumes of fuel used in period *t* on the basis of forecasts of vehicle miles of travel (VMT). Finally Equation 14 specifies that when vehicles reach the vintage age *A* they are taken out of service.

### Data and Implementation

This model is specified for the South Coast Air Basin for the years 1996 to 2010. The year 1996 is when California Phase 2 gasoline must be introduced; it also reflects early stages of LEV technology. The year 2010 reflects the time period when vehicle and fuel production technology can reasonably be assumed to have advanced and when many of the problems of implementation have been solved. The vehicle-fuel systems examined in the present study include gasoline, methanol blends, neat methanol, CNG, and electricity.

On the basis of the fuel economy projections of the on-road vehicle fleet by the Office of Technology Assessment of the U.S. Congress (*8*), the present study assumes an annual rate of increase of 2.57 percent in fuel efficiency for the 19 years between 1991 and 2010. To give some perspective, the annual rate of increase in fuel efficiency for passenger cars for the 16 years from 1975 to 1991 was 3.59 percent. The annual rate of increase of 2.57 percent is applied to the average fuel efficiency of 25.0 mi/gal (MPG) for the combined fleet (cars and light-duty trucks) in the 1991 model year (*9*) to yield the average MPG of the fleet used in the present study.

The annual quantity of GEGs used by light-duty vehicles from 1996 to 2010 is determined by combining the vehicle age, mileage relationships, and vehicle mix from California's on-road mobile source computer simulation model, EMFAC7E (*10*), with projected VMT and MPG rates. VMT projections are by the South Coast Air Quality Management District (*11*) for spark-ignition passenger cars and light-duty trucks. Finally the emissions of vehicles used in the present study are the 50,000-mi certification standards for light-duty vehicles. These certification standards can be found in CARB (*1*).

## PHYSICAL PROPERTIES OF FUELS

The physical properties of the different alternative fuels are very important determinants of their emissions, performance characteristics, and energy equivalency factors. Determination of the volume of each alternative fuel that could be used in the time frame of the present study involves determination of the volumetric energy equivalency of each of the alternative fuels in terms of GEGs. The estimation of GEGs consists of two portions: one part is due to the pure energy content of the fuels, and one part is due to thermal efficiency differences among different vehicle types.

The pure energy conversion factors for the various fuels are shown in Table 1. In the case of CNG the multiplier is for one therm; the others are based on 1 gal.

These volumetric energy conversion factors need to be adjusted to account for engineering efficiency differences. These differences represent the gains in effective heating value of alternative fuels relative to Phase 2 gasoline. Efficiency gains for intermediate years are interpolated assuming equal annual rates of change. These energy efficiency factors have been chosen after consulting the available literature, but they still represent subjective judgment. These efficiency adjustments are shown in Table 1.

## FUEL COSTS

The estimation of the future prices of different transportation fuels needs to consider many factors including the costs of feedstocks, the technological maturity of processes to convert feedstocks to final products, and assumptions about the political and economic environments. Indeed there is no one correct price for each fuel. The best that can be done is to narrow the range of uncertainty and make sure that the various estimates are made on a consistent set of assumptions.

The present study assumes that energy markets are global and well connected. In particular the present study uses the approach taken by the National Research Council (*5*) in defining prices for the various energy and nonenergy feedstocks (where appropriate) as functions of the price of crude oil. This approach has the advantage of providing a unifying structure over the price forecasts of each fuel's costs. Simulation results are then interpretable as being due to emissions benefit and cost differentials of the various fuels rather than to the different assumptions made in different price forecasts. The drawback to this approach is that it can overstate the degree to which fuel markets are linked, and it does not allow for relative changes in the prices of fuels.

Retail incremental vehicle costs were estimated by using published sources and conversations with experts in the field. These costs (in present-value dollars) are given in Table 2. They represent the additional costs to consumers over those for conventional vehicles. For example gasoline vehicles with TLEV technology emission levels are estimated to have retail costs equal to an ad-

**TABLE 1 Volumetric Conversions and Engineering Efficiency Gains of AFVs**

| Fuel-Vehicle System | Volumetric Fuel Multiplier | 1996 Model Year | 2010 Model Year |
|---|---|---|---|
| M85 FFV | 1.74 | 5% | 5% |
| M85 dedicated | 1.74 | 10% | 15% |
| M100 | 1.99 | 15% | 20% |
| Phase 2 gasoline | 1 | 0% | 0% |
| CNG dual-fuel | 1.26 | 0% | 0% |
| CNG dedicated | 1.26 | 5% | 10% |

**TABLE 2 Retail Incremental Vehicle Costs Used for Present Study (Per Vehicle Costs, 1992 U.S. Dollars)**

| Fuel/ Vehicle | TLEV | LEV | ULEV | ZEV |
|---|---|---|---|---|
| Phase 2 | 70 - 200 | 200 - 300 | 500 - 1000 | na |
| Methanol FFV | 200 - 300 | 276 - 400 | nc | na |
| Methanol Ded. | 0 - 200 | 100 - 300 | 400 - 600 | na |
| CNG Dual-Fuel | 1532 - 2544 | 1532 - 2544 | 1532 - 2544 | na |
| CNG Dedicated | 900 - 1500 | 1050 - 1650 | 1250 - 1850 | na |
| EV | na | na | na | 4,179 - 15,869 |

na: not available.
nc: not considered.

ditional $70 to $200 over those for gasoline vehicles with conventional emission abatement equipment and emission levels.

One problem with these cost numbers is that they sometimes represent different stages of technological development. That is they are reasonable estimates, but they represent technology at different points in time. The exceptions to this are EVs. The EV numbers are explicitly based on different assumptions about the applicable technology. To compensate for different technological maturities, ULEVs are not allowed to exist until 1998. As it turns out the more expensive ULEVs are generally not chosen by the model until later years, when standards become tighter.

Fuel taxes are added to fuel costs and combined with incremental vehicle costs to yield the low-cost and high-cost prices for the various fuels. Incremental vehicle costs are converted into cents per gallon by dividing the costs by the total number of miles driven by each type of vehicle and multiplying by the MPG of the vehicles in each year. The low-cost estimates are given in Table 3. Each price represents the cents per gallon (1 gal equals 3.785 L) of fuel on an efficiency-weighted basis. For example under the low-cost scenario the CNG used in dedicated vehicles with LEV technology will cost $1.30 in 1996 on a gasoline equivalent basis. This cost includes fuel costs and incremental vehicle costs. For this same fuel and year the high-cost estimate is $1.44. Additional details are provided elsewhere (*12*).

## SIMULATION RESULTS FOR JOINT-COST MODEL

A number of simulation scenarios were run by using the model identified in Equations 7 to 14 and the data described above. As a first look into the implications of the model, Figure 1 shows the optimal choice of fuels and vehicle technology for fuel-vehicle systems introduced in 1996 through 2010 under the high-cost scenario, when the banking of HC, CO, and $NO_x$ is allowed. These fuel-vehicle systems represent the least-cost means of attaining the fleet average standard for HC and the implied fleet average standards for CO and $NO_x$ emissions for the new vehicle fleet introduced starting in 1996. That is the emission standards and fuel and vehicle use are based on the entire fleet of vehicles of model year 1996 and beyond. As discussed previously the standards used in this model are different from those for California vehicle manufacturers, who face an HC fleet average standard based only on vehicles sold in each model year.

The units in Figure 1 are 100 million GEGs. The fuel volumes shown represent the aggregate volumes in each year for each fuel type used by all vehicles that use each fuel (e.g., the sum of all fuel used by vehicles of all model years and all age classes). The total fuel volume (the top curve in Figure 1) increases greatly from 1996 to 2010. This reflects the fact that as time passes a greater percentage of the on-road fleet is composed of vehicles produced after 1996. By 2007 100 percent of fuel use is attributed to vehicles produced in 1996 and beyond. The small decline in fuel use in the years 2008 to 2010 reflects predictions that annual fuel efficiency gains increase at a greater growth rate than VMT. The total costs for the fuels (including incremental vehicle costs and taxes) are $34.22 billion and $39.24 billion for the low- and high-cost scenarios, respectively. Table 4 shows these costs and the costs from additional scenarios.

As seen in Figure 1 dedicated vehicles that use 100 percent methanol (M100 vehicles) and dedicated CNG vehicles that use LEV and ULEV technology use the bulk of the fuel in each year in the high-cost scenario. This is also true for the low-cost scenario, although the results are not shown. EVs are also chosen, even though no explicit number of EVs was required. Absent are gasoline vehicles that use conventional or any of the various LEV technologies. Thus if these AFVs are viewed as close to or perfect substitutes for gasoline vehicles and can be made for the incremental costs indicated above, then it appears that AFVs represent a viable low-cost means of attaining emission goals. Especially for the EVs, but also for the CNG vehicles, the high capital costs are effectively offset by the low fuel costs over the vehicles' life spans. Changing the real discount rate in a range of 0 to 15 percent did not appreciably change the chosen mix of fuels and vehicles. Running the model with low incremental vehicle costs for gasoline vehicles (conventional, TLEV, LEV, and ULEV) and the high-cost scenario for AFVs does not bring gasoline vehicles into the solution set.

Several investigators (*13–15*) have performed work that suggests that individuals prefer the attributes of gasoline vehicles to the hypothesized attributes of AFVs. To test the magnitude of this bias toward gasoline vehicles, a number of simulations were run with low incremental costs for gasoline vehicles, with the high-cost scenario for AFVs, and with the price of reformulation lowered by 10 cents (equal to about $350 in incremental vehicle costs). In this scenario significant numbers of gasoline vehicles that use LEV and ULEV technology (with incremental vehicle costs equal to $200 and $500, respectively) displace CNG and M100 vehicles that use ULEV technology (costing $1,850 and $600, respectively). Gasoline reformulation costs are not, however, expected to be this low. Nonetheless if consumers view gasoline vehicles as providing additional value over M100 and CNG vehicles equal to 10 cents per gallon ($350 incremental vehicle costs), then gasoline vehicles become a cost-effective alternative to achieving emission standards. This observation should be viewed as conservative (favoring the status quo of gasoline vehicles), however, since this uses the low-cost estimates for gasoline vehicles and the high-cost estimates for AFVs. Interestingly the inclusion of gasoline vehicles only slightly affects the optimal number of EVs. Nonetheless M100 (and to a lesser extent CNG) remain important fuels in vehicles that use LEV technology (using the high incremental vehicle cost estimates). When the price of gasoline is lowered by 16 cents (zero reformulation costs equal to

TABLE 3 Cents Per GEG Including Incremental Vehicle Costs, Low-Cost Scenario[a] (1992 U.S. Dollars)

| Year | EV | CON. GAS | GAS TLEV | GAS LEV | GAS ULEV | M85 DED. TLEV | M85 DED. LEV | M85 DED. ULEV | M85 FFV TLEV | M85 FFV | M100 TLEV | M100 LEV | M100 ULEV | CNG TLEV | CNG LEV | CNG ULEV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1996 | 463 | 152 | 154 | 157 | 164 | 162 | 164 | 171 | 174 | 176 | 164 | 167 | 174 | 127 | 130 | 135 |
| 1997 | 440 | 157 | 158 | 161 | 169 | 164 | 167 | 174 | 177 | 179 | 166 | 168 | 176 | 130 | 134 | 139 |
| 1998 | 418 | 161 | 163 | 166 | 174 | 166 | 169 | 177 | 180 | 182 | 168 | 170 | 178 | 134 | 138 | 142 |
| 1999 | 398 | 166 | 167 | 171 | 179 | 169 | 171 | 179 | 183 | 185 | 169 | 172 | 180 | 138 | 142 | 147 |
| 2000 | 380 | 171 | 172 | 176 | 184 | 171 | 174 | 182 | 187 | 189 | 171 | 174 | 182 | 142 | 146 | 151 |
| 2001 | 362 | 174 | 176 | 179 | 187 | 171 | 174 | 182 | 187 | 189 | 170 | 173 | 181 | 146 | 150 | 155 |
| 2002 | 346 | 177 | 179 | 183 | 191 | 171 | 174 | 182 | 188 | 190 | 169 | 172 | 181 | 150 | 154 | 160 |
| 2003 | 331 | 181 | 183 | 186 | 195 | 171 | 174 | 183 | 189 | 191 | 168 | 171 | 180 | 155 | 159 | 164 |
| 2004 | 316 | 184 | 186 | 190 | 199 | 171 | 174 | 183 | 189 | 192 | 168 | 170 | 179 | 160 | 164 | 169 |
| 2005 | 303 | 188 | 190 | 194 | 203 | 171 | 174 | 183 | 190 | 192 | 167 | 170 | 179 | 164 | 169 | 174 |
| 2006 | 291 | 192 | 194 | 198 | 207 | 171 | 174 | 184 | 191 | 193 | 166 | 169 | 178 | 169 | 174 | 180 |
| 2007 | 279 | 196 | 198 | 202 | 211 | 171 | 174 | 184 | 192 | 194 | 165 | 168 | 177 | 174 | 179 | 185 |
| 2008 | 268 | 200 | 202 | 206 | 216 | 171 | 175 | 184 | 193 | 195 | 164 | 167 | 177 | 180 | 184 | 190 |
| 2009 | 258 | 204 | 206 | 210 | 220 | 171 | 175 | 185 | 194 | 196 | 163 | 166 | 176 | 185 | 190 | 196 |
| 2010 | 248 | 208 | 210 | 215 | 225 | 171 | 175 | 185 | 194 | 197 | 162 | 166 | 176 | 192 | 196 | 203 |

a. 1 gallon equals 3.785 liters.

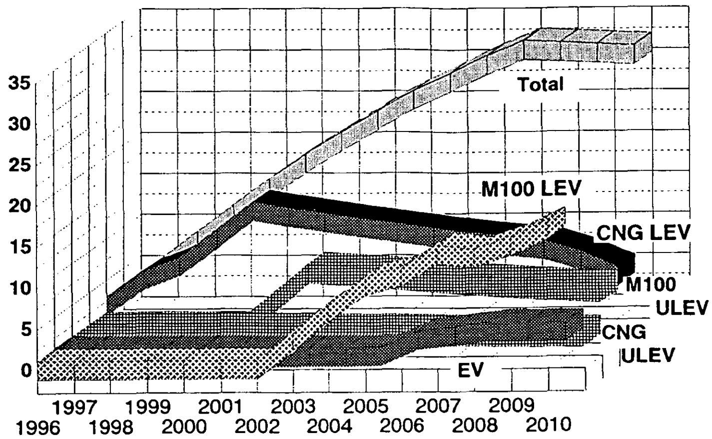


**FIGURE 1 Fuel-vehicle combinations for high-cost scenario (100 million gallons; discount rate = 5 percent; 1 gal = 3.785 L).**

$566 in incremental vehicle costs), the optimal mix of vehicles includes mainly gasoline vehicles that use LEV and ULEV technologies. At this price for gasoline, M100 LEVs still continue to contribute to fuel needs in the latter part of the time horizon.

EVs are chosen as a cost-effective means for meeting emission standards for two reasons. First, EVs are treated under CARB's regulations and in the present model as having zero emissions, even though their use generates additional power plant emissions [power plant emissions have been estimated previously (*6*)]. Thus EVs are given an unfair advantage in the regulations, which explains why some are used in 1996 when standards are at their least-stringent levels over the time horizon. Second, the implied emission standards used here have such tight $NO_x$ emission restrictions for 2003 and beyond that they can only be met with the use of some EVs. That is the CARB's HC standard combined with its expected implementation schedule for LEV technologies implies an $NO_x$ standard that can be met only through the use of some EVs.

As discussed CARB requires a certain percentage of the new vehicle fleet to be EVs in each model year starting in 1998. When these EV requirements are imposed on the model, the number of EVs chosen increases; the cost of meeting the emission standards also increases. For both the low- and high-cost scenarios the costs rise about 1 percent, varying slightly with the discount rate. These results are shown in Table 4.

All the above scenarios were conducted by using the basic model that allows emissions of HC, CO, and $NO_x$ that are less than the standards to be put into separate emission banks and carried forward to be used in later periods. When emission banking is not allowed the cost of meeting the standards rises. For both the low- and high-cost scenarios, the cost savings from being able to bank the three separate emissions range between 2.5 and 5.5 percent, depending on the interest rate. The cost savings represent the savings due solely to allowing the mix of fuels and vehicles to be chosen such that emission reductions are made in early periods, to be used later to relax emission standards.

Since CARB's regulations, in strict terms, require only an HC fleet average standard, it is also interesting to examine the cost savings and the mix of fuels and vehicles from this scenario. In this case HC emissions become the only banked pollutant and the total costs of the fuels and incremental vehicle costs falls to $33.08 billion (representing a 3.30 percent decrease in costs) and $36.43 billion (representing a 7.14 percent decrease in costs) for the low- and high-cost scenarios, respectively. The cost savings from banking fall to 0.75 to 1 percent of total costs, depending on the interest rate and assumed costs. Banking of HC emissions is thus 2.5 to 5 times less valuable than banking of CO and $NO_x$ emissions in the presence of all three constraints.

As discussed earlier for the scenarios in which all three pollutants had their own constraints, significant numbers of EVs were voluntarily chosen. With only an HC constraint, no EVs are voluntarily chosen. Imposing CARB's EV mandates (for the case of only an HC standard) raises the costs of meeting the HC pollution standard by about 3.11 and 7.5 percent for the low- and high-cost scenarios, respectively (Table 4). When banking is also restricted the EV mandates cost an additional 3.88 to 8.33 percent for the low- and high-cost scenarios. Under the base case assumptions (HC, CO, and $NO_x$ standards and banking is allowed) the percent cost increases for EV mandates could be viewed as fairly small (approximately 1 percent of costs). However the 3.11 to 7.59 percent cost increases found in the HC-only constraint or the 3.88 to 8.33 percent cost increases found in the HC-only constraint, no-banking scenario bring into question the burden imposed by the EV mandates. The additional burden of EVs is all the more rel-

**TABLE 4 Present-Value Cost Estimates for Various Scenarios[a] (5 Percent Discount Rate, US$1 Million, 1992)**

| HC, CO, and NOx Standards | Base Case | No Banking | EV Mandates | EV High-Cost, All Else Low |
|---|---|---|---|---|
| Low-Cost | 34,218 | 35,202 (2.88%) | 34,524 (0.89%) | 36,062 (5.39%) |
| High-Cost | 39,236 | 41,394 (5.50%) | 39,635 (1.02%) | na |
| **HC Standard Only** | **Base Case** | **No Banking** | **EV Mandates** | **EV Mandates No Banking** |
| Low-Cost | 33,088 | 33,381 (0.88%) | 34,117 (3.11%) | 34,372 (3.88) |
| High-Cost | 36,435 | 36,745 (0.85%) | 39,200 (7.59%) | 39,470 (8.33%) |

[a]The numbers in parentheses represent the percent cost increases from the "low-cost" and "high-cost" scenarios as applicable; na: not applicable.

evant considering that EVs are falsely assumed (by California regulations) to produce zero emissions. This suggests that CARB's EV mandates are an excessively expensive way to achieve emission goals; the same emission standards could be met more cheaply with other low-emission fuels and vehicles.

That scenario, with only the HC constraint, no banking, and mandated quantities of EVs, most closely matches CARB's regulations. It still differs significantly from CARB's regulations, though, that require vehicle manufacturers to meet standards on vehicles in each model year independently; in contrast these simulations ensure that the fleet average standard is based on the whole fleet in every time period.

## FINAL REMARKS

There is widespread agreement that both vehicle emission control systems and fuel type simultaneously affect mobile source emissions. This paper argues that placing emission regulations on fuel suppliers will encourage the use of alternative transportation fuels such as CNG, methanol, and electricity. By using marketable emission permits, these regulations can be designed to minimize the cost of meeting emission standards. It was argued that the regulation of fuels should be based on the emissions of vehicles that use the fuels.

Previous studies that have looked at alternative transportation fuels have made single-period, "snapshot" estimates of the costs and emission impacts from their introduction. The research presented here has examined the impact of meeting emission goals for transportation fuels with a multiperiod dynamic model that includes emission banking and the coordination of the on-road stock of vehicles and fuels.

A theoretical model based on the concept of marketable emission permits was built for gasoline suppliers, given that the current and future stock of vehicles is not a choice of gasoline suppliers. This model shows that a fleet average emission standard placed on gasoline suppliers will encourage the production and distribution of clean fuels that would otherwise not be profitable because clean fuels will generate valuable emission permits. This permit system, however, does not minimize the total (fuel and vehicle) costs of meeting emission standards because the fuel and vehicle production decisions are made by different decision makers.

Next a multiperiod empirical model was built. That model determines the least-cost solution to meeting emission standards for new vehicles and fuels. The model explicitly makes vehicles a separate choice variable and takes vehicle vintages into account. The base simulations use three independent constraints for HC, CO, and $NO_x$ emissions. Under the assumption that individuals view all types of alternative-fuel and gasoline vehicles as perfect substitutes, both the low- and high-cost scenarios determined that the least-cost combination of fuels and vehicles consists mainly of dedicated methanol vehicles and dedicated CNG vehicles that use LEV and ULEV technology. Some EVs were also chosen.

Absent from the selected fuel and vehicle systems are any vehicles that use Phase 2 reformulated gasoline, which will be the required fuel for all gasoline vehicles in 1996 and beyond. Only when the price of reformulation was dropped by 10 cents per gallon, equal to $350 in incremental vehicle costs, were significant numbers of gasoline vehicles chosen. This suggests that if consumers view gasoline vehicles as providing $350 in additional value over methanol and CNG vehicles, then the use of gasoline vehicles that use LEV and ULEV technology becomes a cost-effective means of achieving emission standards.

Although there are CO and $NO_x$ standards implied by California's LEV program, only HC emissions have a predefined schedule. When the model is estimated with only the HC constraints, fuel and incremental vehicle costs fall by 3.30 and 7.14 percent for the low- and high-cost scenarios, respectively. In addition the cost savings from banking fall to about 1 percent, but the costs of the EV mandates rise substantially to 3.11 to 7.59 percent for the low- and high-cost cases, respectively. The low value of banking is understandable given that the fuel volumes covered under the emission regulations are a fairly small proportion of fuel sales in the early years of the scenario. The fairly substantial percent cost increases for EV mandates found in the HC-only constraint scenario (3.11 to 7.5 percent) bring into question the burden imposed by the EV mandates. This suggests that CARB's EV mandates are an excessively expensive way to achieve emission goals.

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# Energy-Based Fuel Consumption Model for FREFLO

KETHIREDDIPALLI S. RAO AND RAYMOND A. KRAMMES

CORFLO is a strong tool for evaluating coordinated freeway corridor traffic management strategies because of its capability of explicitly simulating freeways and surface streets within a single environment. The lack of a fuel consumption estimation capability in FREFLO, the freeway simulation component of CORFLO, however, limits its application for evaluating corridor management strategies directed at the much needed conservation of scarce petroleum resources. The objective was to develop and implement a fuel consumption model based on the most currently available fuel consumption data. A review of previous work on fuel consumption modeling indicated that a model based on the energy consumed to overcome the forces resisting a vehicle's motion is suitable for implementation in FREFLO. The relation between acceleration noise and density was used to estimate the acceleration owing to vehicle interaction. The model was calibrated by using fuel consumption data obtained from FHWA; these data are representative for 64 percent of the passenger vehicle fleet from 1980 to 1992. The model explains 99.5 percent of the variation in the constant-speed fuel consumption data and 86.1 percent of the variation in fuel consumption due to acceleration. Air drag and rolling friction coefficients computed from the model parameters were near the lower bounds of the range of theoretically possible values. The fuel consumption estimates obtained from FREFLO and INTRAS for a small segment of I-35 near Austin, Texas, were comparable under most traffic conditions.

The oil shortages of the recent past have increased attention in the United States to the conservation of petroleum resources through better vehicle and road network design and traffic management schemes. The transportation sector is a primary target for conservation efforts because it accounts for 60 percent of the total petroleum consumed, and improved transportation management has significant petroleum conservation potential.

Any attempt to conserve fuel through traffic management schemes requires a means of estimating fuel consumption. A traffic model with a fuel consumption module provides the only practical means of estimating the fuel savings resulting from a particular traffic management strategy (*1*). The use of such a model also facilitates preimplementation evaluation and selection of management strategies for further study and eventual implementation.

TRAF is an integrated system of five traffic simulation models and a traffic assignment model developed by FHWA as a tool for use in transportation planning and traffic engineering to test transportation management strategies. CORFLO is a subset of the TRAF system consisting of FREFLO, NETFLO, and TRAFFIC. FREFLO is a macroscopic freeway simulation model, NETFLO is a macroscopic arterial simulation model, and TRAFFIC is an equilibrium traffic assignment model.

CORFLO is the only available public-domain traffic simulation model that can explicitly simulate freeways and surface streets within a single environment. Hence it has found use in several corridor traffic management studies. Because CORFLO is an integrated system of two simulation models, both models in CORFLO need a fuel consumption submodel to estimate systemwide fuel consumption. Only NETFLO, however, currently has a fuel consumption estimation capability. The lack of a similar capability in FREFLO reduces the efficacy of CORFLO in estimating the fuel savings through implementation of alternative coordinated freeway corridor traffic management strategies.

The main objective of the study documented in this paper was to identify a model that can be used to estimate fuel consumption by using the traffic variables generated by FREFLO, calibrate the model parameters to represent traffic conditions in the United States, incorporate the model into FREFLO logic, and check the accuracy of the estimated fuel values by comparing them with those estimated by INTRAS. INTRAS is a microscopic freeway simulation model designed to represent traffic and traffic control in a freeway and surrounding surface street environment (*2*). The scope of the study is limited to fuel consumption estimates for passenger vehicles only.

First, the background literature related to fuel consumption modeling is summarized. Then, the model implementation is discussed and the results of validation are presented. Finally, a summary and recommendations for further work are presented.

## BACKGROUND

### Use of Power Generated by an Engine

To understand the fuel consumption characteristics of an automobile, it is necessary to understand the different forces resisting its motion. The power generated by the engine is mainly used in overcoming rolling resistance, air resistance, grade resistance, inertial resistance, curve resistance, and power transmission resistance.

Rolling resistance results from the frictional slip between the tire and pavement surfaces; flexing of tire rubber at the surface of contact; rolling over rough particles (stones or broken asphalt); climbing out of road depressions; pushing wheels through sand, mud, or snow; and internal friction at the wheel, axle, and driveshaft bearings and in transmission gears. For speeds of up to 97 km/hr (60 mph) the rolling resistance per unit weight of modern passenger cars on high-type pavements is nearly constant (*3*).

Air resistance is composed of the direct effect of air in the pathway of vehicles, the frictional force of air passing over the surfaces of the vehicles, and the partial vacuum behind the vehicle. Its magnitude is a function of the frontal area of the vehicle and the square of the vehicle speed.

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Grade resistance is the additional resistance a vehicle experiences in traversing grades. It is equal to the component of the vehicle's weight acting along the grade.

Curve resistance is the force acting through the front wheel contact with the pavement needed to deflect the vehicle along a curvilinear path. This force is a function of speed. Curve resistance is not considered in the models described herein.

Inertial resistance is the force that must be overcome to change speed. It is equal to the product of vehicle mass and rate of acceleration.

The power transmission resistance is the frictional resistance offered by the clutch, transmission, driveshaft, differential, and axle and other bearings. The total power loss due to this resistance is approximately 10 percent for an average passenger car with manual transmission in direct drive (*4*).

Apart from the power required to overcome the resisting forces described, in modern passenger vehicles power is also consumed by accessories like the cooling fan, power steering, air conditioner, and alternator. The power requirements to run these accessories also contribute to the overall fuel consumption of the vehicle.

## Fuel Consumption Models

The power generated by the engine is a function of engine speed and throttle opening and not the road speed of the vehicle. In most traffic simulation models, however, variables like engine speed and throttle opening are not readily available. Therefore fuel consumption is generally estimated by using vehicle speed and acceleration. In the following paragraphs recent work on fuel consumption modeling is discussed.

A hierarchy of fuel consumption models has been established by Akcelik et al. (*5*); this hierarchy includes models ranging from basic, instantaneous types of models to the more aggregate, average travel speed models. The choice of the fuel consumption estimation function depends on factors including the availability of traffic variable estimates, either modeled or measured on the road, and the required level of accuracy (*1*).

Kent et al. (*6*) showed that the instantaneous fuel consumption can be related to the instantaneous power demand experienced by the vehicle by using a simple linear relation. This model is often referred to as the *power-related* model of fuel consumption in the literature.

Using data collected from carefully controlled on-road acceleration, deceleration, and steady-speed fuel consumption tests, Biggs and Akcelik (*7*) showed that the power model in the form proposed by Kent et al. (*6*) gave adequate estimates of fuel consumption over trip segments of at least 60 sec duration and during cruising and slow to medium accelerations, with mean errors of generally less than 5 percent. During hard acceleration, however, fuel consumption was grossly underestimated, with mean errors of up to 20 percent, depending on the acceleration rate and final speed. Akcelik (*8*) also showed that since the power-related model uses an average (constant) efficiency factor for all modes of driving, its adequacy is limited for predicting fuel consumed in different modes of driving. Therefore this form of the model is unsuitable for fuel estimation if it is used to predict fuel consumption at different speeds and accelerations, irrespective of the mode of driving.

One of the findings of the analysis of the power-related model (*7*) was that the efficiency factor is dependent on the speed and acceleration rate of the vehicle. On the basis of that finding, and also including grade effects, Biggs and Akcelik (*9,10*) proposed a model of the following form:

$$f_x = \frac{\alpha}{v} + \beta_1 R_T + \beta_2 [a_e R_{IG}]_{a_e > 0}, \quad \text{for } R_T > 0 \tag{1}$$

$$f_x = \frac{\alpha}{v}, \quad \text{for } R_T \leq 0$$

where

$f_x$ = fuel consumption per unit distance,
$\alpha$ = idle fuel consumption per unit time,
$v$ = vehicle speed,
$R_T$ = total tractive force required to drive the vehicle ($R_D + R_I + R_G$),
$R_D$ = total drag resistance,
$R_I$ = inertial resistance,
$R_G$ = grade resistance,
$R_{IG} = R_I + R_G$,
$a_e = a + (G/100) * g$,
$G$ = percent grade, and
$g$ = acceleration due to gravity.

This form of the model is often referred to in the literature as the *energy-related* model of fuel consumption.

Biggs and Akcelik (*10*) suggested the calibration of the idle, drag, and efficiency parameters using three different data sets. This method of calibration would result in a model that can estimate the contribution of each energy component to fuel consumption. The calibration of all model parameters on the basis of one data set containing all modes of driving may not result in a model capable of estimating the contribution of each energy component to fuel consumption.

Before the work by Biggs and Akcelik (*10*), Bester (*11*) proposed a model similar to the energy-related model discussed above. Bester's model has two components. The first component estimates fuel consumption at constant speed and is similar to the power-related model.

The second component of Bester's model (*11*) estimates the additional fuel consumption due to vehicle interaction, as shown in Equation 2.

$$F_a = \frac{\beta M_e a}{\eta} \tag{2}$$

where

$F_a$ = additional fuel consumption per unit distance,
$\beta$ = efficiency factor,
$M_e$ = effective mass, which is a function of engine resistance,
$a$ = acceleration due to vehicle interaction, and
$\eta$ = driveline efficiency.

The effective mass $M_e$ reflects the increase in the vehicle mass because of the inertia of the engine, wheels, tires, and driveline. Biggs and Akcelik (*10*) argue that the effect of this increase in vehicle mass is reflected in the efficiency parameter, which relates to overall vehicle efficiency, not just engine efficiency.

The method proposed by Bester (*11*) to estimate the acceleration due to vehicle interaction is discussed later.

It is impossible for motorists to drive at a constant speed, although they may wish to do so. The presence of high volumes and the geometric characteristics of the highway often force the motorist to change speed. Montroll and Potts (*12*) showed that these accelerations follow a normal distribution. The standard deviation of these accelerations, which is called *acceleration noise*, gives an indication of the severity of speed changes. Therefore the acceleration due to traffic interaction could be estimated by using acceleration noise.

Acceleration noise has two components: natural noise ($\sigma_n$), which can be ascribed to the driver and the road, and the traffic noise ($\sigma_t$), which is generated by traffic interactions (*13*). Drew et al. (*14*) showed, assuming a linear speed density relationship, that

$$\sigma_t = \sigma_{tm}\left[1 - 6.75\left(\frac{k}{k_j}\right) + 13.75\left(\frac{k}{k_j}\right)^2 - 6.75\left(\frac{k}{k_j}\right)^3\right] \quad (3)$$

where

$\sigma_t$ = acceleration noise due to traffic interaction,
$\sigma_{tm}$ = maximum acceleration noise due to traffic interaction,
$k$ = density, and
$k_j$ = jam density.

Herman et al. (*13*) found that under nearly ideal geometric conditions and no traffic the natural component of acceleration noise $\sigma_n$ is 0.0976 m/sec$^2$ (0.32 ft/sec$^2$). Jones and Potts (*15*) showed that the natural acceleration noise increases for nonideal geometric conditions. Drew et al. (*14*) examined the effectiveness of using acceleration noise as a measure of level of service and found that the maximum acceleration noise due to traffic interaction varied between 0.305 and 0.732 m/sec$^2$ (1 and 2.4 ft/sec$^2$), with a few observations greater than 0.732 m/sec$^2$ (2.4 ft/sec$^2$).

The total acceleration noise $\sigma$ is equal to the sum of $\sigma_t$ and $\sigma_n$. The acceleration due to traffic interaction is calculated assuming that the accelerations follow a normal distribution $N(0,\sigma^2)$. The method of calculation can be explained, see Figure 1, which shows the normal probability density function. The shaded area under the curve gives an indication of the proportion of time (or distance) during which the acceleration is between $a_1$ and $a_2$. With the band sufficiently narrow, it can be assumed that the acceleration is $(a_1 + a_2)/2$. After the acceleration is estimated, the total fuel consumption can be estimated by adding the constant-speed fuel consumption and the additional fuel consumption due to vehicle interaction. For densities less than one-third jam density, it was found that the additional fuel consumption due to vehicle interaction is negligible (*11*).

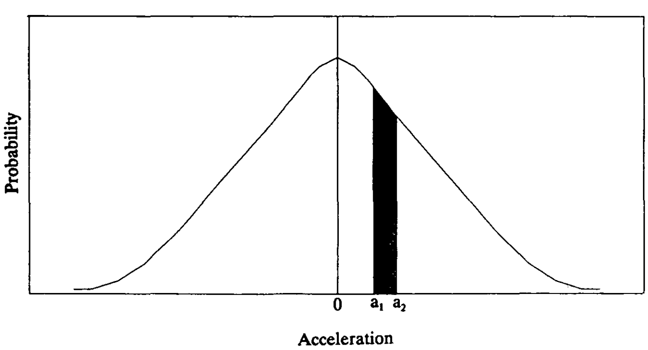


**FIGURE 1 Normal probability density function.**

## MODEL IMPLEMENTATION

The review of previous work on fuel consumption models indicated that a relation of the form shown below is suitable for implementation in FREFLO, considering the traffic variables generated by FREFLO logic and the available fuel consumption data.

$$F_x = P_1 + \frac{P_2}{V} + P_3V^2 + P_4a_e + P_5[a_e^2]_{a_e>0} \quad (4)$$

If the expression $P_1 + P_3V^2 + P_4a_e$ is negative, then

$$F_x = \frac{P_2}{V} \quad (5)$$

where

$F_x$ = fuel consumption per unit distance;
$V$ = average speed;
$a_e$ = effective acceleration;
$P_1$, $P_3$, $P_4$ = constants derived from the rolling, air, and effective inertial resistances, respectively;
$P_2$ = a constant related to idle fuel consumption; and
$P_5$ = a constant related to the product of inertial energy and acceleration.

Acceleration noise, which is a function of link density, was used to approximate the acceleration due to vehicle interaction because FREFLO does not generate information on the instantaneous acceleration of individual vehicles. Density is one of the measures of effectiveness generated by FREFLO.

The fuel consumption data used for calibrating the parameters in Equations 4 and 5 are based on the results of a study by McGill (*16*) and are the most recently available data. The vehicles used for the study are representative of 64 percent of the 1980 to 1992 passenger vehicle fleet, which includes pickup trucks. The test vehicles were selected on the basis of an exhaustive study by FHWA, resulting in passenger vehicle fleet projections up to 1992 (*17*). The results of McGill's study (*16*) include tables and graphs that relate fuel consumption and emissions to vehicle speed and acceleration. From the results of that study FHWA is currently updating fuel consumption and emissions estimation algorithms in traffic models including NETSIM and TRANSYT-7F.

As mentioned earlier fuel consumption is a function of engine speed and throttle opening and not on-road vehicle speed. Therefore fuel consumption was related to engine speed and throttle opening in one data base, and in a second data base engine speed and throttle opening were related to the on-road vehicle speed and acceleration. The two data bases were then merged to produce the final tables and graphs that relate fuel consumption to vehicle speed and acceleration.

The proportion of the vehicle population represented by each test vehicle was used by FHWA to combine the individual fuel consumption tables and generate a composite fuel consumption table that is representative of the vehicle fleet in the United States. The percentages represent the 1985 vehicle fleet.

The composite fuel consumption table obtained from FHWA was used to compute fuel consumption in gallons per mile at

different speeds and accelerations. Perhaps because the fuel consumption rates of vehicles with different operating ranges were combined, the composite fuel data exhibited a drop in the rate of fuel consumption at high speeds, as shown in Figure 2. At higher speeds the power requirements would increase, leading to a higher rate of consumption. Because of this inconsistency these data were not used for calibration.

The model was calibrated for constant speeds and for the additional fuel consumed because of acceleration separately to reduce the correlation between parameters. The air drag and rolling friction coefficients computed from the model parameters would be unreliable if the correlation between them is high. A comparison of the computed and theoretical values of coefficients was made as a partial validation.

### Constant Speed

The following equation explains the variation in fuel consumption as a function of speed when the acceleration is zero:

$$F_0 = P_1 + \frac{P_2}{V} + P_3V^2 \qquad (6)$$

The parameter $P_2$ was calculated separately on the basis of the composite idling fuel consumption rate, which is a weighted average of the individual vehicle idling fuel consumption rates presented by McGill (*16*) as part of study results. Assigning a fixed value to $P_2$ would thus reduce the correlation between parameters. The remaining parameters, $P_1$ and $P_3$, were calibrated by using the constant-speed fuel consumption rates (zero acceleration).

### Additional Fuel Due to Acceleration

The following equation explains the additional fuel consumed to overcome inertial forces:

$$F_a = P_4a_e + P_5[a_e^2]_{a_e>0} \qquad (7)$$

Parameters $P_4$ and $P_5$ were calibrated by using the additional fuel consumed because of positive accelerations. The additional fuel was obtained by subtracting the constant-speed fuel consumption rate at a particular speed from the fuel consumption rate at positive accelerations for the same speed. Negative accelerations were not used for calibration because the additional fuel consumed for negative accelerations, obtained as described above, was negative.

It should be noted that the additional fuel consumption rates at low speeds [generally less than 16 km/hr (10 mph)] have not been used for calibration. At very low vehicle speeds the power is relatively high (because the vehicle starts from rest), and the engine speed is low. The assumption that the fuel efficiency factor $\beta_1$ in Equation 1 is constant is invalid because under these power and engine speed conditions the fuel efficiency is less than average (*18*). The exclusion of fuel rates at low speeds would result in an underestimation of fuel consumption at these speeds. However speeds below 16 km/hr (10 mph) are not very common in typical on-road driving on freeways. Therefore the error due to this underestimation would not be substantial.

### Resulting Model

The relation resulting from the calibration is shown in Equations 8 and 9:

$$F_x = 12.76 + \frac{700}{V} + 0.0023V^2 + 39.21a_e + 0.0033[a_e^2]_{a_a>0} \qquad (8)$$

If the expression $12.76 + 0.0023V^2 + 39.21a_e$ is negative, then

$$F_x = \frac{700}{V} \qquad (9)$$

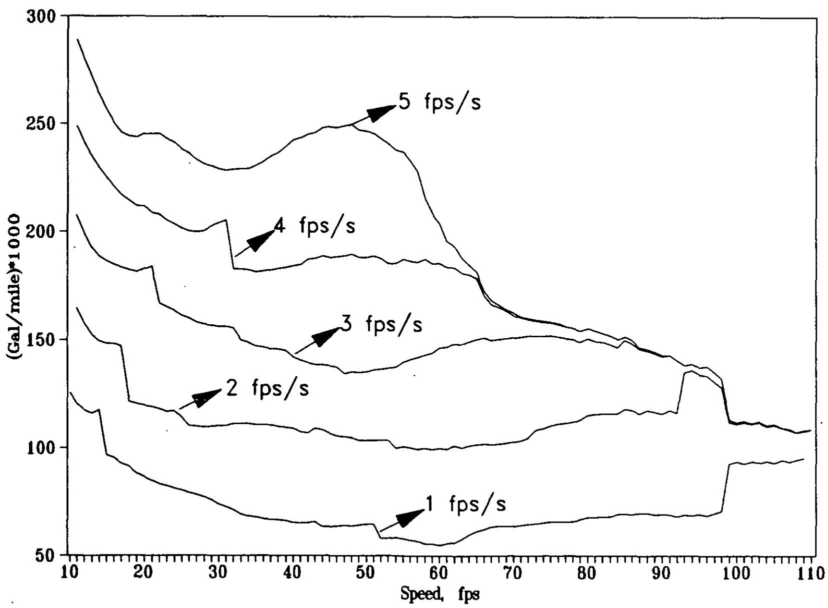


**FIGURE 2 Composite fuel consumption data.**

where

$F_x$ = fuel consumption (in gal/mi * 1,000),
$V$ = speed (in ft/sec), and
$a_e$ = acceleration (in ft/sec$^2$).

The value of 700 for the parameter $P_2$ in Equation 9 corresponds to an idling fuel consumption rate of 0.5 ml/sec, which is the weighted average of the idling fuel consumption rates of all the test vehicles. Equation 8 explains 99.5 percent of the variation in the observed constant-speed fuel consumption data and 86.1 percent of the variation in fuel consumption because of acceleration.

At negative accelerations it was observed that the estimated fuel consumption rate is lower than the observed fuel consumption rate. For constant speed, that is, zero acceleration, the estimated fuel consumption rate compared very well with the observed fuel consumption rate. For positive accelerations the observed and the estimated fuel consumption rates match very closely at lower speeds. The deviation between the observed and the estimated fuel consumption rates at higher speeds is due to an illogical fall in the rate of consumption at higher speeds (Figure 2).

At low speeds it was observed that the estimated fuel consumption rate is always lower than the observed rate. The amount of underestimation depends on the rate of acceleration. The difference between the observed and the estimated values at high acceleration rates is greater than that at lower acceleration rates. This underestimation is due to a decrease in fuel efficiency at high accelerations and low engine speeds. However the error due to this underestimation is not expected to be large because speeds below 16 km/hr (10 mph) are not very common over long periods of time on freeways. Moreover most traffic models are not sufficiently capable of simulating facilities that operate under extremely congested conditions over prolonged periods of time. Hence the measures of effectiveness generated would not be reliable in any event.

### Model Incorporation in FREFLO

The two segments of the model calibrated as discussed above were combined, and the resulting fuel consumption model was built into FREFLO logic. The flow chart in Figure 3 shows how the fuel consumption algorithm fits into FREFLO logic. As can be seen from the flow chart, fuel consumption is calculated at every time interval.

The changing conditions that prevail over a roadway network are either endogenous or exogenous. The exogenous data, specified by the user, include changes in traffic volumes, turning movement percentages, lane channelization, and so on. CORFLO allows the user to partition the simulation time into a series of "time periods" (TPs) of various durations. Each set of exogenous input data applies for and remains constant during one TP.

Each TP is further subdivided into a sequence of time intervals (TIs). Each simulation model requested is brought into and out of computer central memory once each TI. The output of cumulative simulation statistics is available only on a TI basis. The TI duration is typically set to the most common signal cycle length in a study network.

Each TI is again subdivided into time slices so that the effect of changing traffic conditions on adjoining links could be considered while simulating traffic on a particular link. Within a time slice traffic simulation on a link is independent of the conditions on any other link.

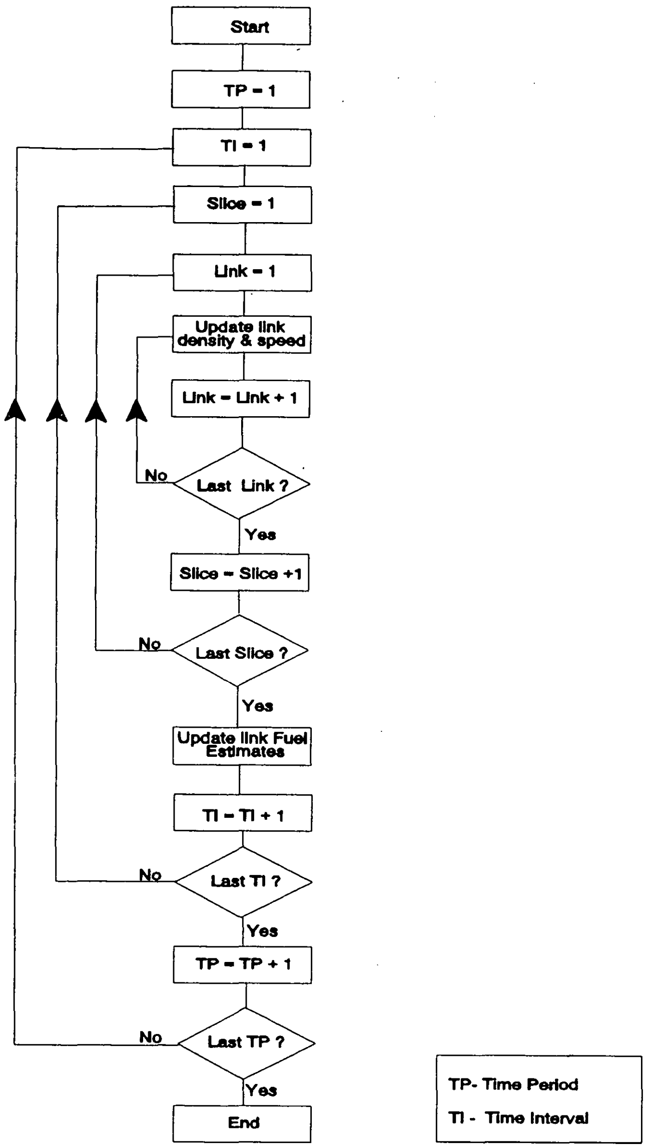


**FIGURE 3 Fuel consumption algorithm in FREFLO logic.**

FREFLO has two substantially dissimilar equilibrium speed-density relationships embedded in its logic. The choice of the relationship to be employed for simulation is specified by the user. The jam density value corresponding to the speed-density relationship employed for traffic simulation is used in the computation of acceleration noise by using Equation 3.

During those TIs when the average speed on the link is zero the total fuel consumed has been assumed to be equal to the sum of the idling fuel consumption of all vehicles stored on the link during the interval.

The width of the band used to estimate the effective acceleration from acceleration noise $\sigma$ (Figure 1) was set at $0.25 * \sigma$. This implies a maximum width of 0.213 m/sec$^2$ (0.7 ft/sec$^2$) at the maximum total acceleration noise of 0.854 m/sec$^2$ (2.8 ft/sec$^2$).

A maximum acceleration noise due to traffic interaction $\sigma_{tm}$ of 0.732 m/sec$^2$ (2.4 ft/sec$^2$) has been assumed on the basis of earlier

findings (*14*). The natural component of acceleration noise $\sigma_n$ has been assumed to be 0.293 m/sec$^2$ (0.4 ft/sec$^2$) (*13,15*). A maximum acceleration noise due to traffic interaction $\sigma_{m}$ of 0.732 m/sec$^2$ (2.4 ft/sec$^2$) implies that at jam density and assuming a normal distribution, about 4.56 percent of vehicles would have acceleration/deceleration greater than 1.71 m/sec$^2$ (5.6 ft/sec$^2$). It is not uncommon to have vehicles accelerating or decelerating at about 1.53 to 1.83 m/sec$^2$ (5 to 6 ft/sec$^2$) under congested, stop-and-go conditions on a freeway.

## MODEL VALIDATION

To validate the assumptions made regarding the form of the fuel consumption relationship, the air drag and rolling friction coefficients estimated from the calibrated model parameters were compared with the theoretically expected values. To validate the estimation of the acceleration due to vehicle interaction and also the incorporation of the model into FREFLO logic, the fuel consumption estimates from FREFLO were compared with those produced by INTRAS.

### Comparison of Coefficients

The air drag and rolling friction coefficients were computed from the calibrated model parameters in Equation 8. The masses of the vehicles were obtained from *Ward's Automotive Year Book* (*19–22*). The composite mass, equal to the weighted mean of individual vehicle masses, was found to be approximately 1590 kg (3,800 lbs). The air density was assumed to be 1.059 kg/m$^3$ (0.0662 lb/ft$^3$). This density is applicable for altitudes up to 1525 m (5,000 ft) above sea level. The frontal area of the composite vehicle was also computed as the weighted average of the individual vehicle frontal areas. The frontal area of individual vehicles was obtained from the vehicle dimensions presented in *Ward's Automotive Year Book* (*19–22*). The area used in the calculations was 2.8 m$^2$ (30.14 ft$^2$).

On the basis of the values given above the coefficients of air drag and rolling friction for the composite vehicle were found to be 0.23 and 0.01, respectively. As mentioned earlier the air drag coefficient for automobiles is generally between 0.25 and 0.55 and the rolling friction coefficient is in the range of between 0.01 and 0.017 (*23*). However it could be seen that the computed values for these coefficients are at the lower boundaries of the range of feasible values. This is because of a high value of the fuel efficiency factor $\beta_1$.

The model in Equation 8 accounts explicitly for air drag and rolling resistance only. Engine drag resistance and fuel consumed by accessories are not represented in the model and therefore are reflected in a high fuel efficiency factor $\beta_1$. The value of $\beta_1$ was found to be 0.63 L/kWh. Because the air drag coefficient and rolling friction coefficient are calculated on the basis of this value of $\beta_1$, they tend to be low.

### Comparison with INTRAS

INTRAS, FHWA's microscopic freeway simulation model, was used as a benchmark against which to compare the fuel consumption estimates from the model incorporated into FREFLO. Unfortunately the fuel consumption estimates from INTRAS have not been validated. Therefore the principal objective of the comparison with INTRAS was to verify the absence of errors in the algorithm incorporated into FREFLO and the reasonableness of the results.

The default fuel consumption data in INTRAS are different from those used in FREFLO. To ensure that the fuel consumption data employed by INTRAS and FREFLO are identical, for comparison of fuel estimates, the default fuel consumption rates in INTRAS were replaced with the rates used in the present study.

Because the scope of the present study was limited to passenger vehicles only, bus and truck traffic was not simulated in either model. No further classification of passenger vehicles was used, although it is possible to have six different classes in INTRAS, to ensure similar traffic conditions in both models.

INTRAS has more than 20 embedded calibration parameters, of which 16 are distributions. Such a large number of calibration parameters would entail a tedious calibration process to make the model replicate known data on a certain site. However it was found that INTRAS produced results comparable to the actual conditions with the embedded calibration parameters for the test site used here (Barnes, unpublished data, 1989).

It was found in an earlier study that FREFLO produced results fairly consistent with the actual operating conditions of the test site when the freeway capacity was between 2,000 and 2,100 vehicles per hour per lane (vphpl) (Barnes, unpublished data, 1989). A capacity of 2,045 vphpl was assumed for the present study.

To ascertain the validity of assigning different jam density values depending on the speed-density relationship used and also to gauge the difference in fuel consumption estimates with either relationship utilized, both speed-density relationships in FREFLO were tested.

The traffic data collected from a 4.7-km (2.9-mi) section of Interstate 35 in Travis County, just north of Austin, Texas (Figure 4) was used for comparison of fuel estimates from FREFLO and INTRAS. It is the southbound roadway of a four-lane freeway in rolling terrain with 3.66-m- (12-ft)-wide lanes, a 3-ft paved left shoulder, and a 3.05-m (10-ft) paved right shoulder.

The differences in network coding requirements between INTRAS and FREFLO render it impossible to specify identical network configurations for the two models. However the differences were kept to a minimum.

The total simulation period of 2 hr was split into 12 time periods each of 10 min in duration. The cumulative measures generated by FREFLO and INTRAS were disaggregated to reflect conditions during each time period. Traffic variables were aggregated over each time period because the 10-min duration of the time periods was assumed to provide a fairly good indication of the varying traffic conditions.

It was observed that the cumulative fuel consumption estimates after 2 hr from the two simulation programs differ by about 11 percent, with the INTRAS estimates being higher. The biggest difference in the fuel estimates between the two programs occurred during a period of transition from congested to normal operations, when the two simulation algorithms also differed substantially in their estimates of the traffic variables. The difference in the traffic variable estimates may have contributed to the overall difference in the fuel estimates produced by FREFLO and INTRAS.

During the early period of simulation the fuel estimates resulting from the application of the two speed-density relations in

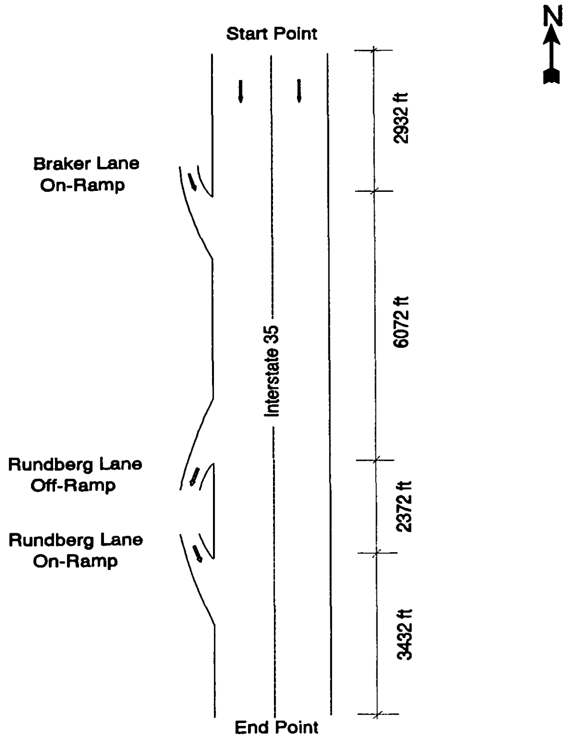


**FIGURE 4 I-35 in Travis County, north of Austin, Texas.**

FREFLO differed fairly substantially. This difference may have been due to the lower value of jam density in the first equilibrium speed-density relationship than in the second relationship, which makes the fuel consumption algorithm more sensitive to increases in the link densities, because the acceleration noise is a function of the ratio of density to jam density.

The assumption that the additional fuel consumed because of vehicle interaction is zero for densities of less than one-third jam density may lead to a small underestimation of fuel consumption because, even under free-flow conditions, it is not possible to maintain absolutely constant speeds. The natural component of acceleration noise contributes to some additional fuel consumption.

In conclusion the fuel estimates from FREFLO and INTRAS were generally comparable during most of the simulation period. The small discrepancies between the estimates may be attributed to the differences in the traffic variables generated by the two programs and also to the minor differences in network coding. It should be reiterated, however, that there was no study to validate the fuel consumption estimates produced by INTRAS with those observed under actual road conditions.

## SUMMARY AND RECOMMENDATIONS

A fuel consumption model for FREFLO was developed, calibrated, and implemented. A limited validation study was also conducted. The ability to estimate freeway fuel consumption makes CORFLO a more powerful tool for evaluating traffic management strategies. FHWA requested and was granted a license to implement the fuel consumption model and the related computer code developed in the present study in the official version of CORFLO.

In this study the fuel consumption characteristics of passenger vehicles operating on an uninterrupted flow facility under hot stabilized conditions, and assuming that the engine is properly tuned, were considered. However it should be noted that the fuel consumption characteristics when the engine is cold, and also when the engine is not properly tuned, could be substantially different and should also be considered to obtain more accurate estimates of fuel consumption.

The scope of the study was limited to passenger vehicles only. It is recommended that other classes of vehicles also be considered for fuel consumption estimation. Without considering bus fuel consumption, it may not be possible to estimate fuel savings from high-occupancy vehicle lane use and transit improvements by using CORFLO.

Although NETFLO, the arterial street component of CORFLO, has a fuel consumption algorithm, it is based on old fuel consumption rates. For CORFLO to be an effective tool for evaluating corridor traffic management strategies, the model in NETFLO should also be updated with the latest fuel consumption data.

The purpose of any traffic simulation model is to evaluate the benefits that could be obtained in the form of reductions in delay, stops, fuel consumption, and so on by adopting alternative traffic management strategies. To estimate fuel consumption most traffic models have a fuel consumption module. However there has been no study in the United States to validate the fuel estimates from those models with those actually observed. Because the fuel estimates are an important output from simulation, which is used in evaluating traffic management strategies and making decisions, it is recommended that a study be conducted to validate the fuel estimates from a microscopic model like INTRAS, which could then be used as a benchmark to validate other more aggregate models like FREFLO. A microscopic model is recommended for this purpose because the actual conditions are represented in greater detail in microscopic models, and the estimates of traffic variables are generally expected to be closer to the actual values.

## ACKNOWLEDGMENTS

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**PART 2**

# Environmental Analysis

# On-Site Treatment of Contaminated Soils and Wastes from Transportation Maintenance Activities Using Oxidative Processes

CYNTHIA J. SPENCER, PATRICK C. STANTON, AND RICHARD J. WATTS

The treatment of contaminated timbers and soils was investigated by using catalyzed hydrogen peroxide, a procedure based on Fenton's reagent [hydrogen peroxide and iron(II)]. The process produces hydroxyl radicals, which oxidize nearly all organic contaminants. Wood posts contaminated with pentachlorophenol (PCP) and creosote were treated by the peroxide process, resulting in 84 percent degradation of the PCP and 74 percent degradation of the creosote with 6 percent hydrogen peroxide and 56 mg of Fe per L. The estimated cost was $18/kg of wood. A natural soil contaminated with 1000 mg of diesel fuel per kg was treated with a matrix of five hydrogen peroxide concentrations (1000, 5000, 10 000, 50 000, and 100 000 mg/L) and four slurry volumes (5, 10, 20, and 30 times the field capacity of the soil). The most efficient treatment was found with 1000 mg of hydrogen peroxide per L at a volume of 30 times the soil field capacity, with an estimated hydrogen peroxide cost of $15/909 kg (1 U.S. ton) of soil. Catalyzed hydrogen peroxide soil remediation may be implemented through a number of process configurations, including in situ and ex situ applications. The methodology also meets the primary policy goals of state and federal regulatory agencies, in that the waste components can be mineralized to carbon dioxide and water, which are nontoxic end products.

The high demand for petroleum results in many possible sources of contamination, including accidental releases associated with highway maintenance, spills during transport, accumulation on roadways from improperly maintained cars, and leaking underground storage tanks (*1*). Of the several million underground storage tanks located in the United States, it is estimated that 10 to 25 percent of them may be leaking (*2*). Therefore approximately 500,000 of the existing underground storage tanks may leak before they are replaced with new ones that have corrosion protection and leak detection systems. As a result of these releases surface soils often become contaminated with petroleum hydrocarbons that may subsequently contaminate groundwater.

The Environmental Protection Agency (EPA) is continually searching for new soil remediation technologies that provide for the destruction of contaminants with lower operational costs. Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act requires EPA to seek permanent solutions and alternative treatment technologies (*3*). The in situ or on-site treatment of contaminated soils has recently gained widespread attention and will become more commonplace as the landfill disposal of toxic residuals becomes more restricted (*4*). The introduction of a strong oxidant, such as the hydroxyl radical, is one possible method for destroying hazardous contaminants. The use of Fenton's reagent, consisting of hydrogen peroxide catalyzed by iron(II), is a documented process that forms the hydroxyl radical (*5*):

$$Fe^{2+} + H_2O_2 \longrightarrow Fe^{3+} + OH^- + OH \quad (1)$$

The hydroxyl radical is a strong, nonspecific oxidant capable of degrading essentially all environmental contaminants.

Fenton's reagent was first applied to the treatment of contaminants in water. Barbeni et al. (*6*) investigated the degradation of chlorophenols, and Murphy et al. (*7*) successfully oxidized a formaldehyde waste stream. Subsequent research showed that catalyzed hydrogen peroxide can be used as a pretreatment process for wastewater that contains refractory organics or compounds that are toxic to microorganisms (*8*).

Watts et al. (*9*) first reported the use of catalyzed hydrogen peroxide for the remediation of contaminated soils, and Tyre et al. (*10*) subsequently investigated the treatment of four biorefractory contaminants in natural soils with varying organic carbon contents. They found that the stoichiometric ratios of contaminant degradation to hydrogen peroxide consumption were sensitive to both the concentration of iron addition and the soil's organic carbon content. Watts and Udell (*11*) compared the standard Fenton's reagent procedure, the sequential addition of $Fe^{2+}$ and hydrogen peroxide, and the use of the mineral goethite as the iron source to treat silica sand contaminated with pentachlorophenol (PCP). The most efficient process for PCP degradation was the mineral-catalyzed system.

Research to date has documented optimum conditions for oxidizing contaminants in the aqueous phase by using Fenton's reagent and has provided initial data on what variables control the efficiency of treatment with contaminated soils. However minimal research has focused on real-world samples. The objective of the research described in this paper was to investigate the effectiveness and cost of treating a variety of matrices including timber samples and a natural soil system contaminated with diesel fuel.

## METHODOLOGY

### Timber Treatment

Contaminated posts supplied by the Washington State Department of Transportation were first analyzed by gas chromatography to

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determine the primary contaminants and their respective concentrations. Before starting the experiments timber pieces were chipped from the outside of the posts to approximately 2 cm in length and 2 mm in diameter. A variety of treatment conditions were tested by using 0.1 g of wood at pH 3.0 along with deionized water controls. The consumption of hydrogen peroxide was monitored daily over a 2-day period.

### Soil Treatment

The soil used was a Palouse loess with an organic carbon content of 0.11 percent and a field capacity of 356 ml/kg of soil. Diesel fuel was selected as the contaminant because of its widespread use. The soil was spiked at a concentration of 1000 mg/kg by adding 0.24 ml of diesel to 0.2 kg of soil.

A two-dimensional matrix was used to investigate the effects of hydrogen peroxide concentration and volume on total petroleum hydrocarbon degradation and stoichiometry. The experiment used a matrix of five hydrogen peroxide concentrations (1000, 5000, 10 000, 50 000, and 100 000 mg/L) and four volumes (5, 10, 20, and 30 times the field capacity of the soil). No iron addition was necessary because the naturally occurring iron minerals provided sufficient iron to catalyze the Fenton's reactions (*11*).

The experiments were conducted by placing 5.0 g of soil into individual vials and then adding hydrogen peroxide and adjusting the pH to 3.0. The hydrogen peroxide consumption was monitored daily; when its concentration dropped below the detection level, the samples were extracted with 6 ml of hexane and analyzed by gas chromatography.

### Analyses

Hydrogen peroxide consumption was monitored by iodate titration for concentrations of >0.1 percent (*12*) and by $TiSO_4$ spectrophotometry for concentrations of $\leq$0.1 percent (*13*). The contaminant concentration was determined by a shake extraction and then gas chromatographic analysis (*10*). The solvent was added to the samples by using a volumetric glass pipet, and then the vials were placed on a wrist shaker for 24 hr. The extract was then analyzed by using a Hewlett-Packard 5890A gas chromatograph with a flame ionization detector and a DB-5 capillary column [10 m × 0.18 mm (i.d.)]. The wood samples were analyzed under the following conditions: initial oven temperature, 140°C; program rate, 7°C/min; final oven temperature, 220°C; injector temperature, 260°C; and detector temperature, 350°C. The samples were analyzed under the following conditions: initial oven temperature, 80°C; program rate, 5°C/min; final oven temperature, 250°C; injector temperature, 260°C; and detector temperature, 350°C.

## RESULTS AND DISCUSSION OF RESULTS

### Timber Treatment

Gas chromatographic analysis, using retention times, showed that the primary contaminant in the wood posts was PCP, which made up approximately 30 percent of the total contaminants. The remaining compounds were assumed to be creosote. The concentration of PCP in the outside 1 cm of the post was approximately 3000 mg/kg, and the total contaminant concentration was approximately 10 000 mg/kg. Initially 73 percent of the total contaminants were degraded by using 20 ml of 6 percent hydrogen peroxide and 56 mg of Fe per L over a 2-day period, as shown in Figure 1. A subsequent experiment with the same hydrogen peroxide and iron concentrations was conducted, but the volume was varied to determine the effect on the ratio of hydrogen peroxide consumed to wood treated. Hydrogen peroxide analysis showed that after 2 days the majority of the peroxide was gone. Figures 2 and 3 show that 20 ml of hydrogen peroxide per 0.1 g of wood remains the optimum volume, with 84 percent degradation of PCP and 77 percent degradation of total contaminants. On the basis of these conditions only limited increases in degradation occurred by increasing the dosage, which may be because of mass transfer limitations. This treatment would reduce the PCP concentration from 3000 to 480 mg/kg and the total contaminant concentration from 10 000 to 2300 mg/kg at a ratio of approximately 12 000 mg of hydrogen peroxide per g of wood. The estimated cost of hydrogen peroxide for this treatment would be $18 to treat 1 kg of wood. The treatment of contaminated wood can be achieved with catalyzed hydrogen peroxide. However the wood posts would

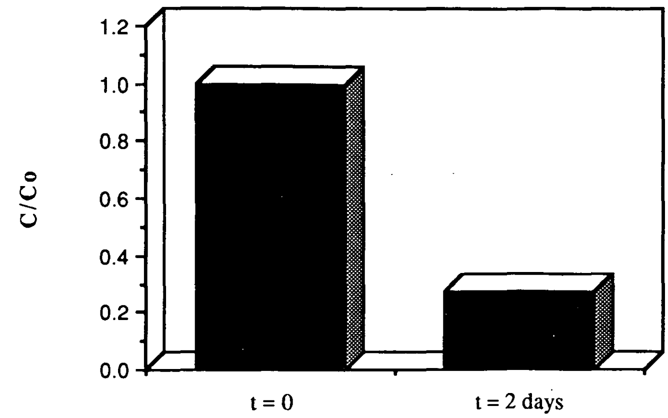


**FIGURE 1 Degradation of wood contaminants using catalyzed hydrogen peroxide treatment.**

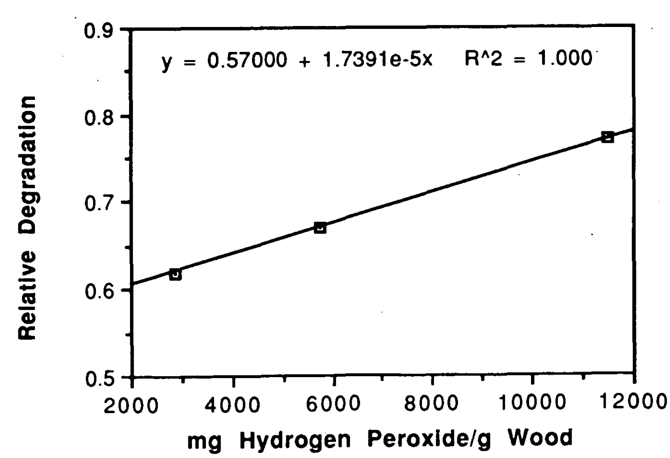


**FIGURE 2 Degradation as a function of efficiency for total wood contaminants using catalyzed hydrogen peroxide.**

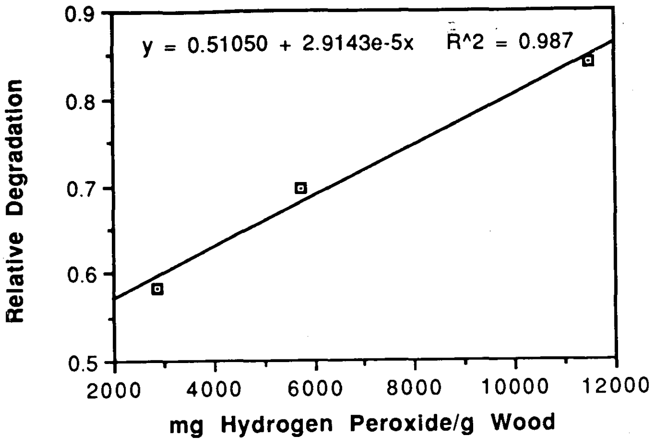


**FIGURE 3 Degradation as a function of efficiency for PCP on wood samples using catalyzed hydrogen peroxide.**

most likely have to be cut into small pieces to provide the necessary surface exposure for oxidative treatment.

A pressure reactor was used to investigate treatment without cutting the wood posts into small pieces. Under a pressure of 200 psi, 74 percent of the total contaminants and 67 percent of the PCP were degraded. Although this procedure would be more expensive and more complex, it offers promise for the treatment of contaminated timbers.

## Soil Treatment

Hydrogen peroxide analysis data show that the oxidant source decomposed more rapidly in the smaller-volume soil slurries and that its concentrations dropped to below the detection level within 8 days. Table 1 shows the removal of diesel fuel from the soils for the matrix of experimental conditions. The highest degradation occurred under the conditions of 5000 mg of hydrogen peroxide per L at a volume of 30 times the field capacity of the soil. An estimated peroxide cost for this treatment is $77/909 kg (1 U.S. ton) of soil. Table 2 gives the results in efficiency (i.e., grams of hydrogen peroxide consumed per gram of diesel treated). The most efficient system was characterized by 1000 mg of hydrogen peroxide per L at a volume of 30 times field capacity. Under these conditions the estimated cost of hydrogen peroxide for this treatment would be $15/909 kg (1 U.S. ton) of soil. These results

**TABLE 1 Degradation of Diesel Fuel in Palouse Loess Soil**

| Hydrogen Peroxide | Percent Degradation | | | |
|---|---|---|---|---|
| | Volume of Hydrogen Peroxide x Field Capacity | | | |
| Concentration | 5 | 10 | 20 | 30 |
| 1000 mg/l | x | 12% | 20% | 59% |
| 5000 mg/l | x | 19% | 41% | 97% |
| 10000 mg/l | 17% | 28% | 35% | 80% |
| 50000 mg/l | 51% | 47% | 53% | 80% |
| 100000 mg/l | 50% | 62% | 61% | 64% |

**TABLE 2 Treatment Efficiency for Diesel Fuel in Palouse Loess Soil**

| Hydrogen Peroxide | Treatment Efficiency (g $H_2O_2$/g diesel) | | | |
|---|---|---|---|---|
| | Volume of Hydrogen Peroxide x Field Capacity | | | |
| Concentration | 5 | 10 | 20 | 30 |
| 1000 mg/l | x | 36 | 42 | 32 |
| 5000 mg/l | x | 112 | 102 | 59 |
| 10000 mg/l | 122 | 148 | 231 | 145 |
| 50000 mg/l | 204 | 428 | 681 | 624 |
| 100000 mg/l | 415 | 636 | 1076 | 1405 |

provide lower costs compared with those for the conditions reported in previous work (*9,10*).

The results suggest that the low concentrations and high volumes of hydrogen peroxide provide optimum conditions for treating diesel-contaminated soils. This could be explained by the fact that the higher volume promotes desorption of the contaminant from the soil particles into the aqueous phase and then hydroxyl radical oxidation.

## Engineering Applications

Watts et al. (*9*) described the advantages of adjusting soils to an acidic pH to promote Fenton-like reactions. They found that although the oxidations occur at neutral pH, hydrogen peroxide use is significantly more efficient at neutral pH. The concerns associated with the adjustment of large quantities of soils to pH 2 to 3 have been well documented (*14*). The problems associated with pH adjustment are related more to logistics than to costs. Mineral acids are relatively inexpensive, and their addition greatly improves the stoichiometry of hydroxyl radical generation. However because of the difficulty of adding acid to large volumes of soil, this may prove to be impossible. In addition interactive conditions related to slurry volume and hydrogen peroxide concentration may provide some process condition in which efficient oxidations may be maintained at acidic pH.

On-site soil remediation can be conducted under either in situ or ex situ conditions. In situ treatment involves treatment of the soil while it is still in place. Ex situ treatment consists of excavation of the soil and treating it in an on-site reactor.

During in situ treatment the hydrogen peroxide would be applied directly to the contaminated soil. Possible modes of applications include intermittent spraying, use of a continuous sprinkler system, or nozzle injection.

Ex situ treatment applications would involve placement of the excavated soil and the hydrogen peroxide solution into a batch reactor. The reactor may consist of a polyethylene tank, a shallow earth basin lined with a high-density polyethylene liner, or a concrete mixer. The mixing action that would be provided by the concrete mixer may enhance mass transfer and reduce the time required for the reaction to take place. Another possibility for ex situ treatment would be to create a leach system, in which the excavated soil is piled onto a concrete barrier with a collection system. The hydrogen peroxide solution could then be applied with a sprinkler system, allowing the solution to leach through the soil. Different soil and contaminant characteristics affect treat-

ment conditions, such as the concentration and volume of hydrogen peroxide and the reaction time required. Therefore pilot studies may be needed to evaluate the scale-up effectiveness of different reactor configurations.

More risks are involved with in situ treatment because of the potential for leaching of contaminants or degradation products. Ex situ treatment is more conservative because there is more control over the process and the system is contained. As research continues emphasis will first be placed on ex situ treatment before in situ application processes are developed.

### Policy Considerations

The implementation of new and innovative remediation processes is based not only on its effectiveness and cost but also on its relationship to policy and the regulatory framework. A primary emphasis of remediation policy is waste destruction rather than storage or containment. As a corollary to contaminant destruction, state and federal regulatory agencies require that the process not produce by-products that are more toxic than the parent compound. Catalyzed hydrogen peroxide remediation of contaminated soils meets both of these criteria, because it has the potential to mineralize PCP and other contaminants (*9*). Because contaminants are mineralized to carbon dioxide and water, no toxic intermediates pose a threat to public health or the environment.

## CONCLUSIONS

The results of the experimental investigation described here show that catalyzed hydrogen peroxide can be used to effectively treat a variety of contaminated wastes. Contaminated timbers were effectively treated to remove 84 percent PCP and 77 percent total contaminants by cutting the timbers into small pieces; this was followed by catalyzed hydrogen peroxide treatment. A possible alternative that can be used to overcome these mass transfer limitations would be the use of a pressure reactor, which may allow penetration of the hydrogen peroxide and iron solution into the wood. Diesel-contaminated soil was effectively treated by using catalyzed hydrogen peroxide. Over 90 percent diesel removal was achieved with 5000 mg of hydrogen per L and 30 times field capacity at a cost of $77/909 kg (1 U.S. ton). However the most efficient system used 1000 mg of hydrogen peroxide per L and 30 times the soil field capacity, resulting in a cost of $15/909 kg (1 U.S. ton). Continued optimization will likely lower the chemical cost for catalyzed hydrogen peroxide treatment.

A number of engineering process configurations, including in situ and ex situ applications, are available for implementation and are currently being evaluated through pilot studies in the field.

Catalyzed hydrogen peroxide soil remediation meets one of the primary policy goals of state and federal regulatory agencies in that the waste components can be mineralized, and therefore the remediation does not result in the formation of more toxic degradation products.

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# Examination of State Policies on Endangered Species and Transportation Projects in the United States

ROBERT P. HANSON AND JOSEPH HUMMER

State departments of transportation have evolved many strategies for dealing with endangered species laws. It is likely that some states could develop more effective and efficient strategies if they knew other states' policies. To aid in an exchange of such information the authors developed and distributed a survey on state department of transportation strategies for dealing with endangered species. The survey involved 21 questions covering 11 policy issues. The mail-in and mail-back survey was sent to an environmental official of each of the 50 state departments of transportation. The survey response rate was outstanding—45 states provided detailed responses. A major pattern that emerged from the survey was the wide diversity of strategies for dealing with endangered species. Responses to questions regarding personnel who performed endangered species work and the effects of state endangered species laws showed wide variations in state strategies. Sixty-two species were named by the 45 responding states as one of their top three species in terms of compliance work. Most states have communities of protected plant species within their rights-of-way. Many differences in the ways that states approach protected species surveys for major corridor studies and for protected aquatic species were evident. The extent to which state departments of transportation have relocated protected species was identified. Only nine states have had projects stopped by endangered species, but most states have had projects delayed or redesigned because of endangered species. Questions regarding compliance with Section 7 of the Endangered Species Act identified national trends. Finally the unique policies of the states were identified.

Much attention has been focused on conflicts between construction projects and endangered species. This paper examines the relative difficulties that endangered species laws have caused state departments of transportation and examines states' approaches to compliance with those laws. To survey state policies a questionnaire was sent to all 50 state departments of transportation. Responses were received from 45 states. The survey responses detailed in this paper allow states to compare their policies with those of other states. Such a comparison may lead to better policy decisions regarding endangered species.

## BACKGROUND

### Federal Law

The U.S. Congress wrote the Endangered Species Act of 1973 to conserve threatened and endangered species and their physical environments. This law is regarded as the most comprehensive species protection program in the world (*1*). The act covers many different areas including the listing of threatened and endangered species; restrictions on the sale, importation, and "taking" of these species; and penalties for violations. The U.S. Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) are the federal agencies that administer the Endangered Species Act.

Of particular concern to transportation departments is Section 7 of the act, entitled "Interagency Cooperation." Section 7 requires federal agencies to ensure that their actions do not jeopardize the continued existence of any threatened or endangered species or adversely modify the habitats of such species. Section 7 also sets forth procedures for federal agencies to consult with FWS and NMFS about the effects of planned agency activities to ensure compliance with the Endangered Species Act. State departments of transportation must follow Section 7 requirements because a high percentage of transportation projects involve federal funding.

### State Laws

Thirty-seven states have laws protecting species that go beyond the federal protection provided by the federal Endangered Species Act (*1*). These laws offer varying degrees of protection. A December 1991 survey by Griffin and French (*1*) found that 12 states have protected species laws considered to be comprehensive (having met a set of criteria established by Griffin and French).

## SURVEY

The authors developed a 21-question survey to examine 11 policy issues. The answers to many additional questions were of interest but would have made the questionnaire too time-consuming and would jeopardize the response rate. Both "open" and "closed" question formats were used. Questions were refined by pilot testing the questionnaire on environmental staff of the North Carolina Department of Transportation. The questionnaire was sent to environmental officials of all 50 state departments of transportation. Respondents were offered a summary of survey results if they desired. The questionnaire was mailed on May 14, 1993, with a requested return date of June 30, 1993. Forty-five states responded to this questionnaire. Because of the high response rate follow-up telephone calls were not used.

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## SURVEY RESULTS

This section provides a discussion of the survey responses and their implications to policy issues. Figure 1 gives the questionnaire, with questions arranged according to the policy issue involved. Responses follow each question. A more detailed, state-by-state matrix of each state's response to the questionnaire is available from the authors.

Because species are protected under two classifications (threatened and endangered), the term *protected species* will be used in this paper.

### Policy Issue A: Difficulties in Implementing Transportation Projects

Media attention on protected species controversies may lead one to believe that these laws are a nearly insurmountable obstacle to project construction. However as indicated in the responses to Questions 1 through 3 (Figure 1), protected species have only rarely stopped projects. Thirty-six states have never had a transportation project stopped by protected species conflicts. Delays and redesign, however, are more common.

Almost all states indicated that protected species have caused delays in or redesign of projects. This shows that protected species are a concern to almost all states. With protected species policies causing delays or redesign in all but three and four states the benefits of information sharing regarding protected species policies are apparent.

The authors reviewed the responses to Questions 1, 2, and 3 to determine whether protected species conflicts are more common in any particular region of the United States, but they could not identify any regional trends. States with the most problems relating to protected species were distributed throughout the United States.

### Policy Issue B: Species Requiring the Most Compliance Work

Table 1 shows the species from each state that required the most compliance work. Table 1 provides an opportunity for information sharing between states. Projects may potentially have an impact on species that a state has not yet encountered. Occasionally FWS and NMFS may update the estimated habitat ranges for protected species. States may be required to evaluate the impacts to species recently identified within a project vicinity. A review of Table 1 will show whether other states have been dealing with these species. Coordination between states will likely save time and money.

Nine species were listed by three or more states. This indicates a high level of effort focused on these species. Coordination between states may prove beneficial to avoid duplication, to receive benefits of information sharing, and to improve protection of species.

### Policy Issue C: Determination of Species Presence on Major Corridor Studies

Protected species evaluations for major corridor studies can be expensive and time-consuming. A 32-km (20-mi) freeway project may have 97 km (60 mi) of preliminary alternatives that must be evaluated. A state's approach to performing protected species evaluations for these projects is an important policy decision.

As shown in Figure 1 21 states identify potential habitat for protected species along all preliminary corridors, but conduct field surveys for the selected alternative only. This saves the expense of conducting a protected species field survey for each preliminary corridor.

Fewer states (12 states) conduct field surveys for all preliminary corridors. A variety of other approaches to this issue were also identified, including the following:

- Two states decide on the level of work after conferring with the local FWS office, and
- One state conducts field surveys for the most likely corridors under consideration, but determines habitat presence for all corridors.

### Policy Issue D: Compliance Work for Aquatic Species

Protected aquatic species are one of the more difficult groups of species to address. Comprehensive field surveys for these species can be very labor intensive. If an aquatic species is not found, it may simply have avoided the subject stretch of water during the field work. The survey examined whether states conduct field surveys for aquatic species or simply make assumptions regarding species presence.

As shown in Figure 1 23 states conduct field surveys for aquatic species and 12 states assume that aquatic species are present without field surveys. Those 12 states avoid costs associated with aquatic field surveys. However the costs of protecting these species (extreme sedimentation controls, longer bridge lengths, etc.) may be excessive if the protected species is not actually present.

Eight states responded differently to this issue. The following were among the other responses:

- Six states coordinate with resource agencies before deciding on field surveys, and
- Two states conduct field surveys for immobile species such as mussels, but not for mobile species such as fish.

### Policy Issue E: State Laws Affecting Transportation Projects

Some state protected species laws do not require additional compliance procedures from transportation departments. Other state protected species laws are very strict and require compliance procedures similar to those required by the federal Endangered Species Act.

Figure 1 shows that 25 states have protected species laws that affect their departments of transportation. In Florida, Michigan, and Vermont state-listed species often play a significant role in locating highway corridors.

### Policy Issue F: Personnel Performing Species Evaluations

State departments of transportation have several options regarding the personnel conducting protected species evaluations. These de-

```
------------------------Policy Issue A-------------------------
1.  Have problems related to protected species stopped
transportation projects of your Department?
    often - 0*;  occasionally - 0;  rarely - 9;  never - 36
2.  Have problems related to protected species delayed
transportation projects of your Department?
    often - 1;  occasionally - 18;  rarely - 22;  never - 4
3.  Have problems related to protected species caused redesign
of transportation projects of your Department?
    often - 1;  occasionally - 16;  rarely - 24;  never - 3
------------------------Policy Issue B-------------------------
4.  List the three protected species which have required the
most compliance work (in terms of workdays) by your Department.
    responses shown in Table 1
------------------------Policy Issue C-------------------------
5.  How does your Department approach Endangered Species Act
compliance with regard to major highway corridor studies?  Note
that major studies are those which require an Environmental
Impact Statement (EIS).
    species habitat identified for all corridors under
    consideration and field surveys conducted later for
    selected alternatives only - 21;  field surveys conducted
    for all corridors under consideration prior to corridor
    selection - 12;  other - 10
------------------------Policy Issue D-------------------------
6.  When transportation projects cross water resources, how
does your Department comply with the Endangered Species Act
with regard to aquatic species (fish, mussels, etc.)?
    conduct field surveys for threatened and endangered aquatic
    species - 23;  assume aquatic species is present (without
    field surveys) and incorporate precautions into project
    design to minimize impacts - 12;  other - 8
------------------------Policy Issue E-------------------------
7.  Does your state have laws requiring additional compliance
procedures for your Department beyond federal Endangered
Species Act requirements?
    yes - 25; no - 20
Questions 8 and 9 applied to those answering "yes" to Q. 7.
8.  Does your Department perform field surveys for state-listed
protected species that are not on the federal Endangered
Species list?
    yes - 23;  no - 1
9.  How often do state-listed protected species play a
significant role in decisions regarding hwy. corridor location?
    often - 3;  occasionally - 11;  rarely - 9;  never - 2
------------------------Policy Issue F-------------------------
10. What personnel does your Department use to conduct
protected species evaluations?
    responses shown in Table 2
```

**FIGURE 1 Questions and responses for policy issues A to J.** *(continued on next page)*

cisions depend on policies regarding privatization, availability of qualified personnel, workloads, or the department's relationship with review agencies.

The survey asked about the type of personnel used by states for protected species compliance work and the percentage of work performed by each type. Table 2 shows that there is wide variation on state policies regarding this subject. Most states use a combination of in-house staff biologists and private firms. Resource agency and university staff are also used by 16 states and 5 states, respectively. One state uses resource agency staff for 100 percent of the protected species work. Other states may wish to consider these resource agency and university sources.

### Policy Issue G: Relocation of Protected Species Communities

The negative impacts of a project may be mitigated by relocating communities of protected species; however, survey results showed that many states have not used this approach. Twenty-five states have never relocated animal species, and 19 states have never relocated plant species.

States that have never relocated protected species may wish to consider this mitigation option. Half the responding states have relocated endangered species at least once, and three states do this often. These responses indicate that relocation of species is not

------------------------Policy Issue G------------------------

11. How often has your Department relocated communities of protected species discovered within the proposed alignment of transportation projects?

11.a. Protected animal species have been relocated. . .
**often - 2; occasionally - 5; rarely - 12; never - 25**

11.b. Protected plant species have been relocated. . .
**often - 2; occasionally - 8; rarely - 13; never - 19**

------------------------Policy Issue H------------------------

12. Does your Dept. have a formal review process to verify that protected species commitments made during Planning/EIS are carried out in the final design plans and construction?
**yes - 24; no - 21**

13. On what types of projects does your Department use the formal review process referred to in Question 12?
**federal-aid projects - 23; 100% state-funded projects - 19; state- and local-funded projects - 11**

------------------------Policy Issue I------------------------

14. Does your State have populations of protected plants within highway right-of-way limits?
**yes - 33; no - 11**

15. Has your Department taken precautions to ensure operations (such as maintenance, mowing, or new driveways) do not impact protected plants found within highway right-of-way?
**mowing restrictions - 13; herbicide restrictions - 11; special instructions to district personnel, construction crews, and contractors - 11; other - 10**

------------------------Policy Issue J------------------------

16. When projects are found to potentially impact federally protected species, what type of consultation with the U.S. Fish and Wildlife Service/National Marine Fisheries Service (USF&W/NMF) does your Department use?
**responses shown in Table 2**

17. Which agency acts as the lead agency during informal consultation with the USF&W/NMF?
**always your Department - 29; sometimes your Department and sometimes the FHWA - 9; always the FHWA - 7**

18. On federal-aid projects, how often does your Department prepare Biological Assessments for federally protected species identified by Environmental Impact Statements?
**always - 10; often - 13; rarely - 17; never - 4**

19. This question relates to Federal-Aid projects processed as Environmental Assessment/Findings of No Significant Impact. How often does your Department obtain concurrence from the USF&W/NMF on protected species findings prior to completion of the Environmental Assessment?
**always - 29; often - 11; rarely - 4; never - 1**

20. This question relates to Federal-Aid projects processed as Categorical Exclusions. How often does your Department obtain concurrence from the USF&W/NMF on protected species findings contained in Categorical Exclusions?
**always - 21; often - 10; rarely - 10; never - 4**

* = Number of states providing that response.

**FIGURE 1** *(Continued)*

impossible. States considering relocation of protected species may wish to contact one of the three states that have done this often (Virginia with animals, Michigan with plants, and Utah with plants and animals).

### Policy Issue H: Formal Processes To Verify Commitments Made for Protected Species

Commitments regarding protected species could include shifting highway alignment, limiting construction during certain seasons, using special construction techniques, and others. Agencies usually make these commitments during the planning and Environmental Impact Statement (EIS) stage of project development. Quite often project construction begins years after the planning and EIS stage, and the personnel involved with a project may change. To ensure that commitments made during early project planning are carried through construction, many states have implemented formal review processes. The authors found that more than half the responding states (24 states) have such a formal review process in place.

**TABLE 1 Species Requiring Most Compliance Work**

| SPECIES | STATES LISTING SPECIES AS REQUIRING: THE MOST COMPLIANCE WORK | THE SECOND-MOST OR THIRD-MOST COMPLIANCE WORK |
|---|---|---|
| Birds | | |
| Crane, MS Sandhill | MS | |
| Eagle, Bald | ID,IL,NH,WA | AK,CO,KS,LA,MN,OR OH,TX,UT,WI,WY |
| Falcon, Peregrine | AK | AZ,NH,WY |
| Murrelet, Marbled | | WA |
| Owl, Northern Spotted | OR | AZ,WA |
| Plover, Piping | | NE |
| Tern, Least | NE | OK |
| Vireo, Least Bell's | CA | |
| Vireo, Black-capped | TX | |
| Warbler,Golden-Cheeked | | TX |
| Waterfowl (Unspecified) | | AK |
| Woodpecker,Red Cockaded | GA,LA,NC,SC | FL,TN |
| Woodstork | | GA |
| Mammals | | |
| Bat, Big-Eared | | KY |
| Bat, Gray | IN | KY |
| Bat, Indiana | KY | IL,IN,IA |
| Ferrett, Black Footed | WY | CO |
| Manatee | GA | FL |
| Panther, Florida | FL | |
| Prairie Dogs | UT | |
| Rat,Stephen's Kangaroo | | CA |
| Squirrel,Northern Flying | | WV |
| Wolf, Timber | | WI |
| Woodrat, Eastern | PA | |
| Reptiles | | |
| Tortoise, Desert | AZ | CA,UT |
| Tortoise, Gopher | | AL,LA,MS |
| Tortoise (Unspecified) | NV | |
| Turtle,Spiny Soft-Shell | VT | |
| Turtle, Flatten Musk | AL | |
| Fish | | |
| Cavefish, Ozark | MO | AR |
| Dace, Red Bellied | | NE |
| Darter, Leopard | | OK |

(*continued on next page*)

The regulations promulgated by FHWA [23 CFR 771.129(c)] refer to this review process as a *consultation.* The survey determined that projects that receive federal aid are the most likely projects to involve a formal review. Many states also have such a procedure for 100 percent state-funded projects and for state-funded and locally funded projects.

## Policy Issue I: Protected Plants on Highway Rights-of-Way

Some protected plants grow in habitats found within highway rights-of-way. This presents problems for state departments of transportation because even routine maintenance can "take" a protected species. Thirty-three states report knowledge of communities of protected plants within highway rights-of-way. The list of techniques for avoiding impacts is broad, with mowing restrictions, herbicide restrictions, and special instructions to field personnel the most popular.

Other means of protection were also identified, including the following:

- Limits on salt application (1 state),
- Erection of signs or fencing indicating sensitive areas and required precautions (5 states),
- Elimination of other competing vegetation (1 state),
- Registration of protected plant communities with the Nature Conservancy (1 state), and
- Special conditions for resurfacing projects or encroachment permits (2 states).

## Policy Issue J: Procedures for Compliance with Section 7 of the Endangered Species Act

The regulations for implementing Section 7 discuss both formal and informal consultations with FWS and NMFS. Table 2 shows

**TABLE 1** (*Continued*)

| SPECIES | STATES LISTING SPECIES AS REQUIRING: THE MOST COMPLIANCE WORK | THE SECOND-MOST OR THIRD-MOST COMPLIANCE WORK |
|---|---|---|
| Darter, Bayou | | MS |
| Darter, Niangua | | MO |
| Madtom, Neosho | KS | |
| Salmon, Chinook | | ID |
| Shiner, Cape Fear | | NC |
| Sturgeon, Shortnose | CT,MA | NJ |
| Clams | | |
| Fatmucket, Arkansas | | AK |
| Mucket, Pink | AK | |
| Mussel, Dwarf Wedge | | NH,NC |
| Mussel, Heelsplitter | | KS |
| Mussel, Higgins Eye Pearly | MN,WI | |
| Mussels (Unspecified) | IA,TN,VA,WV | AL,IL,IN,OH |
| Snails | | |
| Snake River Snails | | ID |
| Insects | | |
| Beetle, Amer. Burying | OK | |
| Butterfly, Mitchell's Satyr | MI | |
| Butterfly,OR. Silverspt | | OR |
| Plants | | |
| Bladder-pod, Missouri | | MO |
| Buckwheat, Steamboat | | NV |
| Bullrush, Eastern | | PA |
| Clover,Running Buffalo | OH | |
| Clover, Prairie Bush | | MN |
| Coneflower,Tenn. Purple | | TN |
| Goldenrod, Houghton's | | MI |
| Knotweed, Blue | | VT |
| Ladies' Tresses | CO | |
| Monkshood, Northern | | IA |
| Pale-Painted-Cup | | VT |
| Pogonia, Small Whorled | NJ | PA |
| Swamp Pink | | NJ |
| Thistle, Pitcher's | | MI |
| Virginia Spiraea | | WV |

that most states successfully coordinate projects through informal consultations (meetings, telephone conversations, etc.). The formal consultation process involves specific correspondence leading to an official "jeopardy opinion" from FWS and NMFS. Reaching agreement through informal consultation can greatly reduce the time involved with the consultation process. Four states conduct 100 percent of their consultation with FWS and NMFS through the formal process. These states may wish to consider informal consultation.

Responses to Question 17 show that most state departments of transportation act as lead agency during informal consultations with FWS and NMFS. The regulations for implementing the Endangered Species Act require federal agencies to act as the lead agency during formal consultations, but they are silent regarding the lead agency for informal consultations. Responses to Question 17 indicate that most states interpret the law to allow them to act as the lead agency during informal consultations.

The Endangered Species Act refers to the preparation of Biological Assessments when projects are found to have a potential impact on threatened or endangered species. Question 18 shows how often states are preparing these Biological Assessments. Twenty-one states rarely or never prepare Biological Assessments. Apparently FWS and NMFS accept other documentation as the equivalent to a Biological Assessment in these states.

The Georgia Department of Transportation (DOT) prepares shortened Biological Assessments that do not include repetitious or extraneous information such as species descriptions. Their shortened Biological Assessments focus on impact analysis, alternative analysis, and mitigation.

Questions 19 and 20 provide information regarding Section 7 compliance for smaller projects (those requiring an Environmental Assessment or Categorical Exclusion rather than an EIS). Section 7 compliance is required for those projects, but regulations do not define the exact procedures for this compliance as they do for EIS-level projects. Responses to Questions 19 and 20 indicate that most states attempt to achieve concurrence regarding protected species early in the planning process, even when projects are smaller. As expected the smaller the project the less likely the

TABLE 2 Responses to Survey Questions 10 and 16

| PERCENTAGE OF COMPLIANCE WORK | 0% | 1%-20% | 21%-40% | 41%-60% | 61%-80% | 81%-99% | 100% |
|---|---|---|---|---|---|---|---|
| QUESTION 10 - PERSONNEL* PERFORMING SPECIES EVALUATIONS: | | | | | | | |
| IN-HOUSE BIOLOGISTS | 9** | 9 | 5 | 7 | 7 | 7 | 1 |
| PRIVATE FIRMS | 7 | 14 | 11 | 2 | 4 | 3 | 4 |
| RESOURCE AGENCY STAFF | 27 | 4 | 5 | 1 | 4 | 1 | 1 |
| UNIVERSITY STAFF | 39 | 2 | 2 | 0 | 1 | 0 | 0 |
| QUESTION 16 - TYPE OF CONSULTATION USED WITH USFWS OR NMFS: | | | | | | | |
| INFORMAL CONSULTATION | 4 | 0 | 2 | 1 | 4 | 25 | 7 |
| FORMAL CONSULTATION | 7 | 25 | 4 | 1 | 2 | 0 | 4 |

* Seven states used other personnel for protected species work including: tribal representatives, landscape architects, environmental planners, staff archaeologists, and other environmental staff.

** Number of states responding.

states will attempt early coordination for protected species. Fewer states attempt early coordination for projects requiring Categorical Exclusions than for those requiring Environmental Assessments.

### Policy Issue K: Other Unique Policies

In an open question the authors asked respondents to explain any unique procedures or policies that the agency uses regarding protected species. Several of the more interesting explanations follow.

#### *Agency Coordination*

Vermont DOT holds bimonthly meetings with state and federal agencies to discuss the status of projects that are controversial because of environmental and engineering constraints.

Texas DOT has a Memorandum of Agreement with the Texas Parks and Wildlife Department. As part of this Memorandum of Agreement the Texas Parks and Wildlife Department reviews endangered species in the vicinity of projects early in the planning process to allow sufficient time for any necessary coordination.

Washington DOT participates in regional working teams for various protected species recovery plans.

#### *Guidance on Procedures*

Florida DOT developed an extensive *Project Development and Environmental Manual* describing the process by which transportation projects are developed to meet the requirements of federal, state, and local laws and regulations. The manual contains 49 chapters, including a chapter on wildlife and habitat impacts. District staff and consultants use the manual.

#### *Protected Species Reviews for Off-Site Highway Construction Activities*

Florida DOT requires protected species investigations for off-site construction activities such as new borrow pits, mixture plants, or construction field offices. Contractors must request a protected species review from Florida DOT district environmental personnel. The investigation must be completed before off-site construction activity.

#### *Drainage Design*

Missouri DOT has used unique drainage designs to lessen the likelihood of roadway spills entering groundwater that might harbor protected species.

## CONCLUSION

The survey of state DOTs described here allows states to compare their practices with those of other states. Although protected species issues have reportedly stopped transportation projects in only nine states, they have caused project delays or redesign in almost all states. A wide variety of state policies regarding protected species laws is evident from the survey responses.

Does your state experience more difficulties than other states regarding protected species? How many states have compliance procedures similar to those of your state? Survey results allow transportation officials to answer these questions. The list of species requiring the most compliance work provides a useful data base that can be used to reduce duplication of effort and improve protection for species.

The survey provides an overview of many different policy issues and should spark many follow-up research questions. In particular analysts may need the degree of species protection and costs associated with different policy decisions. A time series of responses to this survey would also be helpful, revealing trends and policy shifts.

## ACKNOWLEDGMENTS

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# Transportation Analysis for Sludge Transport Routing Design and Landfill Site Selection

M. HADI BAAJ, SULEIMAN ASHUR, AND ATMAM ANWAR

A solution framework for the sludge landfill site selection problem that arises in the context of environmental planning is presented. The problem may be defined as follows: given a set of environmentally acceptable candidate landfill sites, identify the site that minimizes a weighted combination of two objectives (system descriptors), the present worth value of the transportation operation costs and the resulting population disturbance of the chosen set of transportation routes. The solution methodology is demonstrated on data developed for the city of Phoenix, Arizona.

The sludge landfill site selection problem (SLSSP) arises in the context of an environmental planning process focusing on sludge landfill site selection. The ideal solution is to identify the suitable landfill site that minimizes a weighted combination of two objectives: the present worth of the transportation operation costs and the associated population disturbance. This paper presents a methodology to generate a best possible solution to the SLSSP on the basis of its bi-objective formulation. The mathematical formulation of the SLSSP and an overview of the sludge landfill analysis algorithm (SLA) are presented first. A demonstration application to the SLSSP for the city of Phoenix, Arizona, is then presented, and finally the results and directions for future research are provided.

Previous solution approaches to the SLSSP (*1,2*) focused on only a single objective, namely that of minimizing the annual relative cost of transporting sludge from water treatment plants (WTPs) to the candidate landfill site. Such approaches were considered inadequate because they did not account for the time value of money and did not address the major objective of minimizing population disturbances along transport routes. It is recognized that transporting sludge via residential neighborhoods is disrupting and undesirable. Thus one can formulate the SLSSP as a bi-objective problem consisting of the selection of a landfill site that minimizes a weighted combination of the present worth of the transportation operation costs and the associated total population disturbance.

$$\underset{(\text{all } i \in \text{SL})}{\text{Minimize}} \; [c_1 \text{PW}_i + c_2 \text{PD}_i] \qquad (1)$$

where

$\text{PW}_i$ = present worth of the transportation operation costs of transporting sludge from all WTPs to landfill site $i$,
$\text{PD}_i$ = total population disturbance associated with the transportation operation of landfill site $i$,
$c_1$, $c_2$ = weights reflecting the relative importance of the present worth of transportation operation costs and the associated population disturbance, and
SL = set of environmentally acceptable candidate landfill sites (known a priori).

By varying $c_1$ and $c_2$ one can generate different nondominated (pareto-optimal) configurations that achieve different trade-offs between the present worth of transportation operation costs and total population disturbance. If $c_1$ is set equal to 0 then the SLSSP becomes one of selecting the landfill site whose total population disturbance is minimum. Alternatively if $c_2$ is set equal to 0 then the SLSSP becomes one of selecting the landfill site whose present worth of transportation operation costs is minimum (historically the earlier formulation of SLSSP).

## PRESENT WORTH OF TRANSPORTATION OPERATION COSTS

The present worth of the transportation costs (over the landfill's design life span) associated with one candidate landfill site $i$ ($\text{PW}_i$) is computed as follows:

$$\text{PW}_i = \sum_{\text{SW}} \text{PW}_{ij} = \sum_{\text{SW}} (\text{PW}_{cc} + \text{PW}_l + \text{PW}_{o,m,f})_{ij} \qquad (2)$$

where

$\text{PW}_{ij}$ = present worth of the transportation operation costs of the chosen route between WTP $j$ and landfill site $i$,
$\text{PW}_{cc}$ = present worth of the chosen route's equipment capital costs (tractor-trailer combinations),
$\text{PW}_l$ = present worth of the chosen route's labor costs,
$\text{PW}_{o,m,f}$ = present worth of the chosen route's equipment operation, maintenance, and fuel costs, and
SW = set of all WTPs.

## POPULATION DISTURBANCE

Future residential population densities were compiled by using data from the Bureau of Census projections. Data compiled for the city of Phoenix SLSSP indicate that an area's residential population density (projected for 2020) can be classified into three categories: (a) low-density areas (population densities of up to 2,000 people in a radius of 1 mi), (b) medium-density areas (population densities between 2,000 and 5,000 people), and (c) high-

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density areas (population densities in excess of 5,000 people). In addition links in outlying areas and freeway links are assumed to have zero population disturbance. The population disturbance ($pd_l$) of link $l$ with length $l_l$ is computed as follows:

$$pd_l = \frac{6{,}000}{3.14} l_{hd} + \frac{3{,}500}{3.14} l_{md} + \frac{1{,}000}{3.14} l_{ld} + 0 * l_{nd} + 0 * l_{frwy} \quad (3)$$

$$\text{subject to } l_{hd} + l_{md} + l_{ld} + l_{nd} + l_{frwy} = l_l \quad (4)$$

where

$l_{hd}$ = length of part of link $l$ in high-density areas,
$l_{md}$ = length of part of link $l$ in medium-density areas,
$l_{ld}$ = length of part of link $l$ in low-density areas,
$l_{nd}$ = length of part of link $l$ in outlying no-density (zero density) areas, and
$l_{frwy}$ = length of part of link $l$ in freeways.

Not all five subcomponents may be present in a given link. The value of (6,000/3.14) equals the number of disturbed people per mile of high-density link length. It is assumed that a high-density area has 6,000 people in a circle with a radius of 1 mi. Thus there are 6,000 people in an area of 3.14 $mi^2$, implying that (6,000/3.14) people are disturbed per 1-mi length along the link. It is assumed that a link of 1 mi in length disturbs the population in an area lying within a disturbance bandwidth of 0.5 mi on both sides of the link. This is not a limiting assumption, because the important issue is the relative ratio of the population disturbances of two landfill sites rather than their absolute values.

Every shipment of sludge from WTP $j$ to landfill $i$ (on the chosen route) disturbs twice the total population living along the route in every round trip. Thus the population disturbance ($PD_{ij}$) of the chosen route between landfill site $i$ and WTP $j$ is computed by multiplying twice the route's total population disturbance by its number of daily shipments ($s_{ij}$).

$$PD_{ij} = 2\left[\sum_{\text{all links } l \in L(i,j)} pd_l\right] * s_{ij} \quad (5)$$

where $L(i,j)$ is the set of all links on route from WTP $j$ to landfill site $i$.

The system population disturbance ($PD_i$) associated with candidate landfill site $i$ is computed as follows:

$$PD_i = \sum_{SW} PD_{ij} \quad (6)$$

## CHOICE OF TRANSPORTATION ROUTES

There are many routes for transporting sludge from a given WTP $j$ to a candidate landfill site $i$. These routes are generated with the application of the $K$-shortest routes algorithm without repeated nodes (*3–6*) to the transportation network. $K$ routes are generated for each pair of candidate landfill site $i$ and WTP $j$. The present worth of the transportation operation costs and the resulting route's total residential disturbance are computed for each route. The route chosen for transportation is the one that minimizes a weighted combination of both objectives of cost and population disturbance. Thus the problem can be formulated as follows.

Choose route $k$ (among $K$ possible routes) from WTP $j$ to landfill site $i$ such that ($c_1 PW_{ij,k} + c_2 PD_{ij,k}$) is a minimum, where $PW_{ij,k}$ and $PD_{ij,k}$ are the present worth of the transportation operation costs and population disturbance of route $k$, respectively. Thus the chosen route for transportation is not necessarily the shortest travel time route, because the latter's resulting total population disturbance may be quite high.

## SLUDGE LANDFILL ANALYSIS ALGORITHM

SLA is an analysis algorithm that evaluates for each candidate landfill site two major descriptors, namely the present worth of the transportation operation costs and the associated population disturbance of the transportation operation. This requires the identification of the collection routes to the landfill site under evaluation from all WTPs. Thus SLA first selects the transport route from every WTP to the landfill site under evaluation. There are many such routes from a WTP to the landfill site. These routes differ in length, average running speed, travel time, link composition (some links may be part of highways, arterials, or streets), and population disturbance. The shortest-time route may require the smallest operation fleet size; however, it may have a high population disturbance. An alternate, slightly longer route (with only a small increase in the resulting transportation costs) may result in a much smaller population disturbance, hence the need to identify and consider many routes between each pair of landfill site and WTP. SLA implements a $K$-shortest routes algorithm without repeated nodes (loopless) to generate $K$ routes in increasing order of round-trip travel time (the selection of $K$'s value is discussed below). SLA then determines for each such route the number of daily shipments, the required fleet size, the resulting present worth of transportation operation costs, and the route's population disturbance. On the basis of two descriptors of each route a decision is made to select the transportation route that minimizes a weighted combination of both descriptors.

The same process is then repeated (with the same site under evaluation) for every one of the remaining WTPs (inner DO loop). Again the $K$-shortest routes algorithm is implemented to determine $K$ possible routes between the candidate landfill site and each WTP. On the basis of each possible route's two descriptors, the transportation route is selected and the resulting route's present worth of the transportation operation costs and population disturbance is determined. The landfill site's system descriptors are then obtained by aggregating the present worth of the transportation operation costs for the chosen routes and their corresponding population disturbances. The whole procedure is then repeated for each candidate landfill site (outer DO loop). Once the two descriptors of each candidate landfill site are determined, the set of nondominated candidate landfill sites is generated. SLA has been described previously (*7*).

The input to SLA can be classified into four categories: transportation network data, population disturbance data, operational characteristics data, and present worth analysis data. The output of SLA can be classified into three categories: route properties, landfill sites' system properties, and the set of nondominated candidate sites. The different cost components are computed by SLA as follows.

### Number of Daily Shipments Between Landfill Site *i* and WTP *j*

The number of daily shipments ($s_{ij}$) depends on the WTP $j$ monthly tonnage of sludge production ($M_j$), the sludge density

(21 lb/ft$^3$), and the dry sludge capacity of a typical truck-trailer combination (5.67 tons of dry solids). $s_{ij}$ is given by

$$s_{ij} = \left\lceil \frac{12 * M_j}{5.67 * \text{YDO}} \right\rceil \quad (7)$$

where [x] is the smallest integer greater than or equal to x, and YDO is yearly days of operation (assumed to be 260 days/year).

### Maximum Number of Round-Trips by One Truck on Each Route

The maximum number of round-trips by one truck on each route ($q_{ij}$) is dependent on the route's round-trip travel time and the duration of the daily collection operation. The round-trip travel time ($RTT_{ij}$) to landfill $i$ from $WTP_j$ is the sum of twice the travel time between $WTP_j$ and landfill site $i$, the loading time at $WTP_j$, and the unloading time at landfill site $i$. $q_{ij}$ is given by

$$q_{ij} = \left\lfloor \frac{\text{DHO} * 60 \text{ min/hr}}{RTT_{ij}} \right\rfloor \quad (8)$$

where [x] is the smallest integer less than or equal to x, and DHO is daily hours of operation.

$$RTT_{ij} = 2\left[ \sum_{\text{all links } l \in L(i,j)} tt_l \right] + (t_u)_i + (t_l)_j \quad (9)$$

where

$tt_l$ = one-way travel time of link $l$,
$(t_u)_i$ = unloading time at landfill site $i$ (assumed to be 15 min),
$(t_l)_j$ = loading time at WTP $j$ (assumed to be 30 min), and
$L(i,j)$ = set of all links on route from $j$ to $i$.

### Fleet Size on Each Route

The fleet size on each route, $(N_t)_{ij}$, necessary to transport sludge to landfill $i$ from WTP $j$ is based on the maximum number of round-trips by one truck on each route, the monthly tonnage of dry solids produced at WTP $j$, and the dry solids capacity of truck-trailer combinations. $(N_t)_{ij}$ is given by

$$(N_t)_{ij} = \left\lceil \frac{12 * M_j}{5.67 * \text{YDO} * q_{ij}} \right\rceil \quad (10)$$

## ILLUSTRATIVE APPLICATION FOR CITY OF PHOENIX

The following assumptions were made for the city of Phoenix SLSSP:

1. Landfill life span ($n$) = 50 years.
2. Truck capital cost ($Truck_{cc}$) = $80,000.
3. Trailer capital cost ($Trailer_{cc}$) = $45,000.
4. Annual cost escalation rate (esc) = 5 percent.
5. Annual interest rate (int) = 8 percent.
6. Life span of truck and trailer = 10 years.
7. Salvage value of truck and trailer = $0.
8. Operation, maintenance, and fuel cost ($C_{mile}$) = $0.90/mi.
9. Yearly truck labor cost (YTLC) = $32,000/truck/year.
10. SL = 16 candidate landfill sites.
11. SW = 7 WTPs.

The K-shortest routes algorithm was adequately implemented with a K value of 100. A decision process is applied to select the route of transportation for a given pair of landfill site $i$ and WTP $j$ [details have been presented previously (7).]. The output of the SLA consists of the following elements.

### Route Properties

Table 1 shows the first five routes of 100 shortest-travel-time routes generated from landfill site at node 11 to WTP 2 sorted in increasing order of round-trip travel time. The shortest travel time route (route 1 with a round-trip travel time of 70.8 min) itself has the least present worth value ($1.65 million) and its population disturbance is 4,299. The cap cost corresponding to a 3 percent margin in excess of the minimum is equal to $1.70 million. Among the remaining 99 routes, SLA searches for a route whose present worth does not exceed $1.70 million and whose population disturbance is the minimum and under 4,299. There is not such a route; thus, route 1 is the chosen transport route and its descriptors are shown in Figure 1.

### Landfill Site at Node 11 System Descriptors

Table 1(b) shows the properties of the chosen routes between the candidate landfill site at node 11 and each of the seven WTPs (only one is shown for brevity). In addition the system descriptors of the landfill site at node 11 are shown at the end of Table 1(b).

**TABLE 1 Route Generation in SLA: Shortest Travel Time Routes Between Landfill Site at Node 11 and WTP 2**

| k- | O- | D- | Nt- | RTT- | PW(m$)- | PD | --> | Nodal Composition of Route | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | 2 | 1 | 70.8 | 1.6480 | 4299 | --> | 11 | 63 | 64 | 65 | 68 | 2 | | |
| 2 | 11 | 2 | 1 | 80.5 | 1.7151 | 6131 | --> | 11 | 63 | 64 | 65 | 68 | 70 | 69 | 2 |
| 3 | 11 | 2 | 1 | 95.2 | 1.7738 | 28184 | --> | 11 | 63 | 76 | 77 | 13 | 68 | 2 | |
| 4 | 11 | 2 | 1 | 95.9 | 1.8030 | 17197 | --> | 11 | 63 | 64 | 65 | 125 | 126 | 127 | 2 |
| 5 | 11 | 2 | 1 | 96.5 | 1.7797 | 11942 | --> | 11 | 63 | 76 | 77 | 64 | 65 | 68 | 2 |

k = order of route, O = origin node, D = destination node, $N_t$ = number of trucks on route, RTT = round trip travel time in minutes, PW = present worth of route, PD = population disturbance of route

From landfill site at node 11 to WTP 1:
The Chosen route corresponds to k = 2
Route is : 11 63 64 77 1
Total distance in miles = 6.51
RTT of this route in minutes = 70.36
Population disturbance = 3224
Number of daily shipments on route = 1.00
Maximum number of round trips by 1 truck = 6.00
Number of trucks needed = 1
Present worth of Capital costs = $ 0.5231 M
Present worth of O, M, & F costs = $ 0.0806 M
Present worth of Labor costs = $ 0.8462 M
Present worth of Total costs = $ 1.4499 M

---*****---SYSTEM PROPERTIES OF LANDFILL SITE AT NODE 11---*****---

The present worth of Capital costs of Landfill Site at node 11 = $ 4.0467 M
The present worth of O, M, & F costs of Landfill Site at node 11 = $ 3.6333 M
The present worth of Labor costs of Landfill Site at node 11 = $ 6.7693 M
The present worth of Total costs of Landfill Site at node 11 = $ 14.4493 M
The population disturbances of Landfill Site at node 11 = 110869

**FIGURE 1 Route generation in SLA: properties of chosen routes between landfill site at Node 11 and WTPs.**

The two system descriptors are the summation of the seven chosen routes' population disturbances and present worth values of transportation operation costs.

### Set of Nondominated Candidate Landfill Sites

Table 2 shows the two system descriptors of the 16 candidate landfill sites. All landfill sites required 8 tractors and 15 trailers; thus, all sites had the same present worth of capital costs ($4.05 million) and labor costs ($6.77 million). The difference in total present worth of transportation operation costs results from the annual operation, maintenance, and fuel costs. The present worth of the transportation operation costs versus the associated population disturbances of 16 candidate landfill sites is shown in Figure 2. The plot shows that 4 candidate landfill sites (those at nodes 11, 12, 13, and 16) dominate the remaining 12 candidate sites. The landfill site at node 16 dominates the six sites at nodes 10, 15, 20, 21, 22, and 26 (less the present worth for the same population disturbance). The landfill sites at nodes 12 and 13 dominate the five landfill sites at nodes 8, 9, 14, 18, and 19 (less population disturbance and less present value). The landfill site at node 11 dominates the site at node 17 (less population disturbance and less present value). Thus the set of nondominated candidate landfill sites consists of four sites at nodes 11, 12, 13, and 16. Final selection from the set of nondominated sites depends on the trade-off between the present worth value and the population disturbance. If preference is given only to present worth, then the landfill site at node 13 is the final selection. Alternatively if preference is given only to population disturbance, then the landfill site at node 16 is the site of choice. Any case other than the two boundary conditions requires the specification of the trade-off between present worth and population disturbance.

## SUMMARY AND CONCLUSIONS

This paper presents a solution methodology to the SLSSP that recognizes, in addition to the cost minimization objective, a second objective in which the population disturbance associated with the transportation network is minimized. The solution methodology relies on an SLA to select the landfill site. All environmentally acceptable candidate landfill sites are analyzed through this algorithm, which identifies *K*-shortest travel time routes of transportation between one landfill site and each of the WTPs. On the basis of a prespecified trade-off between the optimization objectives, SLA selects the routes of transportation and then evaluates the two system descriptors of each landfill site, namely the present worth of the transportation operation costs and the resulting population disturbance of the associated set of transportation routes.

**TABLE 2 System Descriptors of 16 Candidate Landfill Sites***

| Landfill Site at node number | PW capital | PW labor | PW o,m,&f ** | PW total | Pop. Dist |
|---|---|---|---|---|---|
| 8 | 4.0467 | 6.7693 | 5.7214 | 16.5374 | 357535 |
| 9 | 4.0467 | 6.7693 | 4.1895 | 15.0055 | 163858 |
| 10 | 4.0467 | 6.7693 | 5.4679 | 16.2839 | 104261 |
| 11 | 4.0467 | 6.7693 | 3.6333 | 14.4493 | 110869 |
| 12 | 4.0467 | 6.7693 | 3.3753 | 14.1913 | 137978 |
| 13 | 4.0467 | 6.7693 | 3.3498 | 14.1658 | 162503 |
| 14 | 4.0467 | 6.7693 | 4.1219 | 14.9379 | 194390 |
| 15 | 4.0467 | 6.7693 | 5.3100 | 16.1260 | 104261 |
| 16 | 4.0467 | 6.7693 | 4.8410 | 15.6570 | 104261 |
| 17 | 4.0467 | 6.7693 | 3.9782 | 14.7942 | 131768 |
| 18 | 4.0467 | 6.7693 | 4.3126 | 15.1286 | 200523 |
| 19 | 4.0467 | 6.7693 | 4.5249 | 15.3409 | 174243 |
| 20 | 4.0467 | 6.7693 | 5.5912 | 16.4072 | 104261 |
| 21 | 4.0467 | 6.7693 | 5.3093 | 16.1253 | 104261 |
| 22 | 4.0467 | 6.7693 | 6.0129 | 16.8289 | 104261 |
| 26 | 4.0467 | 6.7693 | 6.2942 | 17.1102 | 104261 |

*) All present worth values are in millions of dollars
**) Operation, maintenance, and fuel costs

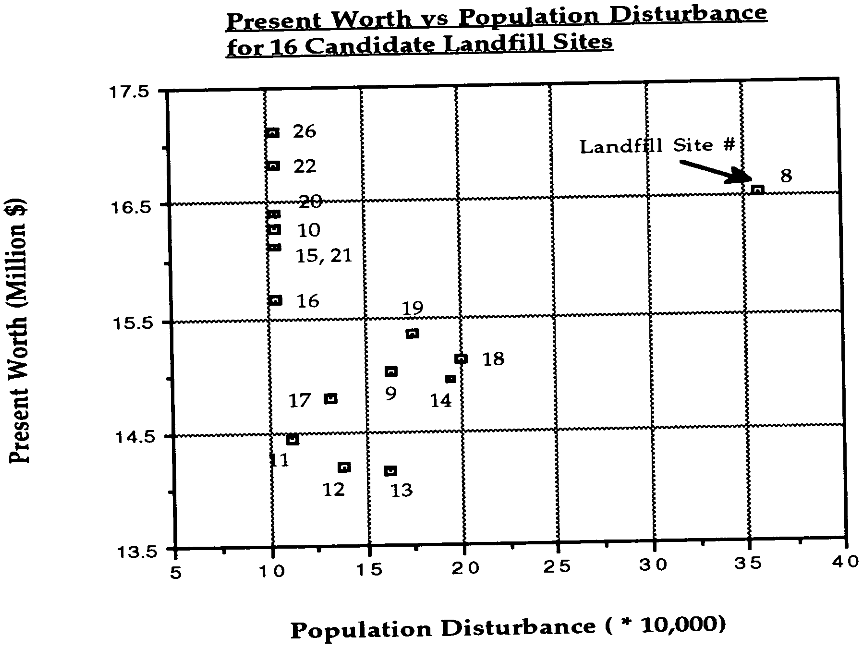


**FIGURE 2 Present worth versus population disturbance of 16 landfill sites.**

The testing of the solution framework on data generated for Phoenix, Arizona, revealed the adequacy of the solution.

The proposed solution approach modeled the transportation operation between a landfill and each WTP as a single origin-single destination system. Each WTP had its own independent fleet size that transported sludge from that WTP only to the candidate landfill site. This assumption increases in validity as the fleet size associated with each WTP becomes larger and operates with a higher frequency of daily shipments. The test application to Phoenix indicated that the fleet size associated with each WTP consisted mostly of one truck conducting one daily round-trip operation. This may encourage the pooling of resources among WTPs and changes the nature of the transportation operation to that of multiple origins-single destination. As a result the system's present worth of transportation operation associated with each site is reduced. For future research the solution framework may be modified to accommodate the above situation.

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# Interstate 287 Wetland Mitigation Project: Turning an Environmental Liability into an Environmental Asset

ANDRAS FEKETE, NICHOLAS CAIAZZA, LEWIS O. MORGAN, AND KENNETH P. DUNNE

As a condition of a U.S. Army Corps of Engineers Section 404 permit for the construction of a 9.5-km section of Interstate 287, the New Jersey Department of Transportation was required to create 4 ha of freshwater wetland. Finding a suitable site was difficult, resulting in a decision to buy a concrete pipe manufacturing plant along the Pequannock River and assuming the liability for contamination remediation. Site remediation was done during construction of the wetland replacement project and involved the excavation of 13,760 $m^3$ of petroleum hydrocarbon-contaminated soil, placement of 13 groundwater-monitoring wells, and development of a precedent-setting methodology for reuse of contaminated soil for the road embankment. To optimize the continued ecological viability of the newly created wetland, a hydrological model was developed and used in the design of the project. A shallow permanently flooded marsh planted with native emergent species was constructed and monitored for 3 years (from 1989 through 1991). An 80 percent success rate for planted vegetation was achieved, and the marsh now exhibits characteristics of a young developing wetland system with high degree of plant and wildlife diversity. The site, once a contaminated industrial facility, is now a thriving freshwater marsh contiguous to the Pequannock River that provides both functional and aesthetic values to the watershed.

The final 32 km of Interstate 287 in northern New Jersey was opened to traffic in November 1993. The entire project filled 31 ha of freshwater wetlands at 29 separate areas. In 1986 a U.S. Army Corps of Engineers Section 404 permit was issued for the "central section," a 9.5-km section within the limits of the overall project. About 3.2 ha of wetland was affected at eight separate areas, each ranging from 0.06 to 1.5 ha.

Nine potential mitigation sites were evaluated for the central section. A 4-ha concrete pipe manufacturing plant, whose access would be severed by the highway, was finally selected and converted to freshwater wetland. Mitigation for the rest of the project, a 12-ha site and a 16-ha site, is under construction. The goal of the mitigation designs approved by the U.S. Army Corps of Engineers and the advisory federal agencies was to provide high-value wildlife habitat and flood storage compensation at a 1:1 impact-to-mitigation ratio.

The conversion of the environmental liabilities associated with the 4-ha concrete pipe manufacturing plant site (Figure 1) into an environmental asset in the form of viable freshwater wetland (Figure 2) is described in the following sections.

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## ENVIRONMENTAL LIABILITY: SITE CONTAMINATION

The site layout of the concrete pipe manufacturing company, which was in business for approximately 50 years, is shown in Figure 3. The operations on the site required the use and on-site storage of fuels (no. 2 heating oil, kerosine, and leaded gasoline), form-release oil (an oil composed of mineral and vegetable oil used to coat concrete molds to prevent the concrete from sticking), and hydraulic oil. The fuels were stored in two aboveground storage tanks (ASTs) and in four underground storage tanks (USTs).

As part of the property acquisition agreement the New Jersey Department of Transportation (NJDOT) assumed the responsibility for the investigation and cleanup of the site. The cleanup of the contamination was done as part of the wetland mitigation site construction and in close cooperation with the New Jersey Department of Environmental Protection and Energy (NJDEPE).

### Soils

After acquisition of the site preliminary soil sampling was carried out in areas of the USTs and ASTs by the NJDOT during construction. The preliminary sampling detected petroleum hydrocarbons at concentrations of up to 45,552 ppm in the areas around

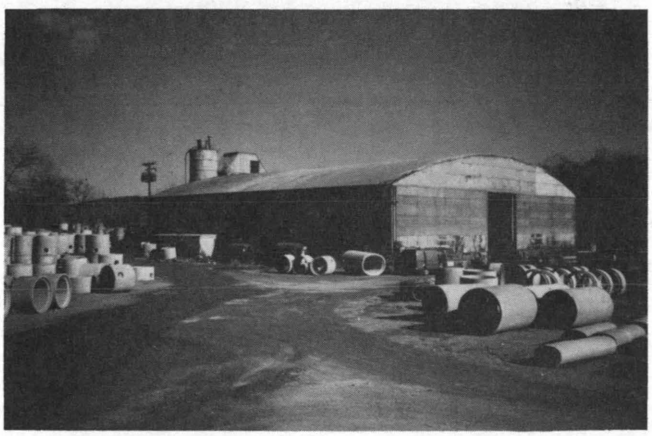

**FIGURE 1 Concrete pipe manufacturing facility before construction (fall 1988).**

FIGURE 2 Created deepwater marsh (August 1992).

the ASTs and the USTs. Additional soil sampling in the interiors of the buildings and drum storage areas identified the presence of other contaminants such as base/neutral organic compounds consisting primarily of polyaromatic hydrocarbons. No volatile organic compounds or PCBs were detected.

### Groundwater

To monitor any potential impact to local groundwater quality resulting from the former operation of the concrete pipe company facility, NJDOT installed a groundwater-monitoring network consisting of 13 shallow monitoring wells. The results of sampling conducted after construction of the wetland were at or below the levels requiring NJDEPE action. It was therefore concluded that there was no further threat to the groundwater.

## ENVIRONMENTAL ASSET: WETLAND MITIGATION SITE DESIGN

The approved mitigation design called for the construction of a shallow, permanently flooded marsh that would be planted with native emergent species. Among the first steps in the design process was development of a hydrologic model for the marsh system. The basis of the hydrologic model is shown in Figure 4. The model, which is basically a mass balance model, compared inflows to the wetland system with outflows from the wetland system to determine water levels in the marsh over a period of record. Inflows to the wetland system included precipitation, riverine inflow, groundwater inflow, and watershed runoff. Outflows from the system included evapotranspiration, exfiltration, and surface water outflow. Input data for precipitation and evapotranspiration were based on daily rainfall gauge data and pan data at nearby weather stations. Inflow data from the Pequannock River were developed by using discharge information from nearby U.S. Geological Survey gauge stations, and rating curve information was calculated by using the U.S. Army Corps of Engineers stepped backwater model HEC-2. Watershed runoff from tributary drainage areas was determined by the Rational Method. A rating curve for exfiltration rates was developed on the basis of the permeability of the proposed clay liner and the variable heads within the marsh system. Variable characteristics of the model included the elevations/heights and lengths of the proposed inlet and outlet control structures. The model is adaptable to most freshwater marsh systems.

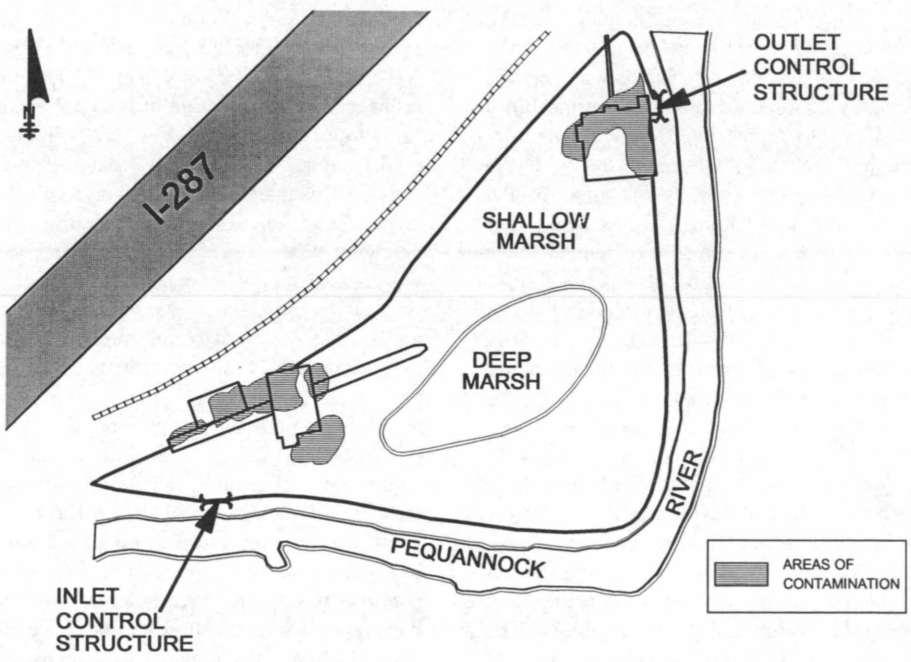


FIGURE 3 Project site map.

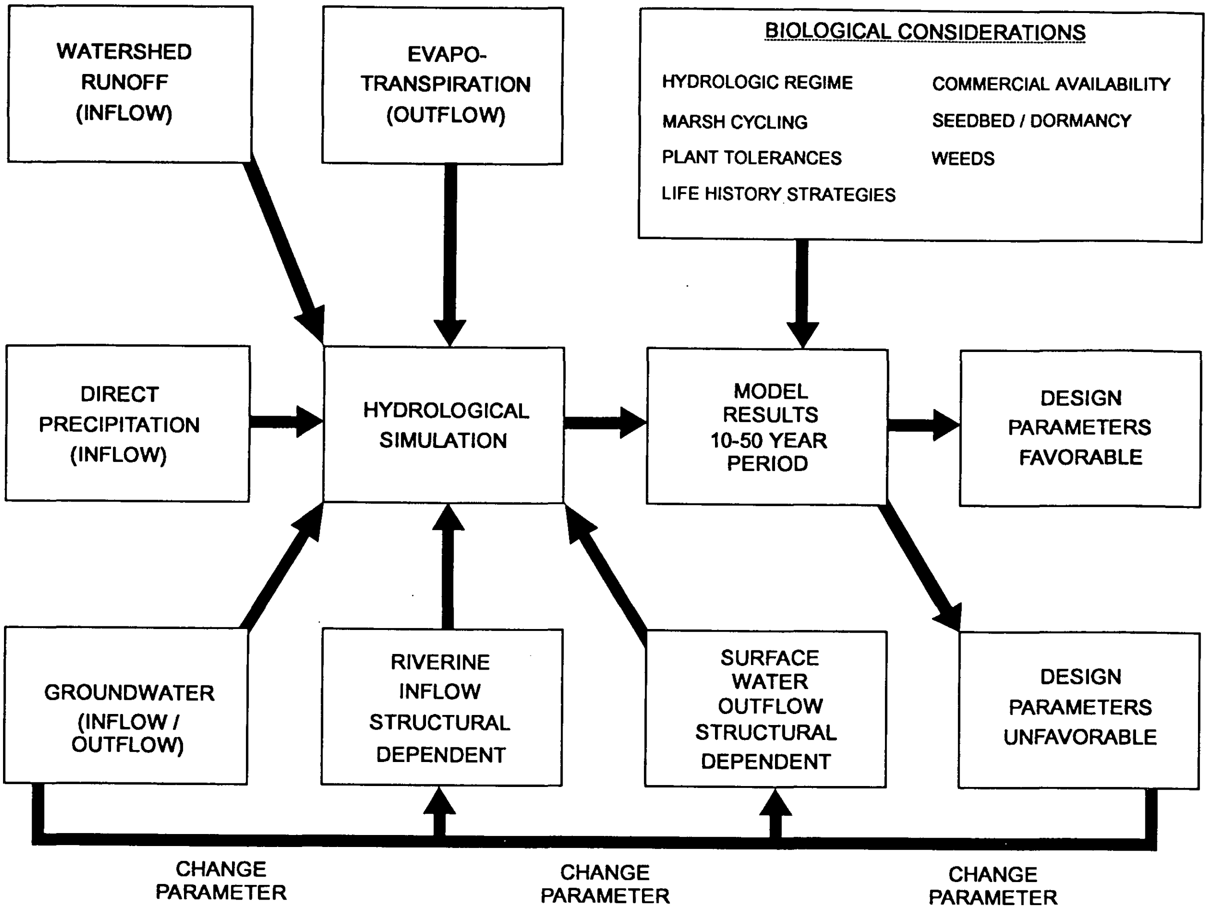


**FIGURE 4 Hydrologic model flow chart.**

Early in the development of the mitigation design it was realized that the on-site soil permeabilities were too high and that the groundwater fluctuations observed were too severe to support the permanently flooded conditions desired. As such it was decided that a buried 15-cm-thick clay liner with a maximum permeability of $1 \times 10^{-6}$ cm/sec would have to be installed to provide the low-permeable soils. Although there is a cost associated with the placement of clay liners, in many cases the cost is offset by the shallower excavation and lower excavation quantities that clay liners allow. The installation of the liner has been judged to be highly successful and has achieved the desired soil permeability.

For the Pequannock River site the hydrological model was run for a continuous 20-year period by using both historical daily precipitation data and historical daily stream gauge data. Among the outputs of the model was a prediction of the daily water height at a reference point in the created wetland. The model was conducted for dozens of different possible design configurations, with the inlet height, inlet length, outlet height, and outlet length being among the parameters with the greatest flexibilities in the design.

The interpretation of the model results required expertise in the fields of both hydrological and biological sciences. From the engineering standpoint the model is a key element in selecting final elevations and determining the overall excavation quantities. The biological interpretation of the model's output takes into account a number of biological parameters, including life history strategies of the targeted plants, plant tolerances to designed water depths, seedbed and plant dormancies, the potential for obnoxious weeds invasion, the potential for desirable plant invasion, and various soil-related characteristics. Among the most important biological influences in the selection of the final elevations is marsh cycling. In many of the productive wetlands in North America the hydrological regime varies widely from season to season and from year to year. This marsh cycling is very typical in the Midwest and the Great Plains, where marshes cycle through the sequence of dense emergent phase, open emergent phase, submergent phase, open-water phase, drawdown phase, and back to the dense emergent phase. Therefore when deciding on the inlet and outlet heights and lengths, the goal of the modeling was to select an elevation that would allow for a natural periodic drawdown of the marsh on a cycle of between 5 and 10 years, but that would allow the marsh to be permanently ponded in most of the years.

Another of the key biological considerations on the marsh design was the potential for invasion by obnoxious weeds, particularly *Phragmites australis* and *Lythrum salicaria*. Both of these plants are common in the Pequannock River watershed and could easily invade a wetland creation site. As such the outlet structure is normally set to produce relatively deep water levels that are not conducive to colonization by these weeds. A depth of approximately 30 cm over most of the emergent marsh was chosen for the project described here, with the central pond area having a

depth of 75 cm. The drawback to this setting is that the planted species are stressed and there is a reduction in the overall emergent vegetative cover.

A final consideration is determining weir heights in relation to nutrient loadings. In an urbanized or agricultural watershed, approximately 90 percent of the pollutant nutrient loading is contained in the runoff derived from the first 2.5 cm of rain. To reduce the pollutant loading entering the wetland, inflows from the Pequannock River do not occur for storm events that produce less than 2.5 cm of precipitation. This was done to limit the potential for nuisance algal blooms.

## CONSTRUCTION OF MITIGATION SITE

### Site Remediation: Removal of Liability

The NJDOT commenced through a single contractor the remediation and construction of the wetland mitigation site in April 1988. The excavated soils from the remedial activities were analyzed for the federal Resource Conservation Recovery Act (RCRA) waste classification parameters of Extraction Procedure (EP) toxicity metals, corrosivity, ignitability, total petroleum hydrocarbons (TPHCs), and reactivity to cyanide and sulfide. The results of these analyses found TPHC concentrations ranging from 340 to 23,000 ppm in all samples except the interior sample from the circular pipe building (Building 1), which contained TPHCs at 74,000 ppm. The stockpile from the Building 1 interior (25 $m^3$) was manifested, transported, and disposed of as a hazardous waste.

Demolition of structures and the removal of building foundations was completed in August 1988. During the demolition all stained soils were excavated and stockpiled on site on plastic sheeting. Soil samples were taken from the excavations and analyzed for the RCRA waste classification parameters. Soil samples found to exceed NJDEPE cleanup levels resulted in an additional 1.5 m of soil being excavated from the bottom and stockpiled. No further sampling was carried out on the additional excavation. An estimated total of 13,760 $m^3$ of contaminated material was generated as a result of remedial activities at the site.

### Wetland Mitigation

Upon completion of the demolition of the existing buildings, ASTs, and USTs and removal of contaminated soils, the proposed 4-ha wetland mitigation area was constructed. The emergent marsh zone of the created wetland was planted with a total of 90,000 individuals on approximately 60-cm centers, including *Peltandra virginica, Sparganium eurycarpum, Pontederia cordata, Sagittaria latifolia, Scirpus validus,* and *Scirpus americanus.* The deeper, central pond area was planted less densely with *Nymphaea odorata, Vallisneria* sp., and *Potamogeton pectinatus.*

### Soil Reuse: Establishing a Statewide Precedent

The NJDOT presented to the NJDEPE's Bureau of Hazardous Waste Classification and Regulation a waste classification sampling plan in November 1988 to characterize the 13,760-$m^3$ soil stockpile. NJDEPE accepted a modified form of the sampling plan because of the large volume of soil to be sampled. The NJDOT plan modified NJDEPE's standard sampling protocol of one five-part composite sample per 75 $m^3$ to one five-part composite sample per 200 $m^3$. The soil stockpile was systematically divided into 72 sampling units, with each unit representing 200 $m^3$ in accordance with the modified sampling plan.

The 72 composite samples were analyzed for EP toxicity metals, TPHCs, reactivity tests for sulfide and cyanide, and PCBs. No values in excess of the maximum concentration for EP toxicity metals, reactivity to cyanide or sulfide, or PCBs were found in any of the 72 composite samples. TPHC concentrations ranged from less than 11.5 to 5,240 ppm. Upon completion of the waste classification testing the NJDEPE reviewed the results of the testing and classified the soil as ID-27 material, which is a contaminated but nonhazardous dry industrial waste.

In New Jersey ID-27 soils that are disturbed as a function of construction must be stabilized so that there is no threat to the general public or to the environment. Various methods of reusing or disposing of the soils were evaluated with respect to cost, implementability, and long-term liability, including (a) landfilling at a licensed landfill facility ($230/$m^3$), (b) reusing the material in the roadway embankment ($9/$m^3$), (c) recycling the contaminated soils at an asphalt recycling facility ($145/$m^3$), and (d) treating the contaminated soils by washing, biologic, or incineration methods.

It was determined that reuse of the 13,760 $m^3$ of contaminated soils as highway embankment material was the most cost-effective solution that would not have a significant impact on the construction schedule of the roadway, the wetland mitigation permit goals, and ultimately the opening of the highway. The contaminated soil was to be placed directly beneath the 70-cm-thick roadway pavement box, which eliminated the potential for infiltration and resultant leaching of contamination into the environment. A soil reuse plan was then prepared. The plan addressed the types of soil contamination present, proposed method of reuse, proposed construction methods, and health and safety requirements during construction. A qualitative risk analysis was also prepared as part of the soil reuse plan. The analysis evaluated short-term and long-term pathways and exposure rates of the contaminants in relation to the guidelines of the National Institute for Occupational Safety and Health and the American Conference of Governmental Industrial Hygienists.

This project was the largest soil reuse plan approved by NJDEPE and the first soil reuse plan prepared by NJDOT that laid the groundwork for other proposed on-site disposal and reuse applications. By reusing the contaminated soils within the project area a savings of approximately $2,000,000 in disposal costs was realized by NJDOT. Aside from the cost savings to NJDOT it had the added benefit of triggering the formation of a Soil Reuse Committee by NJDEPE and the development of a precedent-setting procedure to be used in future cases.

## LONG-TERM MONITORING

Special Condition C of the U.S. Army Corps of Engineers Section 404 permit required that the created wetland exhibit an 80 percent success rate for planted vegetation. This was documented by three annual, written reports submitted by NJDOT to the U.S. Army Corps of Engineers in the fall of each year following completion of construction. Density of emergent and submerged vegetation was estimated and recorded as percent cover. Evidence or direct

sitings of fish and wildlife use of the marsh were also recorded during these and any other visits to the site during each of the 3 monitoring years.

The following plant species were observed in and around the shallow marsh during the 3-year monitoring period: *Echinochloa crusgalli, Typha* sp., *Acorus calamus, Cyperus* sp., *Eleocharis* sp., *Polygonum* sp., *Scirpus validus, Heteranthera reniformis, Ludwigia palustris, Alisma triviale, Pontederia cordata, Sparganium* sp., *Sagittaria latifolia, Leersia oryzoides, Juncus effusus, Salix nigra, Impatiens capensis, Bidens* sp., *Scirpus purshianus, Scirpus atrovirens, Phragmites australis, Setaria* sp., and *Peltandra virginica.*

The central pond area was vegetated by *Nymphaea odorata, Myriophyllum* sp., *Potamogeton* sp., and *Elodea canadensis.* Intermittent patches of *Sagittaria latifolia, Typha* sp., and *Eleocharis* sp. were also scattered throughout this area.

Wildlife observed over the 3-year monitoring period included large amounts of freshwater snails clinging to submerged portions of vegetation in the wetland. Minnows, sunfish, and young smallmouth bass were also observed. Waterfowl regularly used the marsh, with mallards and Canada geese almost always seen swimming or feeding when one visited the site. Other birds seen in or near the marsh included black duck, great blue heron, killdeer, chimney swift, great egret, green heron, snipe, and greater and lesser yellowlegs. Mammals seen using the marsh or surrounding the berm area include muskrats, raccoons, and whitetail deer.

At the end of the 3-year monitoring period, taking both emergent and submerged vegetation into consideration, the average plant cover requirement of 80 percent specified in the U.S. Army Corps of Engineers permit was determined to be satisfied.

Presently the created marsh exhibits several characteristics and functions of a young, developing wetland ecosystem. Plant diversity has been maintained at a high level, with *Scirpus* sp., *Pontederia cordata, Sparganium eurycarpum, Sagittaria latifolia,* and *Nymphaea odorata* dominating (Figure 2). Numerous small fish are present in the marsh, which provides a nursery area for them. Local anglers have reported taking game fish (bass) from the site. Wildlife habitat is also well established, and waterfowl have reproduced successfully at the site. Situated along the banks of the Pequannock River, the created wetland also provides additional flood storage and desynchronization, which are considered valuable to developed areas downstream.

## SUMMARY

Under normal circumstances NJDOT attempts to avoid acquisition of potentially contaminated industrial sites for projects. However because of the limited availability of land for wetland mitigation, the need to expedite right-of-way negotiations, and the site's ideal location, NJDOT took a calculated risk. The concrete pipe manufacturing facility, located immediately adjacent to the Pequannock River, in the floodplain, was a source of environmental contaminants with direct pathways to both surface and groundwater. The NJDOT, by using the site for freshwater wetland mitigation, removed the sources of contamination and converted the environmental liability inherent to the site into a 4-ha environmental asset and an aesthetically pleasing, ecologically functional wetland habitat. In the course of doing so, a precedent-setting contaminated soil reuse process was developed. The process was significantly less expensive than previously used disposal methods.

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# PART 3

# Air Quality

# Improving Road Link Speed Estimates for Air Quality Models

KHALED HELALI AND BRUCE HUTCHINSON

A methodology developed to improve travel speed estimates for air quality modeling is described. The proposed methodology, which is applied after the traffic assignment process, consists of an arterial module and a freeway module. It modifies speeds through the use of a new set of congestion functions based on the Davidson formulation, a modified version of the Dowling and Skabardonis postprocessor methodology, and a modified version of Boston's Central Artery/Tunnel freeway queuing procedure. The methodology was applied to the greater Toronto area, and the arterial module of the methodology was validated by using observed speed data from the region. The model improved average travel speed estimates for arterial roads significantly compared with those calculated from the transportation planning model.

The greater Toronto area (GTA), similar to many large conurbations around the world, suffers air pollution problems. In 1989 the ozone air quality criterion (AQC) at the 20 monitoring stations in GTA was exceeded at least once, whereas in downtown Toronto the AQC was exceeded 265 times. Road vehicles and, more specifically, automobiles contributed significantly to the degradation of air quality in the area. In Ontario automobiles have accounted for about 33 percent of the volatile organic compounds (VOCs) and 20 percent of the nitrogen oxides ($NO_x$), the precursors of ground-level ozone.

In 1990 the Canadian Council of Ministers of the Environment (*1*), in recognition of the negative impacts of elevated levels of ground-level ozone, developed a $NO_x$/VOC management plan. Improvements in mobile emission inventories and implementation of effective transportation control measures were among some of the initiatives recommended by the plan for nonattainment regions. The achievement of these two initiatives requires an air quality model to be linked to a traffic model, in which the latter provides the air quality model with traffic-related inputs, average speeds, and traffic volumes.

Average travel speeds, representing the driving cycle, have a significant effect on automobile emissions. Hydrocarbon emissions are most sensitive to low speeds [i.e., those that occur at high volume-to-capacity (*V/C*) ratios] and to a lesser extent to very high speeds. In other words errors in speed estimation at high *V/C* ratios have a more significant impact on the accuracy of air pollution emission estimates than those at uncongested conditions.

The use of regional transportation planning models in air quality analysis is essential for two reasons. First, the quality of mobile emissions inventories is improved by using link-level travel characteristics (*2,3*). Second, air quality analysis of ozone requires areawide analysis (*4*) and photochemical models (e.g., the Urban Airshed Model), which are used to conduct such analysis, require traffic-related data for grid cells of 5 × 5 km. Traffic operations models, on the other hand, could be used to estimate these data, but only for limited scale applications. For example Matzoros and Van Vliet (*5*) applied an air pollution model that they developed coupled with SATURN, the traffic operations model, to the Manchester, England, central area. The model was tested against observed data and showed reasonable agreement. However for large metropolitan areas the use of traffic operations models is not feasible because of their extensive data requirements such as traffic signal data, which include cycle length, green time to total cycle length, sequence of the traffic signal phases, and so on.

The analytical methodologies used to estimate regionwide average travel speeds vary with the air quality modeling technique used. For example TRFCONV (an air quality program developed for use in Phoenix, Arizona, for carbon monoxide emissions and applied in Tucson, Arizona, and Las Vegas, Nevada) (*6*) uses a nominal average daily speed on each link, whereas DTIM (an air quality program developed and used in many areas in California) (*7*) uses *V/C* versus speed curves to estimate speeds. Existing methodologies except for those of Dowling and Skabardonis (*8*) and Dehgani et al. (*9*) do not address the effect of *V/C* ratios of greater than one on speed estimates and the related emissions calculations. The latter two procedures, which are reviewed in more detail in the following sections, apply simple queuing analysis to adjust travel speeds estimated by regional transportation planning models. In addition most of the above procedures use the Bureau of Public Roads (BPR) congestion function or modified versions of it, despite its drawbacks when dealing with arterial streets.

This research, recognizing the importance of valid average travel speed estimates to automobile emission estimates, proposes a methodology for obtaining improved speed estimates. This analytical methodology combines parts of the procedures developed by Dowling and Skabardonis (*8*) and Dehgani et al. (*9*) and uses calibrated congestion functions based on the Davidson's function.

## DOWLING AND SKABARDONIS POSTPROCESSOR METHODOLOGY

Dowling and Skabardonis (*8*) have developed a postprocessor methodology to improve average travel speed estimates that result from the transportation planning model calculations. The postprocessor approach was developed in response to the requirement for a more stringent set of air quality guidelines for new highway projects. This methodology uses a modified congestion-flow curve and simple queuing analysis to improve travel speed estimates. Hourly traffic volumes on each link are compared with the corresponding capacity of that link, and if demand exceeds capacity a queue is calculated and average speeds are recalculated. Recal-

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culated speeds are the weighted averages of queue speeds and uncongested speeds, as explained later in this section.

Dowling and Skabardonis have reviewed a number of existing link congestion functions (LCFs), sometimes called *speed-flow curves*, and have shown that the original (BPR) function, which is shown in Equation 1, overpredicts congested travel speeds and does not accurately represent speed-flow conditions when queuing exists. A modified version of the BPR function was fitted to the 1985 *Highway Capacity Manual* (HCM) freeway speed-flow curves, and the modified function had a $V/C$ coefficient of 1 and $V/C$ power of 10 (instead of 4).

$$\text{Speed} = (\text{free flow speed})/[1 + 0.15 \times (V/C)^4] \quad (1)$$

They also investigated the use of the 1985 HCM procedure for determining average speeds on arterials to establish an LCF for arterials. However that attempt was unsuccessful because of the wide variation in estimated average speeds for different green times per cycle, traffic signal cycle times, and $V/C$ ratios. The authors decided to use the modified BPR congestion function for arterials as well.

Because the postprocessor operates after traffic assignment, it must assume that queuing occurs on the same link where demand exceeds capacity. The effect of this assumption on the accuracy of the queuing analysis is more significant for a freeway section than for an arterial section. More details on the spatial treatment of the postprocessor of queuing can be found elsewhere (*8*).

Dowling and Skabardonis (*8*) suggested that the temporal variation in demand be treated by dividing the peak period into a sequence of 1-hr-long time slices. Within each time slice the demand and capacity are assumed to be constant, and for each 1-hr slice the average link speed (AVSPD) is calculated as follows:

$$\text{AVSPD} = \text{QUSPD} \times (\text{QULEN/LEN}) + \text{UNSPD} \times [1 - (\text{QULEN/LEN})] \quad (2)$$

where

QUSPD = average speed in queue = capacity/lane × 7.6 m/vehicle (25 ft/vehicle),
UNSPD = uncongested speed = free flow speed/[1 + $(V/C)^{10}$],
QULEN = average queue length = AVGOU × 7.6 m/vehicle (25 ft/vehicle),
LEN = link length [in km (mi)],
AVGOU = average queue = (queue at start of time slice + queue at end of time slice)/2,
Queue at end of time slice = Q1 + demand rate × (1 hr) − capacity rate × (1 hr), and
Q1 = queue at start of time slice.

The authors used a spacing of 7.6 m/vehicle (25 ft/vehicle) in the calculation of queue length and queue speed. However the more precise (typical) spacing for vehicles queuing on an arterial street at a traffic signal is 6.7 m (22 ft), or a density 150 vehicles/km (240 vehicles/mi) (*10*), and it might be that the authors wanted to use a more conservative value for this calculation.

The postprocessor methodology was applied to the highway network of the city of Hayward, California, and was compared with the output of the traffic operational models FREQ and TRANSYT7F by using the output of their transportation planning model for both a four-lane freeway and a four- to six-lane arterial street. The results of the comparison indicated that the processor methodology improved the average speeds that resulted from the planning model. However the authors pointed out two limitations of this methodology: (a) applying the BPR congestion function with a power of 10, which was calibrated for freeways, to arterials, and (b) applying the 7.6-m (25-ft) spacing value, which is suitable only for arterials, to freeways. The first limitation would result in the overestimation of speeds on arterials, whereas the second would result in the underestimation of congested speeds on freeways.

## BOSTON'S CENTRAL ARTERY/TUNNEL FREEWAY QUEUING PROCEDURE

Boston's Central Artery/Tunnel (CA/T) freeway queuing procedure was developed to provide Boston's CA/T project with a tool of reasonable accuracy to assess traffic operations and air quality impacts when congested traffic flows occurred [level of service (LOS) F]. The original formulation of this queuing methodology was developed by J. Kahng and J. Setteducato of Parson's Brinkerhoff Quade and Douglas, Inc., and J. Gluck of Urbitran Associates on the basis of the queuing procedure employed in the FREQ8PE freeway simulation model (*9*). It should be noted that the queuing procedure used in FREQ was originally developed by Makigami and Woodie (*11*). The procedure was subsequently simplified, calibrated, and applied to the CA/T project by Dehgani et al. (*9*).

Queuing analysis similar to that of the Dowling and Skabardonis (*8*) processor was conducted for the freeway segments when the estimated volume exceeded capacity. Because of the sensitivity of the analysis to roadway capacity, Dehgani et al. (*9*) considered capacity as a varying magnitude that changes as roadway geometry and vehicle mix change from section to section. The necessary adjustment was achieved by using capacity reduction factors at weaving areas and isolated merge sections. These capacity reduction factors were the outcome of an iterative process reconciling the 1985 HCM (*12*) weaving areas LOS analysis and the 1965 HCM (*13*) capacity reduction factors for weaving sections. Table 1 shows the capacity reduction figures developed for both weaving areas and isolated merge sections.

By using Table 1 a calibrated unit capacity is assigned to each freeway segment on the basis of its LOS, which is estimated by using 1985 HCM weaving area analysis. Queues are formed when forecast volume exceeds capacity (modified by using Table 1), and the queue lengths are then estimated. To accomplish this the au-

**TABLE 1 Capacity Reduction per Lane in Weave Sections and Isolated Merge Sections (*9*)**

| LOS | Weave Sections | Isolated Merge Sections |
|---|---|---|
| C | < 80 | 80 - 100 |
| D | 180 - 220 | 80 - 100 |
| E | 220 - 270 | 100 |
| F | > 270 | 100 |

*Note: entries are in vehicles/hour*

thors estimated two densities in vehicle per lane-mile values for both jam density (stop-and-go traffic) and capacity density (traffic flowing at capacity). The two density values were 113 and 38 vehicles per lane-km (180 and 60 vehicles per lane-mi), respectively. These values are based on figures given in the 1985 HCM and local observations from Boston. A storage capacity is then derived by subtracting the capacity density from the jam density. The excess demand (QU) forming the queue is divided by the total storage capacity ($S_c$) to yield the maximum queue length as follows:

$$\text{QULEN} = (\text{QU}/S_c) \times 0.5 \times 1{,}000 \text{ (m/km)} \quad (3)$$

where

QULEN = queue length (in m),
QU = excess demand forming queue per lane, and
$S_c$ = storage capacity = (113 − 38) = 75 vehicles/km (120 vehicles/mi).

It should be pointed out that the result of dividing 1,000 by $S_c$ is a density of 13.3 m (44 ft) per vehicle, which is very close to the value of 12.2 m (40 ft) value per vehicle for stop-and-go movement in the queue used in the analysis of breakdown conditions in Chapter 6 of the 1985 HCM. The 0.5 value in Equation 3 is based on the assumption that the delay per queued vehicle varies linearly from 0 sec for the first vehicle to a maximum value for the last vehicle in the queue.

The final step is to calculate the delay associated with the queue and the average queue speed. This is done by calculating two terms, the unconstrained travel time (Tu) and the average delay time (Td). The unconstrained travel time (characteristic of the flow at capacity) is based on a speed of 48 km/hr (30 mph), which is a threshold speed with LOS F and is calculated as follows:

$$\text{Tu} = (\text{QULEN}/48 \text{ km/h}) \times (3{,}600/1000) \quad (4)$$

The estimation of Td, in seconds, attributed to the queue is calculated as follows:

$$\text{Td} = (\text{Vd}/\text{Cd}) \times (3{,}600)(\text{sec/hr}) \quad (5)$$

where Vd is (first vehicle delay + last vehicle delay)/2 or Vd is QU × 0.5, and Cd is the downstream capacity.

Similar to the unconstrained travel time, the average delay time is based on the assumption that the delay per queued vehicle varies linearly from 0 sec for the first vehicle in the queue to a delay time of 2 Td for the last vehicle in the queue. Finally the queue speed (QUSPD) is calculated by dividing the queue length (QULEN) by the total travel time (Td + Tu) as follows:

$$\text{QUSPD} = [\text{QULEN}/(\text{Tu} + \text{Td})] \times (3{,}600/1{,}000) \quad (6)$$

The CA/T queuing model was applied by using 1987 data as a base year, and it showed reasonable agreement with observed queuing spots as well as queue lengths and speeds.

## PROPOSED SPEED IMPROVEMENT METHODOLOGY

The proposed procedure, similar to the above-mentioned procedures, is applied after the traffic assignment process, and its main objective is to improve average travel speed estimates. The proposed methodology combines both of the above-mentioned procedures and avoids some of their limitations. It consists of two modules, namely the arterial module and the freeway module. The arterial module modifies speeds on links with any V/C ratio, whereas the freeway module modifies links with V/C ratios equal to or greater than 1. The arterial module modifies speeds through the use of a new set of congestion functions based on the Davidson formulation and a modified version of the Dowling and Skabardonis (*8*) methodology. On the other hand the freeway module applies a modified version of the CA/T queuing procedure to modify speeds.

### Arterial Road Module

The arterial road module uses the same steps followed in the Dowling and Skabardonis (*8*) postprocessor. Queues are formed on links when demand exceeds capacity, and queue lengths and speeds are calculated on the basis of a density value for vehicles queuing on an arterial street at a traffic signal. However the proposed methodology differs from the Dowling and Skabardonis methodology in the following aspects:

1. It uses a new set of congestion functions based on the Davidson formulation instead of the modified BPR function to calculate uncongested speeds in Equation 2. These congestion functions were calibrated on the basis of observed speed and volume data obtained for the Toronto region, and a detailed description of the calibration process is presented later in this paper.
2. A spacing of 6.7 m (22 ft) per vehicle instead of the 7.6-m (25-ft) spacing used by Dowling and Skabardonis (*8*) is adopted. This 6.7-m magnitude, or 150-vehicle/km (240-vehicle/mi) density, was suggested by Pedersen and Samdahl (*10*) to calculate queue lengths and queue speeds on arterials.
3. Average travel speed is calculated as the average of queue speed and uncongested speed [i.e., (QUSPD + UNSPD)/2] rather than the weighted average used in Equation 2. This modification was made to avoid amplifying any errors in speed estimation because of the aggregate nature of the network (as explained below).
4. Because only one peak hour instead of the peak period is dealt with, average queue (AVGQU) is equal to demand minus capacity (similar to QU in the CA/T procedure).

The aspect of dealing with one peak hour implicitly assumes that demand is constant during that hour, and this contradicts findings of several empirical researchers (*14,15*), who have shown that some commuters shift their departure times during peak hours in response to traffic congestion. This limitation warrants further research on how to incorporate the proposed methodology within the transportation planning system and to account for departure time models.

A number of researchers have identified several limitations of the BPR congestion function. These limitations include that the function underestimates travel time as it approaches oversaturation conditions (especially for arterials) compared with the travel times suggested by traffic flow/queuing theory (*8,16*). In addition the function does not have a parameter that accounts for different types of roadways or different types of traffic operations (*17*). The effect of this is that the use of the BPR function, or the modified forms of it, results in an underestimation of the travel time on the road network, particularly on the arterial road network.

Because of the limitations of the BPR function mentioned above and because of the theoretical appeal of the Davidson function because it is based on queuing theory, a new set of congestion functions based on the Davidson formulation, defined in Equation 7, were calibrated and used in the proposed procedure.

$$t = t_0\{1 + J[V/(C - V)]\} \quad (7)$$

where

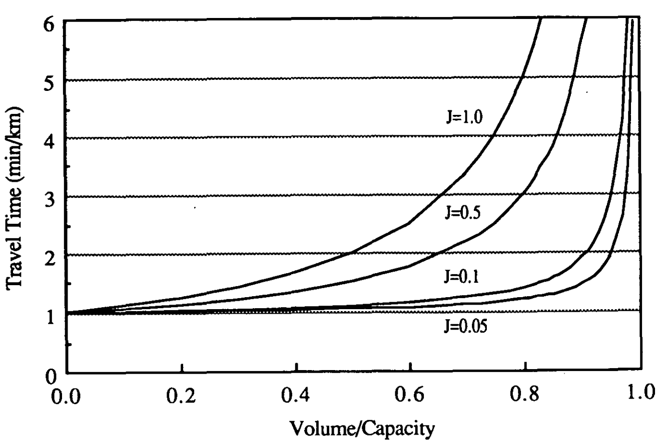
$t$ = travel time,
$t_0$ = free flow travel time, and
J = Davidson parameter (unitless), which determines the rate of change of the function.

Figure 1 shows the effect of the Davidson parameter on the shape of the curve.

The J-parameter, which is also called the *delay parameter* or the *quality of service parameter* (1 − J), can differentiate between different roads that have the same capacity and free-flow speeds but that have different midblock edge frictions. Therefore different J-parameters should be calibrated for different facility types, especially because it is not feasible to calibrate a function for each link on the network. The issues and problems associated with the calibration of the Davidson function are discussed by Rose et al. (*18*), Rose (*19*), Tisato (*16*), and Akcelik (*20*).

Traffic studies in which both traffic volume and travel time data were collected together are not available for the Toronto region. The lack of such studies has led several researchers such as Rose et al. (*18*) to consider collecting each of these two data sets separately as the most likely source of data required for LCF calibration.

The original Davidson function was used in the postprocessor rather than the modified Davidson function introduced by Akcelik (*21*), because the queuing analysis within the postprocessor deals with V/C values of greater than 1. The Akcelik modification avoids computational problems of the original function at V/C ratios equal to or greater than 1. However the computational problems for a V/C ratio of exactly 1 had to be solved. This was solved by restricting the traffic volumes to 0.9 of the capacity, because this value produced travel times that were consistent with the travel times calculated from the queuing analysis for a V/C just greater than 1.




1 km = 0.625 mi.

**FIGURE 1 Effect of J-parameter on Davidson function.**

Matching both sources of data was difficult and time-consuming because traffic volume data are collected on a yearly basis, whereas travel time data are collected for a particular year (1991). Traffic volume information for 1991 was checked against traffic volume information for other years for its reasonableness (i.e., unusually low volumes that occurred because of construction for example). V/C ratios versus average travel speeds were then plotted for different levels of aggregation and scale (e.g., link versus corridor data and a.m. peak versus summation of data for both peak hours). The best-fitting curve between V/C ratio and average speed was obtained by using the data of road segments, both traffic directions (e.g., northbound plus southbound), and both peak hours (i.e., a.m. peak plus p.m. peak). This yielded the expected V/C-versus-speed trend and included V/C ratios of between 0.52 and 0.87. This V/C range covers most of the V/C range identified by Rose (*19*) and Rose and Raymond (*22*) as the most critical for the accuracy of the J-parameter estimation, which is between 0.66 and 1.0.

Nonlinear regression analysis was used to calibrate the Davidson function. Both free-flow travel time and capacity were externally determined as recommended by Tisato (*16*) and Akcelik (*20*) to avoid overprediction of capacity in the calibration process as it occurred to Taylor (*23,24*) in his analysis of the Davidson function. Free-flow travel times and capacities used in the present research were adopted from the Data Management Group (DMG) (*25,26*) road network; their data were collected from the six regional municipalities of the GTA. It should be noted that the capacities used in the calibration were in agreement with the definition of capacity that was recommended by Akcelik (*21*) and Tisato (*16*) for the Davidson function (i.e., the absolute capacity, which is the saturation flow multiplied by the ratio of green time to the total cycle time).

The speed-delay data used for calibration were for Jane Street and Yonge Street, two major north-south arterials in Toronto. The latter street (or more precisely the stretch of street for which the data were available) is a central-area arterial with very intense land use activities on both sides of the road. The other street is a higher-class arterial located outside the central area of Toronto but within metropolitan Toronto. Other speed-delay data were available for a number of central business district (CBD) arterials but could not be used because of the difficulty of matching the data with their corresponding traffic volumes.

Table 2 shows the Davidson J-parameter magnitudes estimated by nonlinear regression analysis. The third J-parameter shown in Table 2 was obtained by a procedure suggested by Rose (*19*) on the basis of the numbers of signals per mile.

The J-parameters listed in Table 2 may be compared with those estimated by Taylor (*23*) for Melbourne, Australia, which ranged

**TABLE 2 Estimated Davidson J-Parameters for the Toronto Area**

| Area | Davidson J-Parameter |
|---|---|
| CBD | 0.211 |
| Metropolitan Toronto | 0.187 |
| Outside Metropolitan Toronto | 0.170 |

from 0.350 to 0.486 for arterials. The lower magnitudes obtained from the Toronto data are consistent with the comments by Tisato (*16*), who showed that Taylor overestimated the capacities. Furthermore Rose and Raymond (*22*) showed that the J-parameter and capacities are highly positively correlated. In other words the overestimation of capacity would result in an overestimation of the J-parameter. In addition the J-parameters estimated in the present research are based on corridor data, whereas the J-parameters estimated by Taylor were based on link data, which might also contribute to this difference.

Figures 2 and 3 show the two calibrated congestion functions and the observed data for Yonge and Jane streets, respectively. Figures 2 and 3 indicate that the Davidson function calibrated for Jane Street is much better than that calibrated for Yonge Street.

### Freeway Module

The procedure applied in the freeway module is similar to the freeway queuing analysis applied to the CA/T project except for a few changes and minor modifications to suit the nature of the present research. The first difference is that there is no weaving area analysis applied in this module. Instead only one fixed freeway capacity of 1,800 vehicles/hr is used along with only one capacity reduction factor of 200 vehicles/hr, as opposed to several values as shown in Table 1. The 1,800-vehicle/hr value of freeway link capacity was obtained from DMG (*25,26*). The reason for using one as opposed to several capacity reduction values is the size of the freeway network for which the analysis is conducted. The CA/T project consisted of a freeway stretch of less than 16 km (10 mi), whereas in the present research it is the entire GTA freeway network. In other words it is not feasible to apply the 1985 HCM weaving analysis for the GTA network or any other regional network as a first step to estimating the capacity reduction figure as was done for the CA/T project. The single capacity reduction value used is 200 vehicles/hr, which is an average value for the values given in Table 1 for LOSs E and F for both weaving sections and isolated merge sections (i.e., the downstream capacity used in the procedure is 1,600 vehicles/hr).

The second difference is the speed used to estimate the $T_u$. Dehgani et al. (*9*) used 30 mph as a threshold value for LOS F. However from the 1985 HCM for an 80-km/hr (50-mph) design speed this value should be less than 45 km/hr (28 mph). Since the GTA freeway network includes all three freeway types, an average value of 45 km/hr was used.

The last of these differences is with respect to the calculation of the resulting travel speed. Travel speed estimated by the CA/T procedure is the queue speed calculated from Equation 6, whereas the travel speed estimated by the proposed procedure is the average of queue speed (calculated from Equation 6) and the uncongested speed (calculated from the BPR function shown in Equation 9). This modification has been made to compensate for the underestimation of travel speeds on the freeway links that would occur for the following reasons:

1. Assigned traffic volumes on freeway links were slightly overestimated. Thus the average travel speeds on these links would be underestimated.
2. If the HCM (*12*) speed-flow curves are assumed to represent real life, then the BPR function to the power of 6 with 60-mph free-flow speed, for example, underestimates speeds compared with those estimated by the 112-km/hr (70-mph) design speed [which is compatible with a 96-km/hr (60-mph) free-flow speed] speed-flow curve for V/C ratios of 0.7 and above, as shown in Figure 4.

## MODEL APPLICATION AND EVALUATION

The proposed methodology was applied to the GTA road network by using the 1986 Transportation Tomorrow Survey data. The GTA consists of metropolitan Toronto and five surrounding regional municipalities. The number of trips generated by the GTA in 1986 was about 2 million during the 3-hr morning peak period. The GTA network was modeled by using EMME/2, the regional transportation model, and included 127 zones and 3,750 links.

The link congestion functions used in the GTA regional transportation model are modified forms of the BPR congestion function, and they are classified for different road categories. The GTA congestion functions have the following forms:

$$\text{Speed} = (\text{free flow speed})/[1 + 1 \times (V/C)^4] \text{ (for arterials)} \qquad (8)$$

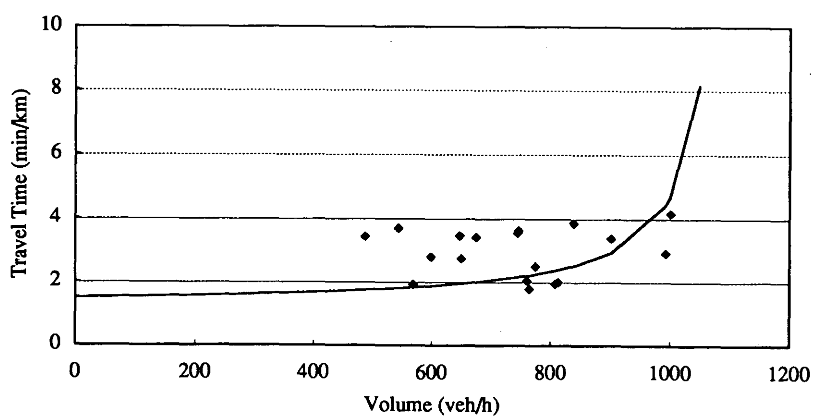



**FIGURE 2 Calibrated Davidson function for Yonge Street (J-parameter = 0.211).**

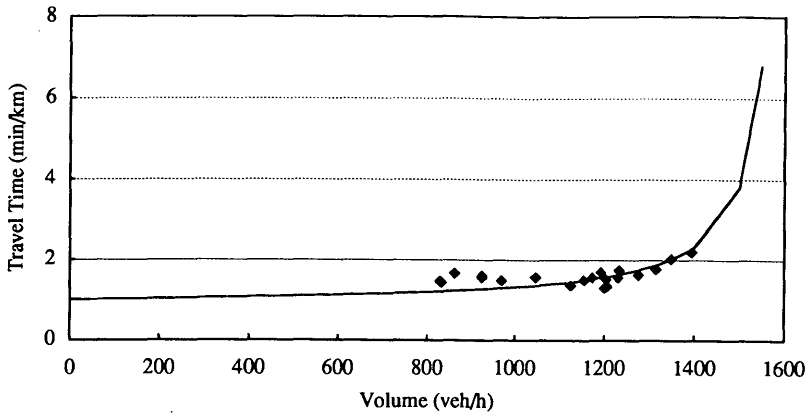



**FIGURE 3 Calibrated Davidson function for Jane Street (J-parameter = 0.187).**

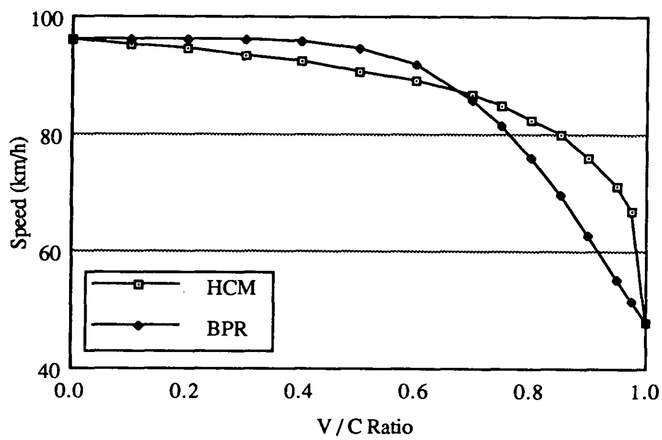



**FIGURE 4 Comparison of speed flow curves.**

Speed = (free flow speed)/[1 + 1 × $(V/C)^6$] (for freeways) (9)

Different free-flow speeds are assigned to different roads within each category. The power of 6 for the V/C term for freeways was adopted because it improved the assigned traffic volumes on freeway sections (*25*).

Because of the large size of the GTA road network and the constraints of the academic version of EMME/2 used in the present research, parallel major and minor arterials were combined to form traffic corridors (*27*), whereas freeway sections were modeled directly. The capacities of the arterial corridors are the sum of the capacities of parallel major and minor arterials, which have approximately the same link lengths. Similar practice has been reported in the literature by Eash et al. (*28*).

The proposed postprocessor was programmed in FORTRAN and was applied to average speeds and traffic volumes that resulted from EMME/2 applied to the GTA road network. The average speeds estimated by this postprocessor were compared with observed average speeds for a number of CBD arterials and Jane Street, as shown in Table 3.

**TABLE 3 Comparison Among Observed, EMME/2, and Postprocessor Speeds**

| Route | Observed Speed (km/h) | EMME/2 Speed (km/h) | Program Speed (km/h) | Percentage Improvement |
|---|---|---|---|---|
| Jane St. (NB) | 36.6 | 43.9 | 38.1 | 15.8 |
| Jane St. (SB) | 41.9 | 51.4 | 46.4 | 11.9 |
| Yonge St. (NB) | 20.8 | 31.9 | 30.1 | 8.7 |
| Yonge St. (SB) | 26.3 | 44.3 | 42.3 | 7.6 |
| University Ave. (NB) | 22.6 | 25.7 | 23.1 | 11.5 |
| University Ave. (SB) | 24.3 | 43.2 | 36.4 | 28.0 |
| Jarvis St. (NB) | 17.1 | 49.9 | 48.1 | 10.5 |
| Jarvis St. (SB) | 30.7 | 47.2 | 41.1 | 19.8 |

*1 km = 0.625 mi.*

It should be noted that average speeds presented in Table 3 are average values for routes (extending over 5 to 10 major intersections) rather than individual link speeds. Average speeds along routes have been used because Florian and Nguyen (*29*) have suggested that the average speeds calculated by EMME/2 for routes are quite realistic, whereas there are some discrepancies in the speeds calculated on individual links within a route.

Table 3 shows that average speeds estimated by EMME/2 by using the modified BPR congestion functions are overestimated and that the postprocessor improves these estimates significantly. These improvements (percent difference compared with the observed speed) vary from a low of 7.6 percent to a high of 28 percent, with an average percent improvement of about 14. Since all these routes on average have V/C ratios of less than 1, these improvements may be attributed to the use of the calibrated Davidson function instead of the BPR function.

The performance of the methodology for oversaturated conditions was then evaluated. For arterials the estimated travel speeds ranged between 8.5 km/hr (5.3 mph) and 18.6 km/hr (11.6 mph), with an average speed of 10.1 km/hr (6.3 mph). Observed travel speeds, on the other hand, ranged from 8.2 km/hr (5.1 mph) to 27.7 km/hr (17.3 mph), with an average value of 18.6 km/hr (11.6 mph). This indicates that the methodology underestimates travel speeds on arterials when V/C is greater than 1. This is consistent with the Dowling and Skabardonis (*8*) conclusion that the procedure underestimates speeds. However this conclusion cannot be generalized because of the very few observations for oversaturated conditions available. One additional observation regarding the performance of the arterial module was that for a V/C of greater than 1.4 (which is unreasonably high) the program calculated higher travel speeds than that estimated by EMME/2, and this was the only occasion when the program speeds were higher than EMME/2 speeds.

Since the proposed freeway procedure deals only with sections with a V/C of greater than 1, the speeds estimated by the methodology for V/C ratios of less than 1 are exactly the same as the speeds produced by EMME/2. The speeds calculated by the postprocessor for V/C ratios of greater than 1 ranged from 15 km/hr (9.4 mph) to 32 km/hr (20 mph), with an average value of 25 km/hr (15.6 mph). Unfortunately, speed-delay data were not available for freeways to allow the same comparisons as for the arterials. However the results seem reasonable because the speeds calculated for freeways were higher than those for the arterials and their values were less than 45 to 48 km/hr (28 to 30 mph), which are the threshold values for freeway sections for LOS F in HCM (*12*).

This analysis indicates that no strong conclusions can be made about the overall capabilities of the methodology until comprehensive observations of network flows and speeds are available.

## CONCLUSIONS

This paper proposed a methodology that improves link travel speeds estimated by transportation planning models. The proposed procedure applies simple queuing analysis and uses calibrated congestion functions based on the Davidson function. The analysis conducted on the methodology shows that it improves travel speeds significantly compared with those estimated by the transportation planning model. It also shows that for arterials with V/C ratios of less than 1 the procedure overestimates travel speeds, whereas for V/C ratios of greater than 1 it underestimates travel speeds, and the net effect of this might be the estimation of better areawide travel speeds.

Freeway speed observations that would allow for a systematic evaluation of the freeway module are not available. However the results seem reasonable when compared with the arterial module and the 1985 HCM.

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# Potential Emission and Air Quality Impacts of Intelligent Vehicle-Highway Systems

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To the extent that intelligent vehicle-highway systems (IVHSs) improve traffic operations and increase the efficiency of the transportation system, emission benefits are expected. However some policy makers are concerned that by increasing the number of vehicle trips and vehicle miles traveled IVHS may have detrimental emission effects as well. Detrimental effects would partially offset the emission benefits gained from improved traffic operations and a more efficient transportation system. There is little evidence, however, that most IVHS strategies will induce travel to the point that increases in roadway supply brought about by efficiency improvements are quickly and completely absorbed by additional traffic. Air quality problems associated with congestion, poor vehicle maintenance, wasted travel, and too many vehicle trips may be alleviated by an array of IVHS products, user services, and technologies that improve the level of service on highways, promote mode shifts that favor travel on high-occupancy vehicles, and supplement conventional emission control programs such as inspection and maintenance.

The potential effects of intelligent vehicle-highway system (IVHS) strategies on vehicle emissions center on the trade-offs between possible increases in travel demand because of increases in roadway capacity or improvements in level of service, possible decreases in travel demand because of more complete travel information and improvements in public transportation systems, and reduced vehicle emission rates resulting from better traffic management. On the one hand IVHS could increase travel demand as a result of faster travel times that may increase the number and length of trips and shift trips from high-occupancy vehicles to single-occupancy vehicles, the induced travel demand that may be realized through significant improvements in the transportation system, or changes in land use patterns that increase trip length (*1*). On the other hand IVHS could reduce travel demand by increasing the attractiveness of mass transit and ride sharing, convincing travelers to forgo or delay trips during poor traffic conditions, generating shorter trips through route guidance, or reducing wasted travel produced by navigational errors (*2*). IVHS will also enable more efficient use of the existing system infrastructure capacity by reducing recurrent and nonrecurrent congestion and improving traffic flow. In turn smoother traffic flow can reduce a vehicle's emission rates during a given trip.

## ANALYTICAL FRAMEWORK

The basis for the timing of IVHS implementation in this paper is technology and system feasibility. This analysis defines the short term to be the years 2000 to 2010 and the long term to be beyond 2010. This definition includes the implementation of first- or second-generation systems in the short term and the implementation of more technologically complex systems in the long term. In addition the geographic scale employed in the analysis focuses on impacts at the regional and corridor levels, although where appropriate effects on high localized emission concentrations are discussed.

It is also important to view the emission impacts of IVHS in light of advancements in vehicle emission control technologies or other mitigation strategies. The eventual penetration of electrically heated catalysts and more advanced combustion control processes into in-use fleets will reduce vehicle emissions. Moreover emphasis on alternative and reformulated fuels in the 1990 Clean Air Act Amendments is evidence of an increasing political preference for different, more effective control strategies. In the long term the emission impacts of IVHS may be negligible under a scenario characterized by an in-use fleet of low-emission vehicles. In the short term, however, evolutionary rather than revolutionary changes in emission control technologies are likely to occur and more concrete projections can be made.

Consideration should also be given to possible changes in the emissions certification process of new vehicles. A recent study by the National Research Council (*3*) concluded that motor vehicles emit two to four times as much hydrocarbon (HC) and carbon monoxide (CO) emissions as estimated by the Environmental Protection Agency (EPA) and the California Air Resources Board. Much of this underestimation may be related to the driving cycle tests used in measuring vehicle emissions, the emissions certification process for new vehicles, and the development of models with existing emission (*1*). The federal test procedure (FTP) is used to certify that new light-duty vehicles and light-duty trucks are in compliance with federal or California emission standards. However this test does not allow for various vehicle operating conditions, such as speeds over 57 mph, accelerations that are greater than 3.3 mph/sec, or sharp decelerations. Activities such as these are believed to be significant contributors to instantaneous vehicle emission rates. In fact a recent report by EPA (*4*) assessed average driving behavior and concluded that driving speeds and acceleration rates are much higher than those represented by the current FTP. EPA will conduct a battery of tests in 1993 to quantify emissions under off-cycle driving patterns (i.e., patterns that are outside the envelope of FTP) (*5*).

Because off-cycle emissions are controlled by new certification processes, emissions under stop-and-go driving conditions will be mitigated. Enrichment and motoring events occur when driving conditions are characterized by congestion. Because possible off-

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cycle emission controls will be geared to reduce emissions under these vehicle operating conditions, the significance of emission benefits associated with IVHS strategies that improve traffic flow may be diminished.

## EMISSION IMPACTS OF IVHS TECHNOLOGY BUNDLES

The distinct characteristics of the technologies and systems that make up IVHS preclude a top-down travel and emission impact analysis that attempts to generalize effects across all systems. Rather emission analyses must focus on individual systems or groups of systems with common transportation network and emission effects. The systems that are likely to have similar effects on the transportation system and on vehicle emission profiles have been grouped into eight technology bundles, which are discussed below.

### Traffic and Incident Management Systems

Traffic and incident management systems include systems designed to reduce recurrent and nonrecurrent congestion levels by improving traffic signalization, incident detection, and corridor control.

- *Advanced traffic signalization systems* allow vehicle movements to be controlled, in real time, through time and space segregation, speed control, and advisory messages.
- *Incident detection systems* minimize delays and network inefficiencies caused by nonrecurrent congestion and detect dangerous road conditions.
- *Freeway and corridor control systems* include ramp metering, express lanes, message signs that allow for variable speed control, and corridor control strategies.
- *Real-time changeable message road sign display systems* provide up-to-date information to travelers who use freeways or arterial roadways.
- *Emergency Mayday systems* reduce delays associated with slow response and incident clearing operations through signals sent by a vehicle communication system to the traffic network.
- *Hazardous material information systems* can help to better identify and clear incidents that involve hazardous materials.

First-generation traffic signalization systems, such as optimized vehicle actuation, have proven effective in reducing delays at traffic lights. But technical as well as operational problems still need to be addressed for later-generation systems, including partially or fully adaptive coordination.

In contrast most freeway and corridor control strategies are being widely applied today. Second-generation ramp metering systems that vary continuously as measured ramp and freeway flows are monitored in real time have been implemented in various urban regions across the country. These ramp metering signals now control traffic at 91 locations along various expressways in the Chicago area (*6*). Advanced ramp metering signals are also found on freeways in the Los Angeles metropolitan area, where two-lane ramps have been deployed on Interstate 405. The penetration of most freeway and corridor control systems can be extensive in the short term. Only corridor control strategies that strive to integrate the entire network of freeways and arterial roads may not see significant penetration in the short term.

As advances are made in traffic signalization systems, incident detection systems, freeway and corridor control systems, and variable message signs, the integration of traffic management strategies that are based on real-time traffic conditions may become a reality. In the short term, however, the impacts of systems in this technology bundle on traffic and travel may be limited to those brought about by the implementation of first- and second-generation traffic signalization, incident detection, and corridor and freeway control systems. Since first-generation systems are not responsive to real-time traffic conditions, their effectiveness in reducing delays and improving the level of service along corridors will be compromised.

The short-term effectiveness of traffic management systems will depend on the sophistication of computer algorithms that mimic traffic conditions. The Los Angeles Automated Traffic Surveillance and Control (ATSAC) system, implemented in the Coliseum area in July 1984, brought about improvements in the level of service. The installation involved 118 signalized intersections and 396 detectors covering an area of 4 $mi^2$. Through partially adaptive coordination systems, automatic adjustments of signal timing plans to reflect changing traffic conditions were deployed. Coupled with incident management systems to detect and manage unusual traffic conditions, such as accidents and special events, ATSAC measured improvements of 13.2 percent in travel time, 14.8 percent in average travel speed, and 35.2 percent in vehicle stops. Models were then employed to translate these level-of-service improvements into potential emission impacts. A 10 percent potential reduction in hydrocarbon (HC) and carbon monoxide (CO) emissions was estimated (*2*). The role of incident management systems is augmented when one considers that more than half the delays that occur on freeways are due to incidents (*2*).

Freeway and corridor control systems can also improve traffic flow along a corridor. The implementation of ramp metering on expressways in the Chicago area was found to reduce peak-period congestion by up to 60 percent and accidents by up to 18 percent. On Houston's Gulf Freeway ramp metering reduced travel times by 25 percent and accidents by 50 percent (*6*).

Although ramp metering does improve traffic flow and the level of service downstream, vehicles may undergo a sharp acceleration as they merge onto the freeway at main line speeds from a full stop. It is not clear whether this enrichment process offsets the corridor-level emission benefits (from smoother traffic flow downstream) that are brought about by ramp metering itself and the other systems in this bundle. The net emission consequences cannot be assessed without a better understanding of modal emissions and other factors that may define this relationship, such as the percentage of vehicles that undergo severe enrichment events relative to the total volume of traffic or the percent increase in the number of these events with and without ramp metering. Given the lack of data and analytic tools the corridor-level emission impacts of traffic and incident reduction systems are uncertain in both the short and long terms.

At the network level the potentially negative emission consequences of ramp meters alone are not likely to offset the potential emission benefits generated by this technology bundle through improved traffic flow and level of service. The combination of traffic signalization systems, incident detection systems, and freeway and corridor control systems is likely to result in higher efficiency gains throughout the network than at the corridor level.

This simply follows from an extension of benefits across a wider area. In the long term these systems may allow for an integrated approach to traffic management on the basis of real-time data on congestion, average travel speeds, and the occurrence of incidents. Such an integrated system can lead to regional improvements in the level of service without significant increases in total traffic volumes (beyond those brought about by demographic and economic factors). At the regional level implementation of traffic and incident management systems may reduce CO and HC emissions, but may increase $NO_x$ emissions as average travel speeds increase. Yet without details regarding the number of ramp meters deployed in a specific network and the emissions significance of their deployment, the regional emission impacts of this technology bundle cannot be fully assessed.

## Route Guidance Systems

The systems included in the route guidance systems technology bundle are designed to provide motorists with information on highway conditions and route availability to help them decide on the best possible route before or during a trip.

- *Radio data systems* use a radio frequency to broadcast traffic information to motorists.
- *On-board navigation systems* inform motorists about their current location and how it relates to the desired destination, but not on a real-time basis.
- *Electronic route planning and information systems* link minimum-path computer algorithms to highway network data bases, accounting for real-time traffic conditions.
- *Externally linked route guidance systems* provide real-time information on traffic conditions and suggest alternative routes to circumvent congested roads during the route-following stage of the trip.

U.S. vehicle owners have traditionally proven to be price sensitive. Elaborate route guidance systems may be very expensive initially (roughly $3,000), reducing their attractiveness to the general motorist public (*7*). The earliest applications of these systems may be in commercial vehicle operations, where productivity gains from better route guidance will be an important financial consideration to commercial carriers. Penetration may increase as prices decrease and benefits are more widely perceived.

First-generation route guidance systems, such as traffic information broadcasting systems, allow motorists to be better informed in the event of heavy congestion along specific corridors. By providing a motorist with information on his or her current location and how that location relates to the desired destination, on-board navigation systems may enhance the motorist's ability to select an alternative route when heavy congestion is encountered. However these systems are not designed to provide motorists with continuous real-time information on traffic conditions and alternative routes.

More advanced systems, such as externally linked route guidance systems, may reduce vehicle hours of delay and improve level of service along a corridor by roughly 7 to 15 percent by providing dynamic routing information that is fully responsive to traffic conditions on the network (*8*).

By diverting traffic from congested corridors to those with excess capacity, traffic flow will be improved along the corridor. However traffic diversion may result in longer trips as motorists select less direct routes to reach destinations. On the other hand on-board navigation systems have the potential to decrease the amount of wasted travel associated with human navigation errors. The net effect on trip distance, or total vehicle miles traveled, is difficult to assess for either the short term or the long term.

Diverting individual drivers from congested corridors to other routes in the network may also result in a rebound effect whereby additional drivers are attracted to less congested routes, possibly increasing emissions along those routes (*9*). However this claim is not supportable because route guidance systems have the potential to improve level of service in the entire network, and often numerous routes with excess capacity exist between an origin and a destination. At this stage exactly what will be the congestion and emission impacts along alternative routes as a result of route diversion is unclear.

Finally the implementation of route guidance systems may facilitate trip chaining, or the linking of different-purpose trips into one extended trip. As more complete and representative travel information is available to motorists before or during a trip, the satisfaction of different needs through trip chaining becomes feasible. The use of route guidance systems for product and service advertising may have this effect. Trip chaining can, in turn, reduce the number of vehicle miles traveled and eliminate those hot and cold starts associated with separate trips.

The potential travel and emission effects of route guidance systems can be summarized as follows. Improved traffic flow will result in decreases in CO and HC emissions. However $NO_x$ emissions may increase with higher average travel speeds. Potential reductions in the number of vehicle miles traveled and hot or cold starts will translate into reduced CO, HC, and $NO_x$ emissions. The net effect on $NO_x$ emissions is uncertain.

## Accident Reduction Systems

Accident reduction systems encompass technologies that provide real-time, on-board warnings to vehicle operators and technologies that automatically assume control of vehicle operations during emergency situations.

- *SmartRamp designs* for commercial vehicles automatically detect the size, weight, and speed of trucks as they approach ramps and advise the driver if there is a rollover hazard.
- *Antilock braking systems* assume control of a vehicle's braking function during moments of excessive braking or severe cornering.
- *Intersection hazard warning systems* prevent accidents that occur when a vehicle enters an intersection and collides with cross traffic that was not visible.
- *Collision avoidance systems* use radar braking and automatic steering control to warn drivers of impending collisions or to automatically assume vehicle control.

On-board warning systems that warn drivers of possible collisions but do not assume vehicle control can be regarded as first-generation accident reduction systems, whereas those systems that automatically control the vehicle to avoid collisions represent second-generation systems. As with other on-board devices, short-term implementation is likely to take place in luxury passenger vehicles and commercial vehicles.

Collision avoidance systems that rely on technologies like radar braking and automatic steering control are still in the development stage. Short-term implementation of the systems in this technology bundle may be limited to SmartRamp designs and first-generation collision warning systems. In the long term advances in radar braking and automatic steering control systems will facilitate the penetration of collision avoidance systems that automatically assume vehicle control during emergency situations.

Traffic accidents directly contribute to nonrecurrent congestion on roadways across the country. By reducing the likelihood of traffic accidents, accident reduction systems can potentially reduce delays associated with nonrecurrent congestion and improve level of service at the corridor and regional levels. Studies suggest that approximately 7 percent of all road accidents could have been prevented if antilock braking systems had been fitted to the involved vehicles (*6*). In the long term collision avoidance systems and intersection hazard warning systems that automatically assume control of the vehicle in emergency situations have the potential to eliminate those accidents that occur because of the inability of drivers to judge speeds and distances correctly.

The implementation of accident reduction systems may translate into reduced HC and CO emissions and increased $NO_x$ emissions as traffic flow is improved and roadways provide higher levels of service. These emission impacts are expected to be greater in the long term with the penetration of systems that assume vehicle control during emergency situations.

### Vehicle Control Systems

Systems in the vehicle control systems technology bundle will allow those vehicles traveling on an appropriately equipped roadway to operate at closer driving distances and at more constant speeds.

- *Radar braking systems* are designed to brake vehicles automatically when predetermined speed and distance relationships are violated.
- *Vehicle speed control systems* include conventional cruise control, speed governors, and variable speed control.
- *Automatic headway control systems* use vehicle sensors to maintain constant distances (brake and speed control) between vehicles traveling on a particular lane of a roadway.
- *Automatic steering control systems* automate the steering process of vehicle operation and allow vehicles to follow a predetermined path along dedicated highway lanes.
- *Automatic highway systems* combine vehicle control strategies with other IVHS products to produce highways on which vehicles drive themselves.

Various technical problems associated with radar braking need to be resolved. These include false alarms that can be caused by roadside obstacles; blinding, which occurs when radar signals from vehicles traveling in the opposite direction block out the return signals from potential obstacles; and problems caused by poor weather conditions, such as backscatter from rainwater (*6*).

The penetration of variable speed control systems may depend on economic factors and vehicle turnover rates, and thus may be significant in the short term. Adaptive cruise control systems are being designed and tested in various programs around the world, including PATH (Partners for Advanced Transit and Highways) and PROMETHEUS (Program for European Traffic with Highest Efficiency and Unprecedented Safety). These systems may be available on some vehicle lines within the new few years.

As a result of the expected staged implementation of the systems included in this bundle, it is possible that short-term and long-term travel and emission impacts may differ. Short-term penetration of vehicle speed control systems may result in smoother traffic flow and improved levels of service on freeways. Vehicle speed control systems, especially adaptive cruise control, may damp out flow disturbances by reducing speed differentials and minimizing the frequency of vehicle stops. The resulting smoother traffic flow should reduce delays, improve energy efficiency, and reduce CO and HC emissions. ($NO_x$ emissions may increase as average speeds increase on a particular freeway). An added benefit may be the reduction of rear-end collisions, with accompanying nonrecurrent congestion relief, that sometimes occur from the propagation of flow disturbances (*2*).

In the long term radar braking systems, automatic steering control systems, automatic headway control systems, and automated highway systems may be implemented, potentially removing the human element from the vehicle operation process. Such applications could double or triple the capacity of a freeway lane (*2,7*).

If the effect of implementing these systems on one existing lane of a freeway is comparable to the effect of adding one or two new lanes, then congestion on the freeway can be replaced by freer-flowing traffic. However if arterial routes in the immediate area of the freeway are also congested, then the new freeway capacity and corresponding improved level of service may cause some of the traffic on parallel routes to be diverted onto the freeway. This diversion may diminish the benefits to freeway users, but may improve level of service on parallel routes (*2*). Therefore potential capacity improvements at the corridor level may also have regional impacts.

Large capacity increases may induce traffic at both the corridor and regional levels as people decide to take trips that they formerly would have forgone because of excessive congestion on the affected freeway or on parallel roads. Results from a recent study conducted by the Institute of Transportation Studies (ITS), University of California at Berkeley, show that capacity expansion induces traffic on the expanded facility, but that this effect occurs over an extended period of at least two decades (*10*). More important the study shows that even after 20 years the traffic induced by expansion falls well short of what would be required to produce the same volume-capacity ratios in the absence of a capacity enhancement project. Therefore capacity expansion will improve the level of service on the expanded facility. This improved level of service will be realized shortly after the project is finalized and is likely to continue for many years. This finding refutes the notion that additions to roadway capacity are quickly and completely absorbed by additional traffic. Increased roadway capacity is not likely to result in a system with equal congestion and more vehicles. The proposition that traffic builds to fill capacity may be true 20 or 30 years after the completion of a project, but this is of little relevance.

The ITS study found that the estimated demand-capacity elasticity 4 years after a capacity expansion ranges from under 0.1 to over 0.3, whereas 10 years after completion the range becomes 0.2 to 0.4. Therefore a 1 percent increase in capacity is expected to result in a 0.1 to 0.3 percent increase in traffic 4 years after the capacity enhancement project is completed. Similarly this 1 percent increase in capacity is expected to result in a 0.2 to 0.4

percent increase in traffic 10 years after project completion. Sixteen years after project completion the demand-capacity elasticity range is estimated to be 0.22 to 0.55. Although capacity-demand elasticity depends on the specific project under consideration, the magnitude of the induced traffic effect resulting from capacity enhancement projects is relatively low, since traffic will not expand to fill capacity until roughly 20 or more years after the capacity enhancement project has been completed.

Similarly results from the ITS study at the regional level indicate that road expansion generates traffic. The study estimates a 0.5 intraregional elasticity and a 0.2 interregional elasticity of vehicle miles traveled on California highways with respect to changes in capacity (lane-miles) in urban regions. However other factors such as population and income have larger effects than road expansion on the generation of traffic. The study indicates that population elasticities range from 0.7 to 0.8, whereas income elasticities are in the range of 0.4 to 0.9.

Because the capacity elasticities are less than unity, highway expansion is also expected to lead to reduced congestion at the regional level. Moreover the study finds that as a result of larger population elasticities and faster population growth, population contributed considerably more than lane-mile growth to the vehicle mile traveled increases in the study region in the past two decades.

Although the focus of the ITS study is on lane-mile additions, many of the results apply to other types of capacity enhancements as well, including those brought about by IVHS. Within the context of this technology bundle, implementation of the systems that may influence roadway capacity probably will not occur until the long term. Even if these systems lead to induced traffic the ITS report shows that capacity expansion reduces volume-capacity ratios, increasing level of service over an extended period of time. Therefore the notion that IVHS will result in a system of equal congestion and more vehicles is not supportable. Moreover satisfaction of latent travel demand confers a societal benefit in terms of increased mobility and potential contributions to economic activity.

In the long term the implementation of vehicle control systems may generate new land use patterns that can lead to increased tripmaking and trip distances. If the effective speed on an automated corridor is twice that on the existing congested corridor, people may locate up to twice as far from workplaces without increasing the durations of their commutes (*2*). However the emission effects of the longer trips that may result from changes in land use are difficult to assess. For example if the longer trip takes place on a freely flowing highway, trip emissions could decrease.

Although the short-term emission repercussions of vehicle speed control systems can be assessed given expectations regarding traffic operations and travel, the complex nature of the relationships between improved traffic flow, induced traffic, and potential land use changes makes it difficult to assess the emission repercussions of vehicle control systems with any degree of certainty.

## Commercial Vehicle Inspection Systems

Commercial vehicle inspection systems increase the productivity of those vehicles engaged in the movement of goods and services and simplify the regulation of commercial vehicles. Only weigh-in-motion and automated safety inspection systems are expected to have an impact on vehicle emissions by reducing congestion at weigh stations and by reducing the number of hot starts.

- *Weigh-in-motion* systems use sensors that can automatically weigh vehicles at main line speeds.
- *Automated safety inspection* systems involve on-board diagnostic systems, scanners, and road-to-highway communication systems situated at safety inspection stations that interrogate vehicles at main line speeds for the condition of safety systems.

Weigh-in-motion stations have been successfully tested, most notably in the California Heavy Vehicle Electronic License Plate Crescent program, and full-scale short-term implementation may be solely constrained by regulatory and institutional barriers. The implementation of weigh-in-motion systems may directly influence congestion at weigh stations. These systems may also eliminate weigh station truck queues that back up onto the highway.

Similarly congestion at roadside inspection stations and along the supporting highway may potentially be eliminated through systems that allow automated safety inspections to be conducted at main line speeds. Roadside safety inspections must be conducted under engine-off conditions. By eliminating the engine-off requirement, automated safety inspection systems can eliminate those emissions associated with hot starts during the inspection process.

## Trip Guidance and Public Transportation Systems

By improving their attractiveness and accessibility to travelers, trip guidance and public transportation systems encourage the use of transit and ride-share facilities, increase the efficiency of high-occupancy modes of travel, and reduce operational costs while offering higher levels of service to the public.

- *Ride-sharing information systems* include on-line computers in business centers, shopping malls, homes, or smart kiosks that tie into a real-time central data base where ride-sharing matches can be identified.
- *Traveler information and service systems* provide travelers with real-time schedule and fare information, pretrip planning information, trip reservation and payment services, and ride-share participant selection and location information.
- *Traffic management systems* give priority to high-occupancy vehicles through traffic signal priority, dedicated highway lanes, ramp controls, and toll strategies.
- *Transit and fleet management systems* better track transit vehicles during service and improve scheduling, ticketing, and planning operations.

From a technological perspective the operational reliabilities of these systems are virtually assured, given that current communications and computer systems are well suited to handle the interface between centralized information clearinghouses and travelers (particularly for work-related trips). For example experimental transit preferential signal priority schemes have been installed in Kent, Ohio; Louisville, Kentucky, and Washington, D.C. These schemes employ automatic vehicle identification technology to identify transit or other types of high-occupancy vehicles when approaching the specially equipped intersection. The penetration of the systems included in this technology bundle may be accel-

erated by the 1990 Clean Air Act Amendments, which emphasize transportation control measures such as ride sharing as a means of reducing impacts of transportation activities on air quality.

The travel impacts of trip guidance and public transportation systems may be fewer vehicle trips and vehicle miles traveled as a result of person-trip shifts from single-occupancy vehicle modes to high-occupancy vehicle modes. Although the number of person-trips may not decrease, reductions in the total number of vehicle trips and total vehicle miles traveled will result in overall reduced levels of congestion and improved levels of service at both the corridor and network levels. Real-time information on traffic conditions at the route level can also induce motorists to delay trips to those times when congestion levels are low.

Under a scenario of full system implementation the potential traffic operation impacts of this technology bundle may translate into reduced CO, HC, and $NO_x$ emissions at both the corridor and regional levels. Although improvements in level of service may increase average speeds and thereby increase $NO_x$ emission rates, total $NO_x$ emission levels may be reduced as the number of vehicle miles traveled and the number of vehicle trips fall. However the effect on $NO_x$ emissions will depend on the types of systems and the extent of their implementation.

### Enabling Technologies for Travel Fees

Examples of IVHS enabling technologies for road pricing programs include automatic vehicle identification, location, and classification technologies, electronic toll collection, and smart cards.

- *Automatic vehicle identification* technologies use transponders, roadside readers, and computers that automatically and uniquely identify vehicles as they pass through specially equipped points on the system network.
- *Automatic vehicle location* technologies provide real-time vehicle location information to a control center by means of on-board computers or sensors.
- *Automatic vehicle classification* systems classify vehicles according to type, gross vehicle weight designation, or other attributes.
- *Electronic toll collection* allows toll collection without vehicle stops.
- *Smart cards* store personalized identification codes linked to centralized data bases.

The enabling technologies included in this IVHS bundle can increase the effectiveness of roadway pricing by minimizing the substitution effect and maximizing the income effect of changes in travel costs. The substitution effect represents the potential increase in congestion on local roads that results from pricing programs implemented on freeways, main lines, or other major corridors in a particular urban area. Automatic vehicle identification and location systems may facilitate the implementation of roadway pricing at the local or regional level, so that travelers are charged appropriate travel fees for using any portion of the transportation network. Strategies can be designed to minimize travel decisions associated with preferential routes on the basis of significant price differentials. In this way the substitution on the part of travelers away from main lines to local roads that may not be equipped for high traffic volumes can be minimized, whereas the increase in travel cost at the network level (i.e., the income effect) may shift trips to alternative modes or delay trips to off-peak periods.

However these strategies are likely to be unavailable in the short term as technological, institutional, legal, ethical, and political barriers inhibit the implementation of local or regional schemes. In the short term those urban areas that implement road pricing programs are likely to do so only at the corridor level. As a result the short-term travel and emission effects of corridor-level projects are uncertain when considered from the perspective of the entire region or transportation network. In the long term, however, the potential does exist for significant travel and emission effects at both the corridor and regional levels.

The short-term corridor-level impact on mode shift may be positive because of the use of high-occupancy vehicle buy-in lanes. On a per-vehicle basis $NO_x$ emissions may increase as reduced congestion facilitates faster travel speeds. However because travel fees may have the effect of reducing the total number of vehicle trips, it is difficult to determine how overall $NO_x$ emissions will change in the short term. In the long term significant changes in the number of vehicle trips may decrease total $NO_x$ emissions at both the corridor and regional levels.

### Emission Control-Enabling Technologies

The emission control-enabling technology bundle includes those devices and systems that have the potential to mitigate mobile source emissions directly by complementing conventional emission control strategies, such as inspection and maintenance programs.

- *Remote sensing devices* measure the concentration of pollutants in the exhaust plumes of vehicles as they pass a roadside monitoring station.
- *Vehicle diagnostic systems* monitor the fuel consumption and exhaust emissions of vehicles and advise drivers on appropriate maintenance practices.

Section 205 of the 1990 Clean Air Act Amendments promulgates regulations requiring manufacturers of light-duty vehicles and light-duty trucks to install emission diagnostic systems beginning in model year 1994. The California Air Resources Board has promulgated similar regulations that require vehicle manufacturers to install on-board diagnostic devices that monitor the performance of catalytic converters. Therefore the short-term penetration of on-board emission diagnostic systems may be accelerated by these statutes, and penetration rates may be constrained only by vehicle turnover rates.

The use of remote sensing devices as an alternative to scheduled, periodic inspection and maintenance programs has several major shortcomings related to the inability of remote sensing devices to obtain readings on all vehicles; to measure evaporative, crankcase, and $NO_x$ emissions; to detect problems with systems designed to control emissions during engine warm-up operation; and to distinguish vehicles with moderately high HC and CO emissions from those that are free from defects.

However as a supplement to conventional inspection and maintenance programs, remote sensing offers two potential advantages.

- Remote sensing can provide a deterrent to the tampering or maladjustment of emission control devices by a vehicle owner that

**TABLE 1 Potential Short-Term, Corridor-Level Impacts of Technology Bundles**

| | Traffic Flow | Vehicle Trips | Trip Distance | Mode Shifts | HC Emissions | CO Emissions | NOx Emissions |
|---|---|---|---|---|---|---|---|
| **Traffic and Incident Management Systems** | Positive | Insignificant | Insignificant | Insignificant | Uncertain | Uncertain | Uncertain |
| **Route Guidance Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Uncertain |
| **Accident Reduction Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| **Vehicle Control Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| **Commercial Vehicle Inspection Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |
| **Trip Guidance and Public Transportation Systems** | Positive | Positive | Insignificant | Positive | Positive | Positive | Uncertain |
| **Enabling Technologies for Travel Fees** | Positive | Positive | Insignificant | Positive | Positive | Positive | Uncertain |
| **Emission Control Enabling Technologies** | Insignificant | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |

Key:
- The short term is defined in this study to be from 2000 to 2010.
- Positive impacts reflect improvements in traffic flow, reductions in vehicle trips or trip distance, or mode shifts from single occupancy vehicles to high occupancy vehicles.
- Negative impacts reflect increases in congestion, vehicle trips or trip distance, and those impacts that reflect mode shifts from high occupancy vehicles to single occupancy vehicles.
- Insignificant impacts reflect no changes (or small changes) in traffic flow, the number of vehicle trips, trip distance, or mode shifts.
- Uncertain impacts are those for which changes in traffic flow, tripmaking, trip distance, or mode cannot be even qualitatively assessed given the current state of knowledge.

TABLE 2 Potential Short-Term, Regional-Level Impacts of Technology Bundles

| | Traffic Flow | Vehicle Trips | Trip Distance | Mode Shifts | HC Emissions | CO Emissions | NOx Emissions |
|---|---|---|---|---|---|---|---|
| **Traffic and Incident Management Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| **Route Guidance Systems** | Positive | Positive | Uncertain | Insignificant | Positive | Positive | Uncertain |
| **Accident Reduction Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| **Vehicle Control Systems** | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant |
| **Commercial Vehicle Inspection Systems** | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant |
| **Trip Guidance and Public Transportation Systems** | Positive | Positive | Insignificant | Positive | Positive | Positive | Uncertain |
| **Enabling Technologies for Travel Fees** | Uncertain | Uncertain | Uncertain | Uncertain | Uncertain | Uncertain | Uncertain |
| **Emission Control Enabling Technologies** | Insignificant | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |

Key:

- The short term is defined in this study to be from 2000 to 2010.
- Positive impacts reflect improvements in traffic flow, reductions in vehicle trips or trip distance, or mode shifts from single occupancy vehicles to high occupancy vehicles.
- Negative impacts reflect increases in congestion, vehicle trips or trip distance, and those impacts that reflect mode shifts from high occupancy vehicles to single occupancy vehicles.
- Insignificant impacts reflect no changes (or small changes) in traffic flow, the number of vehicle trips, trip distance, or mode shifts.
- Uncertain impacts are those for which changes in traffic flow, tripmaking, trip distance, or mode cannot be even qualitatively assessed given the current state of knowledge.

TABLE 3 Potential Long-Term, Corridor-Level Impacts of Technology Bundles

| | Traffic Flow | Vehicle Trips | Trip Distance | Mode Shifts | HC Emissions | CO Emissions | NOx Emissions |
|---|---|---|---|---|---|---|---|
| **Traffic and Incident Management Systems** | Positive | Insignificant | Insignificant | Insignificant | Uncertain | Uncertain | Uncertain |
| **Route Guidance Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Uncertain |
| **Accident Reduction Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| **Vehicle Control Systems** | Positive | Insignificant | Negative | Insignificant | Uncertain | Uncertain | Uncertain |
| **Commercial Vehicle Inspection Systems** | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |
| **Trip Guidance and Public Transportation Systems** | Positive | Positive | Insignificant | Positive | Positive | Positive | Uncertain |
| **Enabling Technologies for Travel Fees** | Positive | Positive | Positive | Positive | Positive | Positive | Positive |
| **Emission Control Enabling Technologies** | Insignificant | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |

Key:
- The short term is defined in this study to be from 2000 to 2010.
- Positive impacts reflect improvements in traffic flow, reductions in vehicle trips or trip distance, or mode shifts from single occupancy vehicles to high occupancy vehicles.
- Negative impacts reflect increases in congestion, vehicle trips or trip distance, and those impacts that reflect mode shifts from high occupancy vehicles to single occupancy vehicles.
- Insignificant impacts reflect no changes (or small changes) in traffic flow, the number of vehicle trips, trip distance, or mode shifts.
- Uncertain impacts are those for which changes in traffic flow, tripmaking, trip distance, or mode cannot be even qualitatively assessed given the current state of knowledge.

TABLE 4 Potential Long-Term, Regional-Level Impacts of Technology Bundles

| | Traffic Flow | Vehicle Trips | Trip Distance | Mode Shifts | HC Emissions | CO Emissions | NOx Emissions |
|---|---|---|---|---|---|---|---|
| Traffic and Incident Management Systems | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| Route Guidance Systems | Positive | Positive | Uncertain | Insignificant | Positive | Positive | Uncertain |
| Accident Reduction Systems | Positive | Insignificant | Insignificant | Insignificant | Positive | Positive | Negative |
| Vehicle Control Systems | Positive | Insignificant | Negative | Insignificant | Uncertain | Uncertain | Uncertain |
| Commercial Vehicle Inspection Systems | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant | Insignificant |
| Trip Guidance and Public Transportation Systems | Positive | Positive | Insignificant | Positive | Positive | Positive | Uncertain |
| Enabling Technologies for Travel Fees | Positive | Positive | Positive | Positive | Positive | Positive | Positive |
| Emission Control Enabling Technologies | Insignificant | Insignificant | Insignificant | Insignificant | Positive | Positive | Positive |

Key:
- The short term is defined in this study to be from 2000 to 2010.
- Positive impacts reflect improvements in traffic flow, reductions in vehicle trips or trip distance, or mode shifts from single occupancy vehicles to high occupancy vehicles.
- Negative impacts reflect increases in congestion, vehicle trips or trip distance, and those impacts that reflect mode shifts from high occupancy vehicles to single occupancy vehicles.
- Insignificant impacts reflect no changes (or small changes) in traffic flow, the number of vehicle trips, trip distance, or mode shifts.
- Uncertain impacts are those for which changes in traffic flow, tripmaking, trip distance, or mode cannot be even qualitatively assessed given the current state of knowledge.

might occur after successful completion of a periodic inspection and maintenance test, and

- Remote sensing allows for early detection of emissions-related vehicular defects unrelated to tampering that can occur between periodic inspections.

Similarly the penetration of on-board emission diagnostic systems has the potential to improve the identification, by vehicle owners, of emission control system malfunctions. Whether vehicle owners who are alerted to malfunctions will repair their vehicles in a timely fashion depends on many factors unrelated to the reliability of on-board diagnostic systems. It is important to combine strategies that facilitate the identification of system malfunctions, such as on-board diagnostic systems, with those that accelerate repair practices and deter tampering with emission control devices, such as remote sensing devices and inspection maintenance programs.

An integrated emissions identification, inspection, and maintenance approach may significantly reduce in-use emissions from motor vehicles. In the short term the benefits may be constrained by vehicle turnover rates and operational deficiencies. In the long term the impact of this technology bundle on in-use emissions will be more significant as all in-use motor vehicles use on-board emission diagnostic systems and the operational reliability of remote sensing devices is improved.

### Summary of Potential Emission Impacts of IVHS

The impact of IVHS on emissions is directly a function of the staged implementation of technologies and systems and the resulting travel and traffic repercussions. Most technologies and systems will lead to improvements in level of service at both the corridor and network levels. These improvements are likely to be measured in small percentage terms rather than in orders of magnitude, and level-of-service improvements are not expected to induce significant amounts of travel. Therefore some IVHS strategies can potentially decrease emissions by improving traffic flow, whereas others can reduce the number of vehicle trips (and the number of cold and hot starts) by promoting travel in high-occupancy vehicles and on public transit systems.

Although better control of off-cycle emissions will reduce the magnitude of the emission benefits that result from improved traffic flow, the emission impacts of most IVHS actions may still be positive. When combined with remote sensing devices, on-board diagnostic systems, and travel fees, IVHS strategies that improve traffic flow and the level of service on roadways have the potential to alleviate air quality problems associated with congestion, poor vehicle maintenance, wasted travel, and too many vehicle trips. Emission benefits may be realized without compromising economic development and the public's need and desire for mobility.

Vehicle control systems have the potential to induce traffic as a result of significant increases in roadway capacity. But it is unlikely that the induced traffic generated by these systems will result in a transportation system characterized by the same level of congestion and more vehicles. Moreover the implementation of those vehicle control systems that can significantly increase capacity, such as automated highways, probably will not occur until the long term. In the long term emissions from motor vehicles may be much lower than current levels, as fuel specifications change (e.g., reformulated fuels) and advanced emission control technologies (e.g., electrically heated catalysts) become feasible.

The potential emission impacts of each IVHS technology bundle are summarized in Tables 1 through 4.

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# Uncertain Air Quality Impacts of Automobile Retirement Programs

SHI-LING HSU AND DANIEL SPERLING

The increasing cost of additional air pollution control has stimulated a search for less expensive market-based regulatory approaches. One market-based approach widely embraced by regulators and politicians is the accelerated retirement and scrappage of old automobiles. Businesses are granted emissions reductions credits by air quality regulators in exchange for removing old and presumably high-polluting automobiles from the road. In reviewing the data from recent programs and exploring assumptions made in evaluations of such programs, it was found that the air quality benefits are uncertain and may be small and that the costs may be higher than those for many other emission control strategies. In some regions and under some conditions, accelerated retirement programs may be much more effective than in other regions and under other conditions.

The growing cost of additional air pollution control has stimulated a search for more efficient market-oriented policy instruments. One approach is to create a market for emissions, whereby emissions credits can be traded among polluters. An example is the marketable permit program created under the 1990 Clean Air Act Amendments for power plants that emit sulfur oxides; power plant operators earn credits for exceeding pollution performance standards. They may sell these credits to other power plant operators that fall short of performance standards. However most of these programs have not been in existence long enough for meaningful evaluation of their success to be made.

This paper examines a specific marketable permit program for which there are some data and which is simple enough to be analytically tractable: accelerated automobile retirement programs, whereby tradeable credits are issued for the early retirement and scrappage of old automobiles, which are thought to account for an inordinately large portion of total vehicle emissions. Such programs, which currently have great conceptual and political appeal, are thought to be more cost-effective than other strategies and are relatively easy to implement, and it is thought that they will stimulate the economy by increasing the sales of new automobiles.

The benefits of accelerated automobile retirement may be illusory, however. A retired vehicle may have been junked soon afterward anyway or might have sat idle, in which case the emissions benefits of accelerated retirement would be minimal. The poor knowledge of the uses of old automobiles and of the in-use emissions of old automobiles creates so much uncertainty as to make it impossible to predict with confidence the amount of emissions reductions achieved by accelerated retirement programs.

## HISTORY

The first accelerated automobile retirement program was carried out in 1990 by the Los Angeles-based Unocal Corporation. The Unocal South Coast Recycled Auto Project (SCRAP) program solicited automobile owners in the South Coast Basin to turn in their old (pre-1971) automobiles for $700 cash. Over a 4-month period Unocal purchased and scrapped 8,376 automobiles. Subsequently other pilot programs have also been carried out, such as the Cash for Clunkers program conducted in 1992 in the Chicago area by the Illinois Environmental Protection Agency (IEPA) and the 1992 Delaware Vehicle Retirement Program conducted jointly by the U.S. Generating Company of Maryland and Resources for the Future. Each of the latter two programs scrapped and studied over 200 automobiles.

## ANALYTICAL FRAMEWORK

It is difficult to determine the amount of emissions reduction attributable to such programs. Accurate quantification of the emissions reduction is difficult, given the poor understanding of key economic and social variables involved. Moreover some air quality plans already contemplate some mobile source emissions reductions, so to avoid double-counting emissions reductions, the air quality benefits accruing from accelerated retirement programs must be distinguished from those already assumed to occur under air quality plans (*1*).

To quantify the emissions reductions resulting from an accelerated retirement program, determinations need to be made with a reasonable degree of certainty. (a) How much earlier were the old automobiles retired than they otherwise would have been without the program? (b) How much would the automobiles have been driven if they had not been retired? (c) What were the emissions levels of the retired automobiles? (d) How were the vehicle miles traveled (VMT) of the retired automobiles replaced? (e) How many VMT will occur on the replacement automobiles, when there is one? (f) What will be the emissions levels of the replacement automobiles?

Unocal retained a marketing research firm, Fairbank, Bregman and Maullin (FB&M), to conduct a follow-up survey of SCRAP program participants to investigate these questions. Although the survey provides valuable insight into the answers to some of these questions, it does not answer them conclusively and moreover raises many other questions. The FB&M survey illustrates how difficult it is to make these determinations with certainty. What follows is an analysis of these areas of uncertainty.

### How Much Earlier Were Old Automobiles Retired Than They Otherwise Would Have Been Without a Retirement Program?

Quantification of the amount of emissions benefit resulting from an accelerated retirement program requires a determination of the

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average remaining life of the retired automobiles at the time they are turned in for early retirement and scrappage. The problem encountered when attempting to make this determination is the lack of knowledge regarding the behaviors of owners of old automobiles. Of the approximately 12 million pre-1974 model year automobiles in the United States, which of them would be turned in under an accelerated retirement program? What conditions make it favorable for automobile owners to scrap their automobiles? A substantial danger exists that accelerated retirement programs will only attract automobiles that were nearing the ends of their natural lives anyway, especially given the modest offer prices of such programs. Predicting which automobiles will be turned in for retirement is thus of paramount importance.

Models of automobile scrappage behavior have been proposed by Parks (*2*) and Manski and Goldman (*3*), but these models are not general enough to serve as the analytical basis for projecting the average remaining lives of old automobiles turned in for early retirement. Alberini et al. (*4*) have carefully studied the Delaware Vehicle Retirement Program and have proposed a model of the determinants of participation in accelerated automobile retirement programs, but their model does not predict the average remaining lives of the automobiles.

Several different approaches have been adopted to deal with this uncertainty, but none of the approaches is satisfactory. The California Air Resources Board (CARB) estimates, using vehicle registration data, that the average remaining life of California automobiles 15 years or older is 6 years (*5*). CARB guesses that the average remaining life of an automobile turned in for accelerated retirement would be roughly half that figure, or 3 years. Although this guess may seem like a fairly sensible assumption, it is not, as CARB admits, supported by data.

Another approach is to use nationwide scrappage rates to calculate the average remaining life of an automobile. The first three columns of Table 1 contain data compiled by Oak Ridge National Laboratory (ORNL) on nationwide automobile scrappage rates for 1978 to 1989 for each automobile age up to 25 years (*6*). The last two columns of Table 1 are calculations of the average remaining life of an automobile at each year of its life and the standard deviation for each year, as derived from ONRL's scrappage and survival data, which are given in columns 2 and 3 of Table 1. Note that the scrappage rate for year 26 is 1.0; this reflects an assumption that all automobiles still in operation after 25 years will thereafter be scrapped.

Note that the standard deviations of the average remaining lives of automobiles are very large in comparison with the averages themselves. For example the average remaining life of a 15-year-old automobile is 4.41 years, but the standard deviation is 3.17 years. This means that roughly two-thirds of all 15-year-old automobiles will be retired between 1.24 years and 7.58 years and that one-third will be retired at times outside that range. Note also that the scrappage rate for year 16 indicates that more than 20 percent of the 15-year-old automobiles were scrapped before the next full year elapsed. Much of this deviation might be explained by variations in the average remaining lives of automobiles across regions of the country. Colder climates tend to shorten the lives of automobiles. However reliable quantitative estimates or means

**TABLE 1 Scrappage Rates and Calculated Average Remaining Lives and Standard Deviations for Automobiles, 1979–1989 (*6*)**

| (1) Age | (2) Scrappage Rate | (3) Survival Rate | (4) Average Remaining Life | (5) Standard Deviation |
|---|---|---|---|---|
| 0 | 0.00000 | 1.00000 | 12.750984 | 5.048669 |
| 1 | 0.00441 | 0.99559 | 11.803035 | 4.998760 |
| 2 | 0.00674 | 0.98888 | 10.876342 | 4.935570 |
| 3 | 0.01025 | 0.97874 | 9.978622 | 4.857109 |
| 4 | 0.01546 | 0.96361 | 9.119612 | 4.761952 |
| 5 | 0.02303 | 0.94142 | 8.311014 | 4.649729 |
| 6 | 0.03368 | 0.90971 | 7.565832 | 4.521683 |
| 7 | 0.04803 | 0.86602 | 6.897099 | 4.380911 |
| 8 | 0.06629 | 0.80861 | 6.315722 | 4.232107 |
| 9 | 0.08790 | 0.73753 | 5.828058 | 4.080584 |
| 10 | 0.11137 | 0.65540 | 5.433148 | 3.930710 |
| 11 | 0.13460 | 0.56718 | 5.122657 | 3.784369 |
| 12 | 0.15557 | 0.47894 | 4.882178 | 3.640301 |
| 13 | 0.17300 | 0.39609 | 4.694290 | 3.494516 |
| 14 | 0.18650 | 0.32222 | 4.541229 | 3.341420 |
| 15 | 0.19641 | 0.25893 | 4.406761 | 3.174873 |
| 16 | 0.20339 | 0.20627 | 4.276573 | 2.988909 |
| 17 | 0.20818 | 0.16333 | 4.138028 | 2.778059 |
| 18 | 0.21140 | 0.12880 | 3.979239 | 2.537536 |
| 19 | 0.21353 | 0.10130 | 3.788115 | 2.263452 |
| 20 | 0.21493 | 0.07952 | 3.551422 | 1.953197 |
| 21 | 0.21585 | 0.06236 | 3.253743 | 1.606221 |
| 22 | 0.21644 | 0.04886 | 2.876286 | 1.225554 |
| 23 | 0.21683 | 0.03827 | 2.395758 | 0.820545 |
| 24 | 0.21708 | 0.02996 | 1.782760 | 0.412367 |
| 25 | 0.21724 | 0.02345 | 1.000000 | 0.000000 |
| 26 | 1.00000 | 0.00000 | 0.000000 | 0.000000 |

of estimation of the average remaining lives of automobiles are still necessary and still lacking.

The SCRAP program attempted to eliminate this uncertainty by asking the automobile owners directly. FB&M, in the SCRAP program follow-up survey, asked 800 SCRAP participants how long they believed their automobile would have lasted had they not turned it in for retirement under the SCRAP program (*7*). Nine percent reported that they were planning to scrap their automobiles anyway. Retirement of this 9 percent achieved no emissions reduction. The estimates of the remaining 91 percent of the respondents ranged from "less than 1 year" (11 percent) to "more than 6 years" (26 percent), with a median estimate of approximately 4 years (*7*). FB&M characterized these estimates of the remaining lives of their old automobiles as "optimistic," noting that respondents' estimates were higher than scrappage data would suggest (*7*).

Another method to reduce the uncertainty regarding the remaining life of an automobile is to require a mechanic's assessment of the condition of the automobile and of its expected remaining life (*8*). Although this method adds some objectivity, it has not been validated empirically.

The large standard deviations and uncertainty might not be an insurmountable problem if the sample of retired automobiles were a representative random sample of old automobiles. However retired automobiles will not be a random sample; because the remaining life of an automobile can be expected to vary inversely with the willingness of the owner to give up his or her automobile, there will exist a bias toward automobiles that have a lower-than-average remaining life. This finds support in the study by Alberini et al. (*4*), which found a strong correlation between the expected remaining life and the offer price that would be required to induce owners to give up their automobiles.

Without the statistical convenience of a random sample and given the large variance of the average remaining lives of old automobiles, the ability to predict the kinds of automobiles that will be turned in for early retirement is very poor. More data are needed before an accurate sample mean for the remaining lives of retired automobiles can be determined. Mobile source trading advocates may argue that it is still possible to ascertain an average that represents scrapped cars in the aggregate, but in light of the large uncertainties associated with old automobiles, it is doubtful that even this is possible.

## How Much Would Automobiles Have Been Driven If They Had Not Been Retired?

Although the average mileage of automobiles by age is fairly well known, it is not known how much a retired automobile would have been used without the retirement program. Once again the problem is that such programs may attract the wrong automobiles—ones that are driven infrequently.

IEPA, in its 1992 Cash for Clunkers accelerated retirement program, relied upon odometer readings from the state's Division of Vehicle Inspection and Maintenance to ascertain the annual mileages of retired automobiles (*8*). Of the 207 automobiles of model years 1968 to 1979 retired by the Cash for Clunkers program, IEPA was able to obtain reliable manual mileage data for only 122 automobiles; many of the remaining automobiles were used very infrequently or not at all. These 122 automobiles had been driven an average of 7,908 mi during the last year, but the standard deviation was 5,776 mi (*9*). The distribution of VMT for these 122 automobiles is shown in Figure 1. Far from approximating a normal distribution, the irregular distribution shown in Figure 1 suggests that there is little predictability with respect to the VMT of retired automobiles. This irregular distribution, the large standard deviation, and the fact that IEPA was unable to obtain mileage data on almost half of the retired automobiles cast doubt on the usefulness of annual mileage data in predicting the results of future programs.

One way of establishing some reliability in the average annual mileage estimate is to obtain data from multiple sources. The Unocal SCRAP program obtained data on the average annual mileage of scrapped automobiles from three sources: (a) California Bureau of Automotive Repair records of smog inspections, (b) estimates from the CARB EMFAC-7E vehicle activity model, and (c) the FB&M telephone survey of SCRAP program participants (*10*). The smog records yielded an average annual mileage estimate of 5,689 mi, whereas the EMFAC-7E model projected the average annual mileage to be 5,368 mi. Telephone survey results varied significantly from those two projections, estimating an average annual mileage of 6,940 mi. The SCRAP program used an average of the first two estimates, yielding an average of 5,528 mi/year. Obtaining data from multiple sources, however, may not always be possible or practicable.

The South Coast Air Quality Management District (SCAQMD) is using a different approach in its Rule 1610 on vehicle scrapping (*11*). On the basis of CARB's BURDEN 7C vehicle activity model it simply assigns an annual mileage figure for each scrapped automobile on the basis of its model year, as follows:

| *Model Year* | *Assumed Annual Mileage* |
|---|---|
| Pre-1972 | 4,600 |
| 1972–1974 | 4,700 |
| 1975–1981 | 6,500 |

To guard against the problem of scrapping already immobile automobiles, Rule 1610 also sets forth some selection requirements that must be satisfied before emissions reductions credits may be granted for an automobile: it requires that the automobile have been registered in the South Coast district as operable for 2 continuous years before scrapping, that it had been continuously insured for at least 1 year before scrapping or have been trans-

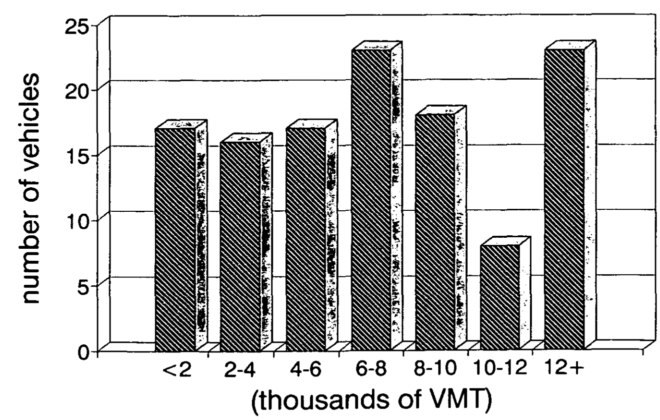


**FIGURE 1 Distribution of VMT (IEPA Cash for Clunkers program).**

ferred to ownership by a South Coast district resident before 1991, and that it have a functional exhaust system, bumpers, doors, fenders, side panels, hood, trunk, windshield, windows, seats, and instrumentation. These requirements will screen some of the most extreme cases of automobile owners rehabilitating their old and immobile automobiles to make one last push to the scrappage site. However making sure that an automobile ''works'' still does not indicate the extent of use before retirement.

In summary variability and uncertainty of use among older vehicles are large; reliable estimates are not available or easily obtainable. Because there is reason to believe that retired automobiles are not a representative sample of all automobiles in their age groups, simply taking the average mileage of all automobiles that are the same age as the retired automobile is not realistic. A great need thus exists for a reliable method of quantifying the amount of use of retired automobiles. This uncertainty is critical; consider that a vehicle driven 6,000 mi/year generates three times the pollution of a vehicle driven 2,000 mi/year.

## What Were Emissions Levels of Retired Automobiles?

Emissions of automobiles scrapped under a retirement program may be estimated either by directly measuring the emissions of each retired automobile or by relying on computer models to predict the emissions of the retired automobiles. The former is expensive; the latter, as indicated below, is inaccurate.

In its 1990 SCRAP program, Unocal, in conjunction with CARB, tested 74 randomly selected automobiles by using the standard federal test procedure (FTP) (*12*). A consulting firm retained by Unocal performed a comparison of the test results with estimated results from California's EMFAC-7E emissions model (*10*). A comparison of hot stabilized tailpipe emissions is given in Table 2.

The EMFAC-7E model made a reasonably accurate prediction of CO and $NO_x$ emissions, erring by 10 and 5 percent, respectively. However EMFAC-7E underestimated HC emissions by 44 percent. Moreover the ranges and the standard deviations for the data were very large relative to the averages. Tested emissions of scrapped automobiles were highly variable, as indicated by the last two columns of Table 2. For example the average HC emission rate for model year 1966 to 1970 automobiles was 16.62 g/mi, which is less than the standard deviation of 18.5 g/mi. Also EMFAC-7E did a fairly poor job of predicting cold-start and hot-start emissions; estimates differed from the FTP results by 25 to 63 percent. Furthermore these figures reflect only tailpipe emissions; nontailpipe emissions, which account for a substantial portion of automobile emissions, must also be predicted with some certainty.

One might also expect large differences across programs and regions. The tested emissions for scrapped automobiles in the EPA Cash for Clunkers program, which tested the retired automobiles by using an I&M 240 test (instead of an FTP test) were quite different from those of Unocal's program. Tested HC emissions averaged 10.6 g/mi versus 16.62 g/mi for the SCRAP program, CO emissions averaged 62.1 versus 84.64 g/mi, and $NO_x$ emissions averaged 4.79 versus 2.39 g/mi. The standard deviations of tested emissions of the Cash for Clunkers program were also large: 13.1 g/mi for HC, 65.0 g/mi for CO, and 7.1 g/mi for $NO_x$. Whether the differences in tested emissions between the two programs are attributable to regional variations or to differences in test procedures, the need for some predictive power is apparent.

As further illustrated by Figure 2, the distributions of emissions of retired automobiles were abnormal. Note that the distribution of HC emissions for the IEPA program [Figure 2(*b*)] shows the same U-shaped pattern as the tested HC levels for automobiles tested in the Unocal SCRAP program [Figure 2(*a*)]. This suggests that the large variances in emissions levels found to exist for these two pilot programs may be an inherent characteristic of accelerated retirement programs.

The abnormal distributions, large variances, and large discrepancies between modeled and tested emissions of retired automobiles are dramatic and underscore the inability to accurately model the emissions characteristics of old automobiles. The alternative to using models such as California's EMFAC or the Environmental Protection Agency's (EPA's) MOBILE to project the emissions of old automobiles is to test each automobile as it is turned in for retirement. However the FTP procedure that was used by Unocal and CARB to test automobiles is expensive and is known to be inaccurate (*13,14*). The I&M 240 test, which produced vastly different results in the IEPA program, is as yet unproven. Thus assigning an appropriate value to the emissions of a scrapped automobile is not straightforward.

## How Will VMT of the Retired Automobile Be Replaced?

As poor as the understanding of the use and characteristics of retired automobiles is, even less is known about the ways in which people would replace their retired automobiles and the air quality impacts of their decisions. CARB assumes that automobile owners who retire their automobile will replace the VMT of the retired automobile by driving a newer, cleaner automobile that has ''av-

**TABLE 2 Tested and Modeled Hot Stabilized Tailpipe Emissions for Scrapped Cars, SCRAP Program, 1990, grams/mile (*10,12*)**

| Pollutant | EMFAC-7E | Average Tested Emissions | Range* | Standard Deviation* |
|---|---|---|---|---|
| HC | 9.16 | 16.62 | 1.9 - 85.4 | 18.5 |
| CO | 76.16 | 84.64 | 11.9 - 248.5 | 50.0 |
| NOx | 2.26 | 2.39 | 0.4 - 9.0 | 2.1 |

*a small speed correction factor was applied to these figures.

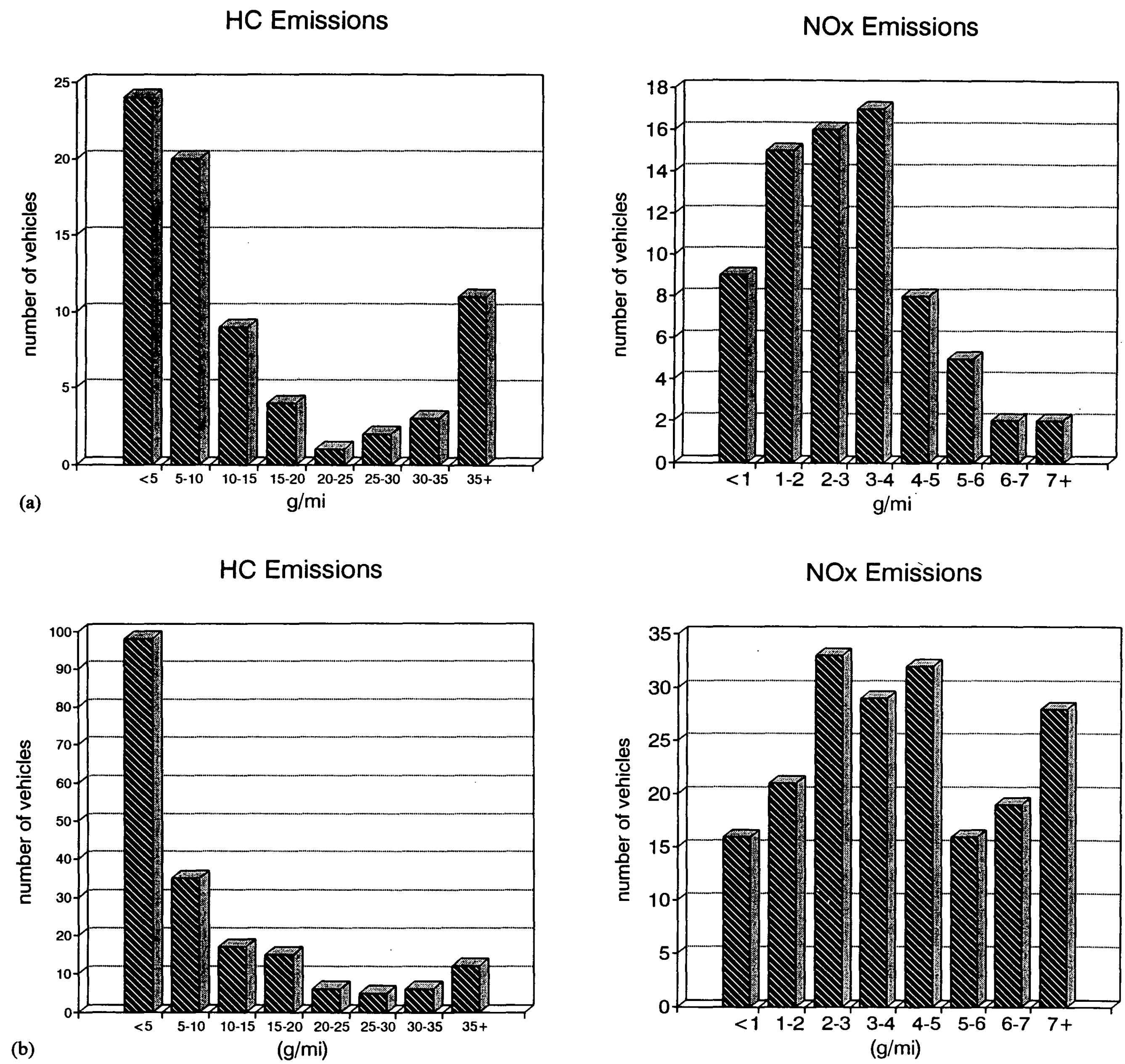


**FIGURE 2 Distribution of emissions levels (*a*) of retired automobiles for Unocal SCRAP program and (*b*) IEPA Cash for Clunkers program.**

erage'' emissions levels. This seems a sensible assumption, yet like virtually all other assumptions that need to be made to justify mobile source emissions reductions programs, it has no empirical basis. Some of the following questions in this regard need to be answered: How many participants will replace their old automobiles with brand new automobiles? How many will replace them with used automobiles? How many will replace their old automobiles with increased use of other, older automobiles that they already own? Will the participant drive the replacement automobile more frequently than he or she did the old automobile? Would an active accelerated retirement program in one region suck in old automobiles from neighboring regions and negate the emissions reductions achieved by retirement?

In its follow-up survey of the SCRAP program, FB&M polled SCRAP program participants as to how they had replaced the miles driven on their old automobile. About 46 percent were driving a newly bought automobile, 42 percent were driving another automobile that they already owned, 8 percent were either getting rides or using public transportation, and 3 percent reported that they did not drive much anymore (*7*). Will this pattern persist in other programs? Would the amount of payment for the old automobiles affect this figure? Will the timing and repeated offerings

of the program affect this figure? Again these are questions that need to be examined before instituting accelerated retirement programs.

### When There Is a Replacement Automobile, How Extensively Would It Be Used and What Would Emissions Levels Be?

Of the 86 percent of the respondents in the FB&M survey that reported that they had already purchased another automobile or were driving an automobile that was already available, 35 percent reported that they were driving the same amount as before, 38 percent reported that they were driving more, and 13 percent reported that they were driving less (*7*). FB&M did not, however, ask the respondents to quantify the differences.

As mentioned above CARB assumes that after an automobile owner turns in the old automobile for scrappage the owner will replace it with an "average" vehicle and will drive the replacement vehicle more frequently than the old automobile because of greater reliability and comfort. Similarly SCAQMD, in its Rule 1610, assumes that for every automobile scrapped under an accelerated retirement program there will be a replacement automobile that will emit, on average, 1.5 g of reactive organic gases per mi and 0.9 g of $NO_x$ per mi and that will be driven an average of 9,800 mi/year (*11*). Although these assumptions may seem sensible and conservative, the lack of research data makes it as difficult to disprove them as it does to support them.

The uncertainty with respect to quantification of the emissions levels of replacement automobiles and the extent of use of replacement automobiles is large. This is not surprising because rarely does an automobile owner know how he or she will replace a retired automobile; it is presumptuous of policy makers to attempt to predict the behaviors of these automobile owners.

## SENSITIVITY ANALYSIS

Uncertainty in the variables discussed will have a profound effect on the magnitude of emissions reductions resulting from an accelerated retirement program not only because the variabilities are large but also because of the multiplicative relationship between the independent variables (the number of automobiles retired under the program and the average remaining life, annual mileage, and emissions levels of the retired automobiles). A sensitivity analysis, presented in Table 3, illustrates this point.

The HC emissions reduction resulting from an accelerated retirement program is quantified as follows. First, the quantities of HC emissions that are avoided by retirement of the old automobiles are calculated by multiplying together the number of automobiles retired (column A in Table 3), the average emissions of the retired automobiles (column B), the average annual mileage of the retired automobiles (column C), and the average remaining life of the retired automobiles (column D). Second, the increase in emissions attributable to use of a replacement automobile is calculated by multiplying together the number of automobiles retired and the average remaining life of the retired automobiles (columns A and D) with the average emissions rates and the average annual mileages of the replacement automobiles (columns F and G).

For the baseline case assume the following:

1. Automobiles turned in for retirement are driven only an average of 4,600 mi, as SCAQMD attributes to pre-1972 automobiles;

**TABLE 3 Sensitivity Analysis for Emissions Reductions Achieved by Accelerated Retirement Programs**

| | (A) No. Autos to be Retired | (B) HC Emissions of Retired Autos (g/mi) | (C) Average Annual Mileage of Retired Autos | (D) Average Remaining Life of Retired Autos (yrs) | (E) tons of HC emissions avoided from retired autos | (F) HC Emissions of Replacement Autos (g/mi) | (G) Average Annual Mileage of Replacement Autos | (H) tons of HC from Replacement Autos | (I) tons of HC reduced (over life of retired auto) | (J) % over Baseline HC Emissions Reductions |
|---|---|---|---|---|---|---|---|---|---|---|
| a) Baseline Estimate: | 10,000 | 16.62 | 4,600 | 3.00 | 2,528 | 1.50 | 9,800 | 486 | 2,042 | (baseline) |
| b) Sensitivity of (B): | 10,000 | 10.0 to 20.0 | 4,600 | 3.00 | 1,521 to 3,042 | 1.50 | 9,800 | 486 | 1,035 to 2,556 | -49 to 25 |
| c) Sensitivity of (C): | 10,000 | 16.62 | 2,500 to 6,500 | 3.00 | 1,374 to 3,571 | 1.50 | 9,800 | 486 | 790 to 2,832 | -57 to 51 |
| d) Sensitivity of (D): | 10,000 | 16.62 | 4,600 | 1.00 to 5.00 | 843 to 4,213 | 1.50 | 9,800 | 162 to 810 | 621 to 3,103 | -67 to 67 |
| e) Sensitivity of (F): | 10,000 | 16.62 | 4,600 | 3.00 | 2,528 | 0.50 to 2.50 | 9,800 | 162 to 810 | 2,186 to 1,538 | 16 to -16 |
| f) Sensitivity of (G): | 10,000 | 16.62 | 4,600 | 3.00 | 2,528 | 1.50 | 4,600 to 9,800 | 228 to 486 | 2,299 to 2,042 | 13 to 0 |
| g) Extreme Estimates: | 10,000 | 10.0 to 20.0 | 2,500 to 6,500 | 1.00 to 5.00 | 276 to 7,163 | 0.50 to 2.50 | 9,800 | 270 to 270 | 6 to 6,893 | -100 to 238 |
| h) High Scenario: | 10,000 | 19.00 | 5,000 | 4.00 | 4,188 | 1.50 | 9,800 | 648 | 3,540 | 73 |
| i) Low Scenario: | 10,000 | 14.00 | 3,000 | 2.00 | 926 | 1.50 | 9,800 | 324 | 602 | -71 |

(E) = (A)x(B)x(C)x(D)x0.000001 metric tons x 1.102 short tons/metric ton

(H) = (A)x(F)x(G)x(D)x0.000001 metric tons x 1.102 short tons/metric ton

(I) = (E) - (H)

(J) = 100 x [(I) - 1862] / (I)

2. The average remaining life of an automobile turned in for retirement is 3 years;
3. The emissions rates of the retired automobiles conform to those measured in conjunction with the SCRAP program (Table 2);
4. Automobiles driven to replace the retired automobiles are driven an average of 9,800 mi/year, as SCAQMD assumes in Rule 1610; and
5. The average HC emissions rates of such replacement automobiles are 1.50 g/mi, as SCAQMD assumes in Rule 1610.

The calculation of the HC emissions reductions achieved under this baseline scenario is contained in line a of Table 3. A hypothetical program that retires 10,000 automobiles would reduce HC emissions from 2,528 tons (column E) to 486 tons (column H), a reduction of 2,042 tons (column I). Lines b through d of Table 3 contain the results of this same calculation when the baseline assumptions regarding the retired automobile are varied. For example, line b contains a range of possible values for the HC emissions of the retired autos (10 to 20 g/mi) and the resulting amounts of emissions reductions are set forth in column E. Lines e and f test the sensitivity of the calculation when the baseline assumptions regarding the replacement automobile are varied. Line g contains the extreme high and low estimates of HC emissions reductions, which are obtained by taking the most favorable and least favorable values of all independent variables; the low extreme is a mere 6 tons, and the high extreme is 6,893 tons, a nearly threefold increase over the emissions reductions from the baseline estimate. Lines h and i of Table 3 contain some more realistic high and low scenarios of HC emissions reductions, taking the most favorable reasonable values of all independent variables for the high scenario and the least favorable reasonable low values for the low scenario. These scenarios indicate that a reasonable range of high and low estimates of emissions reduction would be from 602 to 3,540 tons.

It is obvious that calculations of the amount of emissions reductions from an accelerated retirement program are highly sensitive to assumptions made regarding the characteristics and use of the retired automobiles, whereas they are less so for the assumptions regarding the replacement automobiles. These simple examples show that the risk and magnitude of error in the quantification of emissions reductions are large. They also suggest that the estimation problem is intractable: for any accelerated retirement program, the numbers that need to be calculated to quantify emissions reductions will invariably be small (and will get smaller as emissions standards are tightened in the future) and will have large variances. Worse still, any error associated with these small numbers will be magnified in an accelerated retirement program, because each error pertains to one of many automobiles scrapped in a retirement program.

## COSTS OF EMISSIONS REDUCTIONS

Because of the large uncertainties inherent in estimates of emissions reductions, estimates of the cost-effectiveness of accelerated retirement programs are uncertain as well. Adding to the uncertainty problem is the lack of a widely accepted methodology for calculating the cost-effectiveness of emissions control strategies.

Several cost-effectiveness studies on accelerated retirement programs are reviewed in Table 4. The cost-effectiveness of a program is obtained by dividing the total program costs by the number of tons of pollutants reduced by the program. However there is no widely accepted methodology that determines which pollutants should be included in the calculation or that apportions the program costs among the different pollutants included. The CARB estimate simply adds together the tons of HC with the tons of $NO_x$ to obtain the number of tons of pollutants reduced; this implicitly equates the value of a ton of HC reduced with a ton of $NO_x$ reduced, a debatable assumption because the ozone-producing effects of HC and $NO_x$ are not only unequal but inverse in some instances because of the unusual shape of ozone isopleths (*15*). The Sierra estimate (*16*) also adds into the calculation one-seventh of the tons of CO reduced. This assumption may or may not be appropriate, depending on whether there is a CO problem in the proposed area. The Sierra Research calculation also differs in that it assumes that the benefits of emissions control strategies are positive only in areas and at times when there are violations of clean air standards; this assumption has not been made in other cost-effectiveness estimates.

Calculation of the costs of accelerated retirement programs is also problematic. The governmental costs of administering such a program are uncertain. Although CARB simply assumes a flat cost of $100 per vehicle, it seems unlikely that this simple linear re-

**TABLE 4 Cost-Effectiveness Estimates of Accelerated Retirement Programs**

| Study | Geographic Area | Cost-Effectiveness ($/ton) | Pollutants Considered |
|---|---|---|---|
| CARB (1993) | California | 2,800 | HC, NOx |
| IEPA (1993) | Chicago | 2,989 | HC, NOx |
| | | 3,461 | HC |
| | | 21,951 | NOx |
| Washington (1993) | Sacramento | 1,303 | HC |
| | | 5,619 | NOx |
| | | 187 | CO |
| Sierra Research (1994) | California | 7,600 | HC, NOx, CO |
| | U.S. | 13,900 | HC, NOx, CO |

lationship is realistic. The assumed offer price for purchase of the automobiles is by far the largest expense of such a program, yet there is no agreement on what such a figure should be. The IEPA study cited in Table 4 assumed an offer price of $750 per car; a reduction in the offer price to $550 per car lowered the cost-effectiveness figures by about one-fourth (*8*). The Sierra Research study assumed an offer price of $700 (*16*). Simply lowering the offer price is clearly not a solution, because the findings of Alberini et al. (*4*) show that the success of such programs is highly correlated to the offer price.

Consider the emissions reduction uncertainties analyzed earlier. A range of cost-effectiveness can be calculated by using the high and low scenarios discussed earlier and given in Table 3 (lines h and i). Assume the following:

1. An offer price of $700;
2. Overhead and administrative costs of $100 per automobile;
3. For retired automobiles a range of average HC emissions of 14 to 19 g/mi, average annual mileages of 3,000 to 5,000 mi, and average remaining life of 2 to 4 years; and
4. For the replacement automobiles, 1.5 g of HC emissions per mi and average annual mileage of 9,800 mi/year.

These assumptions and ranges of uncertainty translate into a range of cost-effectiveness of $2,260 to $13,289/ton of HC. This range is reasonably consistent with the comparable estimates made by IEPA ($3,461) (*8*) and Washington ($1,303) (*17*), although it is somewhat less optimistic.

Comparison of these figures with the cost-effectiveness of alternative emissions reduction strategies is problematic. Calculations of emissions reductions from alternative strategies suffer from the same methodological problems of determining which pollutants to include in the calculation and how to apportion program costs among the different pollutants. EPA has nevertheless used a rough rule of thumb that the marginal control costs of alternative emissions reduction measures are $3,050/ton of HC, $2,750/ton of $NO_x$, and $300/ton of CO (*18*). The congressional Office of Technology Assessment (OTA) has estimated the marginal control costs for various emissions reduction strategies to be $2,200 to $6,600/ton of HC for reasonably available control technology (RACT); $120 to $770/ton of HC for higher standards of gasoline volatility; and $2,100 to $5,800/ton of HC, $NO_x$, and CO for enhanced inspection and maintenance programs (with one-third of program costs being attributed to HC, one-half to $NO_x$, and one-sixth to CO) (*19*). The Sierra Research study included cost-effectiveness estimates for a number of emissions reduction strategies, including on-board refueling vapor recovery ($6,870/ton of HC) and evaporative emissions controls ($6,347/ton of HC) (*16*).

Thus when compared with the cost-effectiveness of alternative emissions control strategies, the range of cost-effectiveness estimates shows that there is some modest hope that accelerated retirement programs might be a more efficient means of reducing air pollution. The optimistic assumptions yield a cost-effectiveness of $2,260/ton of HC, which compares reasonably favorably with the EPA's rule-of-thumb estimates and OTA's low-end estimates for RACT and enhanced inspection and maintenance. The pessimistic assumptions on the other hand yield a cost-effectiveness of $13,289/ton, higher than those of most other strategies currently being considered. It should be remembered, however, that marginal control costs for alternative pollution control strategies vary greatly from region to region. SCAQMD, for example, has already implemented the least expensive emissions control strategies and is forced to consider more costly strategies to further reduce emissions. Moreover the effectiveness of accelerated retirement programs can be expected to vary greatly from region to region; the retirement of long-lasting Southern Californian automobiles can be expected to have a larger air quality impact than the retirement of those in snowy midwestern states.

## CONCLUSION

The uncertainties of the air quality benefits that would accrue from accelerated automobile retirement programs cast doubt on the present usefulness of such programs. Although the range of emissions reduction cost figures for accelerated retirement programs leave some room for optimism, no definitive statements can be made about their cost-effectiveness until better estimates of air quality benefits can be made. Similar problems arise for other proposed types of mobile source emissions trading programs as well. Accurate predictions of the emissions levels of buses and fleet vehicles are necessary before regulators become too enamored with the idea of trading credits for the purchase of or conversion to low-emission buses or fleet vehicles. The inherent estimation problems of accelerated retirement programs caused by the small numbers representing emissions levels and the relatively large degrees of uncertainty associated with such numbers are common to all mobile sources. With respect to any mobile source trading program, it appears safe to say that the level of uncertainty and estimation error will inevitably be great. Furthermore regional variation must be taken into account; differences in marginal control costs and automobile characteristics require that evaluations of accelerated retirement programs be done at a regional level.

Mobile source trading advocates may dismiss the concerns regarding uncertainty raised in this paper, arguing that as long as one knows roughly the characteristics of old and replacement automobiles in the aggregate there is no need to bother with the characteristics of individual automobiles. However accurate predictions of such factors, even in the aggregate, are not feasible at this time. The irregular distributions of emissions and VMT of retired automobiles presented in this paper are evidence that statistical averages are unreliable in predicting emissions reductions accruing from accelerated retirement programs. Current estimates of the air quality impacts of accelerated retirement programs are merely guesses.

Better predictive power will not come easily; more pilot programs such as the SCRAP program and IEPA's Cash for Clunkers program are necessary before accurate predictions can be made about the characteristics and uses of both retired automobiles and the newer automobiles that replace them. Research is needed to improve understanding of the behaviors and motivations of automobile owners who might be candidates for participation in such programs and the kinds of automobiles that these people will turn in for accelerated retirement programs. The study of Alberini et al. (*4*) represents a large step in this regard, but for accelerated retirement programs to be effectual, a model of participation that is able to predict the key variables discussed in this paper is needed. In the meantime continuing research into technologies such as remote sensing devices is also very important, because such tools may not only improve the predictability of automobile emissions but may themselves also prove to be a tool for reducing mobile source emissions (*20*).

How successfully and honestly the inherent uncertainties of mobile source trading programs are dealt with will determine the success of such programs. It is too early to pass judgment on mobile source trading programs, but it is not too early to scrutinize the implementation of such programs and examine ways to improve their design to ensure that their adoption will truly result in air quality improvement.

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# Transportation-Related Air Quality and Economic Growth in American Cities, 1981 to 1991

WALTER E. MARTIN, DAVID T. HARTGEN, AND ANDREW J. RESER

Can urban area economic growth be maintained while reducing transportation-related air pollution? To answer this question trends in transportation-related air pollution, employment, traffic, and population were traced for 98 nonattainment U.S. cities over the period 1981 to 1991. Data on 18 measures of pollution (ozone and carbon monoxide), three measures of traffic (vehicle miles traveled and roadway miles), five measures of economic activity (employment), and five measures of climatological circumstances are analyzed. Cities were ranked in order of progress on reducing air pollution while holding down traffic growth and encouraging economic activity. Simple repeated-measures analysis of variance models were used to analyze the data. Results show that (a) spurred by federal emissions standards, U.S. transportation-related air pollution declined 85 percent for carbon monoxide (CO) and 35 percent for ozone from 1981 to 1991, whereas employment increased 25 percent and traffic increased 52 percent; (b) progress in CO reduction was unrelated to city size, employment growth, or traffic growth, being caused primarily by improvements in automotive technology; and (c) generally cities with the most rapid population, traffic, and employment growth showed the greatest reductions in ozone. It is suggested that economic growth is compatible with progress toward cleaner air.

The Clean Air Act Amendments of 1990 place considerable pressure on many U.S. cities to make concerted progress in reducing air pollution. Cities are classified into categories of nonattainment status for carbon monoxide (CO), ozone, and particulates. In the higher categories specific actions are required along with a time frame for making progress. The cities with moderate or worse ozone nonattainment status must reduce volatile organic compounds (VOCs) by 15 percent from 1990 to 1996 and these reductions must be over and above reductions that will be caused by continuing vehicle fleet turnover. If the present plans cannot be shown to produce the required reductions, they must be modified and expanded with transportation control measures (TCMs) (*1*). Given the rapidly approaching dates and delays in rule making, it is likely that many cities will not meet the substantive reductions called for (*2*).

Meanwhile motor vehicle emission standards continue to tighten. Table 1 shows historically mandated emissions standards for automobiles and light trucks as enacted in the Clean Air Act Amendments. Partially as a result, air quality in most metropolitan areas is projected to continue to improve, and (except in a few areas such as Southern California) it may not be necessary to implement very low (Tier II) new car emissions standards (*4*). But despite emission controls and fleet turnover, analysts note less-than-forecast reductions in emissions (*5*) per mile (1 mi = 1.6093 km). And for the future some forecast increasing emissions (*6*), as travel [vehicle miles of travel (VMT)] increases. Because VMT growth is also historically linked with economic activity, the implication is clear: tighter emissions requirements or TCMs that constrain VMT also have the potential to slow economic growth.

A particularly severe issue is ozone. A by-product of photochemical reactions, ozone has emerged as a threat to air quality for nearly 120 million Americans and much of the nation's crop and forest harvests. The concentration of surface ozone depends on several factors including emission levels of hydrocarbons (HCs), emission levels of nitrogen oxides ($NO_x$), as well as geographic factors such as terrain and meteorological factors. Because higher levels of ozone are associated with concentrated levels of anthropogenic (human-caused) emissions found in and downwind from larger cities, economic growth and population growth are often assumed to be positively associated with higher levels of photochemical oxidants such as ozone. But trends in ozone pollution have also been obscured by short-term changes in weather, long-term changes in levels of fossil fuel combustion and evaporative emissions, and longer-term changes in the effective level of emission control. Thus the link between traffic, economic activity, and ozone pollution has been difficult to resolve.

Can economic growth be maintained while making significant reductions in transportation-related air pollution? This is perhaps the central issue in the air quality era. The nature of trade-offs among jobs, economic growth, and environmental quality is examined by Hahn (*7*), who discusses Wisconsin's attempt to balance economic and environmental objectives. This study shows that there is a tendency for the political process to ignore market mechanisms for rationing scarce environmental resources. Rapid economic growth can harm the environment, and if mismanaged the environment can severely limit economic growth. From a global perspective development can support many environmental benefits, first through improvements in technology that prevent environmental damage and second through higher income levels that are correlated with greater environmental concern and a willingness to value environmental protection (*8,9*). Additional questions concerning the seemingly different goals of improved transportation and improved air quality should be raised.

This paper focuses on several critical questions underlying the air quality-transportation debate.

1. Are U.S. cities getting cleaner? How much, for what pollutants, and where?
2. What is the relationship between air quality, city size, economic activity, and VMT?

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**TABLE 1 U.S. Light-Duty Vehicle Emission Standards, 1967–1994 (3) (40 CFR 86)**

| | Autos | | | | Light Duty Trucks[a] | | | |
|---|---|---|---|---|---|---|---|---|
| Model Year | HC | CO | NOx | Particulates | HC | CO | NOx | Particulates[b] |
| 1967* | 8.7 | 87.0 | 3.6 | —[c] | 6.5 | 75.0 | 3.6 | — |
| 1970 | 2.1 | 22.0 | 3.6 | — | 2.2 | 22.0 | 3.6 | — |
| 1976 | 1.5 | 15.0 | 3.1 | — | 2.0 | 20.0 | 3.1 | — |
| 1979 | 1.5 | 15.0 | 3.1 | — | 1.7 | 18.0 | 2.3 | — |
| 1980 | 0.41 | 7.0 | 2.0 | — | 1.7 | 18.0 | 2.3 | — |
| 1981 | 0.41 | 3.4 | 1.0 | — | 1.7 | 18.0 | 2.3 | — |
| 1982 | 0.41 | 3.4 | 1.0 | 0.6 | 1.7 | 18.0 | 2.3 | 0.60 |
| 1984 | 0.41 | 3.4 | 1.0 | 0.6 | 0.8 | 10.0 | 2.3 | 0.60 |
| 1987 | 0.41 | 3.4 | 1.0 | 0.2 | 0.8 | 10.0 | 2.3 | 0.26 |
| 1988 | 0.41 | 3.4 | 1.0 | 0.2 | 0.8 | 10.0 | 1.2[d] | 0.26 |
| Tier I 1994 | 0.25 | 3.4 | 0.4 | 0.08 | 0.25 | 3.4[a] | 1.2[d] | 0.26 |
| Tier I 1995 | 0.25 | 3.4 | 0.4 | 0.08 | 0.25d | 3.4[d] | 0.4[d] | 0.08 |
| Tier II 2003 | 0.125 | 1.7 | 0.4 | 0.08 | 0.25 | 3.4 | 0.4 | 0.08 |

Notes: a: trucks <6000 GVW to 1978, 8500 GVW 1979+
b: diesel engines only
c: no standard
d: trucks <2750 LVW
*: pre controls

3. What has been the role of technology in transportation-related air quality change?
4. What will happen in the future?
5. Are the TCMs in the 1990 Clean Air Act Amendments misplaced in their emphasis?

Fundamental to this debate are hard data. Although it is widely recognized that air pollution has generally improved even as cities have grown, as yet the link between urban growth and transportation-related air pollution has not been extensively investigated. Two competing hypotheses about this relationship were tested.

1. A direct-correlation model, hypothesizing that as cities grow they get dirtier and more congested, thus increasing air pollution. In this model air pollution is positively correlated with economic growth [Figure 1(*a*)].
2. A more complex model, hypothesizing that population growth and economic growth permit changes in technologies that reduce air pollution. In this model air pollution is negatively correlated with economic growth [Figure 1(*b*)].

Although temporal cross-sectional analyses emphasize the generally inverse association between city size and air quality, the long-term effects of cleaner technologies are ignored. Longitudinal studies by contrast might show the opposite effect: that implementation of technology-based emission control strategies during the 1980s achieved reductions in air pollution while cities also experienced population growth. The nature of these relationships and the direction and magnitude of change are examined in this paper.

Reduced atmospheric levels of particulates, lead, and CO during the past 15 years are results of effective emission control strategies. Ozone presents the greatest challenge to continued improvements in air quality and will receive the greatest attention.

## OZONE'S HEALTH AND ECONOMIC IMPACTS

The health effects of photochemical oxidants are primarily respiratory. Acute, short-term, reversible effects include reductions in one-sec forced expiratory volume (FEV) and forced vital capacity. Reduced lung function at concentration of less than 300 parts per billion (ppb), unsubstantiated before 1980, have been confirmed at levels of between 120 and 240 ppb (*10–13*). Recent work by Folinsbee et al. (*14*) has found decreases in mean FEV of between 7 and 13 percent in subjects performing moderate exercise for more than 6 hr at ozone concentrations of between 80 and 120 ppb. The onset of symptoms, coughing and pain when breathing deeply, occurs in young healthy adults exercising heavily for 1 to 3 hr at ozone concentrations of as low as 120 ppb (*10–13,15*).

Long-term effects of ozone on human health remain difficult to determine. Suspected potential effects of low-level exposure, between 80 and 250 ppb, include permanent changes in lung function and structure (*16–19*), effects on growth or aging of the lung (*20*), and increased susceptibilities to bacterial and viral infections (*21,22*). Evidence that long-term low-level exposure is linked with disease does not exist; the long-term studies have not been done. Acute changes, especially among sensitive individuals, athletes, and outdoor workers, are well documented, and many researchers are concerned that permanent damage to the lung may result from exposure over many years (*23*). Although several studies suggest that levels of as high as 120 ppb are unhealthful and levels of between 80 and 120 ppb are potentially unhealthful, the issue of precisely where the health threshold for ozone may lie remains persistently unresolved (*23–25*).

Many effects of ozone and other oxidants on vegetation are well documented (*26–28*), and current research is now beginning to uncover the mechanisms by which crops and trees are damaged (*29,30*). Because prevailing levels of ozone during the growing season in most U.S. agricultural regions are double the biogenic background level (25 to 30 ppb), plants cannot repair cell damage

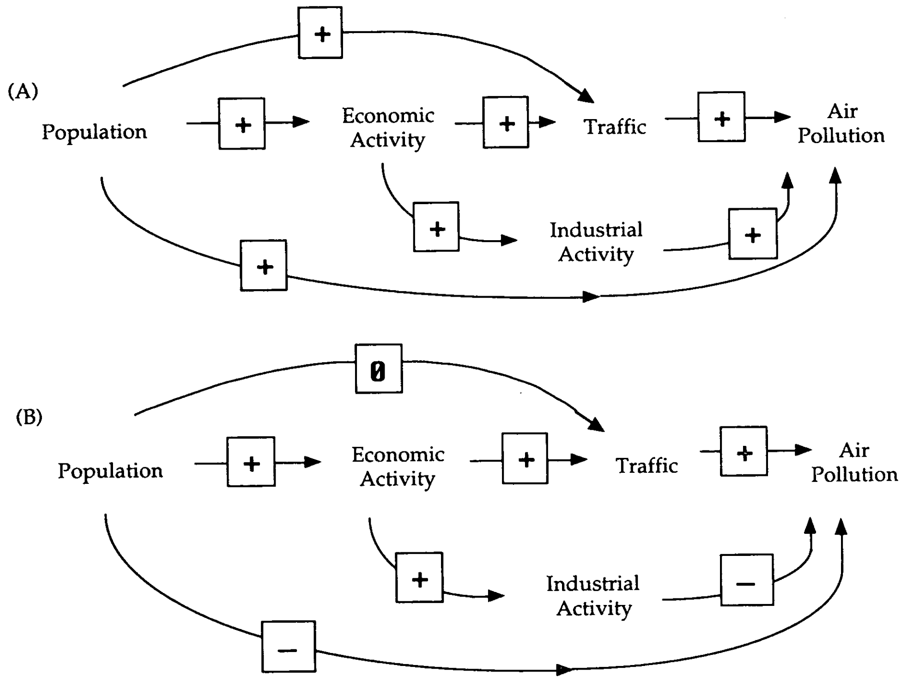


**FIGURE 1 Alternative models of air pollution and economic activity.**

quickly enough. Effects include yellowing, reduced growth, lower yields, and poor quality. Total ozone pollution is estimated to reduce crop yields by 5 to 10 percent, with high yield losses for soybeans, corn, wheat, and peanuts. U.S. agricultural losses from ozone pollution were estimated to be as much as $5 billion in 1987 (*31*). Heck (*32*) states that cutting ozone levels by 40 percent would increase yields for eight major crops by up to $3 billion annually. Although factors contributing to declines in forest productivity may include root fungi, bacteria, viruses, insect pests, and climatic stresses, the direct and chronic effects of oxidants such as ozone may also be a significant factor (*33*).

Theoretically ozone that forms and accumulates in the lower troposphere is derived from several sources, some natural and others anthropogenic. At least four categories of tropospheric ozone are recognized: natural or "background" ozone either from biogenic emissions or stratospheric origin, locally generated anthropogenic ozone, regional ozone from precursors accumulated in high pressure cells, and ozone formed in urban plumes downwind from cities (*34*).

These diverse origins for ozone suggest that (a) control of a single source (e.g., transportation emissions) cannot be completely effective and (b) if only one source is controlled, ozone reduction may not be dramatic. Compared with CO, which is largely transportation based, ozone is not so easily traceable or controllable (*4*). According to recent estimates transportation accounts for 69.92 percent of CO emissions, 38.7 percent of $NO_x$ emissions, 30.1 percent of VOC emissions, and 21.2 percent of particulate emissions (*3*).

## METHOD

In the study described here 98 nonattainment metropolitan statistical areas (MSAs) in the United States were examined to determine recent changes in four data components. These components were

1. Air quality,
2. Traffic and transportation,
3. Economic and population, and
4. Climatological indicators.

Air quality data were obtained from the Environmental Protection Agency's (EPA's) Aeromatic Information Retrieval System (*35*). The 1981 and 1991 Pollutant Standard Index (PSI) summaries were used. The PSI is a ratio (1.0 = 100) of local air pollution measurements (by hour) compared with the National Ambient Air Quality Standard (NAAQS) for that pollutant. Thus an ozone concentration of 150 ppb would be assigned a PSI of 125 (150/120). Since 1990 the transportation provisions of the Clean Air Act Amendments have emphasized ozone and CO reductions. Data for these two pollutants were used. Note that air quality data for some metropolitan areas may not be as complete or as accurate as desired owing to a limited number of sites, poorly located sites, and variations in the age and accuracy of monitoring equipment. Local and state commitments to clean air and budgetary support for air quality monitoring may vary. Information included in the data set include annual number of days good (0 to 50 PSI), moderate (51 to 100 PSI), unhealthful (101 to 200 PSI), very unhealthful (201 to 301 PSI), and hazardous (301 to 400 PSI) air quality.

Additional summary statistics used are (a) total number of days of unhealthful or worse (in each calendar year), (b) average PSI (year), (c) highest PSI (year), and (d) 75th percentile PSI (year). Although the NAAQS indicates unhealthful conditions (i.e., total days unhealthful or worse), the 75th percentile PSI may be a better indicator of air quality because it reduces the effect of rare or extreme events in the trend of high pollution episodes.

Transportation data included (a) total daily VMT (DVMT), (b) DVMT per capita, and (c) total roadway miles for 1980 and 1991. Wherever possible data were obtained at the MSA level; however, the transportation data prepared by the U.S. Department of Transportation are reported only for urbanized areas (*36*). Because of this the data for this component were analyzed only in a very general way to indicate basic traffic trends. As with air quality data VMT estimates are difficult to verify and may suffer for some spatial and temporal variations. Economic, population, and climatic profile data were retrieved from the American Chamber of Commerce Research Association (ACCRA) Community Profiles data base (*37*).

Employment and population data from the 1980 and 1990 censuses were used for the economic component, which included (a) nonfarm employment, (b) manufacturing employment, (c) retail employment, (d) service employment, and (e) population.

Climate data included (a) heating degree days, (b) cooling degree days, (c) maximum yearly temperature, (d) mixing potential and turbidity, and (e) forecast days of high air pollution per 5 years (*38*).

Data were analyzed in simple tables and charts. Analysis of variance (ANOVA) techniques were used to determine the strengths of the models.

## FINDINGS: GENERAL

Figures 2 and 3 suggest that, using cross-sectional data (1981 and 1991), an apparent positive correlation between city size and air pollution exists for both years. This appears to confirm the model shown in Figure 1(*a*). However closer inspection of the data for individual cities over time reveals that most cities in the data base experienced a decline in average PSI (pollution) and an increase in population more similar to the model shown in Figure 1(*b*). Temporal change is masked by the use of simple cross-sectional data. Most cities saw increases in air quality and population in 1991 compared with the values in 1981.

Table 2 shows the aggregate U.S. trends that confirm this interpretation. Transportation-related air pollution (ozone and CO) both improved considerably during the 1980s, despite significant

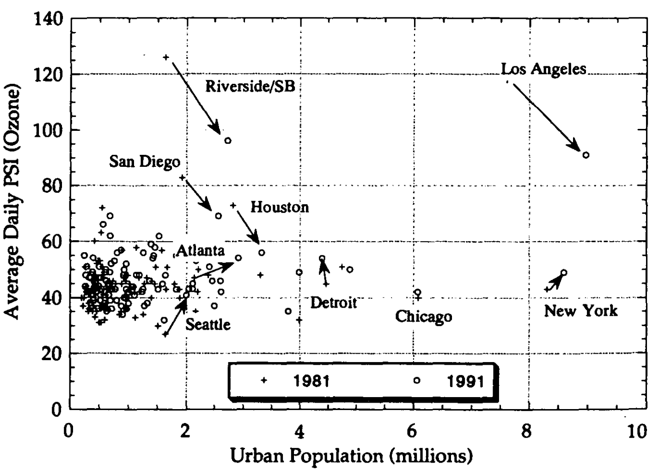


**FIGURE 2 Changes in ozone concentration and population size.**

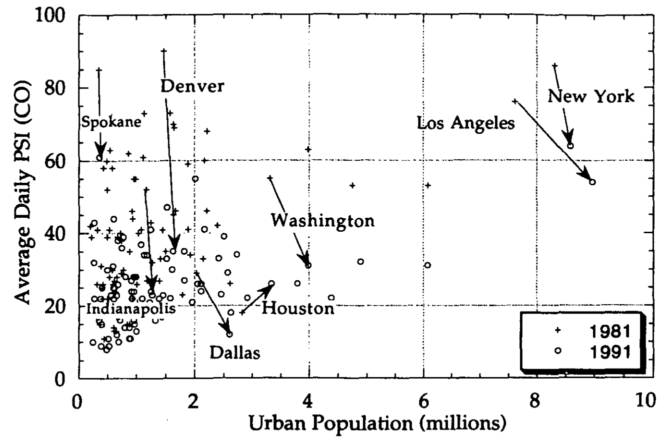


**FIGURE 3 Changes in CO concentration and population size.**

increases in economic activity and traffic. Reductions for CO were generally greater than those for ozone. Meanwhile economic activity, measured in jobs and population, grew 25.4 and 12.4 percent, respectively, and VMT increased 52.5 percent.

As an aggregate index of air quality the PSI remains a standard statistic; however, it is also necessary to examine measures of individual pollutants. Ozone and CO show trends similar to those for CO, but the changes are much less substantial for ozone. Indeed a few ozone parameters show increases in pollution (Table 2), whereas most show modest reductions. On the key statistics (CO and ozone days over NAAQS), average reductions were 85 and 35 percent, respectively.

### Findings: Cities Making Most Progress

To better understand some of the trends across the country, a ranking scheme was created to compare MSAs according to air quality, economic growth, and traffic. The higher-ranking MSAs are the ones that improved air quality while also maintaining economic growth and keeping traffic growth modest. Ranks were computed for each of four measures, which included:

1. Number of unhealthy days (PSI 100) for ozone in 1991,
2. Number of unhealthy days for CO in 1991,
3. Percent change in nonfarm employment for 1980 to 1990, and
4. Percent change in DVMT (reversed) for 1980 to 1991 (traffic figures are for urbanized areas).

The four ranks were summed, with the lowest sum receiving the highest overall score. The best overall cities (the fewest days of unhealthy air, but with economic growth and traffic control) were

1. Tampa–St. Petersburg, Fla.;
2. Jacksonville, Fla.;
3. South Bend, Ind.;
4. Orlando, Fla.; and
5. Fort Lauderdale, Fla.; Fayetteville, N.C.; and Omaha, Nebr.

TABLE 2 Aggregate Trends in Air Pollution and Economic Growth

| Air Pollution | Averages for 88 Non-Attainment U.S. Cities* 1981 Average | 1991 Average | %Change |
|---|---|---|---|
| Carbon Monoxide | | | |
| # days unhealthful | 12.49 | 1.95 | -84 |
| # days very unhealthful | 1.35 | 0.06 | -95 |
| # days hazardous | 0.02 | 0.00 | -100 |
| # days >100 PSI | 13.86 | 2.01 | -85 |
| highest PSI | 145.48 | 91.59 | -37 |
| 75th percentile PSI | 49.39 | 31.78 | -36 |
| Average PSI | 40.15 | 26.27 | -35 |
| Ozone | | | |
| # days unhealthful | 9.20 | 6.61 | -28 |
| # days very unhealthful | 2.40 | 0.94 | -61 |
| # days >100 PSI | 11.60 | 7.56 | -35 |
| highest PSI | 141.4 | 123.08 | -13 |
| 75th percentile PSI | 57.80 | 58.78 | +2 |
| Average PSI | 45.57 | 47.31 | +4 |
| Economic Activity | 1980 Average | 1990 Average | % Change |
| Nonfarm employment | 709,584 | 889,615 | +25.4 |
| Manufacturing employment | 126,204 | 115,702 | -8.3 |
| Retail employment | 113,565 | 144,777 | +27.5 |
| Service employment | 173,240 | 269,427 | +55.5 |
| Population (1981-1991) | 1,379,759 | 1,550,423 | +12.3 |
| Traffic (urbanized area) | 1980 Average | 1991 Average | % Change |
| Daily VMT** | 19,434,133.0 | 29,638,651.0 | +52.5 |
| DVMT/capita | 15.5 | 20.9 | +34.5 |
| Roadway Miles | 4,257.1 | 4,984.3 | +17.1 |

* A number of (generally smaller) cities had missing data items and are not included.
** One mile equals 1.6093 kilometers.

Cities with the lowest index scores were

98. Los Angeles–Long Beach, Calif.;
97. Fresno, Calif.;
96. El Paso, Tex.;
95. New York, N.Y.; and
94. Worchester, Mass.

A similar ranking is achieved when 1991 VMT per capita is substituted for the change in VMT. Florida cities still held four of the top eight scores, while Philadelphia, Pennsylvania; Modesto, California; and the New York City area made some minor gains in rank. One potential contributing factor in the case of New York was the relatively high rate of job loss within the New York metropolitan area during the nationwide slowdown that began in 1990 and 1991. New York is also typical with regard to its relatively high rate of transit use and consequent low VMT per capita. Cities that dropped because of high VMT per capita were Atlanta, Georgia; Raleigh-Durham, North Carolina; and Nashville, Tennessee. Florida cities were the overall big winners because of rapid economic growth and climate conditions that were not conducive to air stagnation and the lack of ventilation that can elevate pollution levels. Generally the losers were California cities and established cities where decennial economic growth was slower.

### Findings: Models of Economic Change and Air Quality

Repeated-measures ANOVA was used to discern changes in air quality with respect to selected measures of demographic, economic, and transportation change between 1981 and 1991. Repeated-measures ANOVA differs from a standard multivariate analysis in that temporal autocorrelation is controlled. Repeated measures is frequently used to investigate identical measurements of each sample member across two or more time steps. In the present case nominal categories such as population decline, moderate population growth, and rapid growth were associated with an interval variable, the annual number of unhealthy days from CO or ozone. So measured, air quality was entered as the dependent variable. The independent variables and their levels are given in Table 3. *P*-values at the 0.05 alpha level were considered significant. The model form is

$$\Delta Y = \mu + \partial T + \beta X + \Psi TX + e$$

where $\Delta Y$ is change in pollution, $\mu$ is a grand mean, $\partial$ is the time (technology) effect, $\beta$ is the effect of $X$, $\Psi$ is the interaction between time and $X$, and $e$ is the error term.

**TABLE 3 Repeated-Measures ANOVA Models of Independent Variables**

| Variable | Level |
|---|---|
| Population Change (percent) | Rapid: >15<br>Moderate: 0–15<br>Loss: <0 |
| Population Density/mi² (1990) (1 mi² = 2.59 km²) | High: >13.658<br>Medium: 4,579–13,658<br>Low: <4,579 |
| Nonfarm Employment (percent change) | Rapid: >40.04<br>Moderate: 13.5–40.04<br>Slow: <13.5 |
| Manufacturing Employment (percent change) | Gain: >8.32<br>Stable: −9.11–+8.32<br>Loss: <−9.11 |
| Value Added by Manufacturing ($/employee, 1987) | High: >$10,044<br>Moderate: $3,570–$10,044<br>Low: <$3,570 |
| DVMT (percent change) | Extensive: >97.05<br>Moderate: 43.58–97.05<br>Nominal: <43.58 |
| DVMT/capita (percent change) | High: >47.86<br>Moderate: 21.54–47.86<br>Low: <21.54 |
| Pollution Potential (number of days) | High: >28<br>Moderate: 10–28<br>Low: <10 |

### *Population Change*

Although cities with rapid growth exhibited the highest levels of CO and ozone, they also demonstrated dramatic rates of air quality improvement (Figure 4). All population change categories showed tremendous improvement in unhealthy CO days, but cities with moderate growth and population losses showed almost no improvement in the number of unhealthy ozone days. Both models (CO and ozone) were significant (Table 4). CO levels improved regardless of the population density. Those cities with the highest densities showed the greatest improvement ($P$ = 0.0002). No significant relationship could be found between population and levels of ozone (Table 4).

### *Economic Indicators*

Total employment within the metropolitan area was measured as nonfarm employment. Each city was assigned to a job growth category (moderate, slow, or rapid growth) on the basis of the percent change in employment between 1981 and 1991. The status of New York City in this classification is somewhat distorted owing to the disproportionate number of jobs lost during 1990 and 1991. Rapidly growing cities demonstrated the greatest improvement in air quality; this was followed by cities that grew moderately and slowly (Figure 5). Although the association with ozone days was not statistically significant, a similar pattern identified for CO days was significant.

Cities with large gains in manufacturing employment displayed slightly greater rates of improvement than those with stable or negative manufacturing job growth, even though the latter groups achieved slightly higher air quality in terms of CO. Reductions in the number of ozone days were not significant, although the general pattern of change resembles the graph of CO-manufacturing employment relationships.

The relationship between value added in manufacturing in 1987 (classified as low, moderate, or high) and air quality is significant for both CO days and ozone days. There appear to be only trivial differences in the rates of improvement between groups. All three trend lines decline in parallel, suggesting that both mobile and stationary source controls have been effective. Cities with relatively low value added in manufacturing appear to begin and end the 10-year period with the worst air quality in terms of both CO and ozone.

### *Pollution Potential*

High air pollution potential advisories are issued periodically as a service to aid those who may need to avoid exposure to high

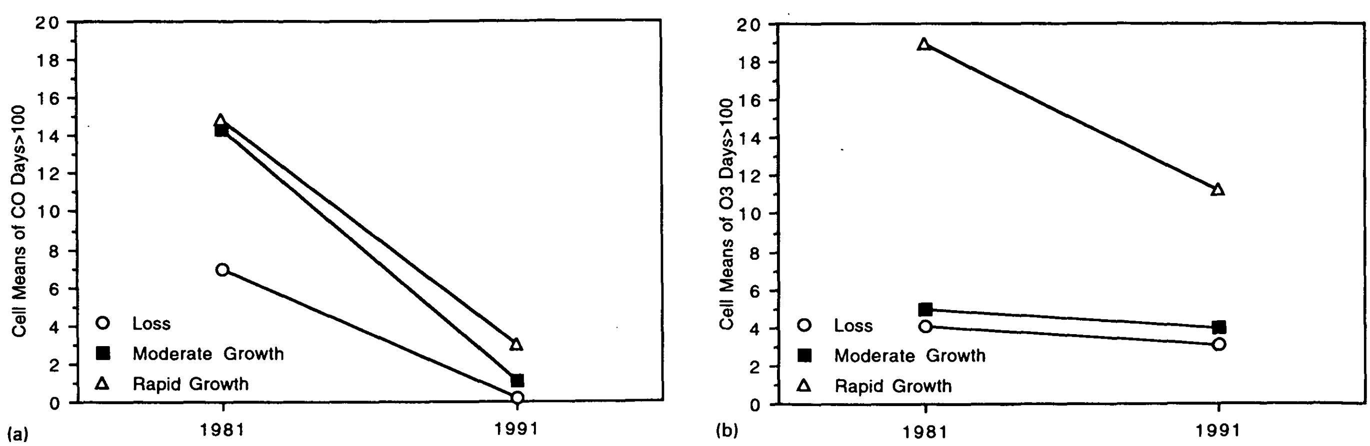


**FIGURE 4 Change in air quality by percent change in population category: (*a*) dependent variable, CO days > PSI 100; (*b*) dependent variable, ozone days > PSI 100.**

**TABLE 4 Repeated-Measures ANOVA Models of Air Pollution, Time, and Economic Indicators**

| Carbon Monoxide and Growth | N | Model Sum of Squares | Error Sum of Squares | Total Sum of Squares | R Squared | Model F-Value | Model P-Value |
|---|---|---|---|---|---|---|---|
| Percent Change in Population | 104 | 7461.99 | 48864.72 | 56326.72 | 0.13 | 5.77 | **0.0001** |
| Population Density | 104 | 6869.51 | 49457.21 | 56326.72 | 0.12 | 5.25 | **0.0002** |
| Percent Change in Non Farm Employment | 104 | 7141.27 | 49185.45 | 56326.72 | 0.13 | 5.49 | **0.0001** |
| Percent Change in Manufacturing Employment | 104 | 7881.39 | 48445.33 | 56326.72 | 0.14 | 6.15 | **0.0001** |
| Value Added by Manufacturing (1987) | 103 | 7075.35 | 49199.56 | 56274.91 | 0.13 | 5.41 | **0.0001** |
| Percent Change in Daily Vehicle Miles Traveled | 99 | 7208.27 | 48645.98 | 55854.25 | 0.13 | 5.31 | **0.0001** |
| Percent Change in Daily VMT per Capita | 101 | 6813.33 | 49300.67 | 56114.00 | 0.12 | 5.06 | **0.0002** |
| Pollution Potential | 104 | 7624.43 | 48702.29 | 56326.72 | 0.14 | 5.92 | **0.0001** |
| Ozone and Growth | | | | | | | |
| Percent Change in Population | 104 | 7296.34 | 97645.49 | 104941.83 | 0.07 | 3.02 | **0.0119** |
| Population Density | 104 | 917.76 | 104024.07 | 104941.83 | 0.01 | 0.36 | 0.8777 |
| Percent Change in Non Farm Employment | 104 | 3882.86 | 101059.02 | 104941.83 | 0.04 | 1.55 | 0.1753 |
| Percent Change in Manufacturing Employment | 104 | 2448.03 | 102493.80 | 104941.83 | 0.02 | 0.96 | 0.4404 |
| Value Added by Manufacturing (1987) | 103 | 5601.46 | 99186.74 | 104788.23 | 0.05 | 2.26 | **0.0500** |
| Percent Change in Daily Vehicle Miles Traveled | 99 | 1173.89 | 103306.81 | 104480.71 | 0.01 | 0.44 | 0.8228 |
| Percent Change in Daily VMT per Capita | 101 | 2371.61 | 102450.67 | 104822.28 | 0.02 | 0.91 | 0.4773 |
| Pollution Potential | 104 | 15882.19 | 89059.64 | 104941.83 | 0.15 | 7.21 | **0.0001** |

concentrations of certain air contaminants. The most important factor that contributes to the high air pollution forecast is limited atmospheric mixing. Many factors such as synoptic barometric patterns, land and sea effects, and terrain effects may conspire to reduce boundary layer ventilation and raise air pollution levels. The average annual number of forecast days of high air pollution potential was used to examine the relative improvements between locations with low, moderate, or high air pollution risk potentials. California and the Southeast have the greatest air pollution potential, whereas cities in the Great Plains, with higher average wind speeds and favorable ventilation, have the lowest air pollution potential.

Only minor differences can be discerned between group rates of CO improvement. Cities with high air pollution potential show the greatest rate of improvement in ozone days, whereas cities with moderate and low air pollution potentials demonstrate flat performance. Both models for CO and ozone are significant.

### *Traffic*

Changes in the percent DVMT compared with changes in air quality suggest that those cities with the most extensive increases in DVMT between 1981 and 1991 did not sacrifice improvement in air quality. Starting with fewer CO events in 1981, cities with extensive increases in DVMT managed to maintain their lead. Unlike the CO model, changes in ozone versus DVMT were not significant (Table 4). Only small differences in improvement rates separate groups of cities on the basis of the percent change in DVMT per capita. Although not so for ozone, CO improvements are significant, suggesting that mobile source controls have generally been effective nationwide.

## DISCUSSION OF RESULTS

The following were observed in the study described in this paper:

1. Transportation-related air pollution (CO and ozone) has improved significantly in recent years and shows promise of continued improvement. Generally CO has been improved much more than ozone.

2. Although the statistical relationships are quite weak, air pollution reductions have been greatest in those cities with the greatest pollution in 1981 and those cities with the most rapid population, economic, and traffic growth. Primarily because of a few high values, the range of the data is great. Consequently the best consolidated model (Table 5) explained only 19 percent of the variation in unhealthy ozone days.

3. Conversely air pollution reductions have been the lowest in those cities with lower pollution levels in 1981 and those cities with slower population, economic, and traffic growth.

4. As a result of these improvements transportation-related air pollution has not been hostile to growth, even in those areas with rapid growth.

Continued technological improvements to automobiles, which result in cleaner combustion and greater pollution control requirements for point-source emitters, have played the most significant role in improving air quality over the past 10 years. But in all likelihood cities may be facing diminished returns in air quality benefits from continued technological improvements. The 1990 Clean Air Act Amendments recognize this and require that metropolitan regions initiate programs to reduce VMT to such an extent that these reductions must outpace those from fleet turnover.

Because some of the most effective measures for reducing air pollution (such as vehicle exhaust regulations promulgated after 1990) cannot be counted toward the 15 percent reduction target, the emphasis of the present act is placed on TCMs. Despite the call to implement TCMs most states have not responded aggressively. As noted earlier all moderate nonattainment areas must show a 15 percent reduction in VOCs by 1996, and serious and worse areas must show a 3 percent a year reduction after 1996. TCMs are directed toward reducing emissions by improving traffic flow, reducing congestion, or reducing vehicle use. These TCMs must be part of a contingency plan, which will take effect if that state fails to meet the 15 percent emission reduction targets re-

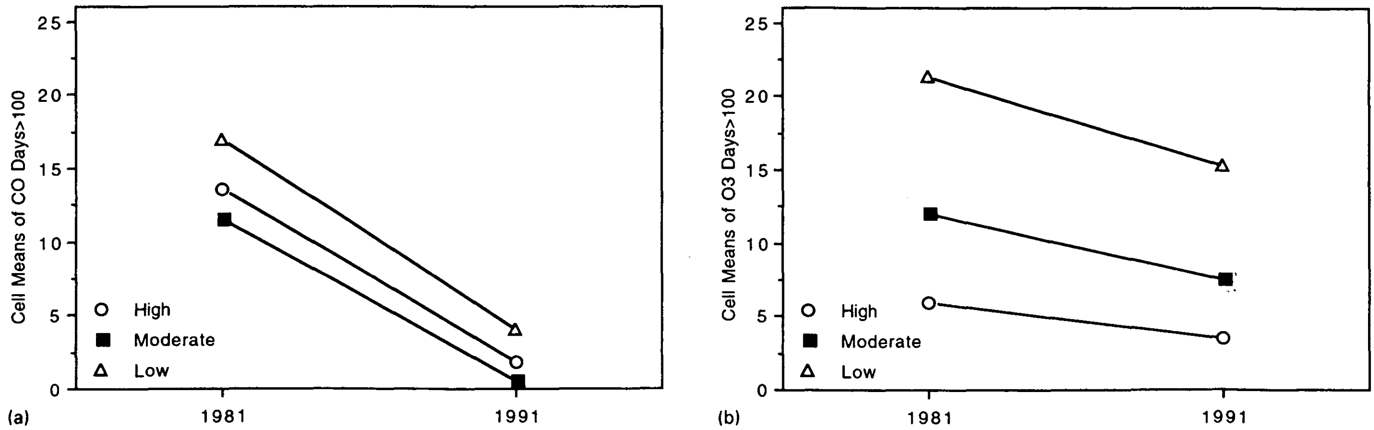


**FIGURE 5 Change in air quality by manufacturing value added category: (*a*) dependent variable, CO days > PSI 100; (*b*) dependent variable, ozone days > PSI 100.**

quired by 1996, fails to attain the NAAQS target date, or in the case of areas designated serious and above fails to meet the 3 percent annual emissions reductions required after 1996. Areas classified as serious or worse must submit a clean-fuel fleet program by May 15, 1994, in addition to carrying out the enhanced inspection and maintenance program. Severe and extreme areas must submit specific TCMs to reduce VMT or the numbers of trips, demonstrate compliance with employer trip reduction programs, and begin a reformulated gasoline program in 1995.

As can be shown from this paper, VMT increased at a rate of about 50 percent in the MSAs during the past 10 years. VMT per capita is also increasing. The rise in automobile traffic, driven by uncontrolled land development and very low cost automobile and truck use, is to many the very symbol of U.S. economic growth and vitality. The new challenge of these cities is to maintain economic prosperity while reducing air pollution and managing traffic growth. Fortunately progress in air pollution reduction and progress in economic growth (as defined by employment and population growth) during the 1980s were not incompatible.

The present analysis has highlighted the importance of technological change and its tie to economic performance in achieving clean air. What should now be the focus of air pollution reduction policy? Given that this progress occurred during a time of rapid traffic growth as well as major reductions in carpooling and transit use, these gains cannot be ascribed either to behavioral shifts (these were shifts in the opposite direction) or to urban densifi-

**TABLE 5 Combined ANOVA Model of Ozone Pollution with Four Key Variables**

**Type III Sums of Squares**
Dependent: Ozone Days >100

| Source | df | Sum of Squares | Mean Square | F-Value | P-Value |
|---|---|---|---|---|---|
| Time | 1 | 745.942 | 745.942 | 1.809 | 0.1802 |
| Pollution Potential | 2 | 10642.556 | 5321.278 | 12.905 | 0.0001 |
| Value Added Mfg. | 2 | 6698.778 | 3349.389 | 8.123 | 0.0004 |
| %Population Change | 2 | 2160.577 | 1080.289 | 2.620 | 0.0753 |
| Residual | 198 | 81646.215 | 412.355 | | |

**Model Summary**
**Dependent: Ozone Days > 100**

| | |
|---|---|
| Count | 206 |
| R | 0.470 |
| R-Squared | 0.221 |
| Adj. R-Squared | 0.193 |
| RMS Residual | 20.301 |

| | df | Sum of Squares | Mean Square | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 7 | 23142.018 | 3306.003 | 8.017 | 0.0001 |
| Error | 198 | 81646.215 | 412.355 | | |
| Total | 205 | 104788.233 | | | |

cation (cities spread out and became less dense during the 1980s). Therefore the authors make the following recommendations:

1. Substantive research should be undertaken to investigate the air quality-economic growth links uncovered here. Particularly fruitful would be research on
   - Climatological versus human factors in ozone pollution,
   - Fleet turnovers in individual cities and industrial modernization versus air pollution trends,
   - Effects of measurement site location on trends,
   - Data accuracy,
   - Changes in city "mix" of industrial-economic base versus pollutant sources over time, and
   - Impacts of transportation investments on air pollution trends.
2. The focus of future air pollution reduction strategies should be on
   - Stronger inspection and maintenance programs,
   - Encouraging the natural fleet turnover process to speed removal of high-polluting vehicles from the traffic stream,
   - Continued reductions in vehicle emissions (tailpipe), and
   - Fuel modifications.
3. Cities not in attainment with ozone standards should be permitted (first) to submit plans to improve inspection and maintenance programs and fuel modifications or remove high emitters. Behavioral (TCM) actions should be maintained in cities with no record of progress, but should be tied to programs that facilitate employment growth.
4. EPA should consider a change from sanctions intended to force compliance to active support for cities, particularly ways to encourage fleet turnover and economic growth.

The data examined here suggest that many cities are attaining the minimum standards for clean air and that most are showing improved air quality. The relationship between growth and improved air quality merits much greater attention. Innovative emission control strategies that pursue a win-win strategy for both economic growth and progress toward cleaner air are advocated.

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# Travel Forecasting Guidelines for Federal and California Clean Air Acts

MAREN L. OUTWATER AND WILLIAM R. LOUDON

Travel forecasting models are being proposed for use in emissions inventories to meet legislative requirements in the federal Clean Air Act Amendments (1990) and the California Clean Air Act (1988). Emissions inventories have requirements for the accuracy and usefulness of the model outputs and the validity of input data and assumptions different from those originally established for travel demand models. The travel forecasting guidelines were developed for the Department of Transportation of the state of California in cooperation with the U.S. Department of Transportation and were designed to meet the legislative requirements in the Clean Air Acts. The development of the travel forecasting guidelines, which involved a series of interactive review sessions with the California Statewide Modeling Group, is described. An overview of the guidelines is presented. These guidelines were developed to represent reasonable travel demand forecasting practice in support of the accuracy required by air quality analysis in four areas: input data and assumptions, travel demand modeling, emissions inventories, and research and recommendations. Since the completion of the travel forecasting guidelines, the document has been distributed by FHWA to all state departments of transportation and to all metropolitan planning organizations that are classified as nonattainment areas. FHWA has suggested that the guidelines be used as a tool for use in conformity analysis. In addition the Office of Traffic Improvement of the California Department of Transportation has distributed more than 300 copies of the report to state and regional transportation, congestion management, and air quality agencies within California.

Travel demand forecasting models have been developed and applied over the past three decades for forecasting travel demand for long-term planning activities such as alternatives analyses, county general plans, and corridor analyses. In recent years these travel demand forecasting models are being proposed for use in emissions inventories, traffic operational analyses, and congestion management planning to meet the legislative requirements in the federal Clean Air Act Amendments (1990), the California Clean Air Act (1988), and the California Congestion Management Program (CMP) (1990). Each of these new uses has requirements for the accuracy and usefulness of the model outputs and the validity of the input assumptions and data different from the requirements originally established for travel demand forecasting models.

The state and federal legislative requirements for modeling, particularly those for California's CMP, have resulted in a proliferation of regional or countywide models. Although regional modeling used to be practiced by only a few metropolitan planning organizations in the state, CMP legislation has led to the development of a countywide model by virtually every county in the state that contains an urban area. Many of the regional or countywide models in the state are reasonably sophisticated and constitute good modeling practice. But some regional agencies are using procedures that have not been updated since the 1960s or 1970s or are using parameters that were transferred from models developed in other areas. As a result there is considerable variation in the level of sophistication and accuracy of regional models within the state. The effort to develop statewide guidelines was designed to raise the overall level of the quality of modeling within the state.

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The primary purpose of regional travel modeling in its early applications in the 1960s and 1970s was to determine the need for major highway or transit investments. This determination was most often made on the basis of projected volumes on particular roadway or transit links. When used for this purpose rough approximations of forecast volumes were sufficient to determine when major new widenings or new facilities were needed. With the new regulatory and legislative environment, the use of travel demand forecasts has expanded to include travel speeds and numbers of trips for use in estimating emissions inventories. These additional uses require significantly greater accuracy and sensitivity from the travel demand forecasting models. With the current emphasis on meeting air quality standards within the state, a primary focus in the project described here was to develop guidelines to improve the forecasting of travel activity data as an input to emissions inventories as part of an overall conformity analysis for regional transportation plans and transportation improvement programs.

The legislative requirements have also prompted concern about the consistency of model parameters, assumptions, and results at different levels of government. Regional agencies are concerned about the consistency requirements among the local governments in their areas, and the state agencies are concerned about the consistency of travel demand forecasting models among the regional areas. Greater consistency at all levels of government is desired to facilitate comparisons of forecasts between regions or between agencies within the same region for the process of prioritizing state project funds. To achieve this objective the guidelines establish more consistent methodologies for travel forecasting and more consistent use of assumptions within the travel demand modeling process.

The development of the travel forecasting guidelines involved a series of interactive sessions with an advisory committee that was a subset of the statewide modeling group. The sessions gave the committee members an opportunity to suggest, review, and respond to the topics covered in the guidelines and the establishment of the guidelines. The process included the development of an outline of topics that the guidelines needed to address; the issues addressed are presented in Table 1. Following the presentation of the issues, or topics to be covered, each topic area was researched for current techniques, both nationwide and within California. The research was blended with the authors' experiences

**TABLE 1 Issues Addressed in Travel Forecasting Guidelines**

| INPUT DATA AND ASSUMPTIONS | TRAVEL DEMAND MODELING | EMISSION INVENTORY NEEDS | RESEARCH AND RECOMMENDATIONS |
|---|---|---|---|
| Socio-Economic Data:<br>• Households, Income, & Auto Ownership<br>• Employment Information<br>• Conformity for Sub-Area Model<br><br>Special Trip Generators Data<br><br>External Stations and Trips<br><br>Network Data:<br>• Transportation Analysis Zones<br>• Highway Networks<br>• Transit Networks<br><br>Travel Cost Information:<br>• Auto Operating Costs<br>• Parking Costs<br>• Transit Fares<br>• Tolls<br><br>Calibration and Validation Data:<br>• Traffic Counts<br>• Highway Travel Speeds/Travel Times<br>• Origin-Destination and Trip Length Information<br>• Vehicle Occupancy<br>• Local Trip Generation Surveys | Four-Step Demand Modeling:<br>• Objective<br>• Calibration/Validation<br>Trip Generation:<br>• Trip Purposes<br>• Trip Production Models<br>• Trip Attraction Models<br>• Non-Home-Based Models<br>• State-of-the-Practice Methods<br>• External Trips<br>• Special Generator Trips<br>Trip Distribution:<br>• State-of-Practice Methods<br>• Impedance<br>• K-Factors<br>• Intrazonal Trips<br>Mode Choice:<br>• Discrete Choice Models<br>• Incremental Mode-Choice Models<br>Trip Assignment:<br>• Impedance<br>• Capacity<br>• Highway Assignment<br>• HOV Assignment<br>• Transit Assignment<br>Time-of-Day Distribution Forecasts<br>Feedback Mechanisms<br>Model Applications:<br>• Analysis of TCMs<br>• Congestion Management<br>Regional and Subregional Modeling<br>Model Documentation | Overview:<br>• Historical Development of Emission Estimation Procedures<br>• Sensitivity of Emissions to Travel Characteristics<br>• California's Direct Travel Input Model<br><br>Trip Volumes by Purpose and Time Period:<br>• Trip Purpose Categories<br>• Time Period Definitions<br>• Travel with External Trip Ends<br>• Special Forecasts<br>• Comprehensive Coverage of Trips<br><br>Vehicular Speeds:<br>• Relationship Between Speed and Emission Rate<br>• Consistent Use of Speed<br>• Averaging of Speeds<br>• Methods for Validating Speed Estimation<br><br>Pre-Start and Post-Park Parameters | Institutional and Resource Requirements:<br>• Legislative Requirements<br>• Modeling Coordination Between Agencies<br>• Consistency of Modeling Approach<br>Data Needs:<br>• Land Use/Socioeconomic Data<br>• Network/Supply Information<br>• Cost Information<br>Model Improvements:<br>• Modeling Assumptions<br>• Data Needs for Models<br>• Four-Step Demand Model Improvements<br>• Other Issues<br>Emission Inventory and Other Air Quality Needs:<br>• Comprehensive Coverage of Trips<br>• Prediction of Starts and Parks<br>• Modeling of Weekend and Summertime Travel<br>• Enhancement of Emission Rates<br>Traffic Management and Demand Management Analysis Needs:<br>• Traffic Management<br>• Demand Management<br>Interface Between Land Use and Transportation:<br>• Urban Design Impacts<br>• Transportation's Impact on Land Use |

with issues concerning the development of emissions inventories to provide a perspective on the use of travel demand models for the purpose of air quality analysis. The guidelines were then developed to represent reasonable travel demand forecasting practice that could support the accuracy required by air quality analysis. Although the guidelines were developed specifically for the use of travel demand models for emissions inventories, other uses of these models were considered and presented, including congestion management, travel demand management, and facilities planning. Clearly the cost of developing a travel demand forecasting model for any of these purposes precludes the development of a model for a singular purpose. Travel demand models should be developed with all significant purposes in mind to enhance the cost-effectiveness of each individual purpose.

## PURPOSE

The driving force behind the development of the travel demand forecasting guidelines was the need to improve the accuracy and consistency of the travel demand models in California for their use in air quality analysis. This led to increasing scrutiny of travel demand models in areas that they were not necessarily designed to address, such as the estimation of accurate link speeds or numbers of trips. For historical transportation planning purposes, the link speeds and numbers of trips were used only as interim measures to validate the volume of travel on the highway or transit networks. Hence the actual estimates of speeds and numbers of trips produced in the travel demand forecasting models were not validated separately from the volume of travel and were perhaps less precise measures as a result. The speed estimated by the model and the total number of trips produced are significant variables in the estimation of emissions inventories, however, and need to be validated for reasonableness in the travel demand forecasting process. Fortunately this is possible with modifications to the existing travel demand forecasting process and additional attention to the validation of these variables.

## AUDIENCE

Although the discussions surrounding the use of travel demand forecasting models covered many areas, the modeling advisory committee concurred that the guidelines would apply only to regional travel models (and regional transportation agencies) used in mobile source emissions inventories. For this audience minimum acceptable practice would vary as a function of the complexity of travel behavior in the region and the resources of the agency maintaining the model. This resulted in different standards for small and medium-sized or large regional agencies. The cri-

teria that distinguished the level of complexity of travel behavior within a region were based on travel patterns, size, and air quality.

- Multimodal travel: a significant percentage of the passenger travel in the region is by rail, bus, vanpool, or carpool, and the model is used to estimate the distribution by the various modes;
- Multicounty: the model produces forecasts for multiple counties and serves as a regional model that supports subarea models;
- Population: the model is used for forecasting in a large metropolitan area with multiple employment centers;
- Congestion: the level of service during peak commute periods is significantly different from the level of service in the off-peak periods, and congestion influences route or mode choice; and
- Air quality: the region is a serious, severe, or extreme nonattainment area.

By using these criteria two categories of regional modeling agencies were identified. Those that would be considered complex with respect to most or all of these criteria constitute the first group; the second group would be all other agencies maintaining models for the purpose of emissions inventories or trip conformity analysis. As defined the first group includes the metropolitan planning organizations (MPOs) for the four major metropolitan areas in the state: Los Angeles, Southern California Association of Governments; San Francisco and Oakland, Metropolitan Transportation Commissions; Sacramento, Sacramento Area Council of Governments; and San Diego, San Diego Association of Governments. These four agencies are expected to maintain modeling methodologies more advanced than those of the other agencies in the state. The guidelines developed specify a minimum acceptable standard that would apply to all agencies throughout the state and a more advanced level of acceptable practice that would be expected from the four larger agencies. Whenever possible, however, it is also desirable for the models for small and medium-sized agencies to meet the guidelines for advanced models.

## INPUT DATA AND ASSUMPTIONS

The discussion of the input data and assumptions required for the different levels of regional travel models in California provided methodologies for obtaining, estimating, coding, and error checking the data. Input data are required for any application of the model in the base year or a forecast year, and model assumptions are typically estimated for the calibration of the model and are adjusted on the basis of any expectations that they may change over time. Many model assumptions are assumed to remain constant over time. The data sources covered in the guidelines were divided into six sections.

- Socioeconomic data,
- Special trip generators,
- External stations and trips,
- Network data,
- Travel cost data, and
- Calibration and validation data.

The minimum acceptable guidelines in the area of input data and assumptions were similar to those used in the advanced approach except in the stratification of employment data and cost of travel data, for which additional data items are recommended for the advanced approach.

The quality of the input data and assumptions is a significant determinant of the accuracy of the results of the travel demand forecasting model. The source and quality of the input data must be balanced against budget and time limitations. The input data requirements will also vary according to the goals and objectives of the model. Travel demand models that are designed to evaluate transit patronage or the effectiveness of transportation control measures (TCMs) will require more input data than models designed to assess local traffic patterns and flows. There are no definitive criteria for evaluating the cost of developing input data and assumptions versus the benefits of increased accuracy of the models, although there is direction for the evaluation of the accuracy of the models in the guidelines as well as other sources (*1*).

The data sources are given in Table 2 for each category of data. The best source of data may vary from one location to another; Table 2 identifies the best source of data available throughout California. Local sources of data may be more accurate at the traffic analysis zone level, but the data need to be consistent with regional forecasts.

There are three concerns for the development of data bases of socioeconomic data.

- Ability to disaggregate the data into traffic analysis zones,
- Ability to forecast the data, and
- Consistency of the data throughout the region and with state and local agencies.

The validation of the socioeconomic data includes verifying regional data against state and city or county totals, comparing existing data with the forecasted data by area, checking densities by zone for reasonableness, and verifying the balance of jobs with the number of employed residents.

The development of highway and transit networks requires establishment of assumptions that generalize roadway and transit operations to meet regional objectives. These generalizations are necessary to provide cost-effective analysis tools, but need to be considered carefully to prevent oversimplification. The roadway network requires information on the travel time or speed, directionality, number of travel lanes, and capacity on a roadway segment. The travel speed on a segment is a significant variable in determining mobile source emissions, yet travel speed has typically been coded to represent posted speed limits or average speeds stratified by functional class and area type; both assumptions have proven to yield erroneous results on the basis of an individual segment. The guidelines identify the free-flow speed as representing the uncongested travel time with traffic control devices in place (the travel speed on a segment at 3 a.m.). This implies an individual assessment of travel speed for each segment in the regional network, which may prove to be a prohibitively expensive exercise and is not useful for forecasting. Recognizing that certain assumptions can provide a cost-effective solution to coding roadway networks, one must balance these savings with the increased accuracy provided by actual (or accurate) data sources. The guidelines suggest that validation of free-flow and congested speeds is an acceptable method for verifying the accuracy of assumptions made for coding speeds throughout the regional roadway network.

## TRAVEL DEMAND MODELING

The guidelines describe the four-step modeling process and methodologies for specifying, calibrating, and validating travel demand

TABLE 2 Sources of Input Data and Assumptions

| DATA TYPE | BEST SOURCE(S) | BACK-UP SOURCE | ALTERNATE ESTIMATION |
|---|---|---|---|
| SOCIO-ECONOMIC INPUT DATA SOURCES | | | |
| Households | Latest U.S. Census. Split Tracts as necessary. | Aerial Photos and Field Counts | Aerial Photos, building permits, utility company records |
| Employment | Latest Census Transportation Planning Package (CTPP). | State Employment Office data by zip code. Split zip codes as necessary. | Derive from surveys of floor space and average employee densities. |
| Median Income or HH Stratified by Income | Latest U.S. Census | Derive stratification from median income | State Franchise Tax Board (Form 540) |
| Average Persons per HH or HH by Persons/Household | Latest U.S. Census | Derive stratification from ave. population/house. | None |
| SPECIAL GENERATOR AND EXTERNAL STATION INPUT DATA SOURCES | | | |
| External Station Counts | Field Survey for Model (actual counts) | Agency Records | NCHRP 187 |
| Special Generators | Actual Counts | Caltrans Progress Report, Traffic Generators, ITE Trip Generation Manual | None |
| NETWORK AND TRAVEL COST DATA SOURCES | | | |
| Highway Network Characteristics (Capacities, Speeds, etc.) | Field survey geometric and speed data. Use HCM to calculate capacities. Contact local office of state transportation department for HOV facility, park-and-ride lots, and ramp metering data. | | |
| Transit Service Frequencies, Distances, Fares, and Speeds | Transit agency route maps and route schedules | | |
| Cost of Parking | Survey of actual costs paid by parkers | Estimate from average parking fees charged for employer/store subsidies | None |
| Perceived Auto Operating Costs per Mile | Home interview survey | State or other MPO estimates | U.S. DOT or AAA annual estimates |
| Speed-Flow Curves by Functional Class | Field survey speed-flow relationships | Use 1995 HCM speed-flow relationships | BPR curve with modifications |
| Intersection Peak-Period Turn Counts | Field surveys | | |
| Intersection Geometry and Signal Timing | Field Surveys and Aerial Photos | | |

models. The chapter on travel demand modeling also reports on time-of-day distributions, forecasts, feedback mechanisms, special model applications, regional and subregional modeling relationships, and model documentation. There has been substantial experience with the four-step modeling process in California during the past 25 years. Much of the significant development in the four-step process occurred during the first 10 years of that period, and many existing models in the state are based on a model structure and specifications that are 15 to 20 years old. The most significant advancements in the past 10 years have been in transferring regional models from mainframe computer software to software that can be run on micro- and minicomputer systems. With this transition has come some simplification of the model systems and some enhancement to improve the sensitivity, flexibility, or accuracy of the models.

The guidelines define criteria that transportation models should meet if they are to provide a sound basis for travel demand forecasting. Each model should rely on sound behavioral theory of how individuals or households make travel choices. The structure of choice sequences and the variables used in each model of choices should reflect a logical process of decision making, and the behavioral theory underlying that process should provide a basis for judging the reasonableness of model estimation results. The models, through their input variables, should be sensitive to relevant influences. The importance of this sensitivity is necessary to capture travel behavior and to evaluate alternatives on the basis

of changes in policy or exogenous variables. If the models are not sensitive to relevant influences then they are not useful for analyzing alternatives based on these influences, regardless of the precision with which they match base year ground counts. Finally the models should be unbiased. Models are often calibrated to reproduce observed traffic counts or travel behavior, but without regard to behavioral theory or econometric principles. Bias in the model because of improper or incomplete model specification, inaccurately measured input data, or multicolinearity in input variables can result in highly inaccurate forecasts for future years. These criteria for developing and applying travel demand forecasting models are specifically designed to address the predictive capabilities of the models. If they do not capture travel behavior and remain biased then they are not useful predictors of future travel demand.

The guidelines describe each step of the four-step demand modeling process (trip generation, trip distribution, mode choice, and trip assignment) in four parts: a description of the objective of the step, methods for specifications of the modeling procedures, methods for calibrating the procedures, and methods for validating the procedures. Specification of the models is the process of defining the model structure and the econometric methods for estimating the model and selecting the variables for inclusion in the model. Model specification should reflect statistical evaluation, as well as policy direction, to evaluate the most reliable and effective variables and structure to meet transportation agencies' objectives.

Calibration is defined as the process of estimation of the parameters of the model from baseline travel data. The guidelines specify that models should be calibrated from local household survey data every 10 years. This directive is with the understanding that the California Department of Transportation (Caltrans) conducts a household travel survey every 10 years [the latest Caltrans Travel Survey was in 1991 (*2*)] for each region in California that needs to develop regional travel demand models and that Caltrans would provide estimated model parameters and structures to regional agencies that did not have the resources to evaluate in-house the survey data.

Validation of the four-step model is the process of determining the relative accuracy and sensitivity of the model as a forecasting tool. This usually involves the application of the modeling process by using aggregate data sources, representing a current or previous year, and the comparison of the results with actual data collected in the field. When possible validation data sources should be different from those used in calibration, but validation can also include application of the model with the calibration data but stratified by socioeconomic characteristics or geographic subdivision. This provides a test of the sensitivity of the model to variation in input data. Validation may also include checks on the reasonableness of model parameters. This can be done by comparison of model results with results from other models in the state or with reported state or national trends. Validation with actual data sources is often limited to verify the entire four-step process, after trip assignment, but each of the other three steps in the process should be validated for consistency or reasonableness, or both. Each step in the four-step process incorporates the results from the previous steps and should be validated separately to reduce the compounding of errors.

### Four-Step Process

Trip generation models should estimate the number of trips by purpose produced by or attracted to a traffic analysis zone on the basis of an econometric relationship of the demographic, socioeconomic, locational, or land use characteristics of the zone. The majority of trip generation models in use today assume that the intensity of travel can be estimated independently of the transportation system or locational characteristics. In California trip generation models are divided into the following areas: home-based trip productions, home-based trip attractions, non–home-based trip productions and attractions, internal/external trip productions, external/internal trip attractions, and external (through) trips.

A central assumption of the trip distribution model is that each traveler making a trip chooses a destination from all of the available destinations on the basis of the characteristics of each competing destination and the relative impedance associated with traveling to each destination. The majority of trip distribution models in California have limited the characteristics of the zone to the most significant factor, measured by the relative attractiveness of a zone or the number of trip attractions. Other socioeconomic factors, such as income or automobile ownership, may influence destination choice and are recommended as areas for further research in applications. The trip distribution model generated considerable discussion in the following areas:

- The use of *K*-factors, or zone-to-zone adjustment factors, that may be used to account for social or economic linkages that have an impact on travel patterns is discouraged because they limit the behavioral response of the trip distribution model in demand forecasting.
- The use of reasonable estimates of intrazonal travel is encouraged to improve the comprehensive coverage of trips required by emissions inventories.
- The value of impedance used in trip distribution should be based on realistic estimates of travel time and speed, should reflect those used in the calibration process, and should reflect congestion through a feedback loop from trip assignment if congestion significantly affects impedance.

Mode choice models separate the person-trip table into the various alternative modes by trip purpose. The available modes have expanded in recent years to include stratifications of the automobile mode by vehicle occupancy (drive alone, two occupants, three occupants, etc.) and the stratification of transit modes into transit technologies and types of operation (local bus, express bus, light rail, heavy rail, etc.) and types of access (walk or drive). The mode choice model should include significant variables, such as income, automobile ownership, travel time, and cost, and provide sensitivity to policy variables, such as parking pricing, carpool facilities, or time of travel. A simplified mode choice approach is acceptable if the regional agency is not testing the sensitivity of carpool or transit policies. Policy-sensitive variables may be tested in a postprocess to the mode choice model to account for policy variables that cannot be well represented in travel demand models. Larger metropolitan areas should evaluate nested logit model structures to evaluate carpool alternatives or multimodal transit systems.

### Feedback Mechanisms

There was considerable controversy among the advisory committee as to the appropriate and reasonable use of feedback mecha-

nisms in demand forecasting models. Feedback mechanisms represent the equilibration of impedance at one or more steps in the modeling process, as shown in Figure 1. Impedance is a function of the travel time and cost from the origin to the destination of a trip and is derived from the transportation system characteristics in response to demand patterns. Although the cost of a trip is generally fixed, the travel time is variable depending on the congestion on the facility at any particular time of day. There are assumptions made throughout the travel demand forecasting process concerning travel time, or speed, that may be affected by the time of travel or the estimated impacts of congestion.

Travel speed is unique among model variables because it is both an input and an output of single modules within the travel demand forecasting model. Travel speed is used as an input in the trip distribution model to estimate the impedance from one analysis zone to another. Speed is used as input to the mode choice model to determine the impedance differential between highway and transit travel choices. Finally travel speed is an input to and an output of the trip assignment model, which analyzes the "free-flow," or input, speeds and the travel volumes to produce the "congested," or output, speeds for the roadway system. There is significant controversy about the consistent use of speeds in the travel demand forecasting process. Some agencies use free-flow speeds in the trip distribution model to estimate the distribution of trips in the transportation network, regardless of congestion, mode, or average delays. Larger agencies have incorporated an estimate of congested speeds in the distribution model applied to trip purposes in the peak period. The mode choice model typically assumes that all home-to-work trips are traveling in the peak period and encounter congested speeds, whereas all other trip types travel in the off-peak period and encounter free-flow speeds. The controversy identifies the discrepancy between assumptions made at different points in the travel demand forecasting process relating to travel speeds.

- The estimation of land use data and trip generation is not significantly affected by travel speeds.
- The estimation of trip distribution is not significantly changed by the deterioration of travel speeds in the peak period, that is, congested travel speeds versus free-flow travel speeds.
- Mode choice for work trips is significantly influenced by congestion in the peak period, and mode choice for other trips is influenced only by off-peak travel speeds, which are typically not affected by congestion in the models.
- Route choice estimated in the trip assignment model is significantly affected by the deterioration of travel speed because of congestion.

Much of the discussion on feedback mechanisms of impedance leads to a need for further research for the benefits of incorporating feedback mechanisms versus the costs associated with the equilibration required in the modeling process. A significant portion of the costs involved will result from the need to recalibrate each model after incorporation of feedback loops (*3*).

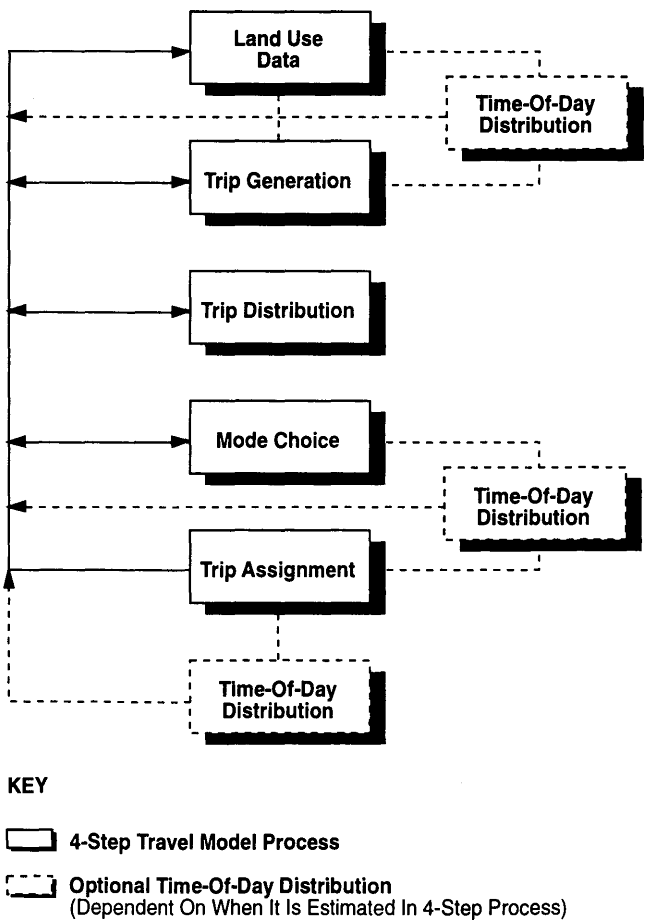


**FIGURE 1 Feedback mechanisms to equilibrate impedance.**

## EMISSIONS INVENTORY NEEDS

In California emissions inventories are developed by applying to travel activity data emissions rates estimated by average speed and vehicle classification. The development of these emission rates from the federal test procedure (FTP) and other cycles has provided a capability to estimate emissions from link-specific volumes and speeds produced by regional travel demand models. In previous years emissions inventories focused exclusively on vehicle miles traveled (VMT) and average link speed (a measure of running emissions) as determinants of emissions. Despite the extensive use of the FTP driving cycle and speed-based emission rates produced from it, the Environmental Protection Agency and the California Air Resources Board (CARB) continued research to identify the more specific determinants of the variations in emission rates. The result of the research has been an identification of four specific categories for vehicle emissions:

- Trip start emissions (cold start or hot start, depending on the period for which the vehicle has been turned off),
- Hot stabilized running emissions (exhaust and evaporative),
- Hot soak evaporative trip end emissions, and
- Diurnal emissions (hydrocarbon emissions from evaporation that are essentially unrelated to the amount the vehicle is driven).

The relative significance of each of these emission categories, which are also referred to as *impact-producing processes*, is demonstrated in Figure 2.

The California emissions rate model, EMFAC7E, produces rates in grams per hour by dividing by the speed (in miles per

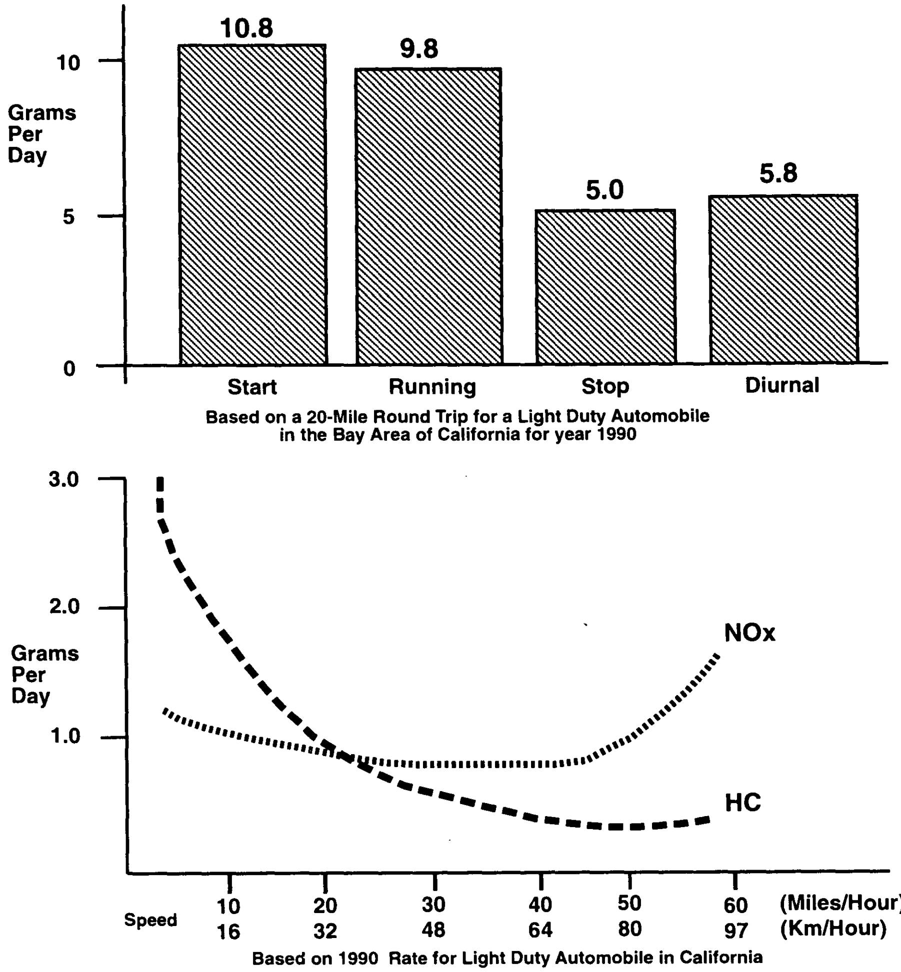


**FIGURE 2 Relationships of trips, VMT, and speed to emissions.**

hour). The rates can be converted to a grams per mile basis like those also illustrated in Figure 2, but the relationship is undefined at a speed of zero (*4*).

The guidelines for emissions inventory analysis in California have been established by the statewide use of the Direct Travel Impact Model (DTIM) (*5*). The methodology contained in DTIM represents the most sophisticated approach to using regional travel model output to produce emissions inventory data for on-road motor vehicle activity. Because of its sophistication and widespread use the input requirements of DTIM define the acceptable level of practice for California.

## Trip Volumes by Purpose and Time Period

Accurate prediction of the air quality impacts of on-road motor vehicle activity is critically dependent on accurate prediction of trip volumes by purpose and time period. If trip purpose is used to estimate time-of-day and vehicle type distributions, at least three trip purposes should be used. The definition of time period should be designed to capture homogeneous characteristics of travel such as congestion, mix of trip purpose, and travel speeds. Whenever congestion has a significant impact on peak-period speeds, peak periods should be modeled separately. Emissions are sensitive to the time that the emissions occur for two reasons: the ambient temperature (at a specific hour of the day) under which a vehicle has been started will affect the start emissions, and the time at which emissions are produced will affect the maximum concentrations and locations of pollutants.

The estimation of trip volumes for emissions inventories should consider two areas that are not typically considered in travel forecasting models:

- Special forecasts (seasonal, day of week, or special event variations) and
- Comprehensive coverage of trips (short trips; truck, recreational, or school trips; or transit vehicle trips).

The most common practice in California is to calibrate regional travel forecasting models for average annual weekday travel. If the emissions inventory is estimating travel for weekend days in a particular month, corrections to the modeled trip volumes should be made on the basis of the observed seasonal and day-of-week variations. Also whenever special events are known to have a significant impact on an emissions inventory, external adjustments should be made to the travel activity data to reflect the impacts of those events.

There are many types of trips that have typically been excluded from regional travel forecasting models because they were not significant for the evaluation of transportation infrastructure needs, which was the main objective of these models. Shorter trips, often defined as intrazonal trips for modeling purposes, are typically excluded from trip assignment because the modeled highway network was not detailed enough to evaluate these trips, but these trips are significant for emissions inventories and need to be included. Certain trip types, such as truck, school, or visitor trips, are frequently underrepresented or excluded from modeling but need to be included in an emissions inventory.

### Vehicular Speeds

Emissions rates developed by CARB represent an average rate on a grams-per-hour basis over a range of operating modes (acceleration, deceleration, cruise speed, and idle). To be consistent with the emission rate models, it is critical that the vehicular speeds estimated in the travel forecasting model also represent an average operating speed over a section of a facility, not the midblock cruise speed or the speed limit on the facility. A postprocess to evaluate an hourly variation in speeds may be warranted to provide additional accuracy for emissions inventories and would not need to be implemented within the regional travel forecasting model. Speed should be estimated for emissions estimation purposes in as detailed a manner as is practical and consistent with the definition of speed used in emission rate models.

The nonlinearity of the relationship between speeds and emissions rates introduces a concern about the effects of averaging speeds across time periods or vehicle classifications. This is a common practice in travel forecasting, but it should be minimized when the speeds are to be used in emissions estimates. Also, emissions rates increase with speed for higher speeds (over 50 mph), which means that the model needs to be accurate for these higher speeds. Many travel forecasting models constrain the free-flow flow speed on a link to the speed limit, when in reality the observed free-flow speeds under uncongested conditions on the facility may exceed the speed limit.

## RECOMMENDATIONS FOR RESEARCH

During the development of the travel forecasting guidelines for California many of the discussions among the advisory committee focused on recommendations for further research. Six topic areas for further research were identified:

- Institutional and resource requirements,
- Data needs,
- Model improvements,
- Emissions inventory and other air quality needs,
- Traffic and demand management analysis needs, and
- Interface between land use and transportation.

The recommendations identified specific, achievable tasks for improving the use and understanding of regional travel forecasting models used for air quality analysis in California.

Three considerations for institutional and resource requirements would benefit from additional information, further research, and a better understanding of the requirements. The legislative requirements are complex and extensive, requiring effort to learn and understand the benefits and costs of each legislative requirement. The modeling coordination between agencies is required by legislation, but the interpretation of what constitutes coordination is flexible. The consistency requirement of the legislation will improve the comparison of transportation impacts from one area to another and may improve the reasonableness of individual modeling assumptions.

The research needs for data are identified in three topic areas that need further research:

- Land use and socioeconomic data (employment stratified by income, land use allocations, role of accessibility, job and housing balance),
- Network supply information [geographic information systems (GISs), traffic counts, pavement conditions, turn penalties, ramp meter delays], and
- Cost information (automobile operating costs, parking cost forecasts).

These research needs are based on the authors' experiences with the areas of potential weakness in current travel forecasting techniques and the areas for which the greatest payoffs (in terms of improved travel forecasts) will be achieved with new research.

Research needs for four-step travel forecasting models were identified in four areas:

- Validation of modeling assumptions,
- Data base management and GIS tools for models,
- Four-step model improvements (impedance in trip generation, choice-based distribution models, socioeconomic variable in distribution, composite costs, walk and bike trips and multimodal trips, and feedback mechanisms), and
- Other research needs (changes in travel behavior over time, limitations on the size of transportation system, cost of model improvements versus accuracy, multiple-purpose trips, intelligent vehicle-highway system evaluation).

Research is ongoing in each of these areas, and in some cases there have been tests to evaluate this research, but none of these areas has been incorporated into the state of the practice in California. In addition to the benefits of this research for air quality analysis much of this research would benefit travel forecasting models for use in other types of analysis.

Adoption of the federal Clean Air Act Amendments of 1990 has renewed interest in the use of regional travel models in developing emissions inventories and in predicting the impact of growth and transportation projects on air quality. Although it is generally recognized that regional models are essential in developing the data for air quality analysis, it is also recognized that there are certain limitations in the models that affect the accuracy of the emission estimates produced from their output. New research is warranted to adapt the regional models more specifically to emissions estimation:

- Comprehensive coverage of trips,
- Prediction of starts and parks (on the basis of limited survey data, differentiate hot and cold starts),
- Modeling of weekend and summertime travel (when ambient air quality standards are violated), and
- Enhancement of emissions rates (which vary by facility type).

As the opportunities to build new highway facilities or widen existing facilities in congested urban corridors have decreased, focus has shifted to transportation management options to accommodate travel demand. Many regional models that were sufficiently sensitive for analysis of new facilities or for significant widening of existing facilities are now insufficient for traffic management and demand management analyses. Substantial research and development are needed to improve the sensitivity of regional models to these increasingly popular options.

With the growing recognition that increasing travel demand from growth cannot be accommodated with new facilities, interest has turned to reducing the amount of new travel from growth by changing the nature of development. There is also concern that the development of new transportation facilities can influence the amount and location of new development and thereby induce growth in travel by the supply of transportation facilities. Both of these are areas in which new research is required if regional forecasting models are to be sensitive to the interaction of land use and transportation.

## SUMMARY

There is growing concern in California that state-of-the-art transportation models produce inconsistent or unreliable data for use in mobile source emissions inventories. The current analytical methods used vary from one region to another and vary in detail and complexity for small, medium, and large regions throughout the state. This has a direct impact on the conformity process for regional transportation plans and regional transportation improvement programs. From a statewide perspective it would be desirable if all agencies used consistent methodologies in travel demand modeling and produced reasonable results. The travel forecasting guidelines provide direction and guidance to regional transportation agencies throughout California in the areas of data sources, modeling assumptions, and results to achieve this consistency.

The travel forecasting guidelines provide specific guidelines separate from the supporting documentation for clarity. In addition the current state of the practice and what constitutes good practice are identified for further information. Although the document was oriented to regional transportation agencies, it is expected that a variety of other audiences may find it useful. These might include executive management officials determining whether existing modeling practice is acceptable or technical staff evaluating their own modeling capabilities. For these audiences, the guidelines can be used for a number of purposes, including the following:

- Ensuring that modeling is performed correctly;
- Achieving a minimum acceptable level of accuracy;
- Providing some standardization and, through it, better understanding of the modeling being performed;
- Adopting universally accepted definitions and terms;
- Meeting the requirements of specific legislation in the state; and
- Conforming to what might be established as a legal basis for acceptable practice.

Forecasting of travel behavior involves representation of numerous complex decisions, and forecasts can only be expected to roughly approximate reality. The state of the art in travel forecasting continues to improve as individuals pursue new methods for analytically representing the complex decisions being made. Although the guidelines are intended to provide some degree of consistency through standardization of methodology, they are not intended to stifle the creativity that will ultimately lead to improvements in the practice. The guidelines are designed to represent a minimum level of acceptable practice and as such are designed to establish a minimum level of consistency and accuracy. To provide this desired consistency without restricting creativity, the guidelines focused on the principles of good forecasting practice rather that specifying which methods should be used.

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# Trip-Based Approach To Estimate Emissions with Environmental Protection Agency's MOBILE Model

PATRICK DECORLA-SOUZA, JERRY EVERETT, JASON COSBY, AND PETER LIM

The Environmental Protection Agency's (EPA's) MOBILE model outputs an emission rate per vehicle mile of travel (VMT). The rate is based on the federal test procedure (FTP), which represents typical driving conditions for an urban vehicle trip. In current practice, however, links instead of trips are used to estimate both VMT and many of the travel characteristics needed as inputs to MOBILE. For example average link speeds are provided as input to MOBILE in current practice, although trip speeds might be more appropriate, given the FTP basis of MOBILE emission factors. A different approach to application of emissions factors from MOBILE is presented. The approach is based on trips rather than on links and therefore more consistent with the trip basis used to develop MOBILE's emissions factors. The approach also allows development of data on travel characteristics from travel model output and travel survey data in a straightforward manner and does not require the special efforts to account for missing VMT needed in the link-based approach. However its most important advantage over the link-based approach is that it facilitates estimation of impacts of transportation control measures on non-VMT MOBILE inputs such as cold-start percentages, vehicle mix, and trip length distribution.

As a result of recent studies (*1,2*) there is a perception that hydrocarbon (HC) and carbon monoxide (CO) emissions from vehicles are underpredicted by both MOBILE and EMFAC. There are several reasons for the inaccuracies. For example the model algorithms are based on average estimates of responses to a particular variable made on the basis of vehicle test results, and emissions estimates may not be truly representative of the entire range represented by the average. Many weaknesses of the models are due to either limited data or faulty assumptions made by their users (*3*). Also travel forecasts or even base travel data inputs to the emissions models may have significant errors (*4*). The focus in this paper is on the inaccuracies that may result from the incompatibility of travel model outputs with emission model inputs and from inaccurate estimation of the non-vehicle miles of travel (non-VMT) transportation data inputs to MOBILE.

The MOBILE model outputs an emission rate per VMT. The rate is based on the federal test procedure (FTP), which represents typical driving conditions for an urban vehicle trip. The Environmental Protection Agency (EPA) has developed and is currently testing a remnant cycle to supplement FTP to provide for emission control under high-speed and high-acceleration events not currently represented in the FTP. However no changes to the basic structure of the model are proposed.

The standard procedure for estimating emissions by the MOBILE emissions model is as follows: emissions = emission factor × vehicle activity. For MOBILE travel activity is VMT. Emission factors vary depending on several characteristics of travel activity such as:

- Vehicle type and age mix,
- Vehicle speed,
- Time of day of travel, which determines ambient temperature,
- Operating mode (i.e., hot or cold start and hot stabilized operation), and
- Trip length distribution.

In current practice estimates of both travel activity and many of the travel characteristics are link based. However MOBILE emissions factors are based on FTP data, which represent trip travel characteristics rather than link-level travel characteristics. In FTP, which is the basis for development of baseline emissions factors, "bags" of pollutants are collected from entire trips about 20 min long. Therefore development of travel characteristics for limited segments of the highway network is inconsistent with the base from which MOBILE factors are developed, that is, entire trips. For example average speeds on which MOBILE factors are based represent speed cycles for an entire trip and not speed cycles on any specific link. This paper proposes a method to derive VMT on the basis of trips instead of links and investigates the magnitude of the possible differences in emissions estimates by using a case study analysis for a large urban area.

## ADVANTAGES OF THE TRIP-BASED APPROACH

Aside from the fact that a trip-based approach is more consistent with the way MOBILE emissions factors are developed, it has other advantages. Many transportation control measures (TCMs) affect not just VMT but also other important emission model variables. For example a TCM that shifts short vehicle trips to the bicycle or walk modes will not just affect impact VMT but also reduce the percentage of cold-start VMT. On the other hand a TCM that shifts single-occupant vehicle trips to transit or car pool modes will increase the percentage of cold-start VMT if the shifts involve park-and-ride access to transit stops or car pool staging areas. Shifts to bus transit affect vehicle mix and operating mode percentages. The current link-based method makes it difficult to estimate such changes. This is where the trip-based approach presented has an important advantage over the link-based approach: it facilitates estimation of non-VMT MOBILE inputs such as cold-start percentages, vehicle mix, and trip length distribution. Thus future estimates of the impacts of TCM policies on emissions will nevertheless improve in accuracy.

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Another advantage of the trip-based approach is that it does not require special efforts to estimate VMT missing in link-based VMT estimates developed from model output, that is, local VMT and park-and-ride VMT. With a link-based approach special efforts are necessary to estimate local VMT because all streets in the urban area are not reflected in the model network, and therefore as much as 15 percent of regional VMT that occurs on local streets may not be accounted for. Also generally trips made by automobile to transit park-and-ride lots or to car pool staging areas are not assigned to the model network, and their effects on percentage of cold starts are ignored. With a trip-based approach park-and-ride VMT and its effects on cold-start percentages are easily estimated.

## ESTIMATING VMT AND AVERAGE SPEED BY TRIP-BASED APPROACH

By the trip-based approach vehicle activity is calculated from trip tables instead of from network links, as follows:

- Zone-to-zone VMT = zone-to-zone trips × zone-to-zone distance. (Note that matrices of zone-to-zone distances are called *distance skims*. Zone-to-zone travel distances are computed from the shortest time path between zones and take into account detours caused by congestion by skimming distances from the loaded network.)
- Zone-to-zone average speed = zone-to-zone distance/zone-to-zone travel time. [Note that matrices of zone-to-zone travel times are called *travel time skims*. If realistic speeds are not output from assignment, link speeds may first need to be adjusted on the basis of the relationships of speed to highway volume-to-capacity ratios derived from the *Highway Capacity Manual* (*5*) and assigned traffic volumes on individual links.]
- VMT in a specific average speed category = sum of all zone-to-zone VMT for trips made at the specific average speed.

The trip-based approach will not overlook vehicle activity that is missing in the travel model output used in the link-based approach:

- Local VMT: intrazonal VMT is not excluded. To get intrazonal VMT vehicle trip tables, which provide the number of intrazonal trips by zone, are multiplied by distance skims in which intrazonal trip distance is based on:
  - –Intrazonal trip lengths (in minutes) output from the trip distribution model and
  - –Assumed average speeds for intrazonal trips (which will be slow speeds, since these trips are made on local streets).
- Park-and-ride VMT: park-and-ride VMT is estimated on the basis of the number of such trips from each zone (on the basis of the output from the mode choice model) and average distance to the zone in which the relevant park-and-ride lot is located (from distance skims).

However the main advantages of the trip-based approach do not relate to completeness of its VMT estimates. More important advantages are (a) its ability to provide average speed estimates more consistent with the average speed expected by the MOBILE model and (b) its ability to estimate the impacts of future TCMs on travel characteristics, which are discussed next.

## ESTIMATING OTHER TRAVEL CHARACTERISTICS

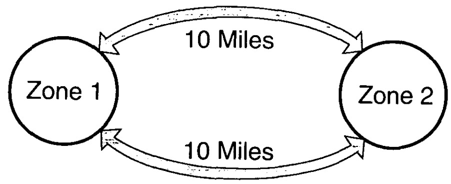
The trip-based approach allows development of base year as well as future year estimates of travel characteristics from travel model output and from travel survey data in a straightforward manner. Two types of data are needed to estimate vehicle travel characteristics: travel model and survey data.

Home interview travel survey data are useful primarily for developing distributions of base travel activity by time of day (for use with ambient temperature and to get average speed estimates by time of day) and to get estimates of base vehicle mix and operating mode. Shifts from these base characteristics that are induced by TCM policies (for example impacts of location-specific flextime or peak period pricing policies on VMT distribution by time of day or impacts of transit park-and-ride lots on percentage of cold-start VMT) are then estimated for future scenarios. In the link-based approach travel characteristics for the base year may be obtained from sample surveys of highway links, but estimating the impacts of TCMs on those characteristics for specific links (or aggregations of links) in future scenarios is difficult. The following types of data are obtained from home interviews:

- Time of trip, by trip purpose, from which appropriate temperature inputs to MOBILE can be developed.
- Operating mode of vehicle, derived from elapsed time between trips, from which shares of trips starting cold versus starting hot can be developed by trip purpose and time of day.
- Vehicle type use by trip purpose, from which estimates of vehicle mix by trip purpose and time of day can be developed. (A special type of travel survey called an *auto log survey* is needed to get this type of information from home interviews. Note that truck trips are often a separate trip purpose in travel demand models. Special surveys are needed to get truck travel data.)
- Travel time, which can be used to develop trip length (i.e., duration) distributions by trip purpose and to check network speeds and average trip lengths estimated by the models.

If home interview survey data are not available for a specific urban area, national data on personal travel can be obtained by urban area size category through analysis of Nationwide Personal Transportation Survey (NPTS) data. Research with NPTS data has recently been completed at the University of Tennessee (*6*). Alternatively individual urban areas that are planning to undertake a home interview survey for the purpose of updating their travel models could add questions relating to vehicle use and time of trip for a small increase in cost. Typically home interview surveys cost about $100 per interview.

Note that home interview survey data could also be used with the link-based approach to get regionwide shares of base (but not future scenario) VMT by operating mode, vehicle mix, and time of day (*7*). In other words the survey data can be used to estimate travel characteristics applicable to base regionwide VMT in an aggregate fashion. However the trip-based approach allows development of travel characteristics for base conditions as well as for future scenarios with TCM policies. The demonstration example that follows shows how estimates of the impacts of a future TCM policy on base travel characteristics may be obtained.




| | |
|---|---|
| 100 | 1500 |
| 1500 | 50 |

HB Work

| | |
|---|---|
| 600 | 2000 |
| 2000 | 300 |

HB Non-Work

| | |
|---|---|
| 300 | 1000 |
| 1000 | 150 |

NHB

**FIGURE 1 Demonstration example and vehicle trips.**

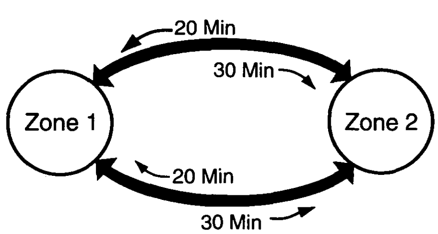
## DEMONSTRATION EXAMPLE

The demonstration example uses ETOWN, a small hypothetical urban area with two traffic analysis zones and a highway network, as shown in Figure 1. ETOWN has proposed express bus service with park-and-ride access for inclusion in its transportation plan and needs to develop transportation data inputs for an emissions analysis to determine conformity with its state implementation plan for air quality.

Future year vehicle trip tables by trip purpose [Home-Based (HB) Work, HB Nonwork, and Non–Home-Based (NHB)] have been developed for the peak period by using ETOWN's mode choice model, as presented in Figure 1. The vehicle trips made to park-and-ride lots do not appear in the vehicle trip table because the model considers them to be transit trips. The vehicle trip table has been assigned to ETOWN's highway network by using an equilibrium technique, and the resulting volume/capacity ratios have been used to compute adjusted travel times on the basis of congestion; the results are shown in Figure 2.

A home interview (automobile log) travel survey was also recently undertaken in ETOWN, from which it was determined that the percentages of vehicle trips starting cold during peak periods were as follows: HB Work, 90 percent; HB Nonwork, 50 percent; NHB, 30 percent.

On the basis of home interview survey ETOWN planners were able to derive light-duty gasoline vehicle (LDGV) use for peak period trips by trip purpose, as follows: HB Work, 90 percent; HB Nonwork, 90 percent; NHB, 60 percent. The focus for this demonstration is on development of peak period transportation data for work trip purposes. Trips for other purposes are handled by simply repeating the steps for each trip purpose. Note that temperature to be used as input is determined by the time of day of the peak period being analyzed.




| | |
|---|---|
| 10 | 30 |
| 20 | 10 |

Travel Time Skim

| | |
|---|---|
| 0 | 10 |
| 10 | 0 |

Distance Skim

**FIGURE 2 Assignment results.**

| | |
|---|---|
| 10 | 30 |
| 20 | 10 |

Times

| | |
|---|---|
| 0 | 10 |
| 10 | 0 |

Distances

| | |
|---|---|
| 12 | 20 |
| 30 | 12 |

Speeds

**FIGURE 3 Speed calculation.**

### Step 1: Estimate VMT by Speed Class

*Step 1(a): Speed Calculation*

In Figure 3 skimmed times and distances are used to calculate average speed for each zone pair. For example speed between zone 1 and zone 2 = (10 miles/30 min) × 60 min/hr = 20 mph. For intrazonal trips a low speed of 12 mph is assumed because this travel occurs on local streets.

Note that the same average speed could result from very different speed cycles, as shown by recent research (*8*) done by the California Air Resources Board. For example an average speed of 35 mph when the majority of travel is on freeways is based on a very different cycle of stops, accelerations, and decelerations than an average speed of 35 mph when the majority of travel is on arterials. However the MOBILE model currently assumes the same speed cycle for all trips of the same speed. If the MOBILE model is enhanced to reflect the effects of varying shares of freeway versus arterial travel for trips with the same average speed, the path skimming process in travel models could be enhanced to keep track of shares of the path on freeways versus arterials.

*Step 1(b): VMT Calculation*

In Figure 4 the vehicle trip table input into traffic assignment and the distance skims are used to calculate VMT for each zone pair.

| | |
|---|---|
| 100 | 1,500 |
| 1,500 | 50 |

Trips

| | |
|---|---|
| 2 | 10 |
| 10 | 2 |

Distances

| | |
|---|---|
| 200 | 15,000 |
| 15,000 | 100 |

VMT

**FIGURE 4 VMT calculation.**

For example total number of trips between zone 1 and zone 2 is 1,500, and the vehicles travel a distance of 10 mi for each trip. Therefore VMT = 1,500 × 10 = 15,000. For intrazonal VMT one first needs to estimate an intrazonal average distance using the intrazonal travel time and average speed of 12 mph assumed previously. For example intrazonal distance for zone 1 = 12 mph × (10 min/60) = 2 mi.

The trip-based approach can be used to easily estimate the VMT impacts of trips to park-and-ride lots that were not included in the vehicle trip table used as input to ETOWN's traffic assignment. Figure 5 demonstrates the process for calculation of park-and-ride VMT. In ETOWN the park-and-ride lot is assumed to be in the zone from which park-and-ride trips are generated, and the park-and-ride VMT is obtained by multiplying the number of park-and-ride trips by intrazonal distance. (Note that bus VMT may be obtained from transit network data.)

*Step 1(c): Classify VMT*

All VMT in a specified speed range is aggregated (Figure 6). For example intrazonal VMT, for which the travel speed is 12 mph, falls in the speed range of 10 to 14 mph. Aggregating all VMT in the 10- to 14-mph speed range gives (220 + 120) = 340 VMT. (Caution: the speed ranges used in this example are too wide for use in practice.)

**Step 2: Estimate Distribution of Trip Lengths**

In step 2 VMT is classified by trip length (i.e., duration) category to get the percentage distribution in each category (Figure 7). For example all intrazonal VMT falls in the range of 0 to 10 min.

**Step 3: Estimate Regional VMT Mix by Vehicle Type**

For the purpose of this demonstration estimates of LDGV VMT percentages are shown. The survey estimates of the percent trips by each vehicle type are used to represent the percent VMT by

Trips (to P/R Lot)

| | |
|---|---|
| 10 | 0 |
| 0 | 10 |

Distances

| | |
|---|---|
| 2 | 10 |
| 10 | 2 |

VMT (P/R)

| | |
|---|---|
| 20 | 0 |
| 0 | 20 |

Total VMT (P/R + all other)

| | |
|---|---|
| 220 | 15,000 |
| 15,000 | 120 |

**FIGURE 5 Park-and-ride (P/R) VMT.**

| Speed Range | VMT |
|---|---|
| 0-4 | ____ |
| 5-9 | ____ |
| 10-14 | 340 |
| 15-19 | ____ |
| 20-24 | 15,000 |
| 25-29 | ____ |
| 30-34 | 15,000 |

**FIGURE 6 VMT classification.**

vehicle type. The percent VMT would be different from the percent trips only if survey data showed that trips by some vehicle types were longer (i.e., in distance) than those by other vehicle types.

Park-and-ride policies can have an impact on VMT mix. In ETOWN it was assumed that the future new trips to park-and-ride lots will be made 100 percent by LDGV, whereas all other trips reflect the vehicle mix from the base year survey. Figure 8 shows how the VMT mix resulting from such an assumption can be estimated.

**Step 4: Percent Cold Start VMT**

The proposed park-and-ride policies in ETOWN will affect operating mode shares. These impacts can be estimated by the trip-based approach. Estimation of percent cold-start VMT or percent hot-start VMT involves similar steps. Below the steps for estimating percent cold-start VMT, as shown in Figure 9(*a*), are described.

1. By using the work purpose's non–park-and-ride vehicle trip table and percent cold-start trips for the work purpose from survey data (i.e., 90 percent), a cold-start-trip table for the work purpose for non–park-and-ride trips was calculated. In ETOWN 100 per-

VMT

| | |
|---|---|
| 220 | 15,000 |
| 15,000 | 120 |

Travel Time

| | |
|---|---|
| 10 | 30 |
| 20 | 10 |

| Time Range (Minutes) | VMT |
|---|---|
| 0-10 | 340 |
| 11-20 | 15,000 |
| 21-30 | 15,000 |
| 31-40 | ____ |
| 41-50 | ____ |
| 51-60 | ____ |

**FIGURE 7 Trip length distribution.**

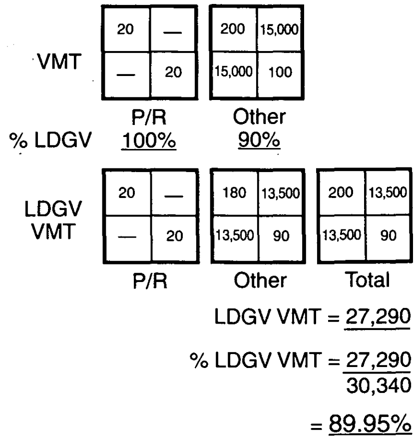



**FIGURE 8 VMT mix by vehicle type.**

cent cold starts were assumed for park-and-ride trips, and a cold-start-trip table for park-and-ride trips was likewise obtained.

2. Next trip lengths shorter than 3.6 mi were identified from the cold-start-trip table. These are trips that are made entirely in the cold-start mode. The 3.6-mi limit is based on the distance traveled in the FTP drive cycle during its start phase. (Note that alternatively 8.4 min can be used as the cutoff, with a slightly more complicated computation procedure. The cold-start VMT for these trips was obtained by multiplying the number of these trips by the appropriate zone-to-zone distance from the distance skim table. Caution: It may be more appropriate in practice to assume that trips shorter than 3.6 mi generate 3.6 cold-start VMT, because most excess emissions from cold starts actually occur in the first minute or about 0.5 mi (*9*). This is shown in Figure 9(*b*).

3. For trips longer than 3.6 mi (i.e., trips that operate only partly in the cold mode), one obtains cold-start VMT by multiplying total cold-start trips by 3.6 mi.

4. Percent cold-start VMT is then obtained by aggregating VMT from Substeps 2 and 3 and dividing by total VMT. [Caution: if trips shorter than 3.6 mi were assumed to be 3.6 mi in Substep 3, then appropriate adjustments must be made to total VMT to include the "excess" miles.]

These steps can similarly be used to estimate hot-start mode VMT (using 0 percent hot starts for park-and-ride trips and 10 percent hot starts for non-park-and-ride trips). The balance of VMT would be in the hot-stabilized mode.

## REAL-WORLD EXAMPLE: COMPARISON OF ESTIMATES FROM TRIP-BASED APPROACH WITH ESTIMATES FROM LINK-BASED APPROACH

Table 1 gives a comparison of HC emissions estimates for the Baltimore, Maryland, urban area by the trip-based approach versus estimates obtained by the conventional link-based approach. The Baltimore travel models estimate trips for six trip purpose categories and for a 24-hr period (*10*). By using national survey data from NPTS (*11*), estimates of cold- and hot-start percents and vehicle mix for each trip purpose were derived for the trip-based approach. Trip length (i.e., duration) distributions were obtained for each trip purpose from the travel models on the basis of congested speeds after traffic assignment.

For the link-based approach link-based VMT was developed from the combined-purpose traffic assignment. To ensure consistency with travel characteristics developed for the trip-based approach, the cold- and hot-start percentages, vehicle mix, and trip length (i.e., duration) distribution used with the combined-purpose VMT from highway network assignment were obtained as weighted averages of the parameters used by trip purpose in the trip-based approach. Table 2 gives these MOBILE inputs. Note here that MOBILE defaults for technology parameters were used (i.e., the emissions factors used do not reflect inventory and main-

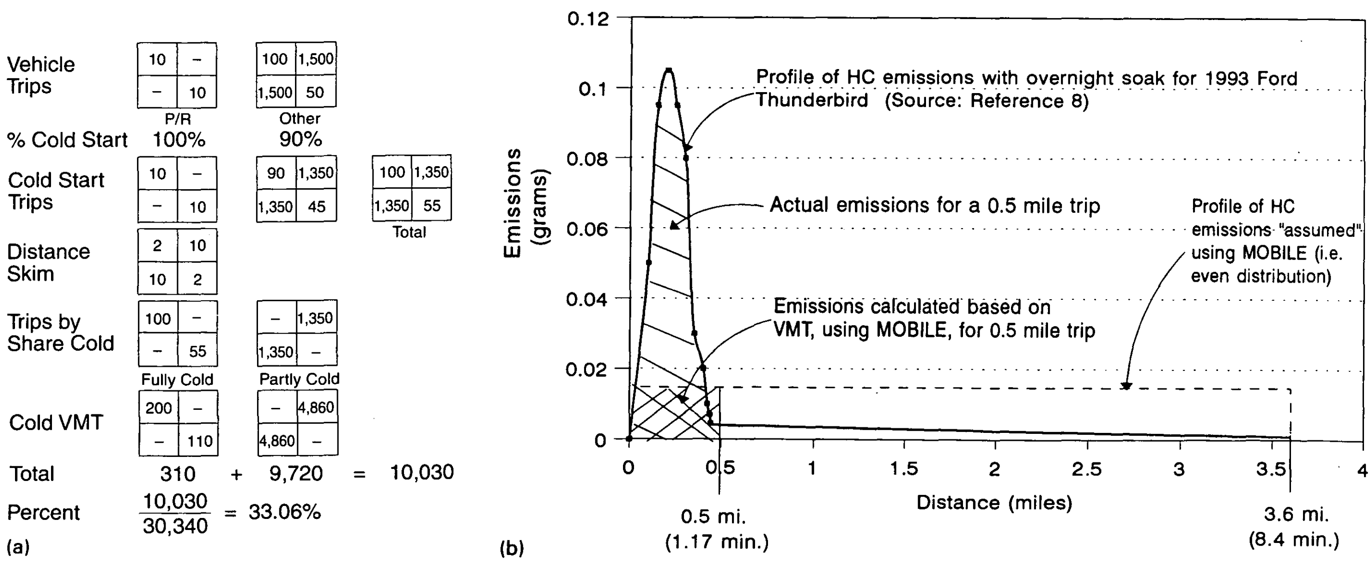



**FIGURE 9 (*a*) Percent cold starts and (*b*) profiles of actual versus model cold-start emissions.**

tenance programs, etc.), and therefore the emissions estimates in Table 1 cannot be expected to match those developed for Baltimore's 1990 base year inventory. Figure 10 shows the process used to conduct the analysis.

Table 1 indicates that the two approaches result in different total emissions estimates for this case study application. This analysis suggests that further investigation is necessary to determine the causes of these differences and to determine whether the differences are statistically significant or merely a chance occurrence. A comparison of the VMT distribution by speed category was developed for each approach; the comparison is shown in Figure 11. The VMT distributions suggest that a possible reason for the higher emissions with the link-based approach is the much larger share of VMT in the lower speed categories and the higher speed categories for which MOBILE generates higher emissions rates.

The particular procedures that were used to apply the link-based approach demonstrate that the two approaches are not necessarily mutually exclusive and can be used in tandem. Estimates of travel characteristics (vehicle mix, operating mode shares, and trip length distribution) used for the link-based approach were in fact obtained as an output from the trip-based approach. Thus urban areas wishing to continue to use the link-based approach could still use the trip-based approach to estimate the impacts of TCMs on travel characteristics other than speed.

**TABLE 2 Travel Characteristics for Combined-Trip Purpose**

**Operating Mode (% VMT):**

| | |
|---|---|
| Cold start | 19.1% |
| Hot start | 12.0% |
| Hot stabilized | 68.9% |
| TOTAL | 100 % |

**Vehicle Mix (% VMT):**

| | | |
|---|---|---|
| LDGV | Light duty gasoline vehicle | 68.0% |
| LDGT1 | Light duty gasoline truck 1 | 17.5% |
| LDGT2 | Light duty gasoline truck 2 | 9.7% |
| HDGV | Heavy duty gasoline vehicle | 0.8% |
| LDDV | Light duty diesel vehicle | 0.8% |
| LDDT | Light duty diesel truck | 0.5% |
| HDDV | Heavy duty diesel truck | 2.2% |
| MC | Motorcycle | 0.5% |
| | | 100.0% |

**Trip Length Distribution:**

| | |
|---|---|
| 0 - 10 min. | 6% |
| 11 - 20 min. | 24% |
| 21 - 30 min. | 28% |
| 31 - 40 min. | 20% |
| 41 - 50 min. | 10% |
| 51 - 60 min. | 12% |
| TOTAL | 100% |

## SPECIAL APPLICATIONS OF THE APPROACH

This section discusses two special applications of the approach: (a) for base year emissions inventory development and (b) for developing gridded emissions estimates for input to dispersion models.

Use of highway performance monitoring system (HPMS) data is currently recommended by EPA for base year emissions inventory development. This recommendation can be satisfied by ensuring that model VMT output for the base year is made consistent with HPMS ground count-based VMT before any output from the model is used. For future year inventories the model can be run without adjustments to estimate future travel, and the ratio of base year HPMS to base year model VMT can be used to factor future model VMT uniformly for all trip purposes.

**TABLE 1 Daily HC Emissions for Baltimore Study Area (1990)**

| | VMT | Emissions (grams) | |
|---|---|---|---|
| **Trip-based approach:** | | | |
| HB Work | 19,960,287 | 64,974,674 | |
| HB Non-work | 13,140,846 | 43,782,673 | |
| Non-home based | 6,816,524 | 23,718,698 | |
| Light truck | 3,026,189 | 13,650,688 | |
| Heavy truck | 723,762 | 4,038,273 | |
| External | 3,833,984 | 11,594,334 | |
| TOTAL | 47,501,592 | 161,759,340 | (178 tons) |
| **Link-based approach:** | | | |
| Network links | 45,519,179 | 174,233,476 | |
| Intrazonal | 1,982,413 | 10,962,744 | |
| TOTAL | 47,501,592 | 185,196,220 | (204 tons) |
| **Difference:** | | | |
| Magnitude | 0 | 26 tons | |
| Percent | 0 | 14.6 % | |

The trip-based approach produces regionwide emissions estimates. If emissions estimates are needed for smaller geographic areas (grid cells), regionwide estimates will need to be disaggregated. Three possible ways of doing this are outlined.

1. EPA's procedures (*12*) can be used to perform geographic disaggregation to grid cells.
2. Emissions can be disaggregated on the basis of relative emissions rates per VMT by volume/capacity (V/C) ratio for various facility classes and area types, and the VMT estimates by link output from the models. (Note: centroid connector and intrazonal VMT would be considered to be on local streets in the grid cell in which the zone centroid is located.) However development of appropriate emissions rates per VMT by V/C ratio for various facility class and area type categories is not easy and requires research, because as discussed earlier the MOBILE model is based on entire trips and not specific links. CARB is considering developing emissions rates by facility type and level of service (*8*).
3. Shares of total emissions in each grid cell developed from emissions calculated on the basis of the link-based approach to allocate total regional emissions calculated by the trip-based approach can be used.

With more sophisticated computer software emissions could be estimated by trip interchange (i.e., each cell of the trip table) and then assigned to the shortest time path between the two relevant zones. The assignment procedure would be similar to current traffic assignment procedures, with proration of zone-to-zone emissions to individual links on the basis of standard profiles of emissions by elapsed time or distance from origin.

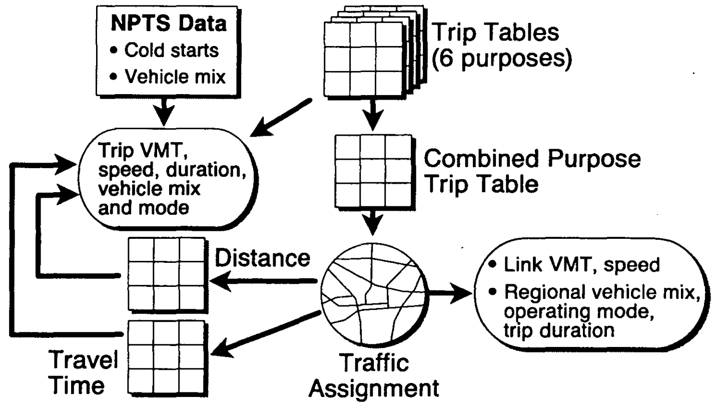



FIGURE 10 Analysis procedures using Baltimore models.

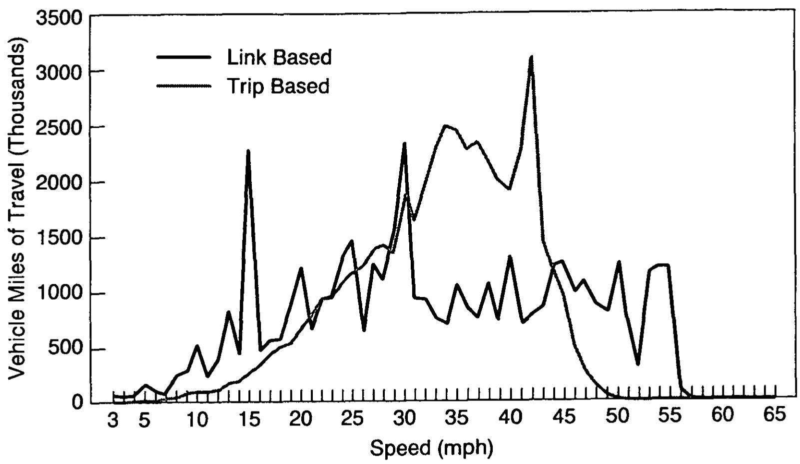



FIGURE 11 Comparison of VMT by speed.

## CONCLUSIONS

This paper has presented a trip-based approach for estimating emissions with the MOBILE model by using travel model output and travel survey data. The approach can overcome some problems with the link-based approach used in current practice. Application of the procedure was demonstrated with a hypothetical example and a real-world example of an urban area, and it was demonstrated that the link-based approach can be used with the trip-based approach to improve estimates of changes in travel characteristics as a result of TCMs. Comparison of emissions estimates by using the trip-based approach with results from the link-based approach for the real-world example indicates differences in emissions estimates. Further investigation is necessary to determine whether the differences are merely a chance occurrence or there are biases in estimates on the basis of the approach used. Also further research is needed to determine if accuracies of estimates are in fact improved by use of the trip-based approach and whether further disaggregation of trips (e.g., into trip categories based on vehicle type or trip length, in addition to average speed) will result in differences in estimates or in improved accuracy.

Notwithstanding accuracy considerations there are many advantages of the trip-based approach.

1. Estimation of local VMT is automated and does not require off-model procedures as in the link-based approach.
2. Impacts of TCMs such as park-and-ride lots on VMT and travel characteristics are more easily estimated.
3. The approach is more consistent with FTP cycle "trips" used as the basis for the MOBILE model, and therefore future enhancements to MOBILE can more easily be reconciled with the trip-based approach.

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# Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment

DAVID C. LEBLANC, MICHAEL D. MEYER, F. MICHAEL SAUNDERS, AND JAMES A. MULHOLLAND

The Clean Air Act Amendments of 1990 place a great deal of importance on the use of transportation controls to meet air quality standards in nonattainment areas. Inherent in the approach to estimating the beneficial impacts of such transportation measures is an estimation of current levels of emissions (the emissions inventory) and then a determination of what changes in emissions would occur given changes in the operation and use of the transportation system. One aspect of vehicle emissions behavior, that is, emissions due to engine power enrichment, which is not well represented in existing models, is examined. A 46-instrumented vehicle data base was used to analyze the importance of enrichment emissions to overall vehicle trip emissions records while relating these emissions to velocity-acceleration characteristics. It is concluded that enrichment emissions can be a significant contributor to overall vehicle emissions. In addition policy implications of these results on current public policy and emissions model development are discussed.

The Clean Air Act Amendments of 1990 place a great deal of importance on the use of transportation controls to meet air quality standards in nonattainment areas. Inherent in the approach to estimating the beneficial impacts of such transportation measures is an estimation of current levels of emissions (the emissions inventory) and then a determination of what changes in emissions would occur given changes in the operation and use of the transportation system. For mobile source emissions (that is, those emissions originating from transportation sources), this estimate is usually based on an activity factor [for example, vehicle miles of travel (VMT) for specified vehicle categories] and then multiplying this by emission rates that are produced from emission rate models. These emission rates are average rates that reflect emissions generated from vehicle tests on typical driving cycles modified by external factors such as ambient temperature and elevation.

Recent studies, however, have suggested that the models currently used to produce estimates of mobile source emissions could possibly underestimate these emissions by a factor of two or three (*1,2*). The reasons offered for this underestimation include inappropriate specification of the emissions models to model insensitivity to emissions generation that occurs under driving conditions in an actual road network. In particular some have hypothesized that one of the major causes of the emissions underestimation is a phenomenon called *power enrichment*, a condition of engine operation that causes the engine management feedback control system (which ensures stoichiometric operation) to be overridden to provide extra power by applying excess fuel, and thus producing high levels of carbon monoxide (CO) and hydrocarbon (HC) emissions (*3–5*). The purpose of this paper is to identify the characteristics of vehicle emissions as they are found in actual roadway driving.

The data base used in the present study consisted of 50 1989 to 1991 model year vehicles instrumented for engine and emissions monitoring. The vehicles were driven in Spokane, Washington, and Baltimore, Maryland, as part of a Motor Vehicle Manufacturers Association (MVMA)-sponsored project that was associated with a larger study of driving behavior being conducted by the Environmental Protection Agency (EPA). One component of the vehicle instrumentation was a wide-range oxygen sensor ($WRO_2$) that was able to detect air/fuel ratios over a wide range of operating conditions, thus providing an indication of when the engine is in an enriched condition. For those vehicles in which mass air flow can be determined, CO throughput can be estimated. In addition to air/fuel ratio, vehicle speed, engine speed, throttle position, a flow parameter, and engine coolant temperature were also recorded for six parameters.

## BACKGROUND

The transportation and air quality professional community has only in recent years begun to explore in some detail alternative concepts for estimating mobile source emissions. Guensler (*6*) provides an excellent overview of some of the more important efforts as they relate to mobile source emissions modeling. Before the empirical evidence from this data base is presented, it is important first to set the context for some of the issues associated with a desire for a different approach toward such modeling. By so doing the empirical evidence of vehicle emissions from the six-parameter data base can be placed in the context of current hypotheses of why there is an underestimation of mobile source emissions.

As noted by Guensler, "For the purposes of estimating emissions, the action being performed by the vehicle (or inaction) at the time emissions occur is an emission-producing vehicle activity" (*6*). During the past several years several researchers have argued that one of the vehicle-producing activities that must be better understood in the context of emissions modeling is engine load-induced power enrichment (*3,7–9*). Some preliminary laboratory data suggest that high acceleration rates (which put heavy loads on the engine) could in fact contribute higher-level emissions due to power enrichment. The results of these preliminary

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investigations suggest that emissions due to power enrichment could possibly be an important contributor to the overall level of emissions due to vehicular sources.

Ripberger and Markey (*10*) provided a more conceptual perspective on the need for a better method of estimating vehicle emissions. They described the results of discussions among a working group of air quality and emissions modeling professionals and identified several elements of a new highway vehicle emissions estimation methodology that needed to be considered during the development of such a methodology. Those elements that relate directly to the character of vehicle emissions include the following:

> • *Modal Testing*—Vehicle emissions are not constant over the range of operating conditions. Certain operating conditions or modes can produce higher emissions and may contribute to a significant portion of the inventory. . . . Modal testing would need to cover the range of modes experienced by in-use vehicles: idle, cruise, acceleration, and deceleration. . . .
> • *Output In Grams Per Hour*—. . . grams per hour is feasible because emissions are linear and nearly constant during all vehicle operating modes (except cold start). . . .
> • *Vehicle Operation Data*—Vehicle in-use models would focus on estimating the number of vehicles and time spent in specified modes (e.g., idle, acceleration, or cruise). (*10*)

The paper by Ripberger and Markey (*10*) has served as a starting point for research efforts at the Georgia Institute of Technology (Georgia Tech) and elsewhere to provide a better understanding of the significance of these modal emissions to overall emissions levels.

Although some researchers and modelers have suggested that emissions due to power enrichment could be an important contributor to vehicular emissions, and in some limited cases laboratory experiments have been conducted, very few emissions data have been collected from real-world driving. The value of the six-parameter data base is that the emissions and engine behavior data represent driving conditions and road network topography that are typical in everyday driving. As will be described the results of the six-parameter study reinforce the concepts already presented by the authors.

## METHODOLOGY AND DATA BASE

In February and March 1992, 79 vehicles were equipped with instrumentation that recorded time of day, day of year, vehicle speed in miles per hour (mph), engine speed in revolutions/min (RPM), throttle position as percentage of full throttle, coolant temperature in degrees Celsius, and either manifold absolute pressure (MAP) in kilopascals, mass air flow (MAF) in kilograms/hour, or LV8. LV8 is a proprietary measure used by General Motors (GM); it appears to be a composite of MAP and MAF. LV8 also varies in implementation from one engine family to another. Without a means of calculating mass air flow from LV8, the analysis of overall emissions presented here omits these vehicles. Each vehicle also was equipped with a $WRO_2$, and the output voltage from this sensor was mapped into an equivalence ratio to represent the air/fuel ratio. Values of all monitored parameters were recorded once per second. Data were recorded for approximately 1 week of driving for each vehicle by a randomly selected population of owner-drivers. Equivalence ratio ($\phi$) is defined as:

$$\phi = \frac{(A/F)_{\text{Stoich}}}{(A/F)_{\text{Actual}}}$$

where $A/F$ is air/fuel ratio.

Of the 79 originally instrumented vehicles, 50 data sets were initially judged by the contractor to have recorded acceptable data and were transmitted by EPA's Office of Mobile Sources to Georgia Tech for analysis. On closer examination four anomalous data sets were excluded from further analysis: one data set was missing four of six data channels, and the other three displayed badly skewed $\phi$ profiles and were excluded because it was not possible to tell whether the vehicle or the instrumentation was malfunctioning. Because of instrumentation requirements, the vehicles used in the study were relatively new (1989 to 1991 model years), and only vehicles manufactured by Chrysler, Ford, GM, Mazda, Mitsubishi, Nissan, and Toyota were represented. The median mileage on these vehicles at the time of instrumentation was 47,266 km (29,370 mi), with a maximum of 165,965 km (103,126 mi) and a minimum of 10,798 km (6710 mi). Young drivers (25 years and younger) were poorly represented, with only one sample taken from that age group. The results of this bias could be significant because the lone young driver was among the most aggressive and also had one of the highest incidences of power enrichment activity. Instrumentation requirements may have produced a biased sample. Manual transmission vehicles may have been underrepresented, as were vehicles with large engines and sports cars. As a result this sample may be somewhat more conservative than the overall population. A much larger sample would better extrapolate this analysis to the overall population.

## ESTIMATION OF POLLUTANT THROUGHPUT

CO concentration was estimated by using either directly measured mass air flow or an estimated mass air flow derived from RPM and MAP and an estimate of the CO concentration based on the measured equivalence ratio. HC emissions tend to be a complex function of engine design parameters, engine speed, and state of maintenance of the engine (piston rings, spark plugs, etc.) and are not addressed directly in this paper. Nitrogen oxide ($NO_x$) emissions have not been modeled at this time. Mass air flow was determined by using the RPM and MAP signals along with engine displacement for vehicles equipped with MAP sensors by using the following equation:

$$\text{MAF} = \left(\frac{1 \text{ intake stroke}}{2 \text{ revolutions}}\right)\left(\frac{\text{RPM}}{60 \text{ sec/min}}\right)\left(\frac{\text{MAP}}{100 \text{ kPa}}\right)(1.2 \text{ g/L}) \text{ (Displacement, } L\text{)}$$

The density of air was assumed to be constant (1.2 g/L) when evaluated at standard pressure and temperature (1 atm and 20°C, respectively). Variations owing to altitude and daily temperature were not included since external air temperature and pressure were not recorded. Temperature variations could induce up to 8 percent error. Altitude variations should not be a problem in Baltimore, but Spokane drivers could experience significant changes in pressure because of altitude. Mass air flow sensor-equipped vehicle

data were converted to grams per second, and LV8-equipped vehicles were not used because the exact relationship between LV8 and flow is unavailable. The contribution of fuel to overall mass flow is taken into account by

$$\left(1 + \frac{\phi}{14.56}\right)$$

where 14.56 was taken to be the stoichiometric air/fuel ratio on a mass basis.

Thermodynamic CO concentrations were determined as a function of $\phi$ by using Sandia Chemical Equilibrium Code [Stanjan (Stanford-JANAF) thermodynamic data tables]. A combustion temperature of 2500 K and pressure of 68 atm were assumed on the basis of typical values (*11*). From the same text the hydrogen-to-carbon ratio in a typical gasoline was assumed to be 13:7. The combustion temperature is a maximum at $\phi$ of approximately 1 and will drop on either side of that value; variation in combustion temperatures over the range of $\phi$ values observed was estimated to result in less than a 1 percent change in CO concentration in this model. More than 50 chemical species were used for the thermodynamic calculations. Under fuel-rich conditions the carbon monoxide/carbon dioxide ($CO/CO_2$) ratio is controlled by the water-gas shift equilibrium expressed as

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The thermodynamic equilibrium equations are not easily reduced to an explicit equation for CO concentration in terms of $\phi$. CO concentration on a mass basis (wet) was calculated for 13 points over the span of $0.76 \leq \phi \leq 1.42$. These datum points were then fit by using a cubic splines method to interpolate between points. Catalyst efficiency was estimated by mapping points from a published curve, and the cubic spline method was then used to model the curve. The resulting equation is

$$CO = MAF\left(1 + \frac{\phi}{14.56}\right)(X_{CO})(1 - \eta)$$

where $X_{CO}$ is the mass fraction for CO and $\eta$ is the catalyst efficiency. It is also possible to explicitly calculate the CO mass fraction by using the water-gas shift equilibrium and mass balance requirements under severe enrichment conditions. Under these conditions one can assume the carbon as CO and $CO_2$, hydrogen as $H_2$ and $H_2O$, and oxygen as CO, $CO_2$, and $H_2O$. The solution of these equations yields a quadratic equation with $\phi$, pressure, and temperature setting $X_{CO}$. This solution breaks down when the assumption that none of the oxygen is in the form of $O_2$ is no longer valid. Because this method is valid only for a segment of the range of $\phi$, it was not applied in calculating the results presented here.

Laboratory data reported by Patterson and Henein (*11*) were compared with these results as well as with data obtained in a related on-road experiment conducted in Atlanta with an MVMA pilot study vehicle and a remote sensing system. A Buick Park Avenue used as part of the MVMA pilot study (*4*), which was outfitted with $WRO_2$ sensors from the same batch as those used in the full-scale study, was driven past a remote sensing unit. The clock on the vehicle data logger was compared with the clock used by the remote sensing computer, and over 50 passes were matched. As can be seen in Figure 1 the resulting CO concentration derived from $\phi$ as measured by the $WRO_2$ and the thermodynamic model (with catalyst efficiency included) is very close to that measured by the remote sensing unit (*12*). A typical catalyst

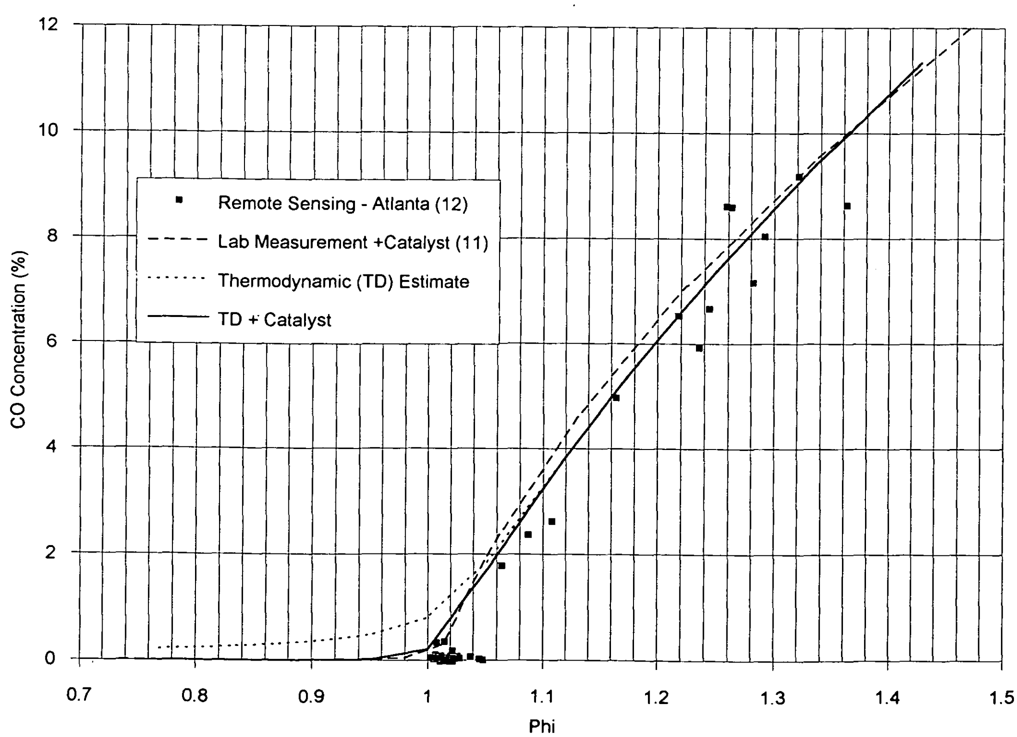


**FIGURE 1 Comparison of thermodynamic model with remote sensing by $WRO_2$.**

efficiency curve (*11*) was applied to the laboratory data and the thermodynamic model. The catalyst efficiency curve is taken as a function of $\phi$ only; however, this may be an oversimplification. Catalytic converters have some capability to buffer short-duration spikes; however, it is not clear how this effect should be modeled. The catalyst efficiency curve does not reflect that different manufacturers may have larger or smaller volumes with respect to flow, and residency time in the catalyst may have an effect on efficiency. A new catalyst coupled with a state-of-the-art engine management system can achieve a higher conversion efficiency than this model, but the model used is appropriate to the vehicle years studied. There is close agreement among remote sensing, laboratory data (with catalyst efficiency included), and the composite thermodynamic estimate-catalyst efficiency curve (Figure 1).

Data from an instrumented car that had an on-board exhaust gas analyzer and a $WRO_2$ sensor from the same batch as those used in the MVMA study and that used the same voltage to $\phi$ conversion as that in the present data set showed that there was excellent agreement between calculated values and measured values. The approximation of $\phi$ from the $WRO_2$ response for the six-parameter data set is considered to be within 10 percent for air/fuel ratios of $\geq$11.5:1 ($\phi \leq 1.27$) (P. J. Groblicki, unpublished data). Because recorded values of $\phi$ range higher than 1.27, there will be some error resulting from the curve fit for values beyond 11.5:1 that would result in the overestimation of $\phi$. To compensate for extremely high values, any air/fuel ratio of less than 10:1 ($\phi = 1.46$) was limited to 10:1 in the calculations. Extremely high values of $\phi$ ($\phi \geq 1.27$) were rare (0.2 percent of all enrichment events), and this solution is intended to minimize the impact of overestimating $\phi$ from $WRO_2$ response because it effectively caps the CO concentration at 10 percent by weight.

## ANALYSIS OF INSTRUMENTED VEHICLE DATA BASE

The analysis of the instrumented vehicle data base focused on the driving modes in which power enrichment occurred and the resulting overall effect of this enrichment. For the purposes of the present study mild enrichment is defined as $\phi \geq 1.03$ (air/fuel $\leq 14.1$) and $\phi < 1.12$ (air/fuel > 13.0). Severe enrichment is defined as $\phi \geq 1.12$. By using these definitions mild enrichment represents an exhaust CO concentration of between 1 and 4 percent by weight, and severe enrichment can range as high as 10 percent.

Enrichment events were examined by treating each excursion past $\phi$ of 1.03 as a whole event. Peak and average values of $\phi$ and acceleration were calculated for each event as well as duration, peak throttle position, average speed, and CO emissions. An offset of 1 sec was applied to correlate each exhaust pulse to the engine and vehicle parameters, taking into account the time for the pulse to reach the $WRO_2$ sensor as well as the response time of the sensor. A careful inspection of the time offset shows that 1.5 sec would be ideal, with 1 sec being best at high mass air flows; however, the data were sampled once per second, making fractional-second offsets impractical. The data were then sorted into 16 bins of 5 mph each for speed and 16 bins of 1 mph/sec for acceleration. All acceleration data were obtained by using a 2-sec running average (central differencing) to reduce noise resulting from the limited resolution of the speed data. All data presented are for engine coolant temperatures of greater than 70°C, thus eliminating cold-start conditions. Under those conditions the catalytic converter should be at full operating temperature.

Mild enrichment tends to be a function of a momentary inability of the engine management system to respond to changes in driver input and operating conditions, whereas severe enrichment frequently results from a commanded enrichment by the engine management system. Many modern electronic engine management systems command either a stoichiometric ratio ($\phi = 1$) or enrichment. Inspection of data taken by using vehicles with the ability to monitor commanded air/fuel ratio and measured exhaust composition shows that variations in CO concentration occur when stoichiometric operation is commanded; however, these fluctuations are not as severe as those resulting from commanded enrichment and do not typically reach the levels found in commanded enrichment. Commanded enrichment occurs at high throttle (*13*) to provide peak demand power and to protect engine components. It can also occur during idle to provide extra power for accessories such as an air conditioner. Enrichment can also occur if the throttle is opened rapidly; a burst of fuel is needed to prevent a momentary stall and ensure drivability. Closing the throttle quickly can also result in enrichment in some engine configurations. Recent analyses have shown that rapid changes in throttle of relatively small magnitude can result in enrichment in some engine management systems.

Figure 2 gives a composite of the speed-acceleration profiles for all vehicles that were analyzed in the study. The three peaks correspond to idle, arterial driving, and highway driving. Severe enrichment events comprise only 15.7 percent of all enrichment events, but result in 58.4 percent of all estimated CO because of enrichment in this data set. Because mild enrichment events tend to occur in less well defined regions of operation and have less of an impact compared with severe enrichment events, the remainder of this analysis will concentrate on severe enrichment events. Severe enrichment events are plotted by using the same technique in Figures 3(*a*) and 3(*b*). The current federal test procedure (FTP) cycle contains no accelerations greater than 1.48 $m/s^2$ (3.3 mph/sec) and no speeds higher than 91.7 km/hr (57 mph). Much of the severe enrichment seen in the present study lies outside the bounds of the FTP cycle, and the further outside these bounds an event occurs the more likely it is to have extremely high pollutant throughput. During normal stoichiometric operation, the median sample from this data set is estimated to have a CO throughput of approximately 0.05 g/sec. Severe enrichment events at high speeds and high accelerations can easily range as high as 8 g/sec, with peak values in some of the larger-engine vehicles exceeding 15 g/sec.

It is also of interest to examine these events by duration. One-sec-duration events tend to occur at lower speeds or accelerations. It is likely that many of these events are in response to rapid changes in throttle position or are idle correction events. These events comprise 42.3 percent of all severe enrichment events, but account for only 14.8 percent of total severe enrichment CO emissions. Events from 2 to 5 sec duration show the effects of high speeds and accelerations much more strongly and account for 47.2 percent of the total number of events and 36.2 percent of total severe enrichment CO emissions. Events of 6 to 10 sec duration tend to occur at higher mass air flows and are relatively few in number (7.7 percent), but account for 20.8 percent of total severe enrichment CO emissions. Long-duration events (>10 sec) are rare

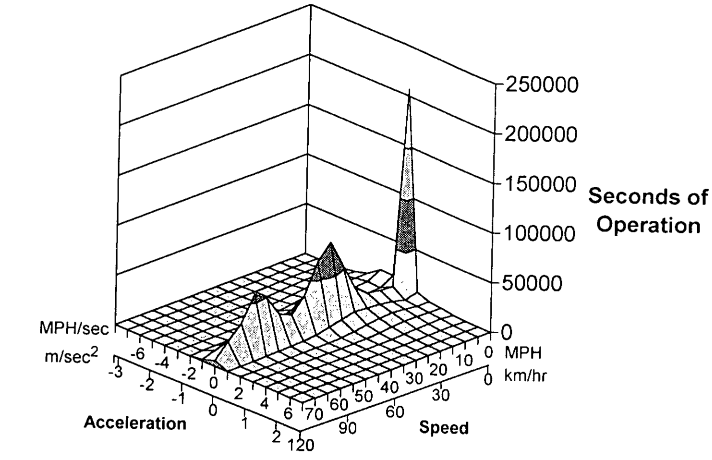


**FIGURE 2 Driving mode distribution for all instrumented vehicles in Spokane and Baltimore (LV8 vehicles included).**

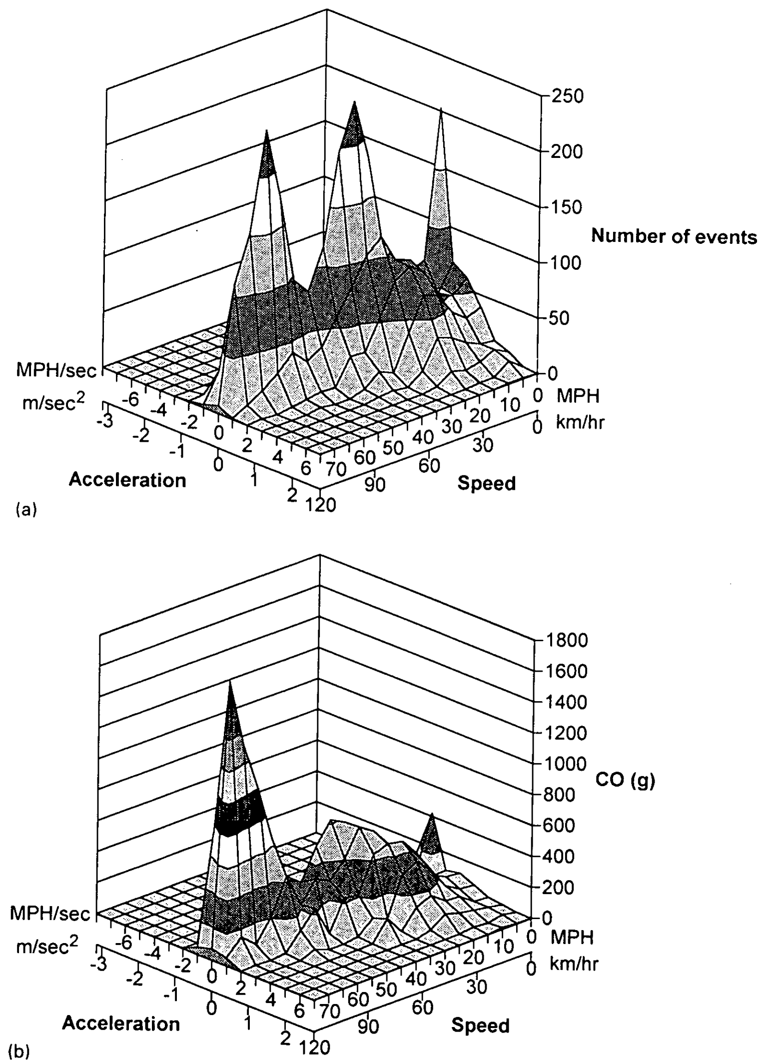


**FIGURE 3 Distribution of severe enrichment events by (*a*) number and (*b*) total CO emissions.**

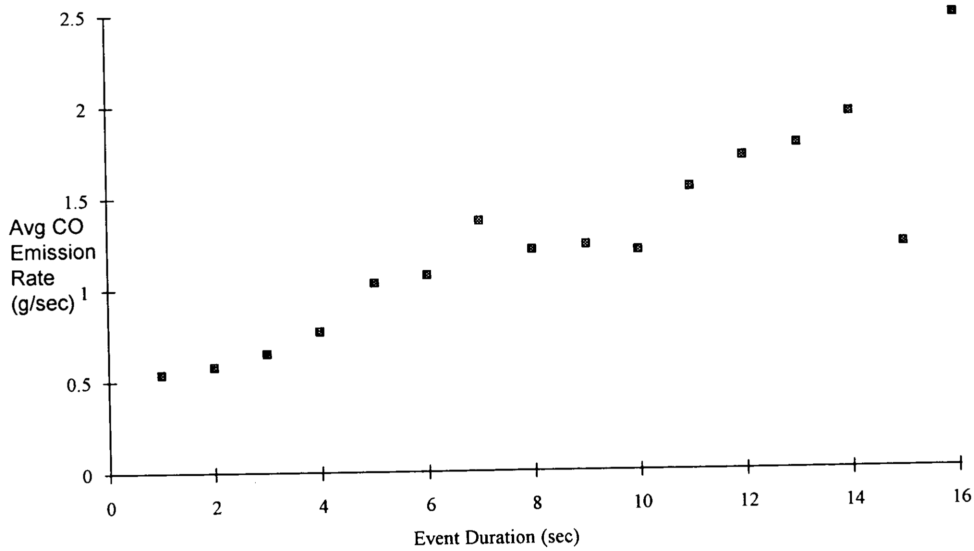


**FIGURE 4 Average CO emissions rate versus event duration for data when more than 10 events were recorded.**

(2.8 percent of all severe events), but tend to occur at very high speeds (≥112.7 km/hr or 70 mph) or at very high accelerations and account for 28.2 percent of all total severe enrichment CO emissions. A plot of average event intensity (Figure 4) shows that average CO throughput during each event increases rapidly as duration increases. A comparison of cumulative percent total severe enrichment CO emissions and cumulative number of events (Figure 5) shows that a control strategy based on a delay would decrease commanded enrichment CO emissions substantially. For example Figure 5 shows that just over 70 percent of total CO due to severe enrichment is created by events of less than 10 sec duration. A 10-sec delay would reduce emissions by much more than 70 percent since an 11-sec event would then become a 1-sec event. Some of these events may not have been commanded, so changes in control strategy would not achieve all of the reductions indicated.

The overall effects of severe enrichment are shown in Figure 6. Although most vehicles spend less than 2 percent of total driving time in severe enrichment, this can account for up to 40 percent of total CO emissions. Furthermore the few vehicles operated in severe enrichment a high percentage of the time (2 to 7 percent) contribute disproportionately to the total CO emissions of the fleet. A typical vehicle-driver combination will produce between 0.05 and 0.10 g of CO per sec overall, whereas the most aggressive drivers in this sample produced as much as 0.25 g of CO per sec. Some vehicles emitted as little as 0.2 g/sec, and a new vehicle

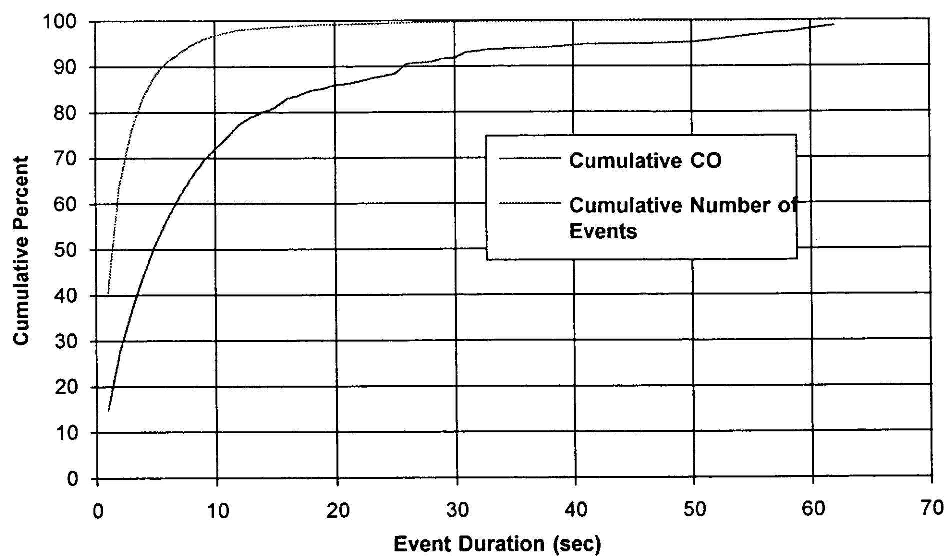


**FIGURE 5 Cumulative CO and number of events versus event duration.**

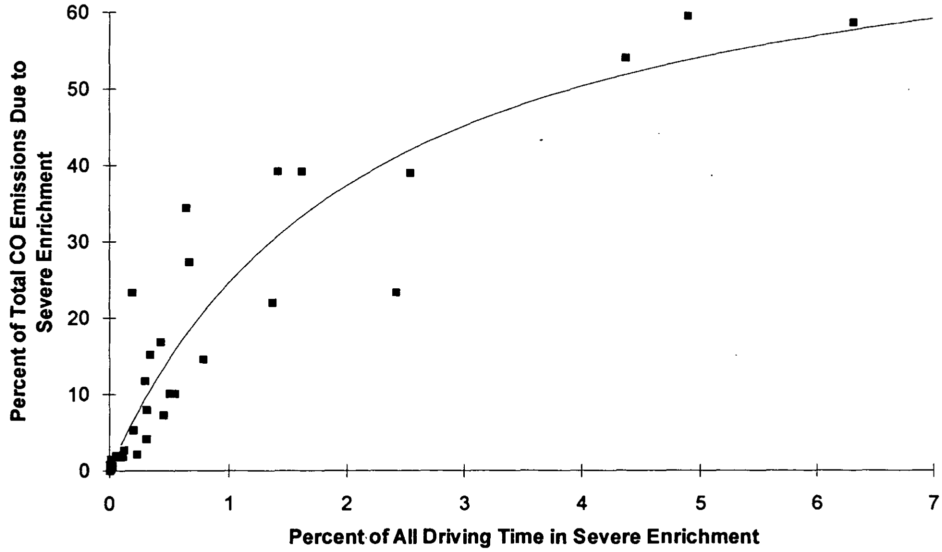


**FIGURE 6 Contribution of severe enrichment to total CO emissions by vehicle.**

with state-of-the-art engine management can be significantly cleaner. It is well documented that elevated HC emissions occur when CO emissions are elevated (*14,15*). However it has been estimated that although CO emissions during an enrichment event can be elevated by more than three orders of magnitude compared with stoichiometric emissions, HC emissions increase by a factor of 40 (*16*).

It is also of interest to analyze total CO emissions (enrichment and nonenrichment) by driving regime. Driving within the FTP cycle typically accounted for a smaller proportion of emissions than the proportion of all driving activity in that regime, suggesting that any estimate of warm engine running emissions based only on the FTP cycle would underestimate total emissions by a significant factor. The driving modes outside of the FTP cycle were divided into three zones: (a) accelerations higher than are present on the FTP, but speeds of less than 91.7 km/hr (57 mph), (b) decelerations outside the FTP at speeds of less than 91.7 km/hr (57 mph), and (c) all accelerations and decelerations at speeds greater than 91.7 km/hr (57 mph). High-speed driving outside the FTP cycle (>91.7 km/hr, or 57 mph) accounted for 28 percent of all CO produced by enrichment (mild and severe) and 15 percent of all enrichment events; however, the fraction of total CO versus total time spent in this region is only slightly elevated. Many drivers spend a significant amount of time in this region, resulting in slightly higher CO emission rates at significantly high mass air flows. When high-acceleration non-FTP driving at less than 91.7 km/hr (57 mph) is plotted comparing time spent in this driving mode with proportion of total CO produced (Figure 7), it is clear that driving in this region accounts for a disproportionate amount of the total CO emissions. On average the CO emission rate within the bounds of FTP cycle is 88 percent of the overall emission rate, at high speeds (>91.7 km/hr or 57 mph) it is 115 percent of the overall emission rate, and at high accelerations outside the FTP cycle it is 377 percent of the overall emission rate. The calculated emission rates found for these vehicles within the bounds of the FTP cycle may differ significantly from the emission rates obtained in an actual FTP test.

## CONCLUSIONS AND POLICY IMPLICATIONS

As noted earlier in this paper several researchers have concluded that existing mobile source emissions models do not adequately estimate emissions as they occur in real-world driving. This paper has presented one of the earlier vehicle data bases that has been available for analysis. In particular this data base has been analyzed from the perspective of one possible cause of emissions underestimation: emissions due to power enrichment.

As shown in this data base severe enrichment events occur under speed-acceleration conditions typical of urban driving. Although severe enrichment conditions represented only a small fraction of overall driving, they contributed substantially to pollutant throughput. Important for public policy, some of the vehicle speed-acceleration regimes in which this enrichment occurred were outside of the speed-acceleration combinations found in FTP. A broader FTP cycle could potentially reduce these emissions significantly because the manufacturers would have to design vehicles to be tightly controlled over a more representative range of conditions. Some vehicles have already been designed so that severe enrichment does not occur except under very extreme conditions. To control for the severe enrichment conditions, which might very well be included in an updated FTP cycle or cycles, other vehicle manufacturers might do likewise. Innovative engine control strategies that use more sophisticated techniques such as "drive by wire" could also have a strong positive effect.

The analysis of the data base raises many important questions regarding the way that mobile source emissions are currently estimated. Many of these questions are the subject of further research, some of which is under way. Some of the more important issues that surface from this analysis include the following:

1. The contribution of severe enrichment emissions to the overall level of vehicle trip emissions could be very significant, given the right combination of conditions that add load to the vehicle engine. The most important parameters identified in this paper were speed and acceleration. However heavy engine loads can be

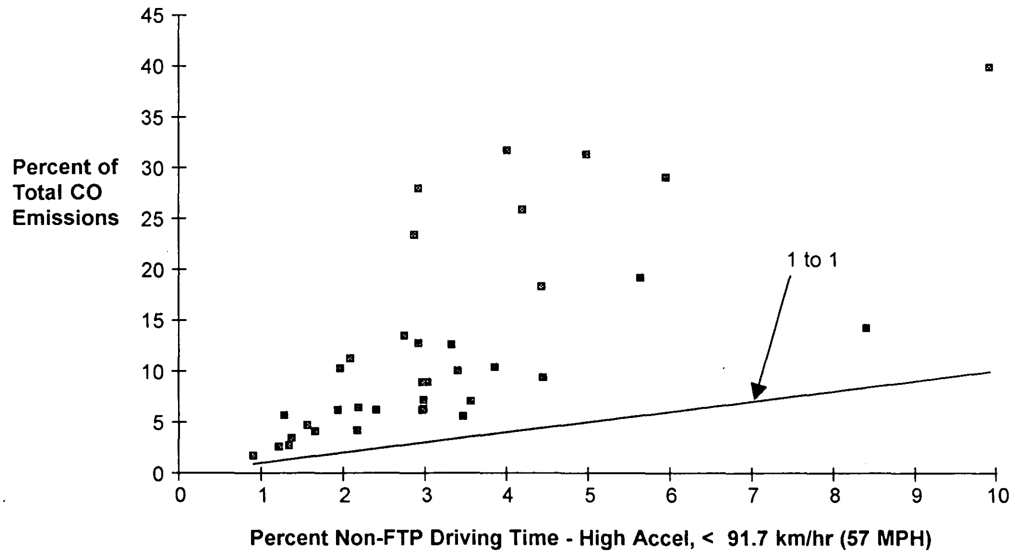


**FIGURE 7 Comparison of time spent at higher accelerations than are present on FTP and <91.7 km/hr (57 mph) to proportion of total CO produced in this driving mode.**

caused by engine power requirements because the vehicle is carrying a heavy weight (e.g., trailers or boat carriers in recreational areas) or vehicles with low power-to-weight ratio are traversing long, steep grades. Engine load because of an air conditioner can contribute to a higher incidence of enrichment, particularly at idle. The six-parameter data base does not include location or road characteristics when enrichment occurred. In fact low-speed or low-acceleration enrichment could be occurring (in the data base) on steep hills. There is no way of knowing what network or driver characteristics caused enrichment to occur. Therefore a significant need exists to better identify the elements of the transportation network that result in high-probability occurrences of severe enrichments (e.g., steep hills, intersections, and ramps where high levels of acceleration might occur or recreational sites with high numbers of vehicles towing trailers). These elements could very well become important activity factors that better define the contribution of enrichment emissions to the overall mobile source emissions inventory.

2. The emissions impact of some of the transportation management strategies adopted in many urban areas could very well be more severe than originally expected. For example some of the preliminary results of research conducted at Georgia Tech suggest that ramp merge areas are likely to show the highest incidence of severe enrichment events in a typical freeway network. In this case the contributing factors are primarily the heavy acceleration rates that are often used by drivers to merge with traffic flow. Efforts to provide an easier merge with such traffic flow, such as ramp meters, could very well cause the types of acceleration rates that lead to enriched conditions. Alternatively efforts under way to apply intelligent vehicle-highway system technologies to traffic systems whose primary intent is to smooth the flow of traffic (that is, reduce the likelihood of stop-and-go traffic) might very well have an important emissions benefit. As additional research is conducted on the types of vehicle behavior that seem most important for emissions, this research should be used in a broader context to better evaluate the likely impacts of the transportation control measures and other transportation management measures that are being proposed and implemented across the country.

3. The occurrence of enrichment at lower speeds and relatively lower acceleration rates raises serious questions about the current methodology for assessing emissions impacts at intersections. Current intersection models do not explicitly take into account the types of enrichment emissions that are shown to occur in this data base. Yet it is at intersections that one might see exactly the type of speed-acceleration combinations that could lead to enrichment emissions. The results of this research and of other projects using second-by-second emissions data should be used in assessing the overall validity of intersection-level emissions modeling.

4. An interesting observation that surfaced from this data base is that a small segment of the population tends to drive very aggressively and contribute an inordinate amount of the overall pollutants. The driver in the present study with the highest average CO emissions rate had approximately three times the median rate of CO emissions. An analysis of a broader data base to determine what portion of the population drives aggressively, and correlated with what types of vehicles they typically drive, should shed more light on this. Preliminary analysis of a larger data base shows significant differences in the driving habits present in Atlanta, Baltimore, and Spokane. Road network topology and climate may have an effect on the incidence of aggressive driving.

Most important, the results of this research indicate the value of second-by-second vehicle emissions and engine behavior data for better understanding the underlying phenomena that cause high levels of vehicle emissions. Only by undertaking such research efforts will investigators be able to better model the cause-and-effect relationships that determine overall levels of mobile source emissions.

## ACKNOWLEDGMENTS

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# Framework for Evaluating Transportation Control Measures: Mobility, Air Quality, and Energy Consumption Trade-Offs

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The successful implementation of a transportation control measure (TCM) and, in particular, appropriate combinations of measures may provide significant benefits to urban areas in the form of congestion reduction, improvements in air quality, and fuel savings. The effectiveness of TCMs in accomplishing these goals will most often be determined by the specific characteristics of the urban environment in which they are implemented. A macroanalysis model—a unified framework that links the transportation planning and air quality analysis models—is developed. The framework can then be used to evaluate the impact of a TCM on mobility, transportation-related emissions, and energy consumption. The results from two sample networks show that the effectiveness of a TCM depends on the characteristics of the networks. The evaluated TCMs are limited to those that affect travel time or travel costs.

Transportation planners, engineers, and air quality planners are increasingly understanding the need for coordinated efforts in providing efficient and effective transportation systems while addressing serious environmental concerns. Policy makers in the present and, particularly, those in the near future must issue policies based on broad, coordinated efforts in transportation, air quality, and energy consumption so that optimal strategies for all three components may be implemented. At present, however, transportation planning and air quality analysis models are incompatible. Emission models require detailed inputs that are not generally provided by transportation planning and analysis tools. Traditionally a set of socioeconomic variables, such as a forecast population, automobile ownership, employment, and land use, are inputs of the transportation planning model that in general comprised four steps: trip generation, trip distribution, mode choice, and network assignment. This planning process does not adequately account for the manner in which individuals make travel decisions. The only travel-related decision that can be predicted by this traditional planning method is the mode of travel, whereas transportation control measures (TCMs) affect trip generation, trip distribution, as well as route and mode choice.

Traffic flow improvement, an intended product of TCMs, may cause changes in travel patterns, for example, travel time and route changes. The traffic flow measurements given by equilibration procedures in the network assignment step are limited in estimating emissions. First, they are average values whereas the emissions estimation models usually require different values of speed, acceleration, and deceleration for different classes of vehicle. Likewise, for fuel consumption estimation, the values of speed, stop time, and number of stops are essential but are not provided by the equilibration procedures. Second, it is very difficult to include all dimensions of travel demand, and the ones that consider frequency, destination, or mode choice in addition to route choice require the use of aggregate demand models, which do not adequately capture travel behavior. Finally, the equilibration models may make large errors in estimating traffic volumes and speeds on network links. Horowitz pointed out that a 30 percent error is not unusual (*1*).

Traffic simulation models that are generally used in optimizing traffic signals and predicting delays can be used to simulate TCMs for some roadway links in a network. Most traffic simulation models track vehicle positions as they move in the network and produce information such as average speed and stop time on a link, which can be used in emissions models. However, they require traffic volume as input, except a few models that are demand responsive and thus are unable to forecast changes in traffic volume caused by a TCM.

A key in the estimation of air pollution is the conversion of traffic data into an account of pollutants. This is accomplished through the use of an emissions factor model such as the Environmental Protection Agency's (EPA's) MOBILE model. The model requires detailed inputs, which often do not correspond to what is commonly available from transportation models, as stated previously. These include various speeds and vehicle miles of travel (VMT) for different classes of vehicle, vehicle type, age of vehicle, accumulated miles of vehicle travel, maintenance program, analysis year, fuel volatility, daily ambient temperature, altitude, and humidity.

These variables, required for emissions estimations, have not been a component of transportation planning models. A methodology for combining transportation planning and analysis models with emissions factor models for predicting the effectiveness of various TCMs is needed. A matrix of strategies that produces the greatest savings in air emissions and energy consumption can then be developed. This paper presents a conceptual framework for bridging transportation planning and air quality analysis models. The framework can then be used to evaluate, comparatively, the impacts of various transportation control measures that influence

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either travel time or travel cost on transportation-related emissions and energy consumption. Two sample analyses are presented in this paper to demonstrate application of the macroframework.

## FRAMEWORK

The framework, given in Figure 1, consists of five models as well as cost-benefit analysis:

1. *Mode choice model.* This model is used to predict individual decision probabilities of mode, destination, and route for various TCMs. The model should encompass all possible modes affected by TCMs. These modes include nonmotorized, drive-alone, carpool, or transit or even whether the individuals choose not to travel, as a result of telecommuting for instance.
2. *Traffic simulation model.* A traffic simulation model can be used to study effects of traffic management strategies on the system's operational performance. This performance is generally expressed in effectiveness measures such as VMT, average vehicle speeds, vehicle stops, and average and maximum queue lengths. These parameters are important in the estimation of pollutants.
3. *Emissions estimation model.* This model takes into account the factors affecting emissions, such as speed, VMT, vehicle classes, and modes of operation.
4. *Fuel consumption model.* This model estimates the fuel consumption changes as a result of TCM implementation.
5. *Dispersion model.* This model is used to estimate emissions concentration as a function of atmospheric conditions, for example, winds, temperature, and altitude.

### Choice Models

The specific TCMs identified in the Clean Air Act Amendments of 1990 (CAAA) are shown in Table 1. The TCMs influence travel decisions primarily in the short term through frequency, route, and mode of travel, but they may have some long-term effects, on workplace location for example. TCMs also encompass decisions of whether an individual chooses to travel, travel to different

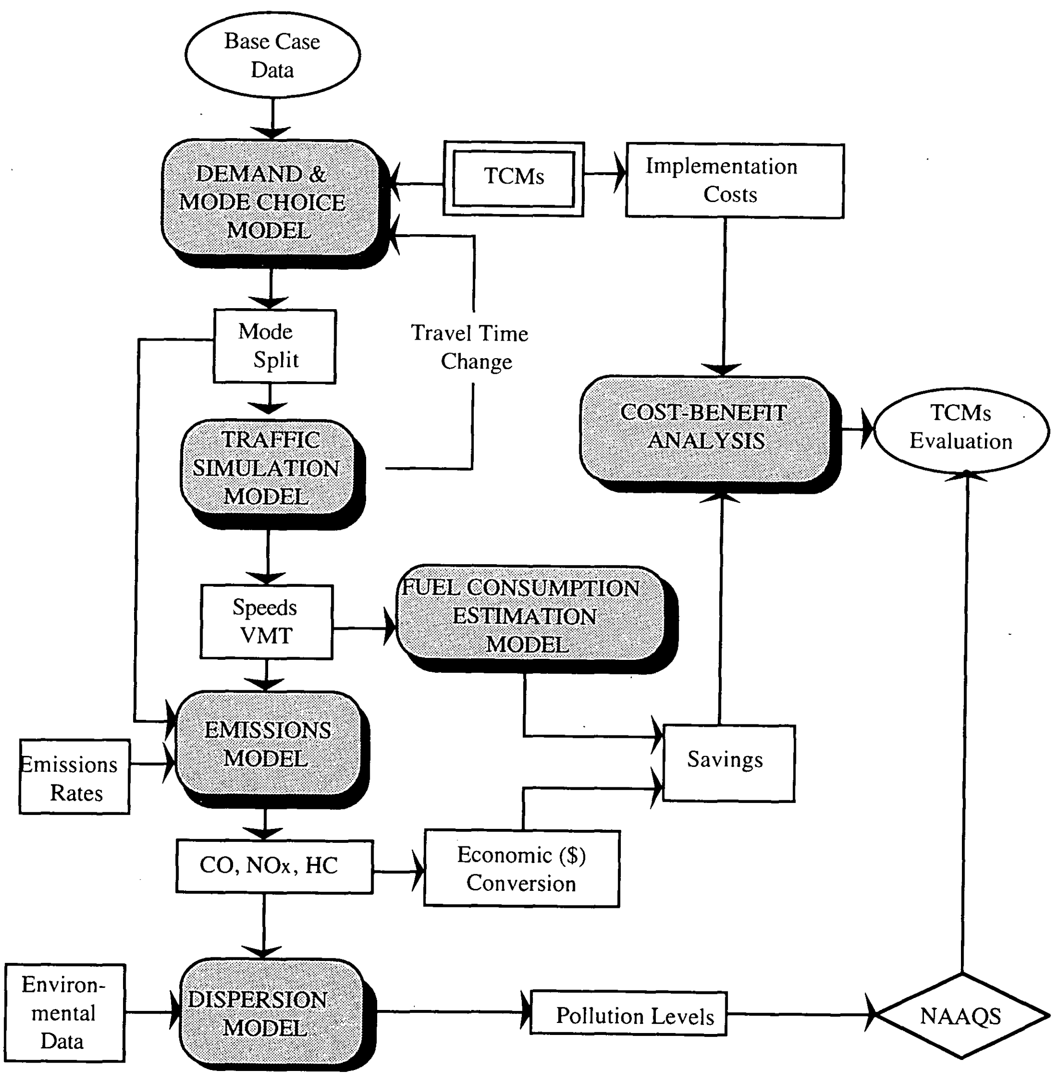


**FIGURE 1 Model framework for evaluating TCMs.**

**TABLE 1 Available Transportation Control Measures**

| | |
|---|---|
| • Improve Public Transit | • High Occupancy Vehicle Lanes |
| • Employer-Based Transportation Program | • Trip Reduction Ordinances |
| • Traffic Flow Improvements | • Park-and-Ride/Fringe Parking |
| • Limit Vehicle Use in Downtown Areas | • Area-wide Ride-sharing Incentives |
| • Bicycle and Pedestrian Facilities | • Control of Extended Vehicle Idling |
| • Reduce Extreme Cold Start Emissions | • Flexible Work Schedules |
| • Programs for Large Activity Centers and Special Events | • Voluntary Removal of Pre-1980 Vehicles |

workplace locations according to different schedules, or telecommute. The influence of TCMs on travel decisions can be explained by discrete choice models, which are flexible enough to accommodate long-, medium-, and short-term decisions.

As discussed earlier the traditional four-stage transportation planning sequence does not account for the manner in which individuals make travel decisions, particularly those in the long- and medium-term time range. As an alternative discrete choice models may be used. Figure 2 gives a broad range of behavioral decision making that may influence the traveler's decision in the long-, medium-, or short-term time range. A transportation system based on this structure was initially developed by Ben-Akiva and Atherton (*2*) to analyze potential energy conservation policies. Emissions estimated for various TCMs are merely an extended application of this model. The impacts of TCMs on air pollution should be assessed for a range of travel decisions. Use of this approach accounts for travel decisions in the long, medium, and short terms. Although this approach is more applicable than the traditional four-stage planning models, its outputs are still not sufficient in meeting the data requirements of emissions factor models that require vehicle type for work and nonwork trips and engine type (gasoline, diesel, or other fuel).

Moreover the model structure should be adaptable to inclusion of new modes into the urban transportation system. For instance if light rail is an option, the model should yield an accurate share of light rail's ridership to investigate the effectiveness of this transit investment. The model should also be able to forecast individual behavior when telecommuting, using compressed work weeks, or operating according to flexible work hours.

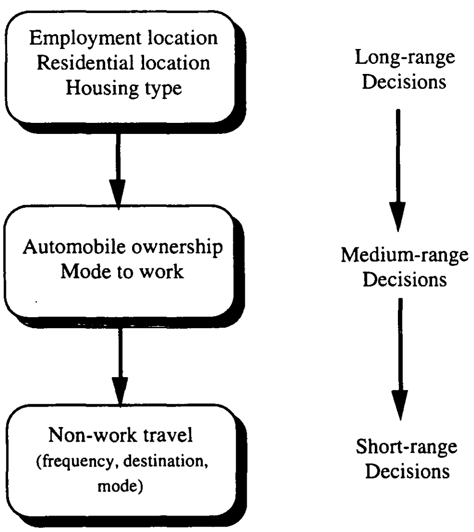


**FIGURE 2 Choice hierarchy (*2*).**

Significant variables in the mode choice model generally are transportation level of service and socioeconomic variables. The transportation level of service variables are travel time (disaggregated to in-vehicle time and out-of-vehicle time) and travel cost. The socioeconomic variables are income, workplace, mode availability, and employment density. Effects of a TCM enter the choice model as shown in Figure 1, changing values of the utility function variables. Some effects are given in Table 2. When route choice is predicted route length can be determined. Then one may assume for example that home-to-work trips are cold start. If the route is longer than 505 sec (the current EPA assumption) or 3.59 mi, the vehicle is in running mode. A fraction of shopping trips may be assumed to be cold start, with the remaining portion assumed to be hot start. This should result in a more accurate estimation of emissions.

## Traffic Simulation Models

Several traffic simulation models are available. TRANSYT-7F (*3*) is one model that can be calibrated to study the traffic flow effects of TCMs.

TRANSYT-7F is a macroscopic model that considers platoons of vehicles, instead of individual vehicles. Inputs to TRANSYT-7F include those that can be obtained from the choice model, such as traffic volume, resulting from a change in modes. Also included as inputs are saturation flows, signal parameters, existing cruise speed, and intersection geometry. TRANSYT-7F generates travel times, delays, and stops that can be linked to an emissions estimation model. Because TRANSYT-7F is a macroscopic model its outputs indicate average values, and therefore it cannot identify specific vehicle classes, yielding less accurate emissions estimates.

The TRAF-NETSIM (*4*) traffic simulation model can accommodate traffic controls and track the positions of vehicles as they move through the network, making it possible to estimate emissions along the links. Up to 16 vehicle classes can be specified in TRAF-NETSIM, with private automobiles, trucks, buses, and carpool vehicles as the default vehicles. However, TRAF-NETSIM requires traffic volumes as an input. This means that it is unable to forecast the changes in the volumes as traffic flow improvement measures are implemented. Several TCMs, particularly the ones affecting travel time, for example, high-occupancy-vehicle (HOV) facilities, traffic signal improvements, and improved public transit, are likely to cause a change in travel time since they affect the individual choice and thus traffic volumes. This requires a number

**TABLE 2 Effects of TCMs on Utility Functions in Mode Choice Model**

| TCMs | Effects |
|---|---|
| Improved public transit | |
| • Increase service frequency | Reduce transit wait time |
| • Extend light rail system | Reduce transit travel time |
| • Add new bus route | Reduce transit access time |
| • Add light rail and bus stations | Reduce transit access time |
| • Decrease fares | Reduce travel costs |
| Park and ride and fringe parking | Reduce transit and auto in-vehicle times<br>Change out-of-vehicle times<br>Change travel costs |
| Traffic flow improvement | |
| • Build new freeway and arterial | May either reduce or increase travel time |
| • Increase parking rate | Increase auto cost |
| • Increase gasoline price | Increase auto cost |
| • Build HOV lanes | Reduce ride-share and bus in-vehicle time |
| • Expand ramp metering with HOV bypass lane | Reduce ride-share and transit travel time |
| • Install bus-actuated traffic signals | Reduce transit travel time |
| Work schedule changes | |
| • Flextime | Reduce travel time |
| • Telecommuting | Affects trip decisions |
| Vehicle use limitations/restrictions | |
| • Auto-free zone | Increase travel time |

of iterations to converge the average travel time value in the traffic simulation model to the value in the choice model.

NETSIM can be used to evaluate the impacts of various congestion mitigation strategies on energy consumption and air pollution. The fuel consumption and emissions calculations are based on vehicle speeds, acceleration, and deceleration. Unfortunately NETSIM measures only automotive emissions; therefore, the emissions analysis is not conclusive. Moreover NETSIM emission factors are based on earlier automobile models and it does not take into account elevation, temperature, vehicle age, and so on, as do other emissions models.

## Emissions Models

A key in estimating air pollution is the conversion of VMT, vehicle speeds, and vehicle types into amount of pollutants. This is accomplished through the use of emissions factor models such as California Air Resources Board (CARB) EMFAC7E model or EPA's MOBILE model. MOBILE accounts for many variables that affect the production of emissions by motor vehicles. Important inputs for use in MOBILE include fuel volatility, daily ambient temperature, altitude, humidity, vehicle type, age of the vehicle, accumulated miles of vehicle travel, average vehicle speed, inspection and maintenance, VMT split, and analysis year.

In estimating emissions two model types are used for different applications. The microscale models determine a vehicle's instantaneous exhaust hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide ($NO_x$) emissions per unit of time as a function of speed and acceleration, whereas the macroscale models determine total vehicle emissions or average emissions per unit of distance traveled, including trip end emissions, during an entire trip or part of a trip. In relation to the framework, both micro- and macroscale models can be used with the traffic simulation model. For example in a large urban network originating and terminating trips, such as the sink/source nodes available in TRAF-NETSIM, may be used to represent the points where trips start or end. With a known number of trips and hot soak and start-up emissions factors for vehicle type, model year, and age (or the weighted average over the model years of vehicles in the area of concern), macroscale emissions can be estimated. When only trip segments are of interest, hot soak and start-up emissions may be disregarded, thus giving microscale emissions.

## Fuel Consumption Models

Fuel consumption can be estimated by the modal choice model with additional computations or by some traffic simulation models, for examples, TRAF-NETSIM and TRANSYT-7F. The latter approach has some limitations. For example in TRANSYT-7F a stepwise multiple regression is used, with the model parameters derived from a study of one test vehicle and the model coefficients adjusted to represent an "average" vehicle. In the cities in which the fuel consumption models have been calibrated to account for specific conditions such as grade, roadway geometry, mix of vehicles, and so on, the outputs from the traffic simulation can be used in that local fuel consumption model. Variables normally significant for fuel consumption estimation are travel time, stops, and stop times, which are generally provided by a traffic simulation model.

## Dispersion Models

Volatile organic compound outputs from emissions factor models are one of the inputs for a dispersion model. Dispersion or dif-

fusion models are quantitative models used for determining the relationship between emissions and atmospheric concentrations of air pollutants. The pollutants, once emitted, are dispersed by winds and may chemically react to form new compounds. An example is the ozone produced by the photochemical reaction of HCs and $NO_x$. EPA-approved models for the estimation of ozone levels are Empirical Kinetics Modeling Approach or the Urban Airshed Model. Emissions, temperature, winds, water vapor, initial concentrations, and the modeling period are model inputs. The models yield ozone concentrations that are compared with National Ambient Air Quality Standards.

### Cost-Benefit Analysis

Finally the effectiveness of TCMs should be measured economically through benefit-cost or cost minimization analysis. The costs should include traditional expenses for new facilities or improvements, that is, HOV lanes, improved transit operations, traffic signal improvements, and so on, but should also include vehicle operating, delay, accident, and environmental costs. Small (*5*) developed a method for estimating the air pollution costs of transport modes by quantifying health and material damage. With some assumptions he arrived at the costs of different modes as shown in Table 3. These costs are based on 1974 economic conditions and technologies. More recently CARB has developed production costs per ton of pollutants for stationary source control measures in California. These going rates are given in Table 4. New estimates for pollution costs are needed for a more robust analysis. Finally some expected costs and benefits to urban transportation systems for different TCMs are given in Table 5.

## SAMPLE ANALYSIS

Application of the framework is demonstrated through two examples. Two networks are created to evaluate a few strategies, namely implementation of HOV lane or increased automobile operating cost, for reducing congestion. For simplicity and illustrative comparison purposes, the sample networks are linear corridors. Evaluation of TCMs for considerably larger or more complex networks can be done by using the same procedures, provided computational time and cost as well as computer capacity are adequate. This was an inherent limitation of the present

**TABLE 3 Air Pollution Emissions and Costs (*5*)**

| Vehicle Type | Emissions[a] (grams/km) | | | | | | 1974 Cost[b] |
|---|---|---|---|---|---|---|---|
| | CO | HC[c] | HC[d] | NOx | SOx | PM | ¢/km |
| **Automobiles** | | | | | | | |
| Pre-1961 Model (in year 1974) | 59.0 | 5.5 | 4.1 | 2.1 | 0.08 | 0.34 | 0.22 |
| 1969 Model (in year 1974) | 42.3 | 3.1 | 1.6 | 3.2 | 0.08 | 0.34 | 0.21 |
| 1974 Model (new) | 23.0 | 2.0 | 1.1 | 1.9 | 0.08 | 0.16 | 0.12 |
| 1974 Model (5 years old) | 29.2 | 2.9 | 1.1 | 2.5 | 0.08 | 0.16 | 0.16 |
| 1974 Composite[e] | 37.3 | 3.5 | 1.5 | 2.4 | 0.08 | 0.29 | 0.17 |
| Post-1977 Model[f] (new) | 1.7 | 0.2 | 1.1 | 0.1 | 0.08 | 0.16 | 0.02 |
| Post-1977 Model (5 years old) | 2.6 | 0.3 | 1.1 | 0.5 | 0.08 | 0.16 | 0.04 |
| 1995 Composite[g] | 2.4 | 0.03 | 1.1 | 0.4 | 0.08 | 0.16 | 0.04 |
| **Diesel Bus or Truck** | | | | | | | |
| Pre-1973 Model | 13.2 | 2.5 | -- | 13.4 | 1.7 | 0.81 | 0.60 |

[a] Emissions assume low altitudes and urban arterial driving at average speed of 30.6 km per hour.
[b] Costs are inflated or deflated by current-dollar gross national product per capita.
[c] Exhaust emissions.
[d] Crankcase and evaporative emissions.
[e] Exhaust emissions from 1974 and earlier models are weighted by the aggregate mileage driven on each model in 1974.
[f] Assuming enforcement of the last reductions called for in the 1970 Clean Air Act Amendments, originally scheduled for 1975 models and subsequently postponed to 1978 models.
[g] Composite exhaust emissions are calculated on the assumption of a steady-state population of post-1977 model cars, with age distribution and estimated deterioration from the U.S. Environmental Protection Agency.

**TABLE 4 CARB Pollutant "Going Rates" in 1990 (6)**

| Pollutant | Average Rate (per metric ton) | Highest Rate (per metric ton) |
|---|---|---|
| HC | \$3,629 - \$9,073 | \$19,960 |
| CO | \$181 | \$1,815 |
| $NO_X$ | \$1,815 - \$9,073 | \$21,774 |

study and the reason for the simple sample networks. Therefore in these illustrative sample analyses, only microscale emissions estimations are considered.

The choice or "split" among several transportation modes depends on both the socioeconomic characteristics of the decision makers and the transportation alternatives available to them. The mode choice model used in both networks is a multinomial logit model developed by Ben-Akiva and Lerman (7). It is assumed that the traveler has the ability to compare all possible alternatives—in this case, car, carpool, and bus—and make the short-range decisions to select the one with the highest utility, which is viewed as the index of his or her socioeconomic attributes. To predict changes in mode split for either the HOV lane or the increased auto operating cost, one can use the choice probabilities in the base case (without TCMs) and the change in utility due only to the affected variable, travel time, or operating cost. The probability of traveler $n$ choosing any alternative $i$ after the implementation of either of the above two TCMs can be expressed as

$$P'_n(i) = \frac{P_n(i)e^{\Delta V_{in}}}{\sum_{j=1}^{3} P_n(j)e^{\Delta V_{jn}}}$$

where $P_n(j)$ is the choice probability in the base case; $j$ equals 1 if automobile is selected, $j$ equals 2 if carpool is the alternative, and $j$ equals 3 if bus is chosen. $DV_{jn}$ is the change of individual utility, which is formulated as

$$\Delta V_{jn} = \beta_1 \times \text{changes in travel time} + \beta_2 \times \frac{\text{changes in operating cost}}{\text{household income}}$$

The values of $\beta_1$ and $\beta_2$ are obtained from a survey. They are assumed as $\beta_1$ equal to $-0.0307$ and $\beta_2$ equal to $-28.7$ in the examples. Similarly \$28,000 is assumed as the average annual household income.

## Network A

In Network A a highly congested urban street is created. The characteristics of the network and the street geometry are shown in Figure 3. All intersections are signalized. Turning volume is prescribed and constant for all cases. A total of 3,520 people are assumed to travel from Node 48 to Node 1 during peak hour. The

**TABLE 5 Some Costs and Benefits Related to TCM Implementation and Air Pollution**

| Costs | Benefits |
|---|---|
| *Improved public transit* | |
| • Operation | • Fuel consumption reduction |
| • Additional initial investment | • Emissions reduction |
| *Traffic flow improvement* | |
| • Construction (HOV lanes) | • Fuel consumption reduction for some users |
| • Operation and enforcement | • Travel time savings for some users |
| *Work schedule changes* | |
| • Construction and operation of work satellite centers for telecommuting | • Fuel consumption reduction |
| • Building energy consumption | • Emissions reduction |
| • Telecommunication and computer use | • Office space savings and reduced parking requirements |
| • Congestion near satellite centers | |
| *Park and ride and fringe parking* | |
| • Facility construction | • Fuel consumption reduction for some users |
| • Traffic congestion near facilities | • Emissions reduction in CBD |
| • Emissions near facilities | |
| *Road pricing* | |
| • Travel costs for users | • Fuel consumption reduction system-wide |
| | • Emissions reduction |
| *Alternative engines and fuels* | |
| • Conversion of engines | • Emissions reduction |
| • Facilities for re-fueling stations | |

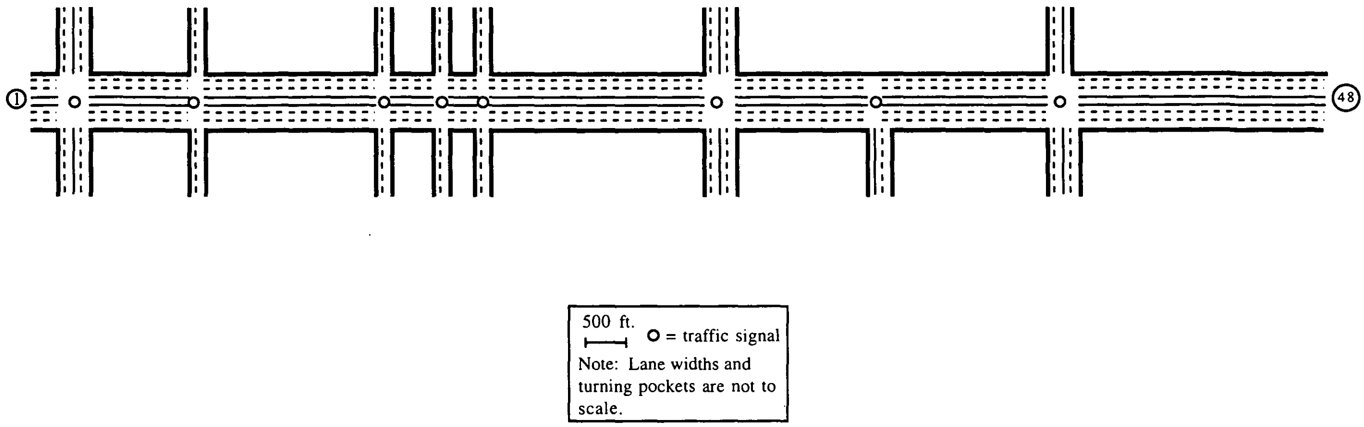


**FIGURE 3 Sample Network A.**

analysis is performed for the peak period, and the choice of time of day is not under consideration. Traffic volumes entering this network are assumed to be the same for all cases except that entering Node 48, which varied according to the modal splits obtained for different cases. Bus service is provided along the main street.

Six different scenarios are examined for Network A. For each case several iterations are required so that the travel time used in the utility function of the mode choice model is, within a specified tolerance level, equal to that obtained from TRAF-NETSIM. These cases are as follows:

1. *Base case.* The network geometry, traffic movements, and entering volumes were described above. The person-miles-of-travel (PMT), average speeds, and fuel consumption from TRAF-NETSIM are given in Table 6.
2. *HOV-4.* The traffic engineering data and basic geometry are the same as those in the base case except that the right lane along the main street is reserved for four-person carpools and buses.
3. *HOV-3.* Same as HOV-4 except that a three-person instead of a four-person carpool is used.
4. *Bus lane.* This case is the same as Scenarios 2 and 3, but only buses are allowed on the HOV lane.
5. *No left turn.* Left turns are not permitted along the main street in either direction.
6. *Pricing.* Operating costs for automobile and carpool are increased by 25 and 10 percent, respectively. Bus prices remain the same.

The center lane in Network A is assumed to be a reversible lane for inbound and outbound traffic for morning and afternoon peak periods. Automobile occupancy is assumed to be 1.3; carpool occupancy is 3 for all scenarios except Scenario 2, which is 4;

**TABLE 6 Mobility and Fuel Consumption Results for Network A**

| | Base | HOV-4 | HOV-3 | Bus Lane | No Left | Pricing |
|---|---|---|---|---|---|---|
| PMT in 15 Minutes | | | | | | |
| Auto | 1,157 | 1,541 | 1,575 | 1,129 | 1,206 | 1,114 |
| Carpool | 548 | 872 | 860 | 535 | 561 | 587 |
| Bus | 313 | 536 | 529 | 555 | 290 | 317 |
| Total | 2,018 | 2,949 | 2,964 | 2,219 | 2,057 | 2,018 |
| Average Speed (kmph) | | | | | | |
| Auto | 10.3 | 16.7 | 17.5 | 9.7 | 10.1 | 11.6 |
| Carpool | 10.3 | 26.9 | 25.6 | 9.7 | 10.1 | 11.6 |
| Bus | 9.8 | 26.9 | 25.6 | 26.2 | 8.5 | 10.0 |
| All Vehicles | 10.3 | 18.3 | 19.1 | 9.7 | 10.1 | 11.6 |
| Fuel Consumption (liters/person-km) | | | | | | |
| Auto | .1487 | .0932 | .0948 | .1294 | .1484 | .1484 |
| Carpool | .0306 | .0179 | .0223 | .0266 | .0303 | .0348 |
| Bus | .0108 | .0066 | .0066 | .0066 | .0111 | .0111 |
| All Vehicles (Avg.) | .0953 | .0548 | .0576 | .0741 | .0964 | .0936 |
| Mode Split (%) | | | | | | |
| Auto | 57.33 | 52.24 | 53.15 | 50.88 | 58.34 | 55.18 |
| Carpool | 27.16 | 29.58 | 29.01 | 24.11 | 27.14 | 29.11 |
| Bus | 15.51 | 18.18 | 17.84 | 25.01 | 14.02 | 15.71 |

bus occupancy is 50 for Scenarios 1, 5, and 6 and 70 for Scenarios 2, 3, and 4. The simulation time is limited to 15 min owing to the limitation of microcomputer memory.

In Scenarios 2 through 6 the speed changes in automobiles, carpools, and buses after implementation of a TCM cause the changes in the utility function and in turn yield the switch among the selection of drive-alone, carpool, and bus. The details of mode split and other traffic measurements at equilibrium are shown in Table 6.

Mobility can be evaluated subjectively by examining PMT in a unit time period or average speed. PMT is the same for all scenarios if a given level of demand is being analyzed. For example 10,560 PMT is the input value in Network A. Because of the difference in congestion levels in peak hour, however, the PMT in a unit time period (in this case, 15 min) may vary. The lower the congestion level the shorter the congestion period and in turn the larger the PMT in a unit time period during the congestion. The calculations in both networks are limited to the simulation period. All of the scenarios improve PMT during the 15-min simulation period over the base case except pricing, which remains the same. The variations in PMT in 15-min are due to the different congestion levels. The average speed improves for the HOV lane and pricing scenarios, but decreases for the bus lane and the no-left-turn scenarios. The nominal changes for the left turn outputs are primarily the result of the low percentage of left turns prescribed in the base case. From an energy standpoint all the scenarios except the no-left-turn option resulted in reduced fuel consumption. When accounting for the change in the modal split, there are some interesting results. All the scenarios except the no-left-turn option resulted in higher vehicle occupancies, that is, fewer automobile trips.

The speed and VMT outputs from NETSIM are the inputs for the emissions model. The vehicle emission results from MOBILE 4.1 are listed in Table 7. (A more recent MOBILE version is now available; however, at the time that the present analysis was conducted MOBILE 4.1 was the current version.) Compared with the results in the base case, only the implementation of the HOV lane (both HOV-3 and HOV-4) in this network resulted in effective air pollution reductions. All other strategies tested achieved minor improvements in air quality. This was because the demand largely exceeds the capacity in the network, which is reflected by the particularly slow speeds in Table 6. The inclusion of a HOV lane can improve the PMT on the HOV lane, whereas the vehicles in the other lanes of the network remain congested. This increases the denominator in calculating average emission results (on a per-person-per-mile basis) and in turn lowers average air pollution.

**TABLE 7 Emissions Results for Network A (gram/person-km)**

| | | | Base | HOV-4 | HOV-3 | Bus Lane | No Left | Pricing |
|---|---|---|---|---|---|---|---|---|
| **Auto** | | | | | | | | |
| | Running | | | | | | | |
| | | HC | 2.033 | 1.265 | 1.239 | 2.046 | 1.994 | 2.247 |
| | | CO | 19.028 | 10.943 | 10.655 | 19.262 | 18.718 | 21.030 |
| | | NOx | 0.622 | 0.518 | 0.526 | 0.597 | 0.602 | 0.687 |
| | Idle | | | | | | | |
| | | HC | 2.119 | 0.797 | 0.968 | 2.109 | 2.065 | 2.111 |
| | | CO | 20.311 | 7.638 | 9.280 | 20.216 | 19.797 | 20.233 |
| | | NOx | 0.273 | 0.103 | 0.125 | 0.272 | 0.267 | 0.273 |
| **Carpool** | | | | | | | | |
| | Running | | | | | | | |
| | | HC | 0.877 | 0.308 | 0.413 | 0.886 | 0.883 | 0.870 |
| | | CO | 8.201 | 2.456 | 3.316 | 8.337 | 8.281 | 8.146 |
| | | NOx | 0.268 | 0.167 | 0.218 | 0.259 | 0.267 | 0.266 |
| | Idle | | | | | | | |
| | | HC | 4.472 | 0.006 | 0.006 | 4.451 | 4.439 | 4.001 |
| | | CO | 42.873 | 0.053 | 0.058 | 42.663 | 42.556 | 38.354 |
| | | NOx | 0.578 | 0.001 | 0.001 | 0.575 | 0.574 | 0.517 |
| **Bus** | | | | | | | | |
| | Running | | | | | | | |
| | | HC | 0.056 | 0.074 | 0.076 | 0.075 | 0.058 | 0.056 |
| | | CO | 0.360 | 0.378 | 0.396 | 0.387 | 0.383 | 0.360 |
| | | NOx | 0.270 | 0.412 | 0.420 | 0.416 | 0.278 | 0.270 |
| | Idle | | | | | | | |
| | | HC | 0.026 | 0.017 | 0.018 | 0.017 | 0.031 | 0.026 |
| | | CO | 0.077 | 0.050 | 0.054 | 0.052 | 0.093 | 0.076 |
| | | NOx | 0.031 | 0.021 | 0.022 | 0.021 | 0.037 | 0.031 |
| **Weighted Average** | | | | | | | | |
| | Running | | | | | | | |
| | | HC | 1.412 | 0.765 | 0.792 | 1.273 | 1.411 | 1.502 |
| | | CO | 13.192 | 6.512 | 6.696 | 11.907 | 13.221 | 14.032 |
| | | NOx | 0.471 | 0.395 | 0.418 | 0.470 | 0.463 | 0.499 |
| | Idle | | | | | | | |
| | | HC | 2.433 | 0.421 | 0.520 | 2.150 | 2.414 | 2.333 |
| | | CO | 23.301 | 4.015 | 4.959 | 20.585 | 23.113 | 22.341 |
| | | NOx | 0.319 | 0.058 | 0.070 | 0.282 | 0.316 | 0.306 |
| **Total** | | | | | | | | |
| | | HC | 3.846 | 1.186 | 1.312 | 3.424 | 3.825 | 3.835 |
| | | CO | 36.493 | 10.526 | 11.654 | 32.493 | 36.334 | 36.373 |
| | | NOx | 0.789 | 0.453 | 0.489 | 0.752 | 0.779 | 0.805 |

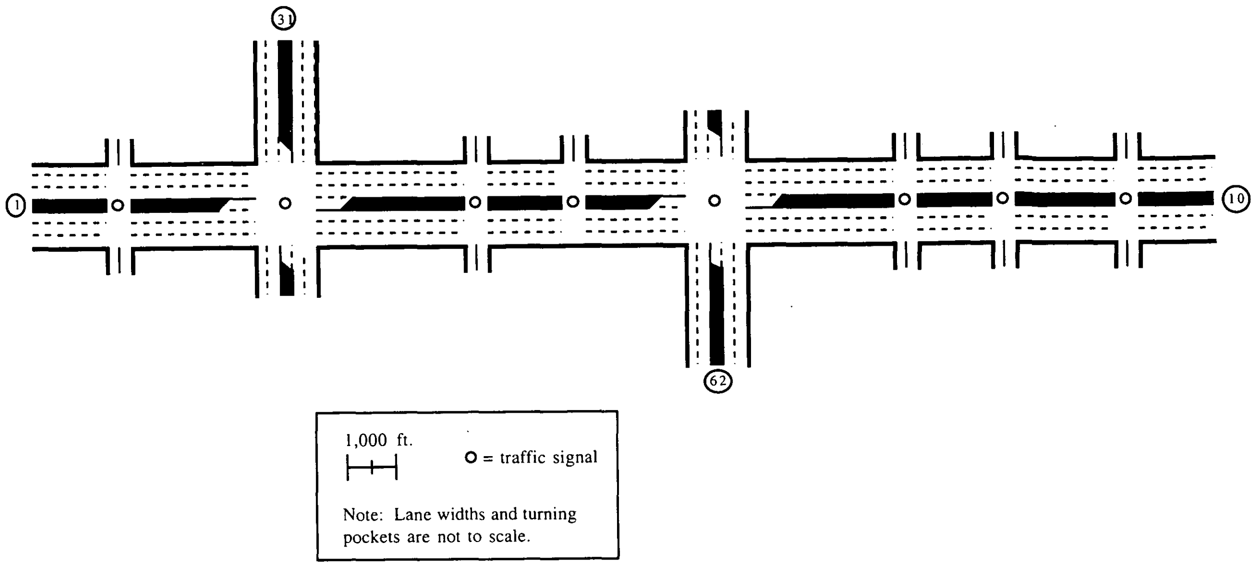


**FIGURE 4 Sample Network B.**

## Network B

In Network B an urban arterial street with three residential zones and a central business district (CBD) is simulated. The street, shown in Figure 4, consists of nine links from west to east. The three residential zones are Node 1, Node 31, and Node 62 and the CBD is Node 10. It is assumed that the number of people living in the residential zones with the mode choice alternatives of drive-alone, carpool, and transit bus includes 3,000 people in Node 1 and 1,000 people each in Nodes 31 and 62. The assumed mode shares are listed as the base case in Table 7. There is a transit route from each residential area to the CBD. Automobile occupancy is assumed to be 1.3, carpool occupancy is 3 for all scenarios, and bus occupancy is 25 for the base scenario and 30 for the other two study cases to meet the demand. Each case was a 1-hr simulation performed on a PC486DX/50 requiring 45 to 50 min of real time.

Because of the computation time only three different cases are examined in the Network B simulation:

1. *Base case.* The base case was as described above.
2. *HOV-3.* The right lane along the main street is reserved for three-person carpools and buses.
3. *Pricing.* Operating costs for automobile and carpool are increased by 25 and 10 percent, respectively. There is no change in bus selection.

The mobility and fuel consumption measurements for the Network B scenarios are shown in Table 8. With respect to the base case, the PMT in the simulation period decreases for the HOV scenario but increases for the pricing option. Likewise there is a decrease in average speed for the HOV option and an increase for the pricing option. Average fuel consumption, however, improved (decreased) for both of the strategies relative to the base case.

The emission results in Table 9 show that the incentives to use existing mass transit systems can achieve a limited reduction in pollution. The most attractive strategy examined is the increase in the automobile operating cost, such as parking costs and gas taxes. The program reduces the emissions of HC, CO, and $NO_x$ by 2 to 3 percent on the average per-person-per-mile basis. The exclusive HOV lane can decrease average emissions from buses by improving the traffic flow on the HOV lane. These results, however, are offset by the slower automobile movements owing to the reduction in the number of regular lanes. Furthermore the carpools that are slowed by the frequently stopped buses at the stations worsen the air pollution in the network.

## CONCLUSIONS

The choice of an emissions model is critical in air quality analysis. EPA's MOBILE model takes into account elevation, temperature,

**TABLE 8 Mobility and Fuel Consumption Results for Network B**

| | Base | HOV-3 | Pricing |
|---|---|---|---|
| PMT in An Hour | | | |
| Auto | 10,665 | 8,688 | 10,122 |
| Carpool | 4,201 | 4,485 | 4,426 |
| Bus | 2,248 | 2,818 | 2,688 |
| Total | 17,114 | 15,991 | 17,236 |
| Average Speed (kmph) | | | |
| Auto | 23.3 | 20.0 | 24.3 |
| Carpool | 23.3 | 23.2 | 24.3 |
| Bus | 18.6 | 23.2 | 19.6 |
| All Vehicles | 22.9 | 21.2 | 23.8 |
| Fuel Consumption (liters/person-km) | | | |
| Auto | .169 | .182 | .173 |
| Carpool | .073 | .079 | .076 |
| Bus | .044 | .035 | .036 |
| All Vehicles (Avg.) | .134 | .130 | .132 |
| Mode Split (%) | | | |
| Auto | 65.00 | 62.92 | 62.35 |
| Carpool | 25.00 | 25.87 | 26.69 |
| Bus | 10.00 | 11.20 | 10.99 |

operating modes, cold starts, and vehicle age, which may not be included in other emission models, yielding more accurate results. The emissions from NETSIM may result in biased conclusions; for example, the inclusion of an exclusive HOV lane in the sample Network B is plausible by NETSIM for reducing HC and CO pollution. However as shown in Table 10 this is not the case when using MOBILE. NETSIM's emissions factors are dated, and its analysis is not nearly as sophisticated as MOBILE's.

The available transportation planning tools cannot be directly used for emissions estimation. A macroanalysis framework that links the transportation planning and air quality analysis models to develop a matrix of strategies to assist decision makers in examining specific mobility strategies for an urban area has been proposed. The purpose of the paper is to illustrate a framework for identifying energy, air quality, and mobility trade-offs of various congestion mitigation strategies. On the basis of this methodological framework two sample networks were developed and evaluated in this paper. In Network A changing the pattern of vehicle flow can achieve the goal of reducing air pollution, whereas in Network B it is more effective to increase automobile operating costs. The reason for the radically different results for Networks A and B may be the extraordinary congestion in Network B, in which the choice of changing the vehicle flow pattern may still leave the roadway system congested. The results of the analyses illustrate the need for careful study before implementation of any TCM. Failure to analyze the implications of TCMs before their implementation may yield results inconsistent with environmental and energy policy objectives.

Use of the framework demonstrated in this paper clearly points to the need for additional modeling work. Existing models may be calibrated for some analyses but cannot be relied upon for directing future transportation investments. They can, however, provide some relative comparisons of TCMs. The framework presented in this paper should assist analysts in the interim while work proceeds on the development of more comprehensive transportation demand air-quality models.

**TABLE 10 Comparison of Emissions Results (gram/person-km)**

| | HC | CO | NOx |
|---|---|---|---|
| **Network A** | | | |
| Base | | | |
| NETSIM | 0.108 | 1.961 | 0.367 |
| MOBILE 4.1 | 3.846 | 36.493 | 0.789 |
| HOV-4 | | | |
| NETSIM | 0.068 | 1.360 | 0.292 |
| MOBILE 4.1 | 1.186 | 10.526 | 0.453 |
| HOV-3 | | | |
| NETSIM | 0.072 | 1.445 | 0.310 |
| MOBILE 4.1 | 1.312 | 11.654 | 0.489 |
| Bus Lane | | | |
| NETSIM | 0.094 | 1.727 | 0.322 |
| MOBILE 4.1 | 3.424 | 32.493 | 0.752 |
| No Left | | | |
| NETSIM | 0.107 | 2.023 | 0.359 |
| MOBILE 4.1 | 3.825 | 36.334 | 0.779 |
| Pricing | | | |
| NETSIM | 0.111 | 2.097 | 0.388 |
| MOBILE 4.1 | 3.835 | 36.373 | 0.805 |
| **Network B** | | | |
| Base | | | |
| NETSIM | 0.169 | 3.623 | 0.786 |
| MOBILE 4.1 | 1.262 | 10.911 | 0.513 |
| HOV-3 | | | |
| NETSIM | 0.164 | 3.436 | 0.733 |
| MOBILE 4.1 | 1.352 | 11.934 | 0.498 |
| Pricing | | | |
| NETSIM | 0.167 | 3.502 | 0.755 |
| MOBILE 4.1 | 1.235 | 10.685 | 0.497 |

**TABLE 9 Emissions Results for Network B (gram/person-km)**

| | Base | HOV-3 | Pricing |
|---|---|---|---|
| **Auto** | | | |
| Running | | | |
| HC | 1.076 | 1.194 | 1.047 |
| CO | 8.778 | 10.025 | 8.486 |
| NOx | 0.535 | 0.545 | 0.535 |
| Idle | | | |
| HC | 0.634 | 0.839 | 0.700 |
| CO | 6.082 | 8.042 | 6.712 |
| NOx | 0.082 | 0.108 | 0.090 |
| **Carpool** | | | |
| Running | | | |
| HC | 0.466 | 0.468 | 0.454 |
| CO | 3.804 | 3.824 | 3.677 |
| NOx | 0.232 | 0.234 | 0.232 |
| Idle | | | |
| HC | 0.275 | 0.364 | 0.303 |
| CO | 2.636 | 3.485 | 2.909 |
| NOx | 0.036 | 0.047 | 0.039 |
| **Bus** | | | |
| Running | | | |
| HC | 0.086 | 0.063 | 0.067 |
| CO | 0.481 | 0.337 | 0.363 |
| NOx | 0.442 | 0.340 | 0.352 |
| Idle | | | |
| HC | 0.026 | 0.018 | 0.025 |
| CO | 0.077 | 0.053 | 0.074 |
| NOx | 0.031 | 0.021 | 0.030 |
| **Weighted Average** | | | |
| Running | | | |
| HC | 0.796 | 0.791 | 0.742 |
| CO | 6.465 | 6.579 | 5.985 |
| NOx | 0.449 | 0.422 | 0.429 |
| Idle | | | |
| HC | 0.466 | 0.561 | 0.493 |
| CO | 4.446 | 5.356 | 4.700 |
| NOx | 0.064 | 0.076 | 0.068 |
| **Total** | | | |
| HC | 1.262 | 1.352 | 1.235 |
| CO | 10.911 | 11.934 | 10.685 |
| NOx | 0.513 | 0.498 | 0.497 |

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# Transportation Activity Modeling for San Joaquin Emissions Inventory

MALCOLM M. QUINT AND WILLIAM R. LOUDON

As the air pollution problem in the major metropolitan areas of the United States has increased, new interest has emerged for greater accuracy in the estimation of emissions from mobile sources. Gridded emissions estimates owing to vehicular travel are generally produced from roadway travel data generated by transportation planning models, but the transportation planning models have generally been designed and used by transportation analysts to evaluate the effects of increased development on roadway level of service and to determine roadway capacity needs for a local or regional area and are not always ideally suited to support gridded mobile source emissions development. The results of a new methodology that significantly enhances the emissions prediction capability of regional travel models are reported. The methodology was developed for the eight counties in the San Joaquin Valley of California. Most transportation models produce travel estimates only on an average basis and only for average weekday conditions. The levels of vehicle travel vary significantly by hour throughout the day and from weekdays to weekends as well. When investigating hour-specific air quality episodes that result from pollutant or precursor emissions generated during previous hours, this poor temporal resolution of the transportation model severely lowers the accuracy of the hourly estimated mobile source inventory. The methodology discussed includes combining regional forecasts with supplemental traffic count data on time-of-day and vehicle type distribution of travel to improve the temporal resolution of the model-based travel activity data.

Air quality in the San Joaquin Valley air basin is governed by a combination of the typography and meteorology as well as the distribution and composition of pollutant emissions throughout the region. The management and control of the air quality problem, as well as planning the level and direction of future growth throughout the San Joaquin Valley, require a full understanding of the cause and nature of these problems. The purpose of the project described here was to develop a model for forecasting the travel activity data for on-road motor vehicles. The project is part of a larger effort that includes the development of models to predict other activities that lead to the production of pollutants. The other areas include agricultural activities, oil production and other mining activities, industrial activities, and the natural biogenic production of pollutants. With the activity-predicting models in each of these areas, gridded estimates of emissions were prepared for an episode period in summer 1990. Air shed, air quality models were then used to estimate pollutant concentrations at selected locations where air quality monitoring was conducted during the 1990 episode period. Previously gathered data indicate that emissions from mobile sources are a major component of emissions inventory, especially in more heavily populated areas of the valley where the highest air pollution levels are measured. Accurate estimation of vehicular traffic within the valley is therefore clearly a key component of the emissions inventory.

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Gridded estimates of emissions owing to vehicular travel are generally produced from roadway travel data generated by transportation planning models. However the transportation planning models were primarily designed and used by transportation analysts to evaluate the effects of increased development on roadway level of service and to determine roadway capacity needs for a local or regional area and are not always ideally suited to support gridded mobile source emissions development. The preparation of an emissions inventory, particularly for the analysis of ozone formation, requires special consideration when using the transportation model data to support the analysis.

For an accurate emissions inventory, motor vehicle emissions need to be temporally resolved. The levels of vehicle travel vary significantly by hour throughout the day and from weekdays to weekends as well. Most transportation models produce travel estimates only on an average daily basis and only for average weekday conditions. When investigating hour-specific air quality episodes that result from pollutant or precursor emissions generated during previous hours, this poor temporal resolution of the transportation model severely lowers the accuracy of the hourly estimated mobile source inventory. Significant effort in the project was devoted to improving the temporal resolution of the model-based travel activity data.

## TRAVEL MODELS

The San Joaquin Valley Transportation Model Development Project covered an eight-county area, as shown in Figure 1. The project included San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare, and Kern counties in California. The emissions inventory developed for the San Joaquin Valley has also become part of a larger project, the SARMAP emissions inventory that covered portions of 30 counties also shown in Figure 1. The model for transportation activity for this project was based on transportation models for each of the eight San Joaquin Valley counties.

The final product of the project was eight county models that, in composite, covered all of the San Joaquin Valley. With models in place for all of the eight counties, input data were prepared for average annual conditions in 1990, and model runs were prepared. As shown in Table 1, the travel demand models for each of the eight counties of the San Joaquin Valley achieved the objective of forecasting average weekday volumes within 5 percent of the counted volumes on a countywide basis. Freeway volumes were forecasted within 7.2 percent or less of the counted freeway volumes for each county, and for the valley as a whole they were within 1 percent on average. Arterial volumes were forecasted within 12.1 percent or less of counted volumes in 1990 for each


**FIGURE 1 SARMAP emissions modeling domain.**

county. Overall the valleywide forecasts for arterials were 2.4 percent greater than the total of the counted volumes. Total forecasted volumes on all facilities valleywide for which they were counted were within 0.1 percent of counted volumes. Adjustments that were made to the parameters used in the models were successful in compensating for potential uncertainties such as data that may have been 10 years old or trip generation rates that were applied from a different county.

The output of the county models provided a starting point for the preparation of the travel activity data but required supplemental procedures to meet the needs of the emissions inventory project. The county models provided only estimates of total daily vehicular travel for an average annual weekday. The emissions inventory project required that forecasts be for summertime travel and that individual estimates be made for four different days of the week: Thursday (representing average midweek conditions), Friday, Saturday, and Sunday. The project also required hourly estimates of travel activity, with that activity stratified by vehicle type: motorcycle, automobile, light-duty truck, medium-duty truck, light heavy-duty truck, medium heavy-duty truck, and heavy heavy-duty truck. To provide the supplemental data required by the emissions inventory, JHK & Associates developed the link-prototype system, which it applied within the software package SYSTEM II. SYSTEM II is both a regional travel forecasting model and a data base management system.

## LINK-PROTOTYPE SYSTEM

To provide the necessary seasonal adjustment, day-of-the-week adjustment, temporal distribution, and vehicle type distribution, JHK & Associates developed the link-prototype system. With the link-prototype system typical adjustment factors for distributions are developed for different types of links in the system. Preliminary data analysis established that there was a significant correlation between certain characteristics of roadway links and the types of adjustments or distributions to be made. It was found that the type of facility represented by the link (freeway, arterial, collector, or local) and the land use characteristics of the zone sur-

**TABLE 1 Model Validation Results**

| Functional Class | County | Assigned Volume | Traffic Count | Percent* Difference |
|---|---|---|---|---|
| Freeway | Fresno | 1,878,274 | 1,746,400 | 7.0% |
| | Kern | 2,987,166 | 3,127,050 | -4.7% |
| | San Joaquin | 2,817,212 | 2,795,900 | 0.8% |
| | Stanislaus | 977,200 | 978,351 | 1.0% |
| | Tulare | 1,937,070 | 1,924,100 | 0.7% |
| | Madera | 1,050,469 | 1,115,678 | -5.8% |
| | Merced | 660,531 | 711,929 | -7.2% |
| | Kings | 727,140 | 682,189 | 6.6% |
| Arterial | Fresno | 4,970,570 | 4,942,100 | 0.6% |
| | Kern | 5,262,103 | 5,292,166 | -0.6% |
| | San Joaquin** | 3,277,264 | 3,272,900 | 0.1% |
| | Stanislaus | 1,252,600 | 1,122,141 | 10.4% |
| | Tulare | 2,698,133 | 2,694,600 | 1.0% |
| | Madera | 638,838 | 561,286 | 12.1% |
| | Merced | 2,473,828 | 2,204,242 | 10.9% |
| | Kings | 798,674 | 762,327 | 4.6% |
| County Hwy | Fresno*** | 449,329 | 462,700 | -3.0% |
| | Kern | 1,601,803 | 1,689,319 | -5.5% |
| | San Joaquin | 589,191 | 506,800 | 16.3% |
| | Stanislaus | 566,200 | 656,457 | -15.9% |
| | Tulare | 2,638,982 | 2,395,800 | 9.2% |
| Collector | Fresno | 1,308,180 | 1,433,300 | -9.6% |
| | Kern | 313,039 | 564,831 | -80.4% |
| | San Joaquin | 1,077,913 | 1,215,300 | -11.3% |
| | Stanislaus | 372,200 | 279,401 | 24.9% |
| | Tulare | 469,329 | 483,300 | -3.0% |
| | Madera **** | 64,249 | 86,641 | -34.9% |
| | Merced **** | 266,915 | 363,253 | -36.1% |
| | Kings | 2,183 | 5,716 | -161.8% |
| Total | Fresno | 8,606,353 | 8,584,500 | 0.3% |
| | Kern | 10,204,625 | 10,730,601 | -5.2% |
| | San Joaquin | 7.761,580 | 7,790,900 | -0.4% |
| | Stanislaus | 3,168,200 | 3,036,350 | -4.1% |
| | Tulare | 7,826,576 | 7,580,600 | 3.2% |
| | Madera | 1,753,556 | 1,763,605 | -0.6% |
| | Merced | 3,401,274 | 3,279,424 | 3.6% |
| | Kings | 1,527,997 | 1,450,232 | 5.1% |
| | All Freeways | 13,035,062 | 13,081,597 | -0.4% |
| | All Arterials | 27,217,515 | 26,562,841 | 2.4% |
| | All Collectors | 3,874,008 | 4,431,742 | -14.4% |
| | All Facilities | 44,126,585 | 44,076,180 | 0.1% |

* A positive percent difference shows that the model over-estimated the average weekday volume compared to the counts; a negative percent difference shows that the model under-estimated the volume compared to the counts.

** San Joaquin "arterial" category includes expressways and arterials streets.

*** Fresno, Madera, Merced and Kings do not use the classification of county highways, the information presented for Fresno represents their classification for expressways.

**** Madera and Merced "collector" category includes collectors and local minor streets.

rounding the link (core commercial, mixed commercial, suburban, or rural) are characteristics that explain significant variation in the temporal and vehicle type distributions.

The link-prototype system uses vehicle count and classification data to create prototype adjustment factors and distributions for each combination of area type and facility type. As shown in Figure 2, these prototype distributions can then be applied to the average annual weekday forecast for daily travel to produce hourly estimates of volume by vehicle type for specific days of the week in summer 1990. Traffic counts with time-of-day and vehicle classification data were sorted into the area type and facility type combinations and were summarized to produce factors such as 60 percent of vehicles on arterials in rural areas between 3:00 p.m. and 4:00 p.m. are automobiles. The link-prototype system provided a mechanism for producing the detailed data required by the emissions inventory without changing the nature of the county models, the cornerstone of the travel activity data forecasting process. While retaining the structure of the county models, development and enhancement of each model could proceed over time under the guardianship of the agency responsible for transportation modeling within each county. The link-prototype system and the valleywide travel activity data forecasting system developed within SYSTEM II provide tools capable of emissions inventory preparation for future year emissions forecasting on the basis of the available countywide modeling procedures available at the time. The forecasting system retains all of the policy sensitivity of each of the county models, and the sensitivity will increase as more policy-sensitive models are developed for each of the counties.

## SUMMARY OF DATA

Each link in the model networks is defined according to facility type (freeway, arterial, collector, or local) and area type (core commercial, mixed commercial, suburban, or rural) that explain significant variation in the temporal and vehicle type distributions. Separate adjustment factors and distributions are created for each combination of facility type and area type from vehicle count and vehicle classification data.

Hourly volumes and speeds for roadway segments provide more accurate inputs for emissions modeling than do daily average volumes and speeds. The information obtained through the data collection effort provided hourly and daily percentages of the seven vehicle types by the area and facility types required for the link-prototype matrix. The forecasted volumes on every link in the model networks were first adjusted from annual averages to summer averages, and then adjustments were made to these summer averages into day-of-the-week averages by using only daily traffic counts from the summer months. Finally, the day-of-the-week averages were distributed into hourly volumes by vehicle by using only traffic counts from the matching day of the week. Separate time-of-day and vehicle type factors were created for a.m. peak-oriented links and p.m. peak-oriented links. If one direction of roadway segment had greater volumes in the a.m. peak hour than the p.m. peak hour it was treated as an a.m. peak-oriented link.

Data on the distribution of travel by time of day reveal some patterns of travel unique to weekdays and weekends. All of the midweek and Friday distributions indicate distinct bimodal distributions, generally including peak volumes between 6:00 a.m. and 8:00 a.m. and another peak between 4:00 p.m. and 7:00 p.m. These weekday patterns generally reflect the morning and evening (home to work to home) commute traffic. The Saturday and Sunday distributions are dominated by a unimodal pattern. On Saturday the peak volumes are clustered around the midday hours, whereas on Sunday the higher volumes are found in the late afternoon. These peaks may be explained at the beginning (Saturday midday) and the end (Sunday afternoon) of weekend recreational trips that are common in the San Joaquin Valley.

The midweek and Friday distributions by facility type illustrate the strong bimodal trend across all facility types, with a slightly greater p.m. peak percentage compared with those at the a.m. peak and the midday hours (see Figure 3 and 4 for midweek and Friday distributions, respectively). The volumes are more evenly distributed throughout the day on freeways than on arterials, with

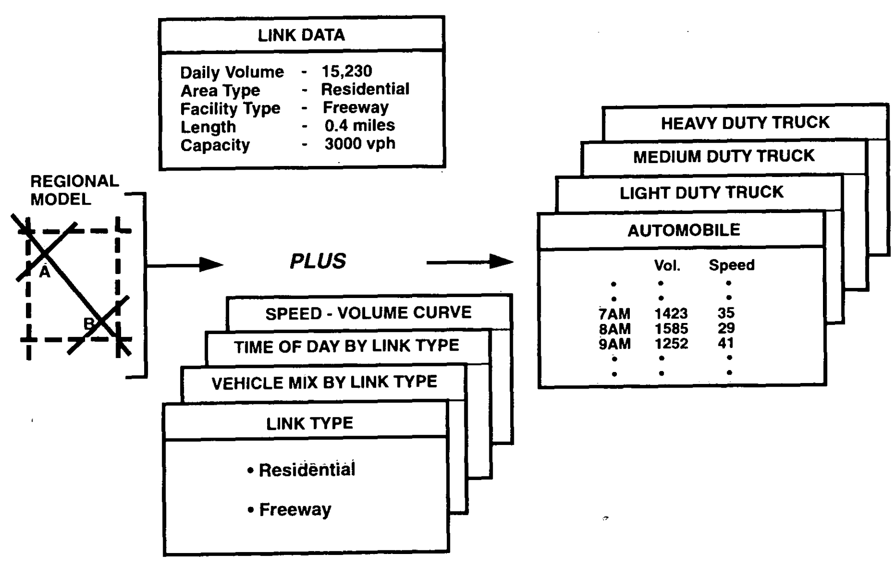


**FIGURE 2 Link-prototype system for regional emissions estimation process.**

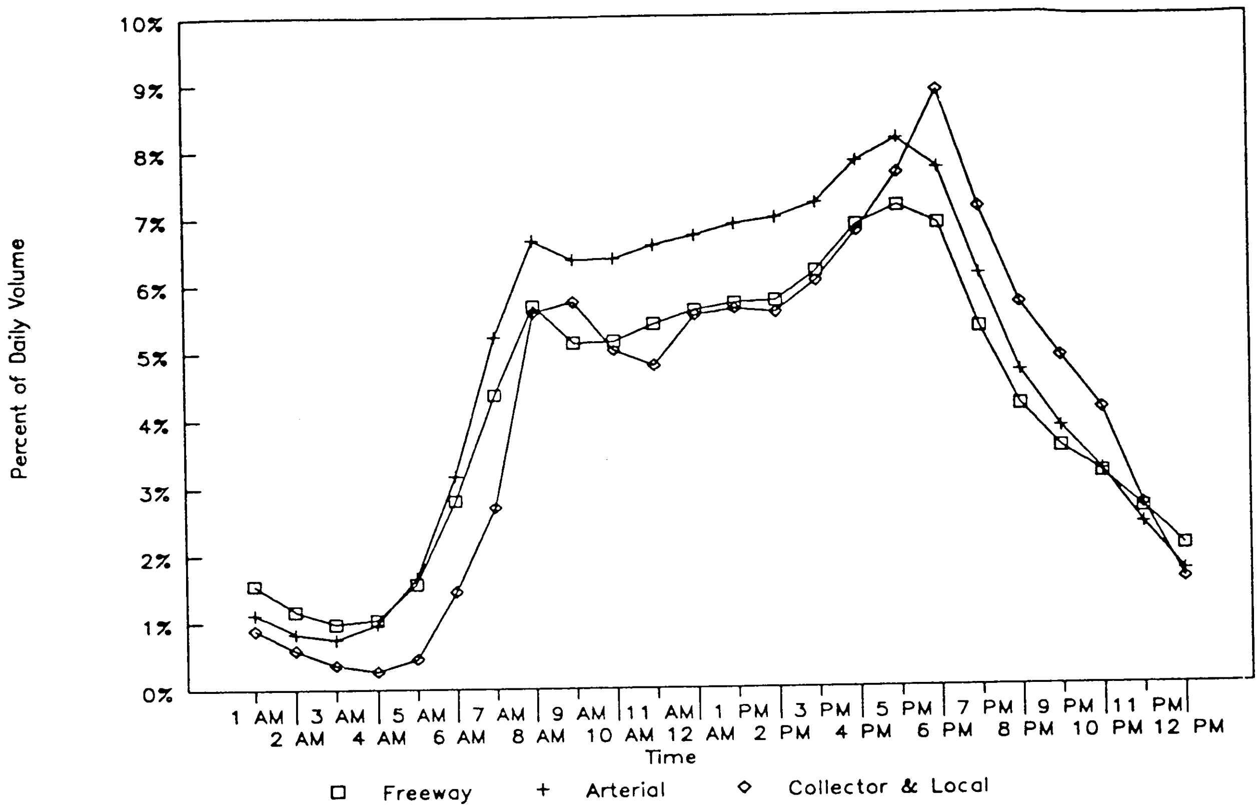


**FIGURE 3** **Time-of-day distribution for midweek.**

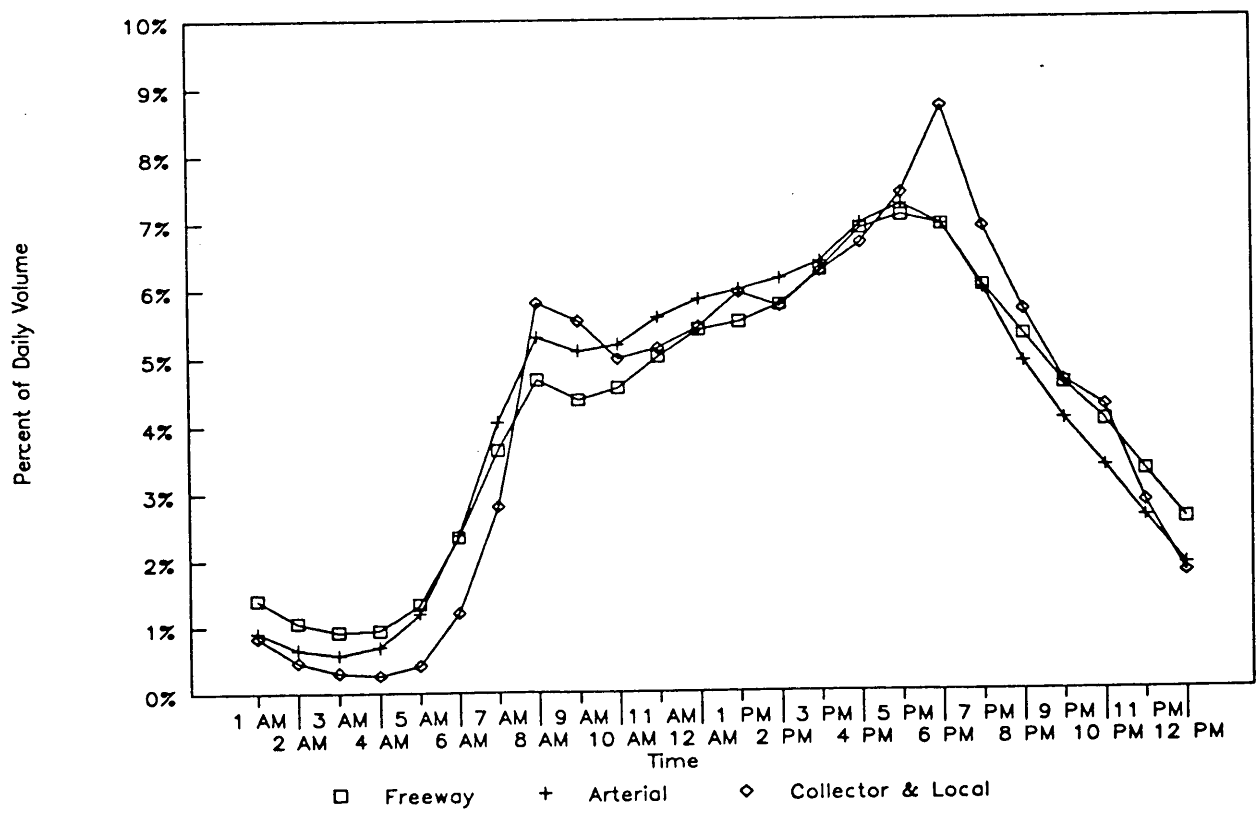


**FIGURE 4** **Time-of-day distribution for Friday.**

the collector and local roadway distributions fluctuating to the greatest degree over the 24-hr period. On collector and local roadways the midweek peaks occur 1 hr after the peaks for arterials and freeways, whereas the a.m. and p.m. peaks for arterials and freeways fall in the same hour.

As in the midweek and Friday distributions, the Saturday time-of-day distributions for collector and local roadway facilities have the greatest degree of variability over the 24-hr period. However the Saturday percentages have greater uniformity across facility types than any other day. The Sunday peak period is distributed over several hours in the late afternoon and early evening for freeways and arterials (see Figures 5 and 6 for Saturday and Sunday time-of-day distributions, respectively). The collector and local roadway distributions fluctuate dramatically throughout the middle of the day, although they still follow a predominantly unimodal pattern.

The explanatory power of the link-prototype system was investigated by using statistical tests. The variation within the data for the four types of facilities and the four area types was compared by using analysis of variance (ANOVA) tests. The statistical tests for the time-of-day link prototypes reveal significance within the two groups of area type and facility type. ANOVA tests were performed on the four different data sets. ANOVA tests the hypothesis that the variances of the means for different populations are equal. If the variance of the populations differs statistically, then the ratio of the variance (called an $F$-statistic) will be greater than unity. The other statistical measure used to test the data is the $t$-test. This task is used to measure the statistical difference in means between a given population and a subset of that population. If the $t$-statistic is below a threshold, approximately 2.0, there is no difference between the means and the data are from the same population.

The variable measured from the time-of-day data base is the percentage of volume in the peak period: 6:00 a.m. to 9:00 a.m. for the a.m. peak orientation and 3:00 p.m. to 6:00 p.m. for the p.m. peak orientation. Both the area type and facility type have $F$-statistics that indicate differences between the categories (such as suburban versus rural) during the a.m. and p.m. peak periods. An $F$-statistic over 3.78 is evidence that the null hypothesis can be rejected with 99 percent confidence.

The number of observations, from traffic counts mean values, and standard deviations for each area type-facility type combination for the a.m. and p.m. peak period percentage of the daily total are shown in Tables 2 and 3, respectively. The one-way ANOVA test indicates that area type and facility type each explains a significant amount of variation in the time-of-day factors, as reflected in the $F$-statistic. The low value of the two-way ANOVA statistic indicates that little variation is explained by specific combinations of area type and facility type that is not already explained by the two separate one-way stratifications. When the number of observations used to estimate distribution factors was less than five, link-prototype cells were combined. For instance the local roadway facility type was combined with the collector facility type before estimating time-of-day factors.

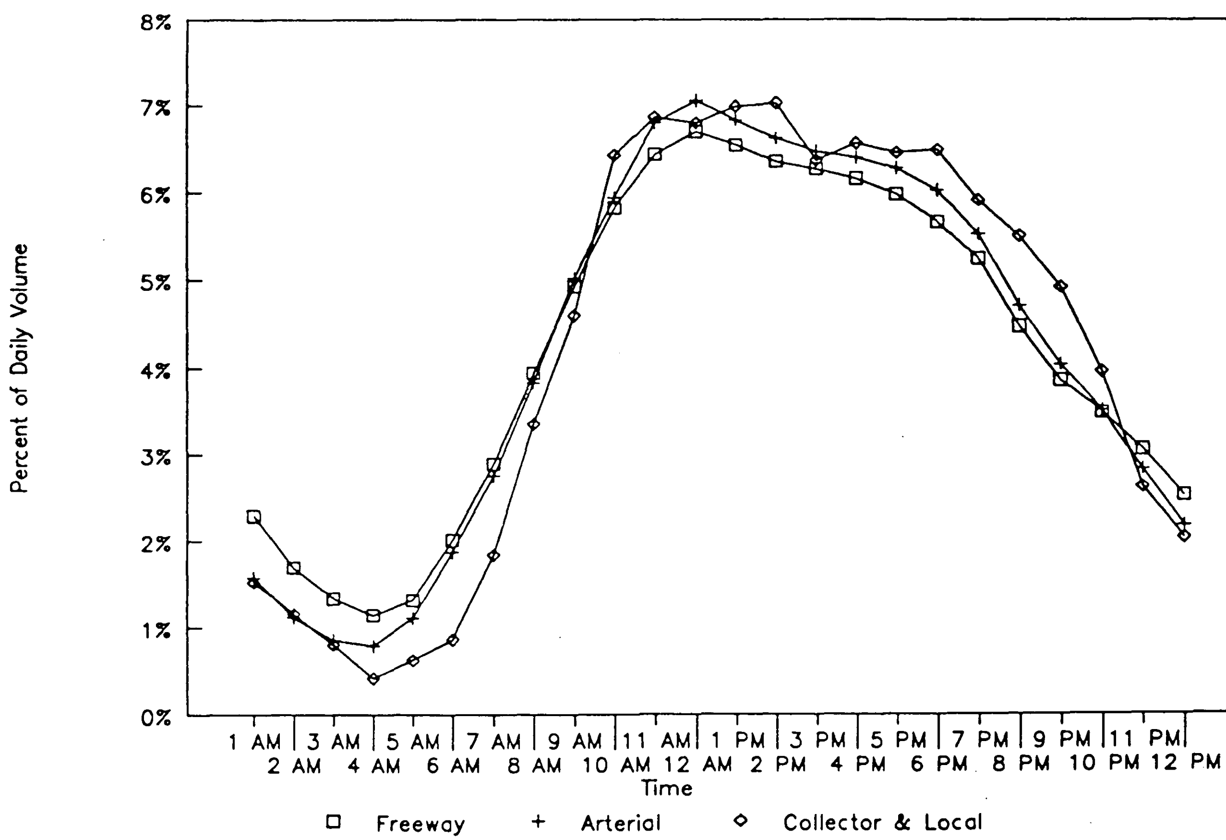


**FIGURE 5 Time-of-day distribution for Saturday.**

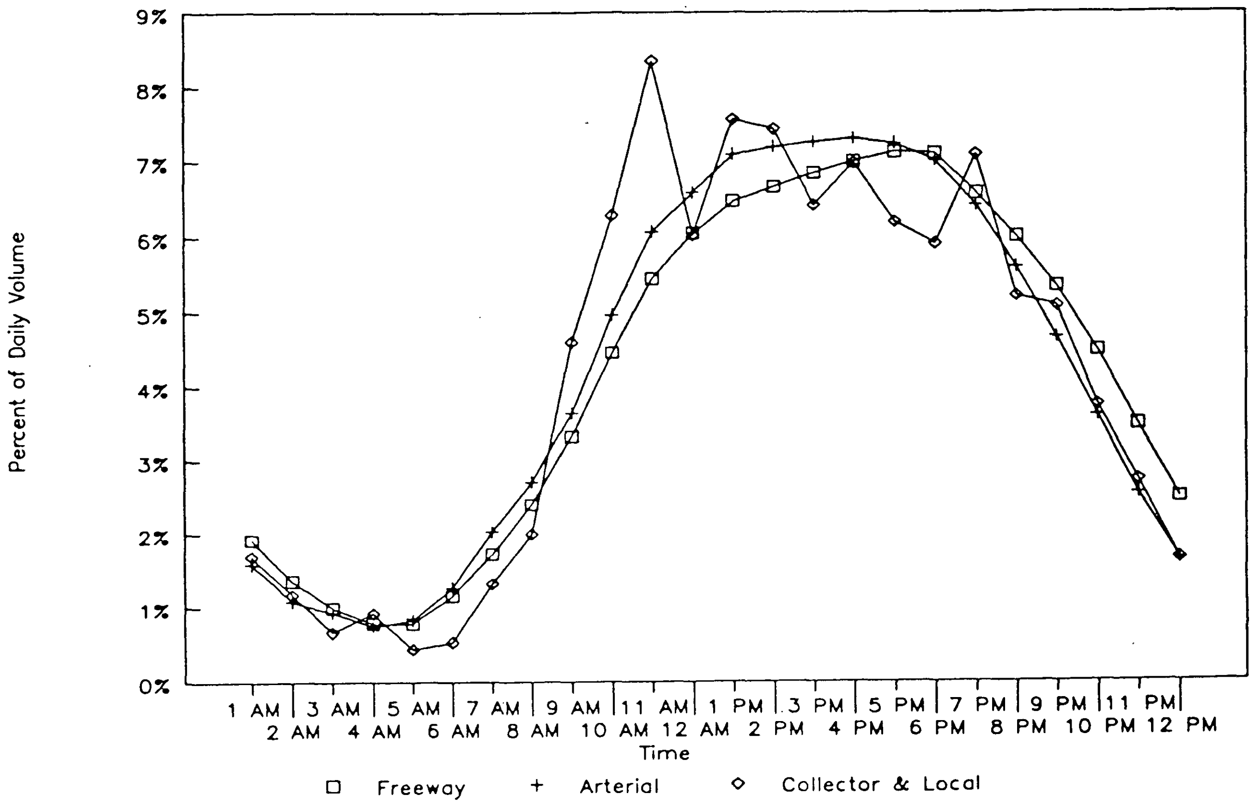


**FIGURE 6 Time-of-day distribution for Sunday.**

## EMISSIONS FORECASTING

For many years the focus on emissions forecasting for mobile source emissions was on the vehicle miles of travel. Research by the California Department of Transportation and the California Air Resources Board has clearly established that vehicle emissions can be identified in at least four specific categories: trip start emissions (cold start or hot start, depending on the period for which the vehicle has been turned off), hot stabilized running emissions (both exhaust and evaporative), hot soak evaporative trip end emissions, and diurnal emissions (hydrocarbon emissions from evaporation that are essentially unrelated to the distance the vehicle is driven). A 20-mi round-trip by a light-duty automobile at roughly 23.9°C (75°F) at an average operating speed of 64.4 km/hr (40 mph) would produce a total of approximately 31.4 g of hydrocarbon. However only about one-third of the emissions is associated with vehicle miles of travel (VMT) from the trip; 50 percent of the hydrocarbon emissions result from the trip being made; this is a combination of the trip start emissions and the evaporative hot soak emissions that occur at the end of the trip. The final one-sixth of the emissions, referred to as the *diurnal emissions*, occurs as a result of evaporation of fuel from the gasoline tank and occurs whether the vehicle is driven or not. This calculation demonstrates the importance of including trip starts and ends as well as VMT in emissions estimations. The importance of VMT as a determinant of hydrocarbon emissions decreases over time; by 2010 the VMT portion of the hydrocarbon emissions for this prototypical trip would be only about one-eighth of the total.

Research by the California Air Resources Board and the Environmental Protection Agency has established that a significant relationship exists between average operating speed and emissions rates, after controlling for trip start, trip end, and diurnal emissions. Because average operating speeds vary significantly across facility types and can be significantly affected by congestion, the ultimate accuracy of the emissions inventory is sensitive to speed estimation. Research on emissions rates has also demonstrated significant variation by vehicle type. Heavy-duty gasoline trucks have significantly higher emissions rates at all speeds, and the emissions rates for heavier vehicles are also more sensitive to speed.

## DESCRIPTION OF FORECASTING SYSTEM

The travel demand models for the eight San Joaquin Valley counties produced the average daily volume as well as the average speed for each direction of travel on the links in the network. This generalized picture of travel activity was greatly improved for emissions modeling by producing hourly volumes by vehicle type. The review of traffic data revealed that the distribution of hourly volumes differs according to area type, facility type, day of the week, as well as vehicle type. The hourly speeds also change in an inverse relationship to changes in volume.

Traffic volumes and speeds serve as the data inputs necessary for the vehicle emissions model. The emissions rates used in modeling different pollutants decrease or increase by speed, and these rates also vary by vehicle type. Emissions rates averaged for all vehicle types assume a universal distribution of vehicle types

**TABLE 2 A.M. Peaking Factors by Area Type and Facility Type Combination**

| | Freeway | Arterial | Collector | Local | Total |
|---|---|---|---|---|---|
| **CBD** | | | | | |
| Mean | 0.211 | 0.149 | 0.201 | 0.181 | 0.192 |
| Std Dev | 0.028 | 0.093 | 0.013 | 0.041 | 0.05 |
| N | 11 | 4 | 2 | 5 | 22 |
| **Commercial** | | | | | |
| Mean | 0.209 | 0.192 | 0.202 | 0.186 | 0.200 |
| Std Dev | 0.017 | 0.023 | 0.026 | 0.00 | 0.022 |
| N | 63 | 79 | 3 | 1 | 146 |
| **Suburban** | | | | | |
| Mean | 0.182 | 0.206 | 0.216 | 0.186 | 0.189 |
| Std Dev | 0.035 | 0.030 | 0.022 | 0.000 | 0.035 |
| N | 244 | 410 | 10 | 1 | 303 |
| **Rural** | | | | | |
| Mean | 0.173 | 0.180 | 0.205 | 0.223 | 0.179 |
| Std Dev | 0.020 | 0.048 | 0.042 | 0.050 | 0.041 |
| N | 244 | 410 | 38 | 4 | 696 |
| **Total** | | | | | |
| Mean | 0.182 | 0.185 | 0.207 | 0.197 | 0.184 |
| Std Dev | 0.029 | 0.045 | 0.037 | 0.043 | 0.038 |
| N | 528 | 575 | 53 | 11 | 1167 |

| | F Statistic | Critical F Ratio | Confidence Level | Degrees of Freedom |
|---|---|---|---|---|
| **One Way Analysis of Variance** | | | | |
| Area Type | 19.712 | 3.78 | 99% | 3, 1163 |
| Functional Class | 23.33 | 3.78 | 99% | 3, 1163 |
| **Two Way Analysis of Variance** | | | | |
| Area by Functional Class | 0.0145 | 3.86 | 95% | 3, 9 |

Note: Peaking Factor = Peak Period Volume (6-9 A.M.)/Daily Volume

$$F \text{ (one way ANOVA)} = \frac{\text{Variance for between sum of squares}}{\text{Variance for within sum of squares}}$$

$$F \text{ (two way ANOVA)} = \frac{\text{Variance for interaction sum of squares}}{\text{Variance for error sum of squares}}$$

across all links. Use of average daily traffic volumes and average daily speeds for the travel activity data for emissions modeling provides a static view of daily activity. Disaggregation of the data into hourly volumes by vehicle type better reflects the dynamic behavior of daily travel activity.

JHK & Associates has used the link-prototype system as the cornerstone for developing more accurate estimates of hourly volumes and speeds by vehicle type for all links in the system. Although most regional models could potentially be restructured to produce forecasts for each hour of the day, this would result in a time-consuming and cumbersome operation. As an alternative, the methodology of JHK & Associates uses the system of link-prototype distributions to produce hourly estimates of traffic volumes and speeds by link.

Because of the highly nonlinear nature of the relationship between travel speed and the emissions of the ozone precursors, prediction of ozone concentrations is sensitive to accurate estimates of travel speeds by location, by time of day, and by type of vehicle. SYSTEM II's program to distribute daily volumes by time-of-day factors provides separate speed estimates for each hour of the day given the capacity of the roadway and the volume of vehicles. The time-of-day module allows the user to specify a different volume delay equation for each facility type, area type, or facility type-area type combination or on a link-by-link basis. The link-prototype factors were also separated into a.m. peak-oriented or p.m. peak-oriented factors, such that one direction of a roadway segment might have the largest hourly volumes and slowest speeds during the a.m. peak period and the other direction might have the largest volumes and slowest speeds during the p.m. peak period. Special a.m. peak hour and p.m. peak hour assignments were performed to determine the peak orientations of both directions for every link in the network.

The forecasts that produced hourly link volumes and speeds for seven vehicle types by four different days of the week are completely based on a modeling system. This modeling system has the capability to produce forecasts for future years or to evaluate

**TABLE 3 P.M. Peaking Factors by Area Type and Facility Type Combination**

| | Freeway | Arterial | Collector | Local | Total |
|---|---|---|---|---|---|
| **CBD** | | | | | |
| Mean | 0.278 | 0.225 | 0.231 | 0.246 | 0.229 |
| Std Dev | 0.00 | 0.083 | 0.008 | 0.0 | 0.072 |
| N | 1 | 8 | 3 | 1 | 12 |
| **Commercial** | | | | | |
| Mean | 0.234 | 0.248 | 0.239 | 0.250 | 0.243 |
| Std Dev | 0.0187 | 0.036 | 0.012 | 0.016 | 0.032 |
| N | 63 | 142 | 3 | 3 | 212 |
| **Suburban** | | | | | |
| Mean | 0.2397 | 0.228 | 0.264 | 0.230 | 0.237 |
| Std Dev | 0.035 | 0.031 | 0.033 | 0.020 | 0.034 |
| N | 197 | 63 | 5 | 2 | 267 |
| **Rural** | | | | | |
| Mean | 0.202 | 0.234 | 0.234 | 0.259 | 0.223 |
| Std Dev | 0.043 | 0.042 | 0.015 | 0.021 | 0.045 |
| N | 294 | 542 | 14 | 4 | 854 |
| **Total** | | | | | |
| Mean | 0.219 | 0.236 | 0.240 | 0.249 | 0.229 |
| Std Dev | 0.042 | 0.041 | 0.023 | 0.022 | 0.042 |
| N | 555 | 755 | 22 | 10 | 1345 |

| | F Statistic | Critical F Ratio | Confidence Level | Degrees of Freedom |
|---|---|---|---|---|
| **One Way Analysis of Variance** | | | | |
| Area Type | 18.48 | 3.78 | 99% | 3, 1341 |
| Functional Class | 18.94 | 3.78 | 99% | 3, 1341 |
| **Two Way Analysis of Variance** | | | | |
| Area by Functional Class | 0.0018 | 3.86 | 95% | 3, 9 |

Note: Peaking Factor = Peak Period Volume (3-6 A.M.)/Daily Volume

$$F\text{ (one way ANOVA)} = \frac{\text{Variance for between sum of squares}}{\text{Variance for within sum of squares}}$$

$$F\text{ (two way ANOVA)} = \frac{\text{Variance for interaction sum of squares}}{\text{Variance for error sum of squares}}$$

the impacts of alternative policies or programs on emissions. All eight travel demand forecasting models used were developed for the entire county, not just an urban portion.

## COMPARISON OF FORECASTS WITH COUNT DATA

The time-of-day volume forecasts were compared with the measured count data for a particular day. The comparison of a forecasted average daily traffic with the count volume was similar to the validation process for the travel demand models because modeled volumes were evaluated against field counts for specific locations. The potential for error was greater in this comparison because two additional adjustments were made to the original forecast volume. The forecasted annual average daily traffic volume was adjusted for seasonal and then day-of-the-week variations. Both the seasonal and day-of-the-week factors were based on the link-prototype system that accounted for facility type and area type differences. This adjusted forecasted volume was compared with a count performed on the same day of the week during summer 1990.

The comparison of the forecasted volumes with the counted volumes was made by using approximately 130 locations. Overall the forecasted urban volumes were 2.8 percent less on average than the counted volumes during midweek. The forecasted volumes for the urban freeways were 10 percent lower than the counted volumes, whereas forecasts for the urban collectors were about 17 percent higher than the count data. For the urban arterials and the rural highways each there was less than a 2 percent difference between the forecasted volumes and the counted volumes.

The overall patterns in the differences for Saturday were similar to those for midweek. The largest difference between the two days of the week is that the forecasted volumes for rural highways were 15 percent lower than the counted volumes. This difference and the slightly larger gap for urban freeways contribute to an overall average difference of 12 percent between forecasted and counted volumes.

## CONCLUSIONS

Travel demand forecasting models have been developed and applied during the past three decades to forecast travel demand for long-term planning activities such as alternatives analyses, county general plans, and corridor analyses. In recent years these travel demand forecasting models have been proposed for use in estimating emissions, traffic operational analyses, and congestion management planning brought about by the passage of the federal Clean Air Act Amendments (1990), the California Clean Air Act (1988), and the California Congestion Management Program (1990). In the project described here new techniques that improve the capabilities of travel demand models as applied to emissions inventories were developed.

The purpose of maintaining a model-based system for projecting traffic volumes and speeds is to create a tool for revealing the impacts of future changes. Future population and employment growth in California will create increased travel. A model-based system will show where the changes in travel demand will occur, provided that the changes in land use are accurately projected and distributed into the correct traffic analysis zones. Travel patterns shift when new roadway capacity is added to the transportation system. Travel demand models were developed in part to provide an understanding of these changes in the distribution of travel after the network is altered. New policy mandates that require changes in travel behavior have been issued. Transportation control measures are being developed in response to legislation on congestion management and improving air quality. The impacts of implementing these measures on the transportation system are better understood by using travel demand models.

The link-prototype system was used to factor average daily traffic into hourly volumes by vehicle type for a day of the week during summer. For most applications these same factors would be used in forecasts for future years. The possibility exists that any one or a combination of these factors may be altered to reflect future changes. Seasonal variation may change in the future, but the California Department of Transportation currently tracks seasonal variation for its districts, and trends in seasonal variations could be projected.

Future changes in the distribution of hourly volumes by vehicle type are more difficult to predict. Perhaps an additional layer that would assist in future year forecasts could be developed for the prototype system. As congestion builds the peaking characteristics on a facility change. Different hourly volume curves reflecting congested versus free-flow roadway segments could be developed. These new curves would be applied according to the projected volume-to-capacity ratio of a specific link.

Changes in travel by vehicle type are also difficult to predict. Significant changes in heavy-duty truck travel are of most concern because the emissions rates are much higher for this vehicle type. Predictions of future heavy-duty truck travel must account for a complex interaction of changes in the economy and policy changes that affect the movement of goods. For most modeling applications the vehicle type distribution will be held constant for the future.

## RESEARCH AND DEVELOPMENT NEEDS

The use of county travel demand models in regional emissions inventories is relatively recent. With this use of the models there are different needs for accuracy and usefulness of the model outputs from those required for the models originally established for travel demand forecasting. Further research and development of this knowledge will improve the usefulness of travel demand models as applied to vehicle emissions inventories. One such area is improvements in the quality and accuracy of land use data. Improved modeling techniques are required to ensure comprehensive coverage of all trips, particularly non–home-based trips and multiple-purpose trips. In addition travel demand models that forecast travel during the weekend are rarely developed. Long-distance commute travel between regions is a relatively new phenomenon not incorporated into the modeling process. Model networks are developed as a schematic of the actual roadway system.

For purposes of emissions inventory, the comprehensive coverage of all trips is important because starting a vehicle has a significant impact on emissions. Research is necessary to develop a better understanding of non–home-based trips, particularly commercial trips, and of multiple-purpose trips or trip chaining. These trip types may be significantly underreported in a home interview survey. Commercial travel is incorporated into the non–home-based category in the trip generation step of the modeling process. This category must capture many different types of travel, such as work-based shopping in addition to commercial travel. Existing travel demand models estimate single-purpose trips, but trip-making behavior is sometimes determined by multiple-purpose trips. Better methods of handling non–home-based trips and multiple-purpose trips will improve emissions inventory estimations.

Regional travel models are designed to represent an average annual weekday, although air quality standards have been violated during summer months and frequently on weekend days. The link-prototype system was used to make adjustments for day-of-the-week and seasonal variations. This method captures the changes in volumes but does not relocate the trips to different links. Better application of knowledge on social and recreational travel to separate models for weekend and summer travel activity is needed to better locate these trips spatially. Weekend travel is clearly different from weekday travel. Adjustments for summer travel based on observed seasonal variations may be adequate, but differences in trip generation rates for different trip purposes should be investigated for both summer and weekend travel.

Every travel demand model has a coordinate system that places the nodes that serve as the endpoints for links into a two-dimensional plane. The past requirements of travel demand models did not include the precise placement of these nodes such that they match the locations of roadway intersections on a U.S. Geological Survey map. The eight county models of the San Joaquin Valley were readjusted to meet air quality modeling requirements. Grid systems of 2 or 5 km are often used in air quality modeling to locate emissions spatially. A systematic method of improving the coordinate system in the link networks for the numerous travel demand models in the state must be developed. The need to improve the coordinate system is one example of the different requirements transportation modelers must address to successfully apply the travel demand modeling system to the needs of vehicle emissions inventories.

*Publication of this paper sponsored by Committee on Transportation and Air Quality.*

# PART 4

# Noise

# La Guardia Airport Ground-Noise Abatement Study

DOUGLAS E. BARRETT AND CHRISTOPHER W. MENGE

An airport ground-noise abatement study was conducted for the Port Authority of New York and New Jersey along the western boundary of New York City's La Guardia Airport between 1986 and 1988. The investigation included measurements to characterize multiple noise sources, analysis of noise abatement options, and postconstruction measurements. The noise barrier design was conducted by using one-third-octave band analysis to predict expected loss of excess ground attenuation, barrier insertion loss, and net noise reduction. The study used the DIFRCT model developed by Embleton, Piercy, and Isei to calculate noise barrier insertion losses in the presence of ground effects. Although an example of one particular application and not a thorough review of the model is provided, the following conclusions were noted. The modified DIFRCT model was useful in predicting the ground effect owing to soft ground, especially at lower frequencies. In addition the study indicated that the model may be limited in its applications to hard-ground situations because of lack of coherent long-distance propagation at higher frequencies.

La Guardia Airport, located in the Borough of Queens in New York City, is operated by the Port Authority of New York and New Jersey (the Port). In response to community concerns regarding noise at La Guardia Airport during the night, the Port commissioned Harris Miller Miller & Hanson Inc. (HMMH) to conduct a noise study along the airport's western boundary. The purpose of the study was to identify major noise sources affecting residents and to assess the feasibility of using noise barriers to reduce noise levels. The residents complained of multiple night-time noise sources, but the loudest and the source of the most complaints were commercial jet aircraft departures on Runway 04.

Well-organized community members complained that noise levels and the number of sources had steadily increased for years along the western boundary of the airport. The Port's proposal to reopen the Marine Air Terminal near the airport's western boundary provoked significant community concern, and the Port agreed to undertake a noise abatement study.

The study focused on the feasibility of a noise barrier, considered to be the most comprehensive form of abatement for the numerous noise sources. In addition to appropriate locations for a barrier, the study addressed attainable insertion loss as a function of frequency, noise source, receiver location, barrier height, and barrier location. Owing to the presence of both soft and hard ground between the various source areas and the community, the analysis accounted for the effects of ground type with state-of-the-art modeling as described below.

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## BARRIER EFFECTIVENESS IN THE PRESENCE OF GROUND

Noise-barrier effectiveness at airports is often limited by restrictions on barrier placement, deleterious wind conditions, and loss of soft ground attenuation. Because of the long propagation distances and the presence of soft ground, it was suspected that ground effect could play a significant role in the La Guardia study.

The upper portion of Figure 1 shows a typical noise source and receiver geometry with the direct and reflected sound paths. The difference in length between the direct and the reflected paths is commonly referred to as δ. The reflected wave must travel an additional distance δ and arrives at the receiver behind the direct wave. Assuming an infinitely rigid ground surface (hard ground), the reflected wave is not significantly affected by the ground itself and is shifted in phase by an amount corresponding to the path difference δ. The phase shift causes constructive and destructive interference (wave addition and cancellation, respectively) at the receiver that is a strong function of frequency.

The assumption of an infinitely rigid surface has been shown to be a good approximation of reflections from very hard surfaces such as old asphalt or concrete (*1*). With softer surfaces, such as grass-covered fields common at airports, phase shift occurs on reflection. In situations with such soft ground the resultant phase difference at the receiver between the direct and the reflected waves is due to the combined effects of the path length difference and the reflection phase shift. This combination causes common soft-ground attenuation when δ is small, and the reflection phase shift is nearly one-half wavelength over a wide frequency range.

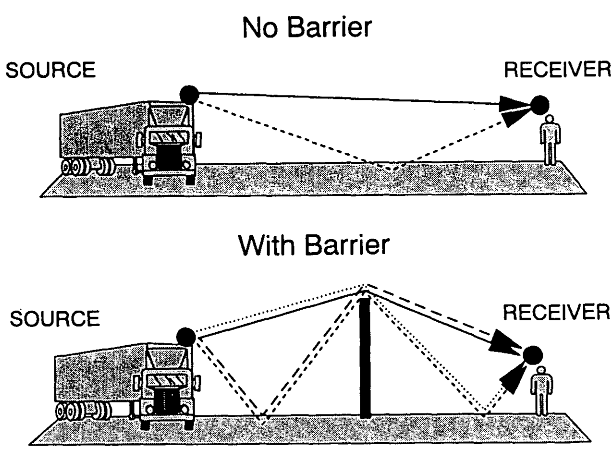


**FIGURE 1 Propagation paths: (*a*) with no barrier and (*b*) with barrier.**

At airports HMMH measurements have confirmed that this attenuation frequently reaches 10 to 15 dB and can span the frequency range from below 200 to above 2000 Hz.

Destructive interference, as described in a situation without a noise barrier, can also occur behind a noise barrier. Although the fundamental causes of the interference pattern are the same as in the no-barrier case, the addition of a noise barrier introduces multiple sound propagation paths. The lower portion of Figure 1 shows the most important of these paths including the direct diffracted path and three diffracted and reflected paths. Traditional barrier models do not account for these additional paths and as a result may overestimate barrier performance (*2*).

A traditional model used for barrier attenuation analysis is commonly referred to as *Maekawa Curves* (*3*). This model is based on Kirchoff-Fresnel diffraction theory and incorporates an adjustment of approximately 2 dB to account for loss of ground effect that is constant across all frequencies (i.e., the Maekawa Curves reduce the barrier attenuation predicted by free-field Kirchoff-Fresnel theory by 2 dB). This is the model used in FHWA's STAMINA 2.0 highway noise prediction computer program (*4*).

In an effort to model the attenuation of barriers in the presence of soft ground more precisely, the DIFRCT model was developed by Isei et al. (*2*). DIFRCT preserves the phase of the sound wave along each path as it propagates from source to receiver and evaluates the net wave at the receiver on the basis of multiple paths. The phase differences caused by differences in path length and the frequency-dependent phase shift on reflection are accounted for by the model.

To determine the phase shift on reflection, DIFRCT uses the specific flow resistance of the modeled ground. Delany and Bazley (*5*) had previously shown that complex ground impedance can be adequately described by flow resistance for a wide range of common materials and surfaces. Although DIFRCT was developed analytically, Piercy and Embleton (*1*) and Nicolas et al. (*3*) tested the model extensively at short distances with various ground surfaces to determine empirically values of flow resistance for modeling different types of ground.

Figure 2 shows output from DIFRCT typical of the type that was used to calibrate the model for different types of ground. The solid curve shows attenuation caused by ground effect only. The broad, deep dip is the result of destructive interference at low frequencies primarily owing to a phase shift on a reflection since the path length difference of the direct and the reflected waves is small compared with a wavelength. The dashed curve shows the ground effect with a 6-m (20-ft)-high barrier in place. This curve includes only the ground effect for the barrier and does not include barrier attenuation. The difference between the two curves is the amount of ground-effect attenuation that would be lost if a barrier were constructed. The difference is as high as about 15 dB and extends from about 400 to 2000 Hz. Because of the loss of attenuation owing to ground effect, the overall sound level (not yet accounting for barrier attenuation) increases by about 5 dB with the barrier present. In this case to depend only on the Fresnel theory without accounting for loss of ground effect could result in a 5-dB overestimation of barrier performance. Use of the Maekawa model with its assumption of an overall 2-dB loss of ground effect could result in a 3-dB overprediction.

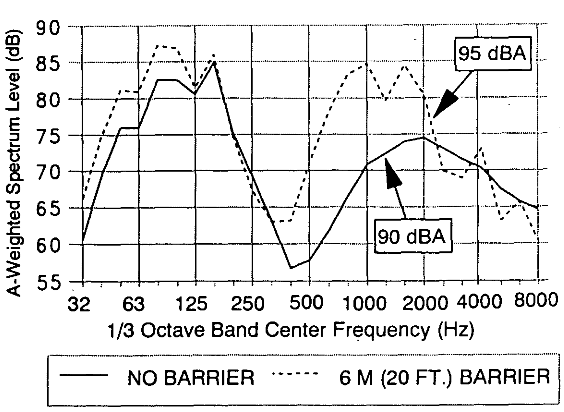


**FIGURE 2 Soft-ground effect only.**

Although DIFRCT correlated well with Piercy's and Embleton's test measurements for a variety of ground conditions, the model had not been used in a study with long propagation distances; therefore, the authors were concerned about the effects of atmospherics and unevenness in terrain. Some encouraging data for such a model existed, however; Parkin and Scholes (*6*) had noted evidence of coherent propagation and interference patterns at distances of up to 1000 m (3,300 ft) in a study of aircraft reverse thrust, especially at lower frequencies. HMMH modified DIFRCT to compute ground-effect interference at one-ninth-octave band center frequencies instead of one-third-octave bands. This modification made the model less sensitive to small changes in geometry and was referred to as *DIFRCT9*. DIFRCT9 combines the ninth octaves to third octaves before output. This approach was chosen instead of a numerical integration method to reduce computation time.

## LA GUARDIA STUDY BARRIER ANALYSIS

Jet aircraft departures on Runway 04 were the source of the most noise complaints from the neighborhood along La Guardia's western boundary. The closest homes are approximately 425 m (1,400 ft) from Runway 04 and located relative to the runway such that they are exposed to the highest sound levels from jet engines during the start-of-takeoff roll (an angle of about 45 degrees from the rear of the engine). Maximum sound levels at one measurement site (Site 1) on the front porch of a home typically ranged from 90 to 100 dBA during jet aircraft departures.

With no noise barrier the reflection point for noise from aircraft starting takeoff roll on Runway 04 occurred on a broad area of asphalt near one of the rental car facilities approximately midway between the runway end and Site 1. The broadness of the area suggests that for slightly different geometries (e.g., as the aircraft begins to move down the runway or for a listener at one of the homes adjacent to Site 1) the reflection point would still be on asphalt. With a 6-m (20-ft) noise barrier the reflection point on the source (airport) side of the barrier is located on an area of soft ground, whereas the receiver (community) side reflection is on asphalt.

The ground-effect attenuation for the Site 1 geometry in the no-barrier case was evaluated with DIFRCT9 and revealed only a shallow and narrow dip at about 2500 Hz. This was because of the hard-ground reflection with negligible phase shift. The selected flow resistance was 20,000 cgs rayls, consistent with Em-

bleton's measurements on asphalt. If the reflection point had occurred on soft grass (300 cgs rayls), the more significant phase shift on reflection would result in a broader and deeper ground-effect dip occurring at a lower frequency.

Figure 3 compares the DIFRCT9 calculations and the Maekawa model for a Boeing 727 departure at Site 1. The solid curve on the graph shows the recorded spectrum with no barrier present and an overall sound level of 91 dBA. The dashed curve is the computed attenuated spectrum with the Maekawa model with a 6-m (20-ft)-high barrier. The Maekawa Curve is fairly smooth, reflecting the assumptions of frequency-independent loss of ground effect and greater attenuation with increasing frequency. The dotted curve shows the prediction of the DIFRCT9 model for a 20-ft-high barrier. At the lowest frequencies (up to about 100 Hz) the output of DIFRCT9 is very close to that of the Maekawa model, but between about 100 and 1000 Hz, there is a broad, deep dip because of the effect of the airport-side reflection point on grass. Above 1000 Hz, DIFRCT9 predicts less attenuation than the Maekawa model. The peak centered at about 2500 Hz reflects the loss of the no-barrier ground-effect dip at 2500 Hz. Although the resultant spectra from the Maekawa and the DIFRCT9 analyses are very different, for this particular case the predictions of overall A-weighted insertion loss are similar: 10 dB for DIFRCT and 9 dB for Maekawa.

Although Embleton and others observed phase coherence at upper frequencies at distances of up to 15 m (50 ft), it is likely that such coherent propagation may break down over long distances because of atmospheric turbulence and small variations in ground elevation. These conclusions are supported by the observations of Parkin and Scholes (*6*), who noted phase coherence chiefly at lower frequencies at long propagation distances outdoors.

In other portions of the study area the reflection points were on hard ground in both the no-barrier and with-barrier situations. In several of these cases DIFRCT9 predicted amplification in some middle and high frequencies, and it is possible that potential insertion loss was underestimated. Because amplification in the high frequencies is not consistent with the experience of HMMH in other barrier studies over hard ground, the traditional Maekawa model was used for these situations.

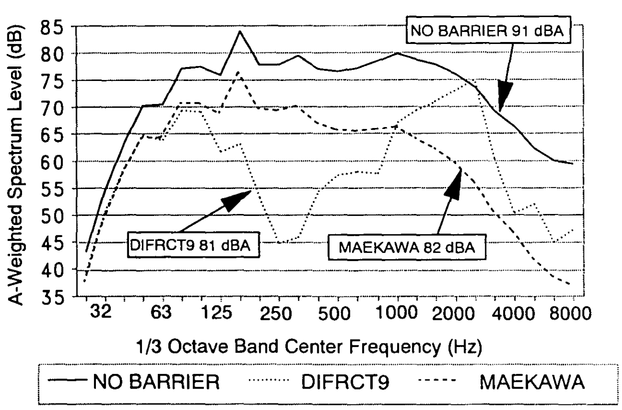


**FIGURE 3 Boeing 727 departure spectrum at Site 1 with no barrier (measured) and a 6-m (20-ft) barrier.**

## POSTCONSTRUCTION MEASUREMENTS

In response to a request by the community, the Port and HMMH perform postconstruction measurements to determine the performance of the completed barrier. Because of dissimilar weather conditions it was not possible to perform comparison of postconstruction measurements in accordance with the standards of the American National Standards Institute (ANSI) (*7*). As a result the postconstruction measurements could not be compared directly with the preconstruction measurements. Instead the ANSI reference microphone method was used.

The data microphone was located in the same position as the microphone in the preconstruction measurements. The reference microphone was located on a post above the top of the barrier to measure the no-barrier sound level. A third microphone was located on the airport side near the base of the barrier, at a height of 1.5 m (5 ft) above the ground, to approximate the ground effect in the prebarrier situation. Adjustments were made to account for the various source-to-microphone propagation distances, for pressure doubling at the base of the barrier, and for reflections from the facade of the house at the data microphone position. Simultaneous tape recordings of approximately 30 Boeing 727 departures were made at these three locations. In addition to postconstruction measurements at Site 1, postconstruction measurements were also made at a hard-ground site on the middle block of the study area.

The postconstruction measurements gave a fair match to the predictions at Site 1, with a measured net noise reduction of 7 dB compared with a predicted reduction of 10 dB. The postconstruction measurements showed better agreement at the hard-ground site, with a measured insertion loss of 12 dB and a predicted noise reduction of 13 dB. The lack of better agreement was not unexpected because of the differences in weather conditions between the preconstruction and postconstruction measurements. Differences in wind, atmospheric turbulence, and refraction because of a temperature gradient could affect the reflection points, possibly moving a reflection point from hard to soft ground or vice versa, thus creating a different ground-effect situation than the one modeled. It is expected that the prediction at the all-hard-ground site would be more stable under various weather conditions because of the smaller role of ground effect and the lack of hard- and soft-ground boundaries.

## CONCLUSIONS AND RECOMMENDATIONS

The La Guardia study demonstrated that the DIFRCT9 model is useful in predicting the ground effect due to soft ground, especially at mid and low frequencies. However the results of the study also indicate that the model may be limited in its application at higher frequencies (above 2000 Hz), particularly over hard ground, because of lack of coherence in propagation over long distances. On the basis of the results of the La Guardia and other studies, the authors continue to use the Maekawa model in the absence of soft ground. In the presence of soft ground the ground-effect portion of DIFRCT9 is used only to predict ground effect in both the no-barrier and with-barrier cases. When possible the authors also perform simultaneous measurements at multiple microphone heights to help predict the potential loss of ground effect. The authors no longer use the barrier portion of DIFRCT9 directly, but instead combine the ground-effect results of

DIFRCT9 with Fresnel theory (evaluated for the direct-diffracted path) to predict net insertion loss.

## POSTSCRIPT

Since completing the La Guardia study, the authors have seen similar results in noise barrier studies at other airports, including those at Dallas Love Field, Baltimore-Washington International, and Syracuse, New York. Most recently at Syracuse HMMH made simultaneous measurements of aircraft start-of-takeoff events with microphone heights of 1.5 m (5 ft) and 7 m (23 ft) above ground level at the same location. The 1.5-m (5-ft) microphone height represented the position of a typical ground-level receiver, whereas the 7-m (23-ft) position represented the diffracting edge at the top of a potential noise barrier. Over soft ground at typical propagation distances of 450 m (1,500 ft) to 600 m (2,000 ft), the measurements indicated that the difference in ground effect between the two heights ranged between 6 and 13 dB over the broad frequency range from approximately 250 to 2500 Hz. This difference represents the loss of ground-effect attenuation that would be caused by the construction of a noise barrier and is similar to that shown in Figure 2. The ground-effect portion of DIFRCT9 agreed well with the Syracuse measurements, predicting a loss of ground effect of 8 to 15 dB over the same frequency range (*8*). This slight overprediction of loss of ground effect produces a conservative underestimation of barrier performance.

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# Helicopter Noise in Rural Communities: Assessment of Existing Knowledge

P. D. PREVEDOUROS

Existing knowledge on helicopter noise focused on the effects of distance and altitude on ground-level noise, the annoyance caused by helicopter noise expressed by people, and the consequences of findings for helicopter operations in rural areas are presented. A nonlinear association between ground-level noise, altitude, and slant distance was identified. A combination of altitude, standoff distance, and cruise speed for each helicopter type at which ground level noise is minimum appears to exist. Also there is a considerable difference between desired and actual noise levels for rural areas even if penalties are not assessed on the measured helicopter noise. A gap in the connection between actual helicopter noise measurements and community annoyance was also revealed. Specific guidelines or regulations that define paths (separation), the frequency of helicopter flights per path, and the minimum standoff distance and altitude may be necessary for semirural and recreational areas.

There are several studies on helicopter noise measurements for certification, design, and modeling purposes as well as an immense amount of acoustical literature on noise measurements, human response and annoyance, and methodologies for the quantification of human response to aviation noise. However much less is known about helicopter-induced annoyance. In addition there are concerns about the applicability of existing methodologies for the assessment of annoyance and community reaction to noise in situations of infrequent helicopter flights over rural communities and recreational areas.

Specifically concerns have been expressed about whether current methods (i.e., those applied to small, propeller-driven aircraft) of measuring and predicting community response to helicopter noise are adequate. These methods are partly based on the A-weighted day-night average sound level ($L_{dn}$). Several researchers have strong objections to using $L_{dn}$ under certain circumstances. Schultz (*1*) reports, "Just as the statement that the average depth of a river is 2 ft. may conceal the existence of a pool deep enough to drown in, the restriction of noise exposure in a neighborhood to an average noise level may still permit quite loud and annoying noises, if they are short enough in duration." Dunholter (*2*) observes that noise problems have been located in areas that, on the basis of the $L_{dn}$ criterion alone, would not be expected to have a severe problem. Firle (*3*) goes further by reporting that $L_{dn}$ is not only inadequate to give a realistic picture of the impact of aircraft noise but also may lead to erroneous abatement programs. Igarashi (*4*), a proponent of the $L_{dn}$, admits that in the case of small number of flights, $L_{dn}$ values are extremely small, thus they may not represent annoyance properly. Such occurrence is predominant in the National Park system, in which otherwise quiet areas are intermittently disturbed by low-level sounds from aircraft flights (*5*).

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Given that $L_{dn}$ may not be an adequate descriptor of noise intrusion and annoyance from infrequent flights, the Environmental Protection Agency (EPA) noise levels (*6*) based on $L_{dn}$ may be inappropriate for evaluating effects of noise from infrequent helicopter flights over rural communities. Consequently discrete noise measurements for each event may be a better way of describing the noise intrusion and annoyance felt (as discussed later).

The issue of helicopter noise is of particular significance to Hawaii because of the large number of tour helicopter flights over rural communities (e.g., Hawaii is only second to the Grand Canyon in terms of tour helicopter operations). Although it was reported (*7*) that $L_{dn}$ levels in rural communities are acceptable, a considerable number of complaints are filed regularly (e.g., 591 and 317 complaints in 1990 and 1991, respectively). The consultants (*7*) performed a number of field measurements. A sample from two locations on Kauai is shown below.

| *Location* | *No. of Daily Helicopter Flights* | *No. of Helicopter Flights Measured* | *Helicopter* $L_{max}$ | *Helicopter* $L_{dn}$ | *Ambient* $L_{dn}$ |
|---|---|---|---|---|---|
| 1 | 29 | 18 | 68 | 47 | 30 |
| 2 | 133 | 28 | 72 | 53 | 50 |

Obviously the EPA standard of $L_{dn}$ = 55 dBA is fulfilled when the helicopter flights are included, but the $L_{max}$ is considerably higher than the ambient noise level. The number of daily flights is also considerable. The issue has reached a point at which representatives in the U.S. Congress and university researchers have been called to address the issue.

## FUNDAMENTALS OF HELICOPTER NOISE

The character of the noise produced by helicopters is diverse. Each of the primary noise sources—main rotor, tail rotor, and engine—produces distinctive noises. The combination of the sound from the tail rotor and the main rotor (the sound of which varies from mid to high frequencies) results in a unique sound signature for each helicopter type (*8*). According to Hilton and Pegg (*9*), the main sources of noise of four helicopters are the following:

| *Helicopter* | *Main Source of Noise* |
|---|---|
| Bell 204 | Main rotor |
| Bell 206 | Tail rotor |
| Bell 47 | Engine |
| Hughes 269 | Engine and tail rotor |

The noises of these individual sources may vary under different operating conditions. At low airspeeds or during hover, the helicopter needs a higher power setting than at intermediate airspeeds. Likewise at high airspeeds increased power is needed. Thus helicopters generally produce a minimum sound level at some inter-

mediate airspeed, with higher sound levels at lower and higher airspeeds (*10*). For example the Hughes 500C helicopter produces lowest ground level noise when flown at about 185 km/hr, whereas the Bell 206L helicopter is quietest at 222 km/hr (*11*).

A primary characteristic of helicopter noise is the blade slap that occurs when one of the rotors passes through the wake created by another blade, especially on descent. A different acoustic mechanism generates blade slap in high-speed forward flight: the advancing side of the rotor combined with the flight speed causes the blade to become transonic (*12*).

During takeoff the interaction that creates blade slap does not occur, and takeoff noise is similar to level-flight noise (*10*). However the total (engine, gearbox, rotors, and interactions) sound level is much louder during take off: the sample of 153 observations analyzed and described below (all of the data are from turbine-powered helicopters) resulted in noise levels of 79 dBA for landing and 85 dBA for takeoff; the difference between the two is significant at the 97 percent level of statistical confidence. Both maneuvers tend to be considerably noisier than most flyovers at 100 m above ground level or higher.

This is significant when the locations of helicopters are considered. Obviously heliports should be sufficiently far away from residential areas, particularly in suburban and rural communities, where low ambient levels of noise are the norm. Noise complaints from takeoff and landing operations are nearly nonexistent in Hawaii, largely because most helicopter flights originate at airports with considerable aviation traffic.

## GROUND-LEVEL NOISE, ALTITUDE, AND DISTANCE

Although at a close range helicopter noise violates community noise standards, at a proper combination of altitude and standoff distance the noise impacts at ground level are reduced to acceptable levels. This section presents existing flight regulations or recommendations as well as the results of analysis of correlations among ground-level noise, altitude, and distance.

FAA Advisory Circular 150/5020-2 (*13*) recommends that the flyover altitude should be chosen to be the highest practicable on the basis of the fact that doubling of the flyover height decreases the peak sound level heard on the ground by more than 6 dBA. FAA Advisory Circular 91-36B recommends a 600-m (2,000-ft) minimum altitude over populated areas. The FAA supports both the designation of visual flight rule corridors specifically for helicopters and the helicopter industry's Fly Neighborly Program (FNP).

A large number of helicopter noise measurements ($L_{max}$) taken at airports and heliports of large U.S. cities have been presented previously (*14*). The altitude, distance, and the executed maneuver during the sound measurement are specified. The data were computer coded and analyzed. The original data contain more than 500 observations. Of those, only 153 were selected and coded because (a) altitude and distance were missing from several observations, and (b) multiple measurements were taken during a given maneuver by the same helicopter. In the latter case, inclusion of measurement other than one of those listed would violate the assumption of independence of observations, which is required for statistical analysis.

Slant or euclidian distances (i.e., straight-line distance between receptor and helicopter) were computed because initial investigation showed that horizontal distance alone and altitude alone did not correlate well with measured sound pressure levels. A nonlinear relationship between measured dBA and slant distance was revealed. The following best-fit model was estimated by regression analysis:

$$L_{max}\ (\text{dBA}) = \underset{[99\%]}{95.3} - \underset{[99\%]}{0.915}\ (\text{slant distance; ft})^{1/2} + \underset{[90\%]}{2.2}\ (\text{L or TO}) \quad (1)$$

where L or TO indicates landing or takeoff (1 if $L_{max}$ is estimated for a landing or take off, and 0 otherwise) ($N = 153$ observations, $R^2 = 0.69$, the significance of the coefficients is given in brackets).

A number of studies (*11,15*) analyzed the noise characteristics of several helicopters. The data indicate that the ground-level noise produced by light-duty helicopters, which are typically chosen for sightseeing and inspection operations, often exceeds 75 dBA in flyovers at a 450-m distance from the observer (i.e., at the minimum altitude or standoff distance of 1,500 ft specified in the Hawaii FNP).

## ANNOYANCE FROM HELICOPTER NOISE

The connection between noise and annoyance is of significant interest largely because annoyance is a key determinant of how acceptable a noise is. Noise is an objective measure of sound levels, whereas annoyance is a complex index of the perception and reaction of people to a given sound. This section reports on the connections (or the lack of connections) between helicopter noise and annoyance.

Fidell et al. (*16*) offer the following model for estimating the percentage of people in a community who are likely to be highly annoyed (HA) by transportation noise sources:

$$\text{HA (percent)} = 78.9181 + 0.0360\ L_{dn}^{2} - 3.2645\ L_{dn} \quad (2)$$

This model incorporates about 40,000 surveys from 32 studies. None of the data used in the estimation of this model is from helicopter operations. Green and Fidell (*17*) also found statistically significant evidence that people are on average more willing to report annoyance caused by aircraft noise exposure than street and rail traffic.

Tolerance to helicopter flyovers diminishes after a certain number of flights is exceeded. At frequencies exceeding eight helicopter flyovers per day the following concerns increase dramatically (*18*):

1. Large numbers of helicopter flights over residences,
2. Low-flying helicopters,
3. Noise, and
4. Inability of the government to regulate or control helicopters.

Fields and Powell (*19*) reported similar results, plus

1. Fear of helicopter crashes,
2. Belief that the helicopter noise could be prevented (increased annoyance if people believe that pilots or regulations could reduce the noise), and
3. Willingness to tolerate helicopter flights if the missions are of high importance.

Qualitative assessments must be connected to quantitative information and to specific recommendations or regulations to reduce the degree of annoyance. FAA Advisory Circular 150/5020-2 (*13*) includes recommendations on the maximum number of helicopter flights per hour when the community sound level is exceeded by a given level. The FAA uses the sound exposure level (SEL). If the ambient noise level of a rural community is approximately 50 dBA (as in Location 2 in the first in-text table) and the helicopter's SEL is 76 dBA, then a maximum of about nine flyovers per hour is recommended on the basis of the corresponding difference of 26 dBA. [This estimate corresponds to that for the popular Bell 206L-1 helicopter during level flight at 183 km/hr at a 330-m altitude and 330-m distance. This combination of altitude and distance results in a slant distance of 425 m, which is close to the 450-m standoff distance recommended in the Hawaii FNP. The SEL was calculated from data presented previously (*15*, p. F-469).] This translates into one flyover every 6.5 min, which may not be acceptable to rural residents. Even if this estimate is acceptable, FAA recommendations apply to heliport planning only. There is no recommendation that SEL should be the preferred noise measurement methodology in rural areas. Such use of the SEL offers an upper bound for the number of operations in rural areas, whereas $L_{dn}$ does not.

A large part of the literature on helicopter noise (and more generally on impulsive noise) focuses on the need for penalties that may need to be added to measured sound levels so that they reflect the degree of annoyance felt by people more accurately. The results of several major studies follow.

A review and evaluation of 34 studies based on psychoacoustic experiments assessed the need for penalties on loudness from helicopter noise (*10*). The main conclusion was that there is no need to measure helicopter noise differently from other aircraft noise, although it was acknowledged that the results of the reviewed studies were often conflicting. A more recent study by Schomer et al. (*20*) involving real-world experiments has found that helicopter noise measured on either the A or the C scale must be corrected to better correspond to human perceptions. They used the A-weighted SEL and found that a 10-dB penalty should be added to the measured SEL of the sound from two-bladed helicopters and an 8-dB penalty should be added to the SEL from multibladed helicopters.

Schomer and Neathammer (*21*) noticed that human reaction is strongly influenced in a negative way when the helicopter noise induces rattle of the objects in the house or vibration of the building in general. [Some complaints in Hawaii include fear and annoyance from rattle caused by helicopter flyovers. Such complaints do not apply to tour operations except when weather confines flights to very low altitudes.] Their results suggest a need for a penalty in the order of 10 dB to assess annoyance from helicopter noise properly when vibration and rattle are produced. Considerable rattle is not likely to occur at slant distances exceeding 300 m, but rattle is nearly certain when slant distance is less than 150 m. The vibration avoidance distance usually varies with the type of helicopter and executed maneuver.

Several sources (*22,23*) indicate that acceptable maximum sound levels to residents are 35 and 40 dBA for bedrooms and living rooms, respectively. They also recommend (with some variance) that these criteria should be increased by about 5 and 10 dBA for suburban and urban residential areas, respectively. A zero increase is recommended for hospitals and recreational and rural areas. In addition a 5-dB penalty should be added to noise measurements in locations in warm climates to account for the more open-air living, including open windows and thinner insulations (*24*).

The desired standards form the one side of the equation (e.g., the maximum desired noise for living rooms in rural areas is 40 dBA). The other side of the equation is the actual noise level: model estimates plus penalties yield a maximum actual helicopter noise of 75 dBA [model estimate of 60 dBA (equation 1 for a helicopter overflight at 450 m) plus the impulsive noise penalty of 10 dBA plus the warm climate location penalty of 5 dBA]. The comparison reveals a large difference between actual and desired noise levels. Even if the penalty for impulsive noise is not assessed, there is still a considerable difference between desired and actual noise levels for warm-climate rural areas (e.g., $60 + 5 - 40 = 25$ dBA).

## DISCUSSION OF RESULTS

A nonlinear association between ground-level noise, altitude, and slant distance prevails. There is evidence that for each helicopter type an optimum combination of altitude, standoff distance, and cruise speed exists whereby ground level noise is minimized. Thus the ground-level noise for a number of altitude and speed combinations for each helicopter type could be identified with field experiments and noise propagation modeling. Then maps with maximum noise tolerances (depending on the land use) could be created. Using these maps, pilots may choose to adjust either their flight path (i.e., avoid the sensitive area altogether) or the flight characteristics (i.e., change their altitude and speed so that the helicopter's ground-level noise will not exceed the specified limit). The feasibility and necessity of such actions should be evaluated, and FAA must decide whether such guidelines should be recommended or mandated.

Tolerance to helicopter flyovers tends to diminish quickly with an increasing frequency of flights and an increasing difference between helicopter noise and ambient sound level. Alternative, separate corridors may need to be established, and traffic may need to be appropriately distributed among them to minimize the impact on the public. Also given the unique characteristics of and the manifested annoyance from helicopter noise, various studies propose penalties on helicopter noise measurements. The imposition of penalties may be appropriate. Penalties that are helicopter type specific should be considered for analysis and evaluation.

Self-regulation of the helicopter operators' industry through FNPs is promising, but a large number of flights are excluded from such programs. [For example, the Hawaii Helicopter Operators Association's FNP specifies, "If it isn't a tour flight, it is not covered (by the FNP)."] FNPs may need to be expanded to cover most types of missions and exclude mainly emergency, security, and court-warranted operations. In addition the public should be given ample opportunity to challenge local FNPs and easy access to state or federal agencies for reporting aviation noise complaints.

This review has revealed a clear gap in the connection between actual helicopter noise measurements and human reaction. Existing studies can be grouped into three categories: (a) studies of helicopter noise measurements that, although many exist, primarily use measurements from airports or heliports taken for certification purposes or for other technical inquiry; (b) studies on community reactions that are of rather limited applicability to rural

residential areas because they were conducted in communities adjacent to military bases, focusing primarily on military helicopters; and (c) studies commissioned by the National Park Service, which generally are market opinion oriented and focus exclusively on the reactions of visitors and naturalists.

Not only is existing knowledge of the connection between actual helicopter noise measurements and rural, residential community annoyance limited, but also the derivations of estimates of acceptable noise levels and community reaction, based on inferences from knowledge gathered in other settings, may be erroneous. Thus study of this topic focusing exclusively on rural and recreational lands where opposition to helicopter flights is strong and growing seems necessary.

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# Procedures for Prioritizing Noise Barrier Locations on Freeways

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The ranking of potential noise barrier locations is not a straightforward process and requires consideration of several criteria. The development of multicriteria ranking procedures for prioritizing the locations with noise problems is discussed. Three ranking methods were developed to determine the priority of each of the candidate projects. They are sequential ranking scheme (SRS), analytic hierarchy process (AHP), and weighted index methods. These methods are presented, and their application to a set of data from the Chicago area is discussed. Each of these methods can be used independently by the users. It is proposed that a combination of the SRS and AHP methods be used to improve computational efficiency when a large number of locations are to be ranked. The ranking variables used in developing these procedures are existing noise level, number of people affected, land use type of the adjacent area, and effectiveness and feasibility of building a noise barrier at that location. The ranking variables and their relative importance are the user-specified inputs to these procedures.

The selection of locations where noise barriers should be put up is not straightforward because several criteria need to be considered. The Illinois Department of Transportation (IDOT) needed prioritization procedures to rank potential freeway Type II noise barrier locations in District 1 of IDOT (the Chicago area). This paper briefly discusses the development of multicriteria procedures for prioritizing the locations with noise problems in the Chicago area. Three ranking methods were developed: sequential ranking scheme (SRS), analytic hierarchy process (AHP), and weighted index (WI) methods. Application of these models to a set of data from the Chicago area is discussed. For further information about the procedures refer to Benekohal et al. (*1*).

## DEVELOPMENT OF NEW PRIORITY RANKING METHODS

### Determining Ranking Variables

Cohn (*2*) provided a brief description of the priority rating methods and variables used by 11 state highway agencies. After reviewing these ranking procedures and consultation with IDOT, it was decided that four variables would be used in developing the ranking methods. These variables are existing noise level, number of people, land use type, and effectiveness/feasibility factor. These variables are listed in decreasing order of importance. For a given condition the appropriate variables and their relative importance factors should be decided by the user.

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### Data Collection for Study Sites

There are approximately 223 centerline mi of Interstate freeway in District 1 of IDOT. The freeways were divided into 1-mi segments. Each side of the roadway was regarded as a separate segment. Therefore 446 segments were identified in the entire area.

For developing the ranking procedures 40 sites were selected from the population of 446 segments. A stratified random sampling with balanced outcome (SRSBO) method was developed and used (*1*). These 40 sites are expected to represent the population of expressways around the Chicago area with respect to land use type, freeway type, and freeway locations.

The land use type for each segment was determined by using the land use maps of the U.S. Geological Survey (USGS) (*3–6*). The predominant roadside development for a segment was used to group them into residential (R), commercial (C), industrial (I), public (P), or vacant (V). The land use types determined from the USGS map were further verified by using recent aerial photographs and video images of selected sites taken by the research team (*1*).

A computerized noise prediction program, STAMINA 2.0 (*7*), was used to compute noise levels. Because barriers are not considered for vacant sites, noise levels were not computed for them. Predicted existing noise levels for study sites are given in Table 1.

Data on the number of people were obtained mainly from 1990 Census data and the ITE Trip Generation report (5th edition). The census data were used to determine the number of people in residential areas. For areas of land use types other than residential, the number of people affected was computed (*1*) by using the ITE Trip Generation report. These numbers are shown in Table 1.

The effectiveness and feasibility of putting up a noise barrier was considered for each site. A value of between 1 and 9 was assigned to each site. The rationale for assigning such values is to determine whether a noise barrier can be physically constructed at that site and whether it can reduce the noise level. A guideline for assigning the feasibility/effectiveness factor (E/F in Table 1) is given below:

9—Ground level, enough space to put barrier, no gap on barrier because of a crossing road, no parallel roads behind.

8—Same as number 9, but with a low-volume parallel frontage road.

7—Ground level, enough space to put barrier, three or fewer crossing roads.

6—Same as number 7, but more than three crossing roads.

5—Elevated or depressed freeway with earth embankments, enough space to put barrier, three or fewer crossing roads.

4—Same as number 5, but more than three crossing roads.

**TABLE 1 Summary of Site Data**

| Site | Noise Level | Land Use | Fwy Type | No. of People | E/F | Site | Noise Level | Land Use | Fwy Type | No. of People | E/F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 72.4 | I | G | 176 | 8 | C43 | -- | V | G | 23 | 8 |
| A2 | 72.3 | C | G | 212 | 7 | C45 | -- | V | G | 13 | 8 |
| A11 | 72.4 | R | D | 141 | 5 | E3 | 65.0 | R | D | 300 | 5 |
| B10 | 71.4 | C | E | 157 | 3 | E12 | 69.6 | R | G | 53 | 7 |
| B14 | 71.7 | C | D | 383 | 2 | E22 | -- | V | G | 5 | 9 |
| B16 | 71.0 | R | E | 189 | 2 | E24 | -- | V | G | 44 | 9 |
| B17 | 66.0 | C | E | 206 | 2 | E33 | -- | V | G | 2 | 9 |
| B19 | 72.0 | R | D | 211 | 4 | F16 | 70.5 | V | G | 43 | 7 |
| B20 | 71.8 | R | D | 190 | 5 | F28 | -- | V | G | 17 | 9 |
| B21W | 74.4 | R | D | 429 | 5 | G0 | 69.6 | C | D | 267 | 3 |
| B21E | 74.7 | C | D | 100 | 5 | G6 | 66.7 | R | D | 147 | 2 |
| B23 | 69.5 | C | D | 286 | 5 | G7N | 67.8 | R | D | 211 | 3 |
| B25 | 73.4 | I | D | 112 | 5 | G7S | 69.9 | R | D | 58 | 2 |
| B26 | 71.3 | C | D | 211 | 5 | G10N | 70.5 | R | D | 139 | 5 |
| B37 | 74.8 | R | G | 131 | 7 | G10S | 70.5 | R | D | 187 | 5 |
| C2 | 69.3 | R | E | 344 | 3 | G16 | 72.2 | R | E | 46 | 4 |
| C7 | 66.8 | I | E | 31 | 5 | H1 | 69.4 | R | G | 107 | 7 |
| C20 | 72.2 | R | G | 70 | 7 | H5W | 70.5 | R | G | 40 | 8 |
| C22 | 70.9 | R | G | 50 | 8 | H5E | 72.1 | R | G | 135 | 8 |
| C26 | 70.5 | R | G | 161 | 8 | H10 | -- | V | G | 9 | 8 |

Notes: Land Use: R = Residential, C = Commercial, I = Industrial, V = vacant;
Fwy Type = Freeway type: G = Ground Level, D = Depressed, E = Elevated;
E/F = Effectiveness/Feasibility.

3—Elevated freeway on structure or depressed freeway with retaining walls, enough space to put barrier.

2—Same as number 3, but narrow space to put barrier.

1—Worse than the above.

### Sequential Ranking Scheme

Harness and Sinha (*8*) proposed a priority ranking approach in which projects were divided into progressively smaller subsets by using various criteria. McGeehan and Samuel (*9*) modified the procedure for prioritizing the road improvement. The method was further modified and improved and was used for priority setting in the project described here. The modified method is the SRS method.

The basic idea of the SRS method is to group candidate projects into different levels by progressively using each of the ranking variables, one at a time. Projects are first grouped into levels by using the most important variable. Then each project is evaluated by using the second most important variable. At this step a project may move to an adjacent higher or lower level or stay at the same level. This process is continued until the last variable is used for grouping (*1*).

The projects were grouped into the following four levels: top, high, medium, and low. The thresholds are decided beforehand on the basis of the evaluation of the range of each variable (*1*). Seven of 40 sites have vacant land use type, and building of noise barriers on those sites is not considered. The thresholds for number of people were 286 (85th percentile) for moving up and 157 (50th percentile) for moving down a rank. Sites that are of the residential type are moved up one rank, whereas sites that are of the industrial or vacant type are moved down one rank. For downgrading the rank of a project, an effectiveness and feasibility factor of 5 or less was considered.

Two additional rules are applied for changing the rank of a project. The rules are as follows. (a) If a project moved up or down in the previous step, it cannot move up again in the current step; however, it may still move down. (b) A project is not allowed to move up at the last step. The rationale for the first rule is to prevent a project from moving down in one step and moving up again in the next step. It also would prevent a project from moving up too rapidly on the basis of less important variables. The second

rule is used to prevent moving a project to a higher level on the basis of the least important variable. These rules may be modified by the users to fit their needs. The results of ranking are shown in Figure 1.

The main strength of SRS is that it is easy to learn and use, and the user can easily see where a project is located after applying each ranking variable. The main weakness of SRS is that it requires threshold values for each ranking criterion. Furthermore projects must be placed in a limited number of groups, and within a given group all projects are ranked the same.

## Analytic Hierarchy Process

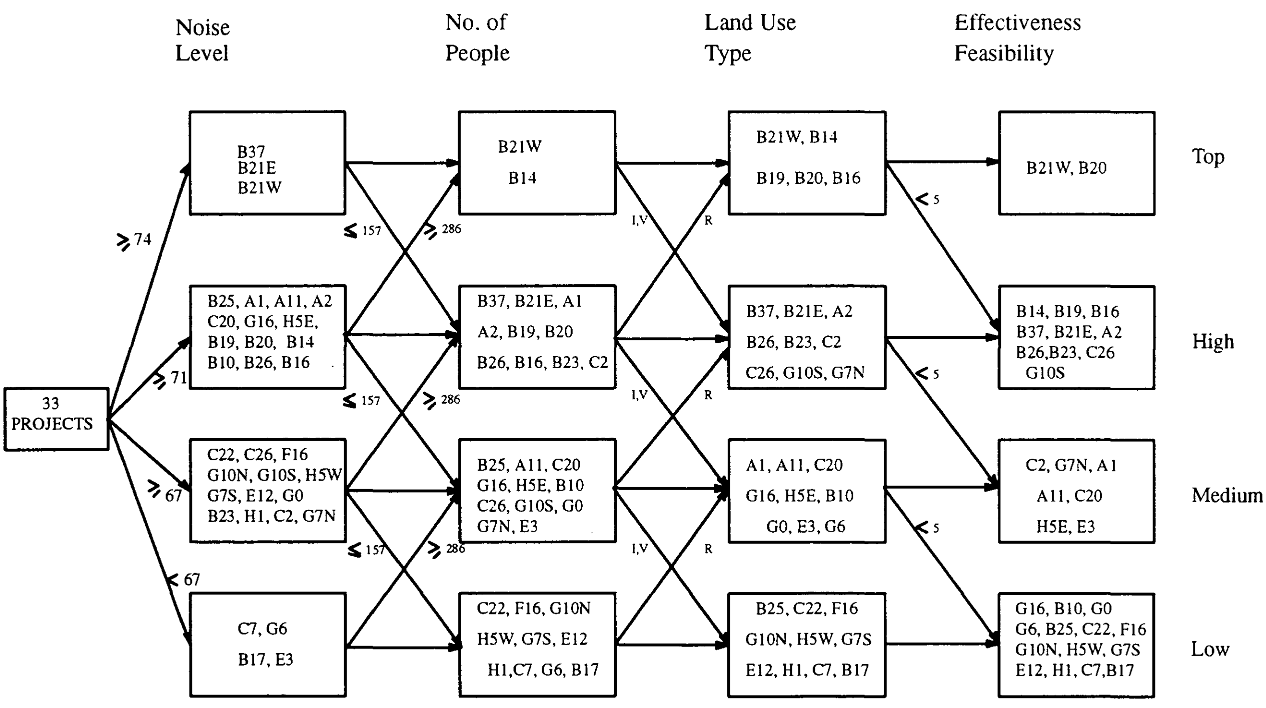
AHP is fully discussed in works by Saaty (*10*) and Saaty and Kearns (*11*). It is used to develop a methodology for modeling unstructured problems in the economic, social, and management sciences. The AHP is a systematic procedure for representing the elements of any problem hierarchically. The main idea is to break a large complex system that is to be dealt with into various independent or dependent subsystems. The decision makers are guided through a series of pairwise comparison judgments to express the relative strength and intensity of impacts of the elements in the hierarchy. The relative comparisons are processed through numerical expressions.

Using AHP for priority ranking the overall evaluation is performed by constructing a connection diagram among the upper and lower levels. Proposed projects are first evaluated among each at the lower levels. The overall priority is achieved on the basis of the priority that each project gained at the lower level and the connection between levels.

The method is applied to the 33 projects with four ranking variables: noise level, number of people, land use type, and effectiveness/feasibility. The AHP method is carried out in three steps. Step 1 is to determine the relative importance among ranking variables. This is done by pairwise comparison of the variables and assignment of numerical importance factors. The assignment is known as *Level 1.* For example, noise level was considered to be 1.5 times as important as number of people, 3 times as important as land use type, and 4 times as important as effectiveness/feasibility. The relative importance matrix is completed by assigning factors for each pair of variables. For the four ranking variables used in this example, six relative importance factors are to be assigned.

It should be noted that the ranking variables to be included and their relative importance factors are decided by the users of this approach. The variables and the relative factors used in this paper are for illustration purposes. The user may decide to include a different set of variables or may assign different relative importance factors. The importance factors assigned to the variables must be consistent. Small changes in the importance factors would not significantly affect the outcome of the AHP method; however, if the factors are significantly changed the ranking may be affected.

The second step in the process is to determine the relative importance between each pair of projects by considering each of the ranking variables, one at a time. This is done by assigning relative importance factors between each pair of projects by considering only one variable. The matrix here will be known as a *Level 2* matrix. The final step, Step 3, in the AHP procedure is to do matrix multiplication of the Level 1 and Level 2 rankings. Step 3 uses the results from Steps 1 and 2 and computes the ranking for




Note: R = residential, I = industrial, and V = vacant, see text for additional rules.

**FIGURE 1 Sequential ranking scheme applied to 33 projects.**

the projects. The result of the ranking of the 33 projects, in descending order, is shown in Table 2.

It may appear that the relative ranking factors used in AHP are arbitrary numbers assigned by the user. In fact they are not so arbitrary, but reflect the assessment of the user when comparing the variables or projects. Minor changes in the relative importance factors may not affect the ranking outcome, but drastic changes may change the order. To show the effects of changing the factors, the Level 1 factors were changed for the 33 projects. This time it was assumed that the noise level and the number of people are equally important and that either one is twice as important as land use type or freeway type. The ranking outcomes obtained with these modified factors were compared with the ones obtained with the original factors. The top 13 projects were the same in both cases. Similar comparisons were made, and it was observed that most of the projects that were ranked in the top half by using the original factors remained in the top half when reasonable changes in the importance factors were made.

The main strength of the AHP method is that it can rank projects on the basis of several criteria. Its main weakness is that it needs a lot of input when the number of projects is large. This weakness can be overcome by computerizing the input process.

### Weighted Index

Candidate projects are evaluated and ranked on the basis of a WI, which is a linear combination of four variables. The basic idea is to standardize each of the variables and assign a weight for each of the standardized variables. Then the standardized value is multiplied by the weight and they are summed to find the WI. The formula is

$$WI = Fn * Sn + Fp * Sp + Fl * Sl + Ff * Sf$$

where Sn, Sp, Sl, and Sf are standardized values (ranging from 0 to 5) and Fn, Fp, Fl, and Ff are weighting factors of variables of noise level, number of people, land use type, and effectiveness/feasibility, respectively.

The WI method is illustrated by using the data for the 33 projects. Weighting factors were assigned as follows: Fn = 4, Fp = 3, Fl = 2, and Ff = 1. Weighted values for each site are given in Table 2.

The main advantage of the WI method is that it is simple and straightforward. Contributions of each variable to the total index value are quantitative. Once the weighting factors and the standardizing formulas are determined, each project would have a WI value. The main disadvantage of the method is that the WI value may be dominated by a single variable.

**TABLE 2 Comparison of Ranking Results**

| Rank | SRS | AHP | | WI | |
|---|---|---|---|---|---|
| | | Site | Priority value | Site | Index value |
| 1 | TOP: B21W, B20 | B21W | 0.057 | B21W | 48.60 |
| 2 | | B37 | 0.044 | B37 | 38.81 |
| 3 | HIGH: | B14 | 0.041 | B14 | 37.74 |
| 4 | | B21E | 0.040 | A2 | 34.81 |
| 5 | B14, B19, B16, | A2 | 0.037 | B19 | 34.65 |
| 6 | B37, B21E, A2, | C2 | 0.035 | B21E | 34.40 |
| 7 | B26, B23, C26, | B19 | 0.035 | B20 | 33.92 |
| 8 | G10S | B20 | 0.034 | H5E | 33.90 |
| 9 | | H5E | 0.033 | C2 | 33.77 |
| 10 | | A1 | 0.033 | A11 | 33.25 |
| 11 | | A11 | 0.033 | B26 | 31.71 |
| 12 | | B26 | 0.032 | C26 | 31.61 |
| 13 | MEDIUM: | B23 | 0.032 | G10S | 31.13 |
| 14 | | B25 | 0.032 | C20 | 31.07 |
| 15 | C2, G7N, A1, | G0 | 0.030 | B23 | 30.92 |
| 16 | A11, C20, H5E, | C26 | 0.030 | B16 | 30.73 |
| 17 | E3 | G10S | 0.030 | A1 | 30.11 |
| 18 | | B16 | 0.030 | G0 | 29.39 |
| 19 | | C20 | 0.030 | G10N | 29.26 |
| 20 | | E3 | 0.029 | B10 | 28.81 |
| 21 | LOW: | B10 | 0.029 | G16 | 28.64 |
| 22 | | G10N | 0.028 | B25 | 28.18 |
| 23 | G16, B10, G0, | G16 | 0.027 | C22 | 28.11 |
| 24 | G6, B25, C22, | G7N | 0.026 | H5W | 26.90 |
| 25 | F16, G10N, | C22 | 0.025 | H1 | 26.74 |
| 26 | H5W, G7S, E12, | H1 | 0.025 | F16 | 26.52 |
| 27 | H1, C7, B17 | H5W | 0.024 | G7N | 25.49 |
| 28 | | F16 | 0.024 | E12 | 25.05 |
| 29 | | E12 | 0.022 | E3 | 24.19 |
| 30 | | B17 | 0.022 | G7S | 23.36 |
| 31 | | G7S | 0.020 | G6 | 20.23 |
| 32 | | G6 | 0.020 | B17 | 19.09 |
| 33 | | C7 | 0.012 | C7 | 11.42 |

### Comparison of Results from Three Methods

Table 2 shows the results of ranking. It should be noted that the results from SRS are in four groups because SRS does not determine the relative standings within a group. The results indicate that the three methods yield very similar rankings, although there is not a perfect match among the outcomes. A general agreement is achieved for most of the projects, especially for the top 10 and the bottom 10 projects.

The three methods in general need different human and computer resources. When threshold values are fixed, SRS and WI are less labor-intensive than AHP. The input data for AHP would increase exponentially when the number of projects increases.

It is easier to add or delete one or more projects to the SRS and WI methods. The addition or deletion of a project does not significantly affect the relative rankings of projects. In AHP, however, when projects are added or deleted one needs to modify the matrices to reflect the changes, and this may affect the previous ranking for other projects.

The three methods are flexible to fit the needs of the users. The users can change the variables on the basis of their own judgment or preference and set the thresholds at levels with which they are most comfortable. For example users may change the thresholds in SRS, extend or shorten the number of levels, modify the values in WI standardization, or assign different relative importance factors in AHP.

### Proposed Priority Procedure

Each of the three methods can individually be used to obtain reasonable results. The WI method is easy to use, but the standardization and weighting factors must be carefully studied so that the outcome is not heavily influenced by a single factor. For this reason the WI method in its current stage is less preferred than SRS. It is proposed that the combination of the SRS and AHP methods be used when a large number of projects are to be ranked because AHP would require a lot of input.

A two-step ranking procedure is proposed here.

Step 1. Use SRS to classify the candidate projects into four groups.

Step 2. Combine two upper groups and two lower groups separately (or two upper groups only) from Step 1. Then use the AHP method to rank each combined group.

By going through Step 1 the low-priority projects will be filtered out and the ranking will be focused on high-priority projects.

## CONCLUSIONS AND RECOMMENDATIONS

Three multicriteria ranking procedures (SRS, AHP, and WI) were developed and used for priority ranking noise barrier projects. These procedures are flexible, and the users can specify the variables to be included and their relative importance factors. It is recommended that a combination of the SRS and AHP methods be used when ranking a large number of projects. For a small number of projects the AHP method may be used alone to obtain the ranking. The SRS may be used to classify the project into different priority levels when ranking of projects within that level is not required.

The variables used for ranking, threshold values in SRS, standardization formula and weighting factors in WI, and relative importance factors in AHP are reasonable parameters used in developing the ranking procedures. The users may decide to change the variables or the parameters, or both, depending on their needs and conditions. Changing the variables or the parameters would not alter the ways that the procedures work; however, the outcomes of the ranking may be different, depending on the changes. The variables and parameters used should be determined by the users. These procedures are developed to provide such a flexibility for the users.

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PART 5

# Enhancements

# Developing Enhancements Program in San Francisco Bay Area

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The Intermodal Surface Transportation Efficiency Act of 1991 requires states to spend 10 percent of the new Surface Transportation Program on transportation enhancement activities, projects that improve the quality of the journey by creating attractive settings near transportation facilities, by preserving scenic or historic transportation sites, or by expanding the range of travel options for bicyclists and pedestrians. In developing the San Francisco Bay Area's enhancements program, the Metropolitan Transportation Commission (MTC) learned to look at transportation facilities in a new light and along the way forged valuable new partnerships with state and myriad local agencies, special districts, and community groups. MTC's experience is described, and some insights that other regional agencies may find useful in making the most of this challenging and innovative program are offered.

The landmark Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) requires states and metropolitan areas to blaze new trails across the nation's transportation landscape. One notable example is the law's requirement that 10 percent of the new Surface Transportation Program—federal funds directed to states and metropolitan areas for flexible spending across modes—be dedicated to transportation enhancement activities (TEAs). Such enhancements, so named because they enhance the transportation system, require veering from the well-worn path of automobile and mass transit-related investments to consider an array of new options.

Lobbying, negotiation, and the cooperative efforts of various agencies contributed to the development of a statewide TEA program in California. The program allows metropolitan planning organizations (MPOs) to fund new and innovative projects.

During an initial phase of selecting enhancement projects the San Francisco Bay Area's Metropolitan Transportation Commission (MTC) faced the challenge of whittling down 152 enhancement project applications totaling more than $94 million to meet a target of $18 million in anticipated funds for fiscal years 1992 and 1993. Over a span of 7 weeks MTC staff grappled with ways to evaluate and rank very different projects, from public art projects to bicycle and pedestrian trails to historic rail depot renovations. MTC learned to look at transportation facilities in a new light and forged valuable new partnerships with state and myriad local agencies, special districts, and community groups.

This paper describes MTC's experience and offers some insights that other regional agencies may find useful in making the most of this challenging and innovative program.

## DEVELOPING CALIFORNIA'S ENHANCEMENTS PROGRAM

ISTEA defines TEAs in 10 divisions: bicycle and pedestrian facilities; acquisition of scenic or historic sites or easements; scenic or historic highway programs; landscaping and other scenic beautification; historic preservation; rehabilitation and operation of historic transportation buildings, structures, or facilities; preservation of abandoned railway corridors (including conversion for use as bikeways and walkways); control and removal of outdoor advertising; archaeological planning and research; and mitigation of water pollution resulting from highway runoff.

The federal requirement that 10 percent of all Surface Transportation Program (STP) funds be set aside for such activities has required new ways of doing business across the country. In California Senate Bill 1435 implemented ISTEA at the state level. Although Senate Bill 1435 established the rules for passing through STP and Congestion Mitigation and Air Quality (CMAQ) funds to the MPOs, no similar rules were established for the enhancements program. Therefore the California Department of Transportation (Caltrans) initially assumed that TEA funds would be used entirely for projects already in line for funding in the State Transportation Improvement Program (STIP), California's 7-year master program for transportation projects.

Caltrans' Division of State and Local Project Development, Office of Landscape Architecture, was initially assigned the task of programming TEA funds to existing STIP projects. The responsibility was taken seriously and the job was begun with careful study of the TEA provisions and the entire ISTEA legislation. In approximately 20 meetings with the 12 Caltrans district offices and FHWA over 4 months, the Office of Landscape Architecture found few eligible TEA projects in the STIP—few projects that fit into any of the 10 TEA categories and that were not considered part of so-called normal activities.

Meanwhile, empowered by ISTEA and Senate Bill 1435, MPOs throughout California were asking Caltrans for a large role in the programming of other state-controlled funds, including the TEA program.

At the same time environmental organizations, such as the Sierra Club and the Rails-to-Trails Conservancy, pressed their local MPOs and the California Resources Agency to use enhancements program funds for non-STIP projects. These groups were convinced that funding for traditional highway projects already in the pipeline was at odds with ISTEA's intent to direct investments to a range of activities going well beyond traditional highway landscaping or other required mitigation projects. The MPOs and the California Resources Agency in turn convinced Caltrans that the state's TEA program must be entirely new and distinct.

Caltrans then convened a task force of MPOs (including MTC), bicycle advocacy groups, local parks and recreation departments, historic preservation groups, the California Coastal Commission, the California Resources Agency, the Bureau of Land Management, the U.S. Forest Service, and FHWA.

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The Enhancements Task Force began meeting in October 1992. Over several months the task force agreed on a number of items, including which Caltrans STIP projects would be "grandfathered" for 1992 funds, a statewide evaluation process and criteria, a statewide application form, and a schedule for developing the program.

### Grandfathered Projects

The state initially proposed a set of projects that would absorb most of the enhancements program money available in the first funding cycle, $56 million for fiscal years 1991–1992 and 1992–1993. This was not acceptable to the other members of the task force, who argued that local and regional needs were not being addressed. Internal Caltrans discussions involved those who wanted earmarks for existing "normal" projects and those who wanted the TEA program called out separately. Caltrans management eventually agreed to limit the grandfathered projects to those previously programmed STIP projects that were clearly eligible—above and beyond a normal transportation activity and not a required mitigation—that would be obligated by September 30, 1994. Furthermore they agreed to open up the process and develop a new program for the balance of the TEA funds. With this Caltrans withdrew the other previously proposed projects.

### Evaluation Process

The task force agreed to give each region the option of a bid target equal to twice its population share, or three projects, whichever was larger. Each region or MPO would solicit applications, evaluate project proposals, and submit a ranked list of projects to the bid limit. Each region would rank projects according to a set of statewide criteria. The state was given a bid target for statewide projects equal to 10 percent of the available funds.

If a region proposed a population-based bid list, Caltrans and the California Transportation Commission (CTC) agreed to give each region its highest-priority projects. CTC, which has ultimate programming authority for TEA funds in California, would then select projects within the remaining portion of all regions' bid lists.

### Evaluation Criteria

The task force was given the job of developing statewide evaluation criteria, a difficult assignment given the range of eligible enhancement program activities.

The task force first referred to ISTEA and FHWA for guidance on project eligibility. The group then determined the screening criteria, or basic eligibility requirements, for the TEA program in California. These were composed of the enhancements program activities in the act: 10 categories listed above and beyond-normal transportation activities or required mitigations and related to the transportation system by proximity, function, or impact. Other screening criteria were added, such as requirements that the project be well defined and supported by a valid financial plan.

The scoring criteria were harder to determine. The task force divided the benefits or measures of project merit into four areas:

1. Regional and community goals: How well does the project meet local goals? Does it implement community objectives? Does the project have a broad base of local support?
2. Cost-effectiveness: How much benefit does the project offer per dollar requested?
3. One-time opportunity: Will the opportunity to do the project be lost if funding is deferred from the current programming cycle?
4. Project-specific benefits: Projects were divided into four categories: (a) scenic aesthetic, (b) historic/archaeological, (c) bike/pedestrian, and (d) water Runoff Purification.

The points that a project could receive in the project-specific category were derived from a combination of the demonstrated need (or opportunity) at the project site and the degree to which the proposed project would address that need (or opportunity). Caltrans made sure that its interests were served by insisting on statewide criteria that each region would use to rank projects, such as functionality, which favors bicycle and pedestrian projects.

The task force discussed the elements of the ranking criteria at length and after 3 months agreed to the final criteria. An application form was designed to be simple to complete and to directly correspond to the evaluation criteria. A variety of interests successfully argued for local flexibility to evaluate projects and to establish priorities. For instance a score of 90 in Ventura County does not necessarily equal a score of 90 in the Bay Area.

### Timing

Some legislators wanted to earmark all enhancements program funds. By the time they communicated that, however, the task force had been formed and momentum and broad support for the programming principles had been established. By agreeing to speed up the statewide process with criterion elements that were satisfactory to the legislators, earmarking was forestalled.

### Outreach to Potential Enhancements Project Sponsors

Using task force recommendations, Caltrans assembled an application packet that described the program and project eligibility. In cooperation with local agencies, Caltrans organized several public symposia on the enhancements program. In the San Francisco Bay Area, MTC participated in those state-sponsored forums and also introduced the program at separate meetings with cities, counties, transit operators, environmental groups, citizens' groups, and MTC citizens advisory committees—a broad cross-section of interests within the nine counties that make up the MTC region.

MTC prepared press releases on the enhancements program that were picked up by a number of area newspapers, and staff discussed the program on two radio talk shows.

MTC sent more than 600 applications with the Caltrans information packet to environmental groups, special water and park districts, public works officials, transit districts, community groups, and any others that MTC staff believed might be interested or eligible.

## MTC PROJECT REVIEW EXPERIENCE

On the application due date, MTC received 152 applications requesting a total of $94 million. Although most of the projects

were imaginative and eligible, according to the state bid target constraint, the MTC region could submit only $18 million worth of projects.

Ranking of the projects was difficult and time-consuming—much more so than staff had anticipated. Interestingly, however, the quality of the proposals and the creativity of many of them energized the evaluation team.

### Project Evaluation Teams

MTC's multimodal priority-setting process—set up in 1992 for ISTEA's STP and CMAQ funds—vividly demonstrated the value of inviting partners from various agencies to participate in the development of regional funding programs. The TEA program particularly lends itself to this sort of team approach, given the variety of eligible projects.

MTC formed an evaluation group composed of individuals familiar with each of the eligible activities, including artists, planners of bicycle facilities, landscape architects, and historic preservationists. Group members included MTC staff, staff from other regional agencies, and city and county staff.

The group was divided into three scoring teams on the basis of their areas of expertise: scenic/aesthetic, historic/archaeological, and bicycle/pedestrian. No water mitigation projects that met basic eligibility criteria were submitted to MTC.

### Ranking the Projects

The TEA evaluation schedule in the San Francisco Bay region was driven by deadlines set by CTC. Once the scoring criteria were officially drafted in February, project sponsors had only 8 weeks to submit applications. California MPOs, including MTC, then had just 7 weeks from the time of receipt of the completed applications to evaluate them and develop a program proposal for CTC.

Immediately after TEA applications were due, the three activity-specific scoring teams met to sort the applications into the above-mentioned project categories and to share first impressions of the applications. Next each team briefly reviewed all the applications in their category and assigned a Good, Medium, Bad, or Ineligible rating to each, which came to be known as a "GuMBI" grade.

Before the GuMBI groupings were presented at the hearing, the ranking nomenclature was changed to High, Medium, Low, and Ineligible to avoid calling any project "bad." At the hearing project sponsors were limited to protesting their relative rating, because their scores were not available to challenge.

### Scoring the Projects

Soon after the three teams began scoring the projects they reconvened to ensure that they were scoring projects consistently. Each of the three teams found the statewide criteria to be subjective in several places and difficult to apply to individual projects. Therefore the group made two types of adjustments to the guidelines.

First, in each of the scoring categories the statewide guidelines awarded a range of 0 to 20 points. Instead the scoring teams chose to award points on a consolidated scale of 0-4-8, 0-5-10, or 0-10-15-20. For instance if a project could receive a maximum of 10 points in a particular category according to the statewide criteria, it was given either 0, 5, or 10 points at MTC. This helped narrow the debate over project scores.

The second modification the scoring group made was to use a more detailed interpretation of various criteria. For example under the statewide guidelines a project could receive up to 8 points for demonstration of local support. The scoring teams standardized this as 4 points for support from any group, agency other than the project applicant, or legislator and 4 more points if the local match exceeded the minimum requirement. Another modification to the guidelines was in awarding cost-effectiveness points. Instead of using the capital recovery approach in the statewide guidelines, which proved to be inconsistent, a ratio of total project points per funding request was calculated. Each project's cost-effectiveness score was then normalized on a scale of from 0 to 10.

Each of the three scoring teams met an average of 20 hr over 3 weeks. A 2-page summary of the statewide scoring criteria was used to record the breakdown of project scores and any comments (Figure 1).

### Developing the Program

As the draft program of projects was developed, MTC management assessed several options in response to public comments that cost-effectiveness was not considered highly enough and that several large projects absorbed too much of the regional bid pot. Finally political considerations required that at least one project be funded in each of the nine MTC counties that submitted applications.

When all of the projects were scored, four scenarios were evaluated:

1. Rank by score;
2. Rank by score, with cost-effectiveness weighted twice as much as the statewide criteria called for;
3. Rank by score, capping the TEA share of each project at $1 million. To accommodate the cap equitably, capped projects were rescored on the basis of the scaled-down project, and the project sponsors were contacted to ensure that they were willing to construct the smaller project or could provide the unfunded portion of the original project; and
4. Rank by score, capping the TEA share of each project at $1 million and guaranteeing each of the participating counties in the MTC region at least one project.

Interestingly, the only effect of doubling the weight of cost-effectiveness was to rearrange the relative ranking of the projects in the draft program, but it did not affect which projects would be proposed for funding. Capping the TEA share of each project to $1 million significantly increased, from 23 to 39, the number of projects that could be funded. The commission agreed that the small size of the Bay Area's TEA bid target relative to the demand for transportation enhancement projects required the unusual action of capping TEA funding for each project after applications had been received. This process led to a program of projects (Table 1) that included many good projects from each of the activity-specific TEA areas (scenic/aesthetic, historic/archaeological, and bicycle/pedestrian).

Project Name: ______________________ TOTAL RAW SCORE _____
Listing Number: ______________________ TOTAL FINAL SCORE _____
Project Type: ______________________

**1. Regional and Community Enhancement**

a. Benefits to quality of life, community, environment. Examples might include provision of safe, aesthetic pedestrian facility at a rail station, removal of billboards, on a rural scenic highway, provision for wildlife corridors or mitigation areas. 0,1, 5, 10 _____
COMMENTS:

b. Increases access to activity centers, such as businesses, school, recreational areas and shopping areas. Connects transportation modes, has multimodal aspects. Reinforces, complements the regional transportation system, fills deficiency in the system. 0,1, 4, 8 _____
COMMENTS:

c. Implements goals in the regional transportation plan, or other adopted federal, state, or local plans. Examples might include water quality plans or elements of general plans. 0, 4, 8 _____
COMMENTS:

d. Increases availability, awareness, or protection of historic, community, visual, or natural resource. 0, 4, 8 _____
COMMENTS:

e. Degree of regional or community support. For example, letter of support from local interest groups and public bodies, additional match. 0, 4, 8 _____
COMMENTS:

f. Encompasses more than one of the activity-specific divisions. (Bike/Ped, Scenic/Aesthetic, Arch/Hist, Runoff: 1 = 0; 2-3 = 4; 4 = 8) 0, 4, 8 _____
COMMENTS:

2. **Cost Effectiveness/Reasonable Cost:** {(Total Score *wo/ Cost Effectiveness*) * 100,000)/TEA Cost}. The natural log of this result is taken. The log results of all of the projects are normalized to 10 points. 0—10 _____

3. **Project Need/One-Time Opportunity:** A one-time opportunity exists to take advantage of this project. The proposed project is threatened. For example, there is an immediate need to do this project, or the opportunity will be lost, or postponing the project could result in substantial degradation of the resource. For example, a historic structure would deteriorate past the point of restoration in two years, or continuing water pollution due to highway runoff would cause irreversible damage to the environment. 0, 5 _____
COMMENTS:

**FIGURE 1 Transportation enhancement activity scoring sheet, first cycle.** (*continued on next page*)

## ISSUES AND LESSONS

### Application Issues

One of the most interesting aspects of the TEA program was the opportunity to work with people whose backgrounds are not in transportation. Many project applicants apparently had a difficult time understanding the transportation context in which their scenic, historic, recreational, or other project could be framed. On the other end of the spectrum, some transportation planners and engineers accustomed to transportation grant applications had to be helped with the qualitative information requested.

### Relationship to Transportation System

Early in the review process it became necessary to clarify the "function, proximity, or impact" relationship needed for a project to be eligible for the program according to ISTEA. When the evaluation process began, every project, by virtue of being somewhere near a roadway, appeared to qualify for TEA funds. However the goal of the program is enhancing the travel experience instead of enhancing a facility or structure per se. For the purposes of evaluating projects at MTC, therefore, proximity was defined as adjacent to or prominently visible from the transportation system in a way that significantly enhances transportation.

**ACTIVITY-SPECIFIC SCORING**

**Bicycle, Pedestrian, Abandoned Rail Right-of-Way (including conversion to ped/bike trail)**

Need for proposed facilities: shortage of bicycle or pedestrian facilities; missing link in connecting the intermodal system, importance of link; necessity of proposed facilities to serve the system.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

Degree to which project meets needs or addresses opportunities for bicycle or pedestrian facilities.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

**Historic/Archeological Specific Divisions**

Current recognized level of historic significance. *(Screening Notes: Cultural properties must be listed in the California Register of Historical Resources, or a locally-designated historic resource, based on locally-adopted, written criteria. Rehabilitation and operation of historic transportation buildings, structures or facilities, and historic sites for acquisition must be listed in the California Register of Historic Resources or the National Register of Historic Places or be eligible for the National Register. Historic highways must be a state or federally designated historic highway).*

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

Degree to which project activity will enhance, preserve, or protect the historic/archeological resource.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

**Transportation Aesthetics and Scenic Values**

Degree to which scenic or aesthetic resources are rare, unique, or significant; degree to which potential for enhancement exists for landscaping or scenic beautification; current degree of blight.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

Degree to which project would preserve, rehabilitate or develop scenic or aesthetic resource.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

**Water Pollution Due to Highway Runoff**

Magnitude of environmental problem.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

Degree to which activity solves problem.

COMMENTS: SCORE: ______

| | |
|---|---|
| High | 20 |
| High-Medium | 15 |
| Medium | 10 |
| Low | 5 |

**FIGURE 1** *(Continued)*

### Project Design Issues

The enormous pool of projects from which to choose vis-à-vis available funds enabled MTC staff to scrutinize the design of proposed projects to a much greater degree than typically occurs at a regional transportation planning agency. For instance one rails-to-trails project would have linked residential and commercial areas, an elementary school, and a planned multimodal transit facility. However one of its termini (the one nearest the transit station) was midblock on a four-lane arterial with no crossing provisions. Consequently this project did not score well and was not in the recommended program. This level of analysis may be extended into other funding exercises at MTC and elsewhere.

### Funding Issues

An issue specific to bicycle projects was the federal requirement of a 20 percent local match, whereas sponsors of scenic/aesthetic and historic/archaeological projects need only provide a 11.5 percent local match. MTC anticipates that this inequitable situation will be addressed in an ISTEA cleanup bill in 1993–1994.

Another funding issue was the FHWA "50 percent rule" requiring a minimum of 50 percent federal funding for each project. After some discussion FHWA agreed that this rule was inappropriate for the TEA program because many projects have substantial local backing.

TABLE 1 TEA's Program of Projects, Fiscal Year 1993–1994

| Rnk | Cnty | Sponsor | Description | Cat | TEA Cost ($1,000s) | Total Cost ($1,000s) | Cumulative TEA Cost ($1,000s) |
|---|---|---|---|---|---|---|---|
| 1 | SF | San Francisco | Embarcadero Promenade Ribbon | Bike/Ped | $360 | $708 | $360 |
| 2 | MAR | City of Larkspur | NWP RR ROW | Bike/Ped | $400 | $500 | $760 |
| 3 | SF | Port of San Francisco | Pier 47A Scenic Vista | Scenic | $528 | $600 | $1,288 |
| 4 | SCL | SClara Parks & Rec | Grant County Park | Scenic | $66 | $75 | $1,354 |
| 5 | SCL | City of Mountain View | Stevens Creek | Bike/Ped | $1,000 | $2,290 | $2,354 |
| 6 | SCL | Caltrans | Rt. 237 bike lane | Bike/Ped | $318 | $398 | $2,672 |
| 7 | CC | EBRPD | Alvarado Park on I-80 | Hist/Arch | $324 | $433 | $2,996 |
| 8 | ALA | EBRPD | Niles Canyon Acquisition | Scenic | $950 | $2,500 | $3,946 |
| 9 | SOL | Solano Cities | Lynch Canyon | Scenic | $1,000 | $4,200 | $4,946 |
| 10 | CC | EBRPD | Antioch Regional Shoreline | Scenic | $300 | $400 | $5,246 |
| 11 | ALA | City of Pleasanton | Arroyo De La Laguna Trail | Bike/Ped | $630 | $870 | $5,877 |
| 12 | Multi | Peninsula JPB | 350 bicycle lockers and racks | Bike/Ped | $350 | $450 | $6,227 |
| 13 | CC | EBRPD | Ferry Point in Richmond | Hist/Arch | $376 | $501 | $6,602 |
| 14 | SF | San Fran Parks & Rec | "Beach Chalet," GGPark Visitors' Center | Hist/Arch | $724 | $823 | $7,326 |
| 15 | SCL | SClara Parks and Rec | Chitactac-Adams Heritage Park/Rest Stop | Hist/Arch | $721 | $820 | $8,048 |
| 16 | SON | City of Santa Rosa | Santa Rosa Historic RR Depot Impr. | Hist/Arch | $400 | $500 | $8,448 |
| 17 | SM | County of San Mateo | Bike trail from Island Park | Bike/Ped | $1,000 | $2,500 | $9,448 |
| 18 | SCL | City of Santa Clara | Santa Clara Historic RR Complex Impr. | Hist/Arch | $36 | $47 | $9,483 |
| 19 | SCL | SClara Transp Auth | Santa Clara County RR Museum Relocation | Hist/Arch | $1,000 | $6,997 | $10,483 |
| 20 | SF | Port of San Francisco | Ferry Building Renovation | Hist/Arch | $1,000 | $2,800 | $11,483 |
| 21 | SOL | Sol County Counsel | Western RR Museum - 3 SP Buildings | Hist/Arch | $1,000 | $3,402 | $12,483 |
| 22 | MAR | City of Novato | Planting at Scottsdale Marsh | Scenic | $555 | $631 | $13,038 |
| 23 | ALA | City of Berkeley | City of Berkeley Bicycle Parking | Bike/Ped | $80 | $100 | $13,118 |
| 24 | SCL | City of San Jose | East Santa Clara Streetscape | Scenic | $63 | $72 | $13,182 |
| 25 | CC | Martinez | Alhambra Ave. Undercrossing | Scenic | $12 | $15 | $13,194 |
| 26 | SON | City of Petaluma | Lynch Creek Trail Undercrossing | Bike/Ped | $224 | $280 | $13,418 |
| 27 | CC | EBRPD | Carquinez Strait acquisition | Scenic | $950 | $2,620 | $14,368 |
| 28 | MAR | GGBHTD | Bicycle Racks at Bus Stops | Bike/Ped | $32 | $40 | $14,400 |
| 29 | ALA | City of Livermore | 1 bicycle/pedestrian bridge | Bike/Ped | $77 | $87 | $14,477 |
| 30 | SCL | City of San Jose | Alum Rock Streetscape | Scenic | $141 | $160 | $14,617 |
| 31 | ALA | Oakland Parks | Gateway Gardens Project | Bike/Ped | $160 | $200 | $14,777 |
| 32 | Multi | BART | 200 BART bicycle lockers | Bike/Ped | $335 | $419 | $15,112 |
| 33 | SCL | City of San Jose | Roosevelt Park Streetscape | Scenic | $101 | $115 | $15,214 |
| 34 | SCL | Town of Los Gatos | Bicycle detector loops | Bike/Ped | $54 | $68 | $15,268 |
| 35 | SCL | City of San Jose | Historic Alameda | Scenic | $278 | $316 | $15,546 |
| 36 | CC | City of Walnut Creek | Iron Horse Trail | Bike/Ped | $731 | $1,432 | $16,277 |
| 37 | MAR | Town of Corte Madera | Paradise Drive Bay Trail Link | Bike/Ped | $426 | $533 | $16,704 |
| 38 | ALA | City of Emeryville | I-80 undercrossing | Bike/Ped | $1,000 | $1,226 | $17,704 |
| 39 | SF | SF Muni | Cable Car Museum, Amenity Improvements | Hist/Arch | $1,000 | $2,247 | $18,704 |

Bike/Ped = Bicycle, Pedestrian, Abandoned Rail Right-of-Way Project Categories
Scenic = Transportation Aesthetics, Scenic Values Project Categories
Hist/Arch = Historic Preservation of Cultural and Transportation Resources and Archaeological Planning and Research Project Categories

## Challenges of Multidisciplinary, Multiagency Process

Despite the appropriateness and attractiveness of the multidisciplinary, multiagency approach to project evaluation that MTC employed, it had challenges. Probably the most conspicuous was the difficult task of recruiting scoring team members with both project evaluation experience and sufficient expertise in one or more enhancement program areas. This challenge is particularly vivid for the scenic/aesthetic team because the nature of aesthetics is, in many ways, the most difficult to quantify.

When recruiting staff from other agencies it becomes important for the MPO or lead agency to clearly state expectations. MTC invited staff from other agencies to score projects but did not make it clear that MTC would ultimately recommend the final program. As a result, by the end of the process, some outside team members believed that MTC had asked for help with the tedious work without sharing the more interesting aspects of the task.

Finally caution should be exercised in enlisting project evaluation volunteers from other agencies, taking particular care to screen out project sponsors. Project sponsors should not be permitted to score projects in categories other than those in which their project belongs, because projects in all three categories ultimately compete with each other.

## Lessons Learned from Time Constraint

At least two important lessons were learned from the short time frame in the first TEA funding cycle in the MTC region. First, as

soon as it is clear that the number of applications to be evaluated grossly exceeds expectations it is critical to resist the temptation to cut corners. Instead the TEA experience has taught MTC to take the time to rethink the entire process. One of MTC's biggest mistakes was to adhere to the public hearing date that had originally been set. Instead of postponing the hearing staff presented a ranking of projects in three general unranked groupings, only the highest of which were still in the running for TEA funds. Staff probably spent more time defending this qualitative ranking than would have been needed to score each project.

Second, MTC learned the importance of allowing project sponsors sufficient time to carefully scrutinize their draft scores before releasing a final program.

### Workshop

After the conclusion of the first TEA cycle MTC held a workshop to get suggestions for improving the process for the next cycle and to help project sponsors improve their applications. The statewide guidelines were reviewed, focusing on the scoring distinctions made in the MTC region. The workshop was attended by more than 250 project sponsors and provided an open forum to establish more consistent and predictable scoring in the region for the next cycle.

## CONCLUSIONS

Enhancements projects create attractive settings at or near transportation facilities, preserve scenic or historic sites or educational points of interest, and build new connecting facilities such as bicycle and pedestrian pathways.

By improving the quality of the journey itself and expanding the range of travel options, the enhancements program gives MPOs and states the opportunity to expand their transportation coalition to new and valuable partners. Every effort should be made to make the most of this innovative program.

Following are some recommendations for other areas developing enhancements programs:

1. Separate the program from other state transportation programs. The enhancements program has a unique purpose.
2. Publicize the program. Prepare a list of interested parties.
3. Involve interested parties in the development of project evaluation criteria and review of project rankings.
4. Carefully define the screening criteria, including the definition of the "transportation experience."
5. Include in the scoring team individuals familiar with each of the eligible project categories, such as artists, bicyclists, and historic preservationists.
6. Allow some time to iron out wrinkles. The enhancements program is different from other project review processes.
7. Enjoy it. The originality and beauty of the projects are energizing.

Like memorable public works projects of the past, today's transportation enhancements can enrich the experience of travelers—and leave something of beauty and imagination to future generations.

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