CHAPTER 2
FINDINGS

2.1 INTRODUCTION

A broad range of activities was undertaken throughout the course of NCHRP Project 8-33 involving specifying the recommended overall analytical framework, investigating in some detail particular aspects of this overall framework, and testing recommended analytical methodologies in cooperation with the Sacramento, California, and Portland, Oregon, MPOs. To make the results of this research available as quickly as possible to state transportation and air quality agencies and to MPOs, detailed findings were made available in three forms as they became available:

Three research results digests were published by the National Cooperative Highway Research Program:

• Research Results Digest No. 217: Relationships Between Implemented Transportation Control Measures and Measured Pollutant Levels, July 1997.
• Research Results Digest No. 223: Development of an Improved Framework for the Analysis of Air Quality and Other Benefits and Costs of Transportation Control Measures, March 1998.

A series of interim reports was produced. These reports are available for loan through the NCHRP. These consist of

• Task 1–Review of Ongoing Research, January 1996.
• Task 2–Improvements to Current Analysis Techniques, March 1996.
• Task 3–Analysis Framework, March 1996.
• Task 4–Relationship Among Implemented TCMs, Emissions, and Measured Pollutant Levels, March 1996.
• Changes in Air Quality and Transportation Associated with the 1996 Atlanta Summer Olympics, April 1997.
• Incorporating Freeway Ramp Speed Correction Factors in Emission Models, April 1997.
• Review of Travel Assumptions Employed in Emission Factor Models, April 1997.
• Task 6–An Analytical Framework for the Evaluation of Air Quality Transportation Control Measures, April 1997.
• Task 7–Sacramento Pilot Testing, May 1997 (Updated March 1998).
• The Use of Remote Sensing and Personal Exposure Monitors to Evaluate the Effectiveness of Transportation Control Measures, March 1998.

In addition, basic project information, the results of the literature and research review, and the research results digests and selected interim reports are available on the Internet at the TRB website.

The purpose of this chapter is to summarize the principal or key findings of the research. (Major portions of two of the interim reports are incorporated as appendixes in order to provide more detailed descriptions and guidance.)

A basic examination of the evolving nature of TCMs is presented in Section 2.2, since one of the major recommendations is that TCM benefits and costs should be evaluated using the same basic analysis methodologies as employed elsewhere in the transportation planning process. Utilizing an unrelated series of special purpose or simplified analysis techniques makes a comparison of impacts difficult and works against the integration of air quality concerns into the ongoing transportation planning process.

A second key finding is that improvements can be immediately implemented to the "four-step” travel demand analysis systems that are in wide use today. While far from ideal, these enhancements will produce important improvements in the accuracy with which emissions are estimated for on-road motor vehicles. Potential improvements are summarized and prioritized in Section 2.3, including the results of testing the effects of these enhancements in analyzing a proposed system of HOV lanes and ramp metering in the Sacramento, California, metropolitan area.

While immediate improvements can be easily made to current transportation and emissions modeling techniques, the longer-term need is for an essentially new and different approach to analyzing the transportation, emissions, and air quality impacts of TCMs and other transportation air quality control strategies. The purpose of the testing carried out in the Portland, Oregon, metropolitan area was to implement
and assess the feasibility of three analytical approaches that differ dramatically from the characteristics of today’s “four-step”-based transportation and emissions modeling systems. The findings from this portion of the work are summarized in Section 2.4, with a more detailed description contained in Appendix A (which is not provided herein, but which is contained on the accompanying CD-ROM).

The objective of the recommended analytical framework is to evaluate the air quality and other benefits and costs of transportation control measures, or TCMs. It is useful in this context to briefly examine the definition of a TCM and how this definition may be evolving over time. It also is useful to identify the potential range of impacts of TCMs, both positive and negative, and how these impacts compare with those of other transportation actions being developed and implemented by state DOTs and MPOs.

Starting with their introduction in the Clean Air Act of 1970, TCMs have developed a highly negative and restrictive reputation as regulatory disincentives. This traditional perception is based in large part on the mandatory role of TCMs as they are formally adopted as part of a State Implementation Plan (SIP), with the associated threat of enforcement and monetary sanctions. The list of TCMs defined in Section 108(f) of the CAAA is contained in Table 2.1. Two points are immediately obvious from an examination of this listing:

- While some of these measures, such as trip reduction ordinances, are regulatory in nature, many others are more properly viewed as incentives that can be used to either increase the multimodal capacity of a transportation system or improve the overall efficiency with which an existing transportation system operates.
- While state DOTs and MPOs have been understandably reluctant to formally include TCMs as part of a legally enforceable SIP, they have proceeded to implement exactly these same kinds of measures as part of their regular transportation plans and programs.

An examination of current transportation planning practice reinforces the conclusion that the traditional view of TCMs no longer is appropriate. Significant attention is being given to the manner in which both existing and new transportation infrastructure is being managed. As a result, an entirely new generation of transportation management strategies are being intensively considered throughout the country, and rapidly being deployed (Table 2.2). (See, for example, the 1997 update of A Toolbox for Alleviating Traffic Congestion prepared by Dr. Michael Meyer for the Institute of Transportation Engineers, Washington, D. C.) These include intelligent transportation systems (ITS), a diverse array of market-based pricing mechanisms, land use and growth management policies, alternate work or trip schedules, and the use of information technologies as a substitute for travel. Typically implemented as part of a larger overall transportation program, each of these emerging strategies and technologies has important implications for the volume and schedule of travel, and thus for the efficiency of both vehicle and system operations.

The emission and air quality characteristics of these new strategies are only now beginning to be understood. Two points, though, are clear. First, future transportation air quality analyses cannot afford to be limited to traditional forms of TCMs, such as HOV lanes, park-and-ride lots, carpooling, vanpooling, and public transportation. Second, improved transportation air quality analytical methodologies need to be responsive to the characteristics of these new transportation management strategies.

2.2 TCMs AND THEIR IMPACTS

The Emerging View of Transportation Control Measures

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Potential TCM Impacts

Transportation control measures often are assessed exclusively on the basis of their potential to reduce emissions and the associated agency costs to implement and operate. This narrow view, though, ignores several important considerations and all other potential benefits and costs. TCMs frequently are stated to be cost-ineffective when only emission reduction impacts are considered. It is, however, not unusual for TCM-style measures to have benefit-cost ratios of approximately 10 when other relevant impacts are included as part of the evaluation process (1, 2).

With particular respect to air quality, emissions are treated as a proxy for air quality improvements and associated health benefits. It is further assumed that the improvement in air quality is proportional to the reduction in emissions without examining potential issues of non-linearity associated with the formation of secondary pollutants such as ozone and the respective role of hydrocarbons and oxides of nitrogen in the formation of ozone pollution.
TABLE 2.2 Examples of emerging transportation management strategies

**Mobility Improvement**
- Intelligent Transportation Systems (ITS)
- Transit service improvements and expansion
- High-occupancy-vehicle priority lanes and facilities
- Bicycle and pedestrian facilities and programs
- Congestion management planning and systems

**Employer-Based Transportation Management Programs**
- Alternative work schedules/Compressed work weeks
- Paratransit and vanpool programs
- Employee financial incentives and subsidies
- Transportation Management Associations (TMAs)
- Guaranteed-ride-home programs

**Traffic Operations and Flow Improvements**
- Incident management systems
- Ramp metering
- Traffic surveillance and control systems
- Interconnected and automated traffic signal control systems

**Market-Based Incentives**
- Congestion pricing and toll programs
- Emission fees
- VMT fees and roadway pricing
- Emissions trading
- HOV lane buy-in
- Accelerated retirement of vehicles
TABLE 2.2  Examples of emerging transportation management strategies (continued)

Telecommunications

- Telecommuting
- Satellite work centers
- Teleconferencing
- Computer networking

Land Use and Growth Management

- Parking requirements in zoning codes
- Growth management/concurrency requirements
- Parking management
- Pedestrian-friendly site design
- Mixed-use development ordinances and zones

Freight

- Intermodal terminals and connectors
- Truck routes
- Goods delivery scheduling and management
- Terminal modernization and capacity expansion
- ITS Commercial Vehicle Operation (CVO) programs

Other

- Public education
- Marketing and advertising
- Episodic control programs
- Special event planning and transportation management
While it has proven to be difficult to either empirically demonstrate or analytically model, it is widely accepted that congestion imposes economic costs on both individuals and businesses by affecting efficiency, productivity, and competitiveness. To the degree that TCMs contribute to the reduction of congestion or at least limit the future growth of congestion, these impacts should be considered as part of the process of evaluating candidate TCMs. Similarly, many TCMs may improve mobility for both individuals and businesses by improving the range of travel options that are available within an urban area or region. Consequently, these potential mobility benefits also should be included in assessing the impacts of TCMs.

In developing and applying improved TCM analytical capabilities, it is useful to also have an idea of both the potential magnitude and the associated uncertainty of the expected travel and associated impacts. Such information is helpful in determining the resources that should be devoted to a more in-depth analysis. A review of existing TCM-related “before-and-after” studies was conducted by Cambridge Systematics, Inc., in association with Energy and Environmental Analysis, Inc., for FHWA’s Office of Natural Environment (3). While empirical before-and-after findings on TCM effectiveness are limited, they nonetheless provide some indication of the potential magnitude of impacts of these strategies. In the case of measures affecting travel demand, while a few site-specific programs have resulted in substantial reductions in single-occupancy-vehicle (SOV) work trips, these cases are exceptional. For any given site or region, there appears to be a measurable, but bounded, market for additional programs such as carpooling, vanpooling, supplemental transit, or non-motorized incentives. Experience in the 1990s with areawide employer-based programs has shown that an overall reduction in SOV work-trip mode share on the order of 5 percent may be realistic. This translates into vehicle miles of travel (VMT) impacts for all trips at a regional level of considerably less than 1 percent. These results are consistent with evaluations of ridesharing programs conducted during the early 1980s, which also showed regionwide VMT impacts of under 1 percent. Road and parking pricing strategies appear to have a potentially much greater impact, although the magnitude depends upon the amount of the pricing and the nature and scale of its application.

Potential impacts of measures affecting traffic operations have been found to be somewhat greater. Traffic signal coordination and control strategies have resulted in fuel use reductions in the range of 8 to 15 percent in corridors or areas for which the improvements are implemented. Nevertheless, even with widespread adoption of these improvements, the regional impacts are diluted to perhaps 1 to 4 percent. Also, as more sophisticated control systems are more widely adopted, the additional benefits that can be realized will diminish. Furthermore, the extent to which latent demand may offset any short-term energy savings has not been adequately determined.

In general, TCMs will have both positive and negative impacts along the same dimensions as other transportation policy and investment decisions and should be evaluated using essentially the same list of factors contained in the Transportation Equity Act for the 21st Century (TEA-21) for metropolitan area and statewide transportation planning (Table 2.3). Consistent with the manner in which other candidate transportation actions are assessed, emissions and air quality become just one of a number of potential impacts that are evaluated. (A more in-depth discussion of the range of potential impacts of TCMs is contained in Appendix B. Appendix B is not contained herein, but is contained on the accompanying CD-ROM.)

### 2.3 POTENTIAL NEAR-TERM IMPROVEMENTS

Although longer-term improvements in the TCM transportation air quality analytical framework are desirable, immediate improvements based on “existing modeling technology” can be made to correct, at least partially, current analytical deficiencies. The immediate strategies that agencies can use to improve their capabilities to analyze TCMs reflect selective enhancements to the current “four-step” set of planning and analysis tools.

Figure 2.1 is a schematic of the current transportation analysis framework and an array of near-term enhancements that can be used to improve an agency’s ability to evaluate TCMs. The focus in Figure 2.1 is on the transportation module, although near-term emissions modeling enhancements are also possible. Shown in the shaded column on the left-hand side of Figure 2.1 are the steps that constitute the current four-step transportation analysis process (i.e., trip generation, trip distribution, mode choice, and traffic assignment) and important supporting procedures (e.g., land use, vehicle ownership, and time-of-day).

The other boxes in the diagram represent areas where immediate improvements can be made to address existing deficiencies. These identified improvement areas represent topics where considerable research and development have been completed in recent years and where proven analytical techniques already exist that can be adopted by MPOs and state DOTs. Although many transportation planning organizations already have implemented at least some of these enhancements, the enhancements may not be as comprehensive in scope as desired and may not be motivated primarily by air quality considerations.

Each enhancement identified in Figure 2.1 has a number corresponding to the following potential improvements:

1. **Incorporation of Feedback Linkage**—Many of the limitations of conventional models lie in their inability to accurately reflect the “travel conditions”– as repre-
sented in the time and cost of travel—throughout the entire set of relevant travel choices. This is a particularly important concern when evaluating measures that may induce changes in behavior (from locational decisions all the way through mode, route, destination and time-of-day choices for a particular trip). It is valuable to have this linkage occur among the steps of trip distribution, mode choice, time-of-day, and assignment (primary link). The linkage yields even more realism (and impact) if the link is extended back to the land use, household vehicle ownership, and the trip generation steps.

2. **Individual Model Enhancements**—Each step in the conventional modeling process has weaknesses relating to the evaluation of TCMs. Any of the following areas can be enhanced:

   **Land Use/Activity Forecasts**—Most areas cannot assess changes that might occur in the location patterns of households and employment activity in response to changes in transportation conditions (e.g., infrastructure, congestion, and pricing). Potential enhancements include adaptation of formal land use models or guidance on the use of submodels that offer insight into household/business response to various policy changes.

   **Vehicle Ownership**—Enhancement alternatives include upgraded, more fully specified and policy-sensitive vehicle ownership and choice models that can simulate household response to vehicle-related policies affecting the number or type of vehicles owned.

   **Trip Generation and Distribution**—Enhancement alternatives include upgraded, more sensitive trip generation models, as well as possible submodels to handle non-motorized trips, telecommuting, and alternative work schedules.

   **Mode Choice**—Enhancement alternatives include upgraded models with the capacity to include more alternatives (e.g., HOV), an improved specification (in terms of variables and policy sensitivity), a more accurate choice structure, or use of submodels to handle bike/walk alternatives or other specialized modal concepts.

   **Time-of-Day**—Enhancements can be introduced in the form of either time-of-day choice submodels or peak spreading techniques.

   **Route Choice**—Current traffic assignment models do not readily account for the impacts of toll roads or allow for route choice response by travelers. There are procedures that allow for more realistic handling of roadway toll issues, and submodels offer a possibility for handling complex travel behavior.
Figure 2.1. Overview of potential near-term enhancements to current transportation analytical framework.
The enhancements characterized above raise questions as to whether all of these procedures must be developed uniquely by each site. The following are potential options:

**Borrowed Models**—Not all sites may be in a position to develop their own models from scratch. One possibility is that models in use elsewhere could be transferred to another urban area, either as an interim or as a permanent solution. This includes model structures, estimated coefficients for important model parameters, and elasticities derived from either modeling analyses or empirical evaluations.

**Survey Data**—If a site wishes to develop or adapt a model, it can call on several sources. The 1990 Census and 1990 National Personal Transportation Survey (NPTS) are important potential sources of transportation data. Many metropolitan areas also have conducted recent household travel surveys.

3. **Traffic Simulation**—The outputs of a traffic assignment do not fully reflect key operational variations that may be important to emissions (e.g., queuing and delay patterns on links, and speed/acceleration profiles) and that are much more relevant to emissions than average speed. Using traffic microsimulation in conjunction with conventional travel demand models is one way to improve the realism of the transportation inputs that reflect these stop-and-go patterns. Microscopic traffic simulation models simulate the movement of individual vehicles and include programs such as FRESIM and NETSIM (this type of simulation is also being incorporated in the TRANSIMS work being performed by the Los Alamos National Laboratory.) Macroscopic traffic simulation is based on higher level deterministic relationships and takes place on a highway section-by-section basis rather than by tracking individual vehicles. Examples include CORFLO and TRANSYT-7F.

4. **Coverage and Precision of Travel Networks**—Coded network descriptions of highway and transit facilities and services are used in the assignment step and form the basis for calculating travel times, estimating levels of service, and producing other performance indicators. The level of detail in which networks are described varies greatly as to the types of facilities represented (in particular, the number of arterials and major collectors included) and the treatment of special network features such as HOV lanes, ramp meters, and intersection movements. The representation of link speed and capacity also varies greatly—particularly in the number of capacity classifications and range of speed-volume relationships included.

Improved modeling accuracy for TCMs can be achieved by including more facilities in the highway network (e.g., minor arterials and significant collectors), explicit coding of special network features (e.g., HOV lanes, ramp meters, and intersection details), and use of more capacity classifications and a wider range of speed-volume relationships. In addition, separate rail transit and bus transit networks are being coded—each with considerable detail describing access modes (and in some cases, extending to separate networks specifically depicting the transit access options). Such network detail may be needed to support nested logit mode choice models.

5. **Emissions and Air Quality**—Among the options available for immediate implementation are three improvements that can be made relatively easily to existing emission factor models to increase their accuracy. These options are to

   **Include Operating Mode Corrections**—The condition (i.e., cold start, hot start, or stabilized) under which a vehicle is operating has a significant impact on vehicle exhaust emissions, and the implementation of TCMs often affects the existing operating mode mix. For example, the implementation of a park-and-ride lot may not eliminate a trip but could decrease its length. Thus, vehicles may never get out of the cold-start mode of operation. Unless MOBILE is configured to account for this effect, the emissions benefit of this TCM will not be correctly quantified.

   **Develop Trip-Based Emissions Estimates**—MOBILE5 accounts for start emissions in the operating mode fractions. One approach to aid the quantification of the emissions impact of TCMs is to separate the start emissions from the running exhaust emissions contained in the MOBILE model by calculating two separate quantities for a vehicle trip: stabilized operating emissions and a cold-start offset.

   **Link Travel Mode to Vehicle Class**—Both MOBILE and the corresponding CARB program, EMFAC, track emission estimates for separate vehicle categories (e.g., cars, light-duty trucks, heavy-duty trucks, and motorcycles). Given the large differences in emission rates between vehicle categories, it is important to quantify the distribution of travel among the vehicle categories correctly. Methods have been developed to translate the vehicle classification system typically used for highway traffic counts to the EPA vehicle classification scheme. This translation helps to create locality-specific vehicle mix estimates based on facility type.

Existing transportation air quality analytical capabilities also can be easily enhanced through the use of post processors and other similar off-line methods. The Post Processor for Air Quality (PPAQ), developed by Garmen Associates, is one example of a widely used post processor. PPAQ accepts as input the highway link physical attributes and assigned traffic volumes produced by the four-step travel demand model. PPAQ then performs a complex process of computing and adjusting time-period volumes; calculating link and signalized intersection capacities, speeds, and delays; and accumulating VMT and average speeds. The system prepares
inputs to and runs the MOBILE model to calculate emissions. Output databases are prepared consisting of VMT, speeds, and emissions. These are summarized by link, area, facility type, and time period. A suite of report generation and support utilities is provided in the system.

Analyses also can be improved through the careful use of simplified analysis techniques. Examples of such methods are described in the October 2000 report *Congestion Mitigation and Air Quality (CMAQ) Emission Analysis Techniques*, prepared by Cambridge Systematics, Inc., for the Federal Highway Administration’s Office of Natural Environment. Such techniques can be used as a screening procedure in conjunction with a larger regional transportation modeling system or on a stand-alone basis for location-specific or small-scale analyses.

**Recommended Priorities**

It is unlikely that an organization will have the resources to implement the full range of possible near-term modeling enhancements. Tables 2.4 and 2.5 suggest a set of priorities for these improvements. In Table 2.4, specific modeling steps such as mode choice models are analyzed and, in Table 2.5, specific tools and procedures are analyzed. The list of improvements identified in the first column of each table generally follows the list of recommended improvements illustrated in Figure 2.1. However, the level of detail differs under different main categories.

Three assessments are provided:

- **Importance to TCM Analysis** is affected by two factors: (1) the importance of the step to the various TCMs (e.g., mode choice is very important to many TCMs, while fewer TCMs are affected by residential location) and (2) the current capabilities to deal with this step, which will vary from agency to agency. Agencies with good mode choice models may find it more important to invest in improving trip generation, while agencies without a strong mode choice model will find it very important to develop one. In ranking the importance, the capabilities of an average MPO are considered.

- **Ease of Implementation** refers to implementation in the short term and is affected by the following factors: (1) a new methodological/analytical tool will result in a more difficult implementation, (2) the need for new data will result in a more difficult implementation, and (3) the existence of experience and applied examples will result in an easier implementation.

- **Priority** gives an assessment of overall implementation priority based on both the importance of the step/tool to TCM analysis and the ease of implementation. High importance with easy implementation will have the highest priority, while low importance with difficult implementation will have the lowest priority.

The importance of any specific improvement to a particular agency depends on the current modeling capabilities of that agency. The most important steps for TCM analysis that are reasonable to apply in the short run are estimating land use effects using scenario approaches, person trip generation models covering all travel modes, and disaggregate mode choice models. These three capabilities should be the first priority for agencies. Tools and procedures of high importance and that can reasonably be implemented are borrowed models, post processors, and incorporation of feedback linkage. Other improvements should be considered based on the agency’s current capabilities, available skills, and the budget available for model improvements.

**Sacramento Testing**

To provide further guidance regarding travel model improvements that can be immediately implemented for purposes of evaluating TCMs, a program of cooperative testing was carried out in conjunction with the Sacramento Area Council of Governments. The objectives of this testing were to design, implement, and test a series of specific improvements to SACOG’s existing transportation air quality modeling system; and then to utilize both the existing and improved modeling systems to analyze the impacts of a regional program of HOV lanes and ramp metering on travel and emissions. An important element of this testing process was to identify the practical problems and issues encountered with implementing the recommended set of enhancements to an area’s existing four-step-based travel demand modeling system.

The desire was to analyze the regional, corridor, and peak-period effects of a proposed regional system of freeway ramp metering and HOV lanes. The existing base case includes a limited deployment of ramp meters and HOV lanes on U.S. 50 and SR 99. The proposed system includes a much expanded deployment of ramp meters and HOV lanes on SR 99, Interstate 5, U.S. 50, and Interstate 80. The HOV lanes represent the addition of new travel lanes and, therefore, increased highway capacity. The evaluation measures of interest included VMT, vehicle hours of travel, average congested speed, average trip length, and the percent of travel for each of seven modes (i.e., drive-alone, shared ride 2, shared ride 3+, walk-to-transit, drive-to-transit, walk, and bicycle).

Working in cooperation with SACOG staff, the following three enhancements were incorporated into SACOG’s existing MinUTP travel demand modeling system:

- Peak spreading for the morning peak period was incorporated in order to identify the potential future spreading of travel from the peak hour to other portions of the peak period resulting from increased congestion and changing travel patterns within the Sacramento region.
A revised set of traffic speed-flow relationships, differentiating the curves by facility type and geographic area, was developed and incorporated. Facility types included freeways and expressways, major arterials, minor arterials, collectors, non-metered freeway ramps, and freeway ramps.

The highway network was recoded in order to apply the updated speed-flow curves and to facilitate the use of facility type speed correction factors in emissions modeling.

Emissions were estimated using both EPA’s MOBILE5 and the CARB’s EMFAC7F models. Both models were modified to implement estimates of facility-specific speed correction factors so that the impacts of the expanded use of HOV lanes and ramp metering on local, corridor, and regionwide

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land Use/Activity Forecasts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>Medium. TCMs can be analyzed through the creation of different scenarios.</td>
<td>Easy</td>
<td>High</td>
</tr>
<tr>
<td>Approaches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land Use</td>
<td>Medium. This is an important dimension for long-term effects of Models</td>
<td>Difficult. The ease of implementation is questionable. Experience, however, is limited and therefore is not considered easy.</td>
<td>Low</td>
</tr>
<tr>
<td>Allocation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Ownership</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Vehicles Owned</td>
<td>Low. Important to the extent that vehicle ownership affects discretionary trips and trip chaining.</td>
<td>Medium. Implementation requires new data to develop a policy-sensitive vehicle ownership model.</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Vehicle Characteristics</td>
<td>High. Vehicle characteristics – type, size, age, fuel – are very important for estimating emissions.</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Trip Generation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All-Mode Person</td>
<td>High. It is crucial to include all</td>
<td>Easy. The same data used to</td>
<td>High</td>
</tr>
</tbody>
</table>

(continued)
### TABLE 2.4  Priority for improvements to specific transportation models (continued)

<table>
<thead>
<tr>
<th>Near-Term</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trips</td>
<td>trips in the trip generation model to be able to analyze the tradeoff between auto trips, transit, and non-motorized trips.</td>
<td>produce auto trip rates can usually be used to produce all mode trip rates or models.</td>
<td>Medium</td>
</tr>
<tr>
<td>Inclusion of Transportation and Cost</td>
<td>High. This is very important as most models do not include trip generation modules sensitive to policy variables.</td>
<td>Medium-Difficult. Implementation requires new data and modeling effort.</td>
<td>Medium</td>
</tr>
<tr>
<td>Disaggregate Households by Vehicle (Income) and Size</td>
<td>Medium. Important for analyzing response by market segments.</td>
<td>Easy</td>
<td>Medium</td>
</tr>
<tr>
<td>Disaggregate Models</td>
<td>High. Disaggregate models can provide all the benefits of the above sub improvements.</td>
<td>Medium-Difficult. Need data and modeling skills.</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**Trip Distribution**

- **Composite**: High. Inclusion of composite Medium. Application is not straightforward. Medium
- **Impedance**: Impedance will enable the modeling of distribution effects of TCMs. Medium
- **Destination Choice Model**: High. Only a destination choice model can properly reflect the behavioral response to a TCM. Difficult. Destination choice models are difficult to estimate and implement and require special skills. Low
### TABLE 2.4 Priority for improvements to specific transportation models (continued)

**Near-Term**

<table>
<thead>
<tr>
<th>Improvement</th>
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<tbody>
<tr>
<td><strong>Mode Choice</strong></td>
<td><strong>High.</strong> Agencies that do not use&lt;br&gt;disaggregate models are very limited in their ability to model TCM responses.</td>
<td><strong>Medium.</strong> Such models require good data and modeling skills.</td>
<td><strong>High</strong></td>
</tr>
<tr>
<td>Special Modes</td>
<td><strong>High.</strong> Including special modes such as bicycle, walk, and sub-transit modes, is essential for many TCMs.</td>
<td><strong>Medium-Difficult.</strong> Good data on such modes rarely exist. In addition, complicated mode choices are hard to estimate.</td>
<td><strong>Medium-High</strong></td>
</tr>
<tr>
<td>Improve Model</td>
<td><strong>Medium-High.</strong> Improving the model structure including use of nested models, market segmentation, and improved specifications is important to capture different TCM effects.</td>
<td><strong>Medium</strong></td>
<td><strong>Medium</strong></td>
</tr>
</tbody>
</table>

**Time-of-Day**

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-of-Day</td>
<td><strong>High.</strong> This is very important in terms of the potential effect of many TCMs, and it is one of the least developed steps in the modeling system.</td>
<td><strong>Medium-Difficult.</strong> Requires new data designed for this purpose and the experience with such models is limited.</td>
<td><strong>Medium</strong></td>
</tr>
<tr>
<td>Peak Spreading</td>
<td><strong>High.</strong> A time-of-day choice model,</td>
<td><strong>Medium.</strong> Different approaches</td>
<td><strong>Medium-High</strong></td>
</tr>
</tbody>
</table>

(continued)
### TABLE 2.4 Priority for improvements to specific transportation models (continued)

**Near-Term**

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>peak spreading, can account for the effect of congestion on the time-of-day of travel to get better estimates of speeds and volumes.</td>
<td>have been applied, but there is no standard procedure that is easy to adopt.</td>
<td></td>
</tr>
<tr>
<td><strong>Traffic Assignment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume-Capacity Curves</td>
<td>Medium. Volume-Capacity curves are the key to having good representation of the effects of congestion and capacity constraints.</td>
<td>Medium. Requires some development and calibration.</td>
<td>Medium</td>
</tr>
<tr>
<td>Route Choice</td>
<td>Medium. Important for limited number of TCMs – mostly toll measures and traffic improvements.</td>
<td>Difficult. The implementation of a route choice model instead of traditional assignment requires a complete new methodology and tools.</td>
<td>Low</td>
</tr>
<tr>
<td>Traffic Simulation</td>
<td>Medium-High. This is important to achieve accurate emission effects for all TCMs.</td>
<td>Difficult. While traffic simulation programs exist, they are difficult to integrate into a regional travel demand analysis, and additional development is required to make these tools easier to use for emission analyses.</td>
<td>Low-Medium</td>
</tr>
</tbody>
</table>
emissions could be evaluated using the Caltrans Direct Travel Impact Model (DTIM).

The enhanced analysis methods and the results of the Sacramento testing are described in detail in the Task 7, Sacramento Pilot Testing, interim report. The estimated VMT for each alternative model run, for each of the three time periods, is charted in Figure 2.2. Individual model runs were designed so as to examine the proposed regional system of HOV lanes and ramp meters individually as well as in combinations. The model runs also were designed to determine the effects of the different model enhancements. In brief

- The implementation of ramp meters and add-a-lane HOV facilities generally increased VMT slightly, but this impact cannot be considered significant (typically less than 1.0 percent). The inclusion of ramp meters without HOV lanes can either increase or decrease VMT, depending on relative congestion in the system. Again, this is not considered to be a significant impact.
- There are significant and larger changes in VMT with the inclusion of the three model enhancements that were tested. The use of increased speeds and steeper volume delay curves increased VMT by 10.5 percent and 1.3 percent, respectively, and the inclusion of peak spreading decreased VMT by 6.9 percent.
- Vehicle hours traveled are highest for Run 3, with increased speeds and steeper volume delay curves. The highest average congested speed occurs in Run 2, with increased speeds but without steeper volume delay curves, as expected. The impacts on vehicle hours traveled and average speed are insignificant when ramp meters and HOV facilities are coded.

### TABLE 2.4 Priority for improvements to specific transportation models (continued)

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Assignment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linked Travel</td>
<td>Medium-High. The use of traffic simulation is most productive if linked to travel demand modeling to estimate the effect of congestion on travel behavior.</td>
<td>Difficult. As for traffic simulation, some programs exist but the practice still lacks widespread application experience and further development is needed.</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Demand and Traffic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation Models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coverage and Precision of Travel Networks</td>
<td>Medium-High. Important for measures such as HOV lanes and ramp metering as well as for overall more accurate VMT analysis. Crucial for TCMs that try to shift travelers to non-motorized modes as these are usually for short trips that may not be well represented by the network.</td>
<td>Easy-Medium. These extensions can usually be easily accomplished by MPOs.</td>
<td>Medium-High</td>
</tr>
</tbody>
</table>
• Changes in average trip length indicate a redistribution of traffic when implementing model enhancements or TCMs such as ramp meters and HOV facilities. These changes are insignificant when comparing the model runs with ramp meters and HOV facilities. The implementation of increased speeds in Run 2 results in an increase in trip length for work travel (4.7 percent) and a decrease in trip length for non-work travel (1.1 percent). The inclusion of steeper volume delay curves had the opposite impact: a decrease in trip length for work travel (3.5 percent) and an increase in trip length for non-work travel (1.4 percent). This is probably because work travel favors freeway facilities, which are typically longer distance trips, and non-work travel favors arterials, which are typically shorter distance trips. In Run 2, the higher speeds provide a greater mobility for travelers to use the freeways and the work trip length increases; in Run 3, the steeper volume delay curves provide more delay for freeway travelers and the work trip length decreases. The non-work trip lengths are less affected by redistribution of traffic, which is a factor in work trips, and the trip length increases or decreases as speeds increase or decrease.

• The impacts of adding ramp meters and HOV facilities on mode of travel are insignificant in all runs, except Run 2 (with increased speeds) where there is a significant increase in non-motorized travel (14.4 percent) and a decrease in transit trips (6.1 percent). The increase in non-motorized travel is primarily non-work walk trips, which increase because of the lower constant for walk trips in the mode split equations. The decrease in transit trips is a result of the increase in mobility for auto trips. The

TABLE 2.5 Priority for implementation of new transportation modeling procedures

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Importance to TCM Analysis</th>
<th>Ease of Implementation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borrowed Models</td>
<td>High. Borrowed models can help for any step, enhancing local capabilities using models developed from data collected in other locations.</td>
<td>Easy-Medium. Borrowing models is easy but there is a need to calibrate them locally and to incorporate them into the local model system.</td>
<td>High</td>
</tr>
<tr>
<td>Post Processors</td>
<td>High. If improvements are not possible, post processors can be used to adjust the results of traditional traffic assignments to get more accurate and more detailed input needed for emissions modeling.</td>
<td>Easy-Medium. Ready-to-use post processors exist.</td>
<td>High</td>
</tr>
<tr>
<td>Incorporation of Feedback</td>
<td>High. Feedback is essential to analyze TCMs that induce travel changes in mode choice, route, destination, and time-of-day.</td>
<td>Easy. By iterating the four-step demand modeling procedures.</td>
<td>High</td>
</tr>
</tbody>
</table>
Figure 2.2. Systemwide vehicle miles of travel by alternative A.M., P.M., and off-peak periods.
comparison of Run 2 with the Base Run produces the mirror image of these impacts, with non-motorized travel decreasing by 13.3 percent and transit trips increasing by 6.1 percent. This time, the decrease in non-motorized travel is caused by the decrease in average non-work trip length and the increase in transit trips is caused by the increased travel speeds for buses compared with non-motorized modes. In Run 3, with steeper volume delay curves, the most significant impact is the increase in non-motorized travel (5.7 percent), probably because of the decline in auto travel speeds.

- The most interesting conclusion from a review of screenlines is that fact inner and outer screenlines often have opposite impacts in terms of VMT. For instance, adding ramps and HOV facilities tends to increase VMT for inner screenlines and decrease VMT for outer screenlines. The ramp meters and HOV facilities tend to redistribute the traffic in the corridors where they are implemented and decrease travel from areas further away. With Run 2, there are higher-than-average increases in VMT for outer corridors; these probably result from the increased trip lengths in this run. There are lower-than-average VMT increases in the inner corridors because of the increased congestion in these areas.

- The coding of ramp meters specific to the demand is critical to the evaluation of VMT, because ramp meters can cause delay rather than alleviate it if the demand is too low. The counter-intuitive results in Run 2 (such as VMT decreases with the implementation of ramp meters and HOV lanes) would probably be eliminated if the ramp meters were implemented only in areas where congestion is a problem.

- The incorporation of facility-specific speed correction factors in the California EMFAC7F model leads to an increase in emissions of total organic compounds (TOG) and carbon monoxide (CO). This reflects the fact that freeway correction factors for both pollutants show higher emission levels at most speeds relative to the current correction factors. Similarly, there are significant increases in TOG and CO levels estimated for metered versus non-metered ramps. The comparison of NOx levels is more complex because the freeway correction factor shows lower NOx levels at most speeds relative to the existing correction factors, whereas the NOx correction factors for metered ramps are above those of non-metered ramps. The estimated overall reduction in NOx reflects the net of these two offsetting effects, with the decrease due to operation on all freeways offsetting the increase in NOx on metered ramps.

It also is useful to step back and examine the results of the Sacramento testing within the context of the larger objectives defined for the NCHRP 8-33 project. The package of travel and emissions modeling enhancements implemented to SACOG’s existing procedures resulted in more accurate estimates of travel volumes, speeds, and emissions, and were accomplished within the resources typically available within an MPO. These modeling enhancements, though, had a larger impact on the performance measures of interest than did the proposed system of HOV lanes and ramp metering. Further, the modeling enhancements tended to result in increased estimates of travel and emissions. Implementation of a peak spreading capability was considered to be the most important of the enhancements implemented. However, the implementation of facility- and area-specific speed-volume relationships, in conjunction with enhanced network coding, is essential if the advances being incorporated in the MOBILE and EMFAC models are to be effectively used by transportation agencies. The Sacramento TCM analyses did not just rely on executing one step of the travel forecasting process (typically mode choice). Rather, the full model chain was run, including traffic assignment. The changes resulting from using these other models, taken both individually and cumulatively, were important in assessing the overall regional effects of the proposed HOV lane and ramp metering capabilities.

Analysis tools often are used only to assess the impacts of candidate transportation strategies. The Sacramento analyses also demonstrate that these results can be useful in refining the design of proposed transportation improvements. The choices of which ramps to meter and the location and type of HOV facility to implement represent important design decisions and ones which are very much dependent on the forecasts of congestion levels in future years. For example, ramp metering may be counterproductive if the locations and time of day of operation are not properly selected.

While the particular set of analytical enhancements were selected primarily because of their potential to improve the accuracy with which the effects of HOV lanes and ramp metering could be estimated, these same enhancements are useful for other types of TCMs as well, especially those affecting the operation of a transportation system and the time of day for both commute and non-commute travel. Importantly, these enhancements serve as a starting point for the implementation of more fundamental, longer time horizon improvements to an agency’s analytical capabilities.

### 2.4 Longer-Range, More Fundamental Analytical Enhancements

The kinds of transportation and emissions modeling improvements described in Section 2.3 and the associated Task 2 Interim Report, and tested in conjunction with the Sacramento Area Council of Governments, can be readily implemented by most MPOs. Although the described techniques improve the accuracy of estimated travel and emission impacts of transportation air quality control strategies, these techniques taken either individually or in combination do not represent a satisfactory long-term solution. More fundamental changes in analytical approaches are required, including the development of the data required to support these new method-
ologies. An important component of NCHRP Project 8-33, therefore, was the development and testing of potential longer range, more fundamental enhancements to the transportation air quality analysis process. Work performed in cooperation with Portland Metro, the MPO for the Portland, Oregon, metropolitan area, focused on changes that could be made by transportation agencies over a mid- to long-range time horizon that would improve the ability of transportation models to predict variables that are important to estimating emissions and air quality impacts of transportation actions accurately. Three specific modeling enhancements were evaluated:

1. The use of activity-based travel demand models;
2. The use of household sample enumeration forecasting techniques; and
3. The use of stated preference surveys and modeling approaches, applied both independently and in combination with traditional revealed preference techniques.

The results of the Portland testing are described in Appendix A (which is not provided herein, but which is contained on the accompanying CD-ROM), including descriptions of the specific data and methodologies used, the TCM policies analyzed, and the estimated impacts that would result from implementation of these strategies. The following represents an overall assessment of the Portland testing, building upon the detailed findings and conclusions presented in Appendix A.

1. The proposed analysis techniques, both individually and in combination, improve the accuracy with which transportation impacts of TCMs, as well as other transportation actions potentially affecting emissions and air quality, are estimated. A wider range of impacts are predicted, and indirect effects are taken into consideration. Most important, travel is accurately modeled as a daily activity, with trips grouped into tours rather than being treated as independent units.

2. While the Portland metropolitan area has unique institutional characteristics, the analytical techniques applied as part of this testing and simultaneously being implemented by Portland Metro, are applicable to other urban areas throughout the country. There is nothing about these particular analytical methodologies that would inherently limit their applicability for either urban area or statewide transportation planning. In fact, the initial U.S. application of tour-based transportation models occurred in Boise, Idaho, followed by a statewide application in New Hampshire. A serious constraint to the expanded use of full activity-based transportation modeling, though, is the limited number of people having the technical skills necessary to successfully develop and apply this style of modeling. The skills requisite to develop and apply activity-based transportation modeling exist in some, but far from most, transportation agencies.

3. The Portland testing indicates that data requirements are increased if the objective is to improve the accuracy of even the meaningfulness of estimated emissions and air quality impacts of transportation actions. The use of improved analytical methodologies is not sufficient by itself. The underlying data necessary to support the development and application of these techniques also must be available. While tour-based travel demand models can be estimated using standard travel survey data, the extension to full activity-based modeling is likely to require the collection of a broader range of data items over a longer period. Further, transportation data collection traditionally has been driven by transportation rather than by air quality or other concerns. Although the 1994 Portland Household Activity and Travel Survey, and the associated series of stated preference surveys, provide a considerable amount of transportation data, even this state-of-the-art data collection effort does not contain all of the information needed in order to accurately estimate vehicular emissions. At the same time, it is recognized that individual urban area and statewide travel surveys are becoming increasingly complex and difficult.

4. The identification of synergistic effects of air quality transportation control measures requires use of the kind of integrated transportation modeling system demonstrated in the Portland testing. The highly complex interactive behavioral effects are unlikely to be captured by either monitoring person and household travel or highly simplified modeling approaches. Residential choice, employment choice, and trip-making behavior simply are too complex to be fully captured in other than an activity-based transportation modeling system. At the same time, the synergistic effects estimated for the particular mix of policies analyzed in this Portland testing were slightly negative rather than positive as normally hypothesized. Once a shift in individual transportation behavior is induced, additional transportation actions directed toward the same end will have a decreasing marginal effectiveness.

5. Household sample enumeration, stated preference techniques, and tour-based activity modeling are well within the resource capabilities of transportation agencies to implement and apply. The use of full activity-based transportation modeling, though, has considerably higher resource implications in terms of the level of professional skills, data, implementation and application costs, and computer capabilities required. Immediate practical barriers to the widespread application of activity-based transportation modeling are the processing time and memory demands placed by this style of modeling on even high-end personal computers. While this type of equipment eventually will be available in the majority of transportation agencies, it does not yet come close to representing the norm.
6. The Portland work carried out as part of NCHRP Project 8-33 and other ongoing FHWA-sponsored projects indicates that the development and application of activity-based transportation modeling is feasible. This is perhaps the most important finding to take away from this Portland testing. The capabilities of such models will only improve in the future. Even this first generation set of Portland models introduce dramatically improved transportation and air quality analysis capabilities when compared with conventional four-step modeling approaches. In particular, activity-based models can provide the information needed to improve the linkage of transportation models with emissions and air quality analytical methodologies.

7. Numerous simplifications were introduced into the current Portland activity-based transportation models to allow the full modeling system to be run within reasonable computer processing times, with the use of five daily periods being but one example. The result is that the capabilities of the current Portland model are significantly less than those contained in an ideal activity-based transportation modeling system. These limitations are both understandable and acceptable from a transportation analysis perspective, but are more limiting with respect to emissions and air quality modeling. The current set of Portland activity models were designed primarily to support the analysis of transportation policies. Different assumptions would have been made if the primary objective were the support of air quality analyses.

8. Household sample enumeration is used as the technique for applying the Portland system of activity models. This same technique, though, can be used in conjunction with other types of disaggregate travel demand models. A major benefit is that it preserves the full distribution of household demographic and socioeconomic variables, thereby facilitating the analysis of distributional effects of a candidate transportation action. Household sample enumeration also facilitates the integration of a series of individual travel demand models so that the full range of potential behavioral impacts can be efficiently and effectively simulated.

9. The Portland testing demonstrates the applicability and practicality of stated preference survey and modeling techniques, used both individually and in combination with traditional revealed preference techniques. Stated preference data can be especially helpful in evaluating candidate policies where a base of existing implementation experience is lacking. Stated preference techniques also can be useful where the potential impacts may be small and difficult to differentiate from those of changes in other variables. The valid application of stated preference survey and modeling techniques, though, is not easy. The determination of the external validity of stated preference data is a particular problem.

10. The evaluated pricing policies have a large impact in reducing travel to the central business district, especially during the morning peak period. Overall regional travel, though, is not significantly impacted. The number of daily tours actually increases slightly, but the total number of daily auto trips decreases slightly. Trips originally destined for the downtown are diverted to other districts, showing the importance of examining changes in trip structure and destination as well as mode choice.

11. Use of the Portland models to analyze the potential impacts of regional telecommuting incentives illustrate use of the activity-based models to understand potentially important indirect or secondary effects. While home-to-work travel declines as expected, a proportion of this reduction comes from transit. In addition, there is an increase in the number of both maintenance and discretionary tours and also in the number of non-work trips, indicating the importance of examining changes in the total daily pattern of trip-making.

12. The proposed comprehensive improvements to bus transit produce the desired decreases in auto travel, although the number of tours occurring by walk and bicycle also are decreased. The total number of tours increase slightly as expected, since overall accessibility to transportation services is being increased. Approximately one-third of the increase in bus travel is forecast to take place for non-work trip-making.

13. Applying an aggressive set of land use and growth management policies is effective at influencing the location of residential choice decisions, although the coefficients of the stated preference residential choice model also indicate that people value housing characteristics associated with traditional suburban living patterns. The forecast changes in residential housing location, though, do not translate into corresponding reductions in household travel.

14. Reductions in VMT and emissions for the combination of the three transportation policies are larger than the corresponding changes in the number of tours and trips, but still relatively modest given the nature of the TCM policies being analyzed. Emissions during the a.m. peak period for the Portland analysis region are estimated to be reduced by approximately 3 percent.

The analytical methodologies applied in the Portland testing add considerable value, demonstrating behavioral insights that simply are not possible with conventional four-step transportation modeling approaches. The Portland testing establishes that the application of these techniques is feasible. While Portland Metro must be considered an example of a state-of-the-art MPO, activity-based modeling and forecasting
will likely begin to be used throughout the United States during the coming years. This introduction, however, will occur in an evolutionary or transitional manner over a period of many years, rather than being undertaken as one large and immediate change. Tour-based modeling applications increasingly will be used, and transportation agencies may even maintain two modeling systems for a period of time—traditional as well as tour- or activity-based. Activity-based systems, either with or without a stated preference component, can be immediately used for a wide variety of research and policy support applications.

2.5 EMISSIONS

The MOBILE and EMFAC models are being used not only to evaluate individual roadway improvement projects, but also to develop and evaluate transportation policy. The assumptions built into the models regarding the relationship between average speed and vehicle emissions do not enable the models to be used reliably to evaluate operational improvements that smooth traffic flow (e.g., ramp metering, signal coordination, and many ITS strategies). To the extent that such operational improvements reduce acceleration events and the queuing of vehicles, they may produce emissions benefits that are inconsistent with estimates based on the use of the speed correction factors built into MOBILE and EMFAC.

Table 2.6 is a prioritized listing of the data desired for modeling emissions from on-road motor vehicles, with a particular emphasis on the parameters needed to estimate the emission impacts of TCMs. Considering all pollutants, VMT is the most critical piece of information in a modeling effort. Errors in these estimates directly affect the emission calculation because emissions are calculated as the product of VMT (obtained from transportation models) and gram per mile (g/mi) emission rates (obtained from emission factors models). Also of note in the table is that the priority of data needs for volatile organic compounds (VOCs) and CO emission estimates are generally similar. This is because VOCs and CO typically are related more to light-duty vehicle travel, their sensitivity to ambient temperature is similar, and their formation in the engine is often tied to specific operating modes (e.g., during cold start). However, heavy-duty diesel vehicles are significant contributors to NOx and PM, and NOx is less sensitive to ambient temperature.

As illustrated by Table 2.6, a wide range of transportation data is needed to accurately characterize on-road motor vehicle emissions. Many, but not all, of the identified parameters generally are available from today’s transportation models. The following are important exceptions: data or modeling improvements in these areas would be particularly beneficial:

- **Speed/Acceleration/Driving Profile**—Although speed is an input to emission factor models, acceleration and driving profile are not. These parameters, in particular acceleration, can have a significant influence on emissions.
- **Fraction of Cold/Hot Starts**—This is an important parameter used by emission factor models. Vehicles in the cold-start mode generally have emissions that are several times higher than during warmed-up operation.
- **Travel by Vehicle Class and Time of Day**—Travel by vehicle class can be specified by the user as an input to MOBILE. However, most analyses let the model calculate this parameter based on forecasts of national vehicle populations and assumed VMT by vehicle class. This is an area in which improvements can be made and linkages with transportation models may help. In terms of travel by time of day, these data would help to better estimate temporally distributed emissions.
- **Time/Location of Starts**—This is not a direct input to emission factor models, but information on the time and location of starts can be used in conjunction with emission factor model output to better estimate spatially and temporally distributed emissions.
- **Travel by Facility Type and Time of Day**—The distribution of travel by vehicle class is not constant across facility types. Because different facility types have different patterns of travel, average speed, and driving profiles, information specific to facility types could be used
<table>
<thead>
<tr>
<th>Priority</th>
<th>VOC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle miles traveled</td>
<td>Vehicle miles traveled</td>
<td>Vehicle miles traveled</td>
<td>Vehicle miles traveled</td>
</tr>
<tr>
<td>2</td>
<td>Fraction of cold/hot starts</td>
<td>Fraction of cold/hot starts</td>
<td>Heavy-duty diesel</td>
<td>Road surface silt loading</td>
</tr>
<tr>
<td>3</td>
<td>Ambient temperatures</td>
<td>Ambient temperature</td>
<td>Speed/acceleration/driving profile</td>
<td>Travel by vehicle class</td>
</tr>
<tr>
<td>4</td>
<td>Time/location of starts</td>
<td>Time/location of starts</td>
<td>Grade/terrain</td>
<td>Travel by facility type</td>
</tr>
<tr>
<td>5</td>
<td>Speed/acceleration/driving profile</td>
<td>Speed/acceleration/driving profile</td>
<td>I/M characteristics</td>
<td>Vehicle weight</td>
</tr>
<tr>
<td>6</td>
<td>Fuel characteristics</td>
<td>I/M characteristics</td>
<td>Travel by vehicle class, time of day</td>
<td>Heavy-duty diesel travel</td>
</tr>
<tr>
<td>7</td>
<td>I/M characteristics</td>
<td>Non-normal travel, e.g., special events/accidents</td>
<td>Travel by vehicle class, facility type</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Travel by vehicle class, time of day</td>
<td>Travel by vehicle class, time of day</td>
<td>Bus and rail transit travel</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Travel by vehicle class, facility type</td>
<td>Travel by vehicle class, facility type</td>
<td>SOV rates</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Hourly temperature distribution</td>
<td>Hourly temperature distribution</td>
<td>Ramp activities</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Average trip length</td>
<td>Average trip length</td>
<td>Vehicle load and A/C use for light- and heavy-duty vehicles</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>SOV rates</td>
<td>SOV rates</td>
<td>Non-normal travel, e.g., special events/accidents</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Bus and rail transit travel</td>
<td>Bus and rail transit travel</td>
<td>Freight mode choice (truck vs. rail haul)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Trip ends with hot soaks</td>
<td>Grade/terrain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Locations of diurnals</td>
<td>Ramp activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Ramp activities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Non-normal travel, e.g., special events/accidents</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
to better estimate motor vehicle emissions. As currently structured, however, emission factor models can only accept average speed as an input parameter.

- **Trip Ends with Hot Soaks**—The location of trip ends would allow better spatial allocation of VOC emissions for input to airshed models. Current emission factor models, however, are not used directly for spatially allocating emissions.
- **Freight Mode (Truck Versus Rail)**—Goods movement via truck can have an important impact on NOx emissions in an urban area. While motor vehicle emission factor models are not equipped to handle rail emissions, they can be better utilized to generate vehicle class-specific emission factors to make comparisons to rail travel.

Both the EPA and CARB recognize the problems associated with using MOBILE and EMFAC to estimate the effect of transportation system improvements. Both agencies are therefore in the process of collecting data and developing new analysis techniques to improve the performance of the existing models.

In addition to improving the accuracy and the level of detail of the transportation data that are input to emissions, it is important that transportation personnel also appreciate the implications of the travel assumptions that may be embedded internally within an emissions model. These assumptions have an important influence on the accuracy of resulting emissions estimates. Further, it may be possible in many cases to adapt these assumptions so that they reflect locality-specific rather than national conditions.

To help develop this improved understanding, the MOBILE5a and MVEI7G emission models were reviewed to identify the important travel assumptions embedded in them. While both models employ a wide range of travel activity assumptions, they can generally be organized into the following categories:

- **Annual Mileage Accumulation Rates**—the difference in the odometer reading between the beginning and end of the year. On average, vehicles are driven less as they age (i.e., new vehicles are driven more than older vehicles). Mileage accumulation has many uses in emission factor modeling, including weighting vehicle activity levels—both within vehicle classes and across vehicle classes, and computing the deterioration in emission control system performance (i.e., emissions increase as vehicles age).
- **Travel Fractions**—the fraction of travel that each model year contributes to the total travel of a vehicle class. This value is computed by combining the registration distribution (i.e., the fraction of vehicles by age making up the vehicle fleet) with the mileage accumulation rate. Both models also track technology categories within each model year and their relative contribution to the vehicle class-specific travel within the model year must also be estimated.
- **Vehicle Miles Traveled (VMT) mix**—the fraction of travel that each vehicle class contributes to the total travel of the vehicle fleet. This value is computed by combining estimates of the assumed vehicle population with the annual mileage for each vehicle class. The average annual mileage of each vehicle class is computed from the travel fraction data.
- **Trips Per Day**—the average number of trips that a vehicle makes per day has been used to estimate the number of times that a vehicle is started per day. This information is used to estimate both the start component of exhaust emissions and evaporative emissions that are a function of the time between vehicle starts.

The data used to develop these estimates are derived from survey results (e.g., travel surveys and vehicle counts); registration statistics; and Inspection and Maintenance (I/M) program data (where odometer readings have been recorded). Generally speaking, the data sources available to characterize light-duty vehicle travel have been more robust than those for heavy-duty vehicles.

State or urban area transportation planning model outputs are used in the development of emission inventories. These data, however, generally are not used to adjust the travel assumptions embedded within the emission factor models. One category of travel activity where there can be a direct link to travel models and surveys is the estimate of vehicle class-specific trips per day. As noted above, trips have been used to estimate the frequency of vehicle starts.

The release of MVEI7G by CARB has changed the approach used to estimate starts. MVEI7G contains estimates of the number of starts, not trips, and is based on the results of data collected by instrumented vehicles placed in customer service. The data show that the light-duty vehicles contained in this sample experience more starts than indicated by the trip data collected in transportation surveys (roughly 50 percent more). The source of the discrepancy is thought to be short trips (e.g., moving vehicles in driveways, shopping centers, and trip chaining). While the capture of these trips will improve the accuracy of emission factor estimates, it complicates the use of travel information in inventory development because a relationship is now needed to adjust the estimate of the number of trips produced by transportation planning models to account for the short trips that are not now captured in the modeling process.

A related issue is that, by embedding an estimate of the trips per day within the emission factor models, the flexibility required to account for changes in the local distribution is curtailed. Stated another way, the effect of local TCMS cannot be evaluated without the use of an elaborate post-processing structure. Because current plans call for MOBILE6 to replace estimates of trips per day with an estimate of vehicle class-specific starts per day, methods will need to be
developed that address MOBILE6 linkage with transportation planning models in the emission inventory development process.

Finally, a review of the methods used to develop heavy-duty truck and bus forecasts shows that the data for these vehicles frequently are derived from forecasts of light-duty vehicles. Given the significance of heavy-duty vehicles to NO\textsubscript{x} emission estimates (typically over 50 percent of the mobile source NO\textsubscript{x} inventory), this practice is a problem. Heavy-duty vehicle travel is not directly proportional to light-duty vehicle travel; it is not distributed in proportion to light-duty travel by hour of the day (in contrast to light-duty vehicles, the peak period of operation for heavy-duty vehicles is typically during the middle of the day); and heavy-duty vehicles do not travel at the same speeds as light-duty vehicles, except under the most congested conditions. New methods need to be developed to address these issues.

**Improved Modeling Procedures**

Two aspects of emissions modeling procedures are of particular concern from a transportation perspective:

- **Representativeness of the Federal Test Procedure (FTP)**—Data collected during the past few years indicate that the driving cycles on which the MOBILE and EMFAC models are based do not accurately reflect the types of vehicle operation that occur under typical in-use conditions.

- **Representativeness of Speed Correction Factor Test Cycles**—Many of the test cycles used to construct the speed correction factors are not representative of in-use driving conditions.

**Facility-Specific Speed Correction Factors**

In response to these concerns, combined with the increasing scrutiny of the emissions impacts of transportation improvements required by the 1990 CAAA, both EPA and CARB have undertaken a series of improvements to MOBILE and EMFAC. EPA, with support from the FHWA, developed facility-specific speed correction factors for incorporation in MOBILE6, the next generation of the model. CARB is developing EMFACX, which also will have the capability to assess the effect of facility-specific correction factors.

Attention by EPA initially was given to incorporating two facility-specific speed correction factors into MOBILE: one for freeway operation and one for arterials, local roads, and so forth. Given the increasing focus on ramp operation as both a capacity improvement and emissions reduction strategy, research was undertaken in NCHRP Project 8-33 to provide a feasibility-level assessment of the differences in vehicle operation and related emissions impacts on metered and non-metered ramps. The results are based on limited data collected from vehicle operation on a sample of ramps located in Sacramento, California.

The investigation was conducted in the following four steps:

1. Documenting vehicle operation on a sample of both metered and non-metered freeway ramps using a laser rangefinder-equipped “chase car”;
2. Constructing “typical” vehicle operating cycles for both types of ramps based on kinematics;
3. Measuring emissions from test vehicles that were driven through the test cycles on a dynamometer; and
4. Comparing the emissions measured using the freeway ramp driving cycles with emissions measured using driving cycles representative of more typical driving conditions.

Two separate driving cycles were developed to represent vehicle travel on metered and non-metered freeway ramps. The cycles were constructed to match the observed speed-acceleration frequency distribution observed on each type of ramp. As shown in Table 2.7, the average speed on metered ramps is 15.1 mph, while the average speed on non-metered ramps is 40.8 mph. There also is a substantial difference in the observed maximum acceleration rates, with metered ramps showing roughly double the rate observed on non-metered ramps. Additional statistics on the maximum observed speed and the length of the resulting cycles are also presented.

<table>
<thead>
<tr>
<th>Table 2.7</th>
<th>Comparison of metered and non-metered ramp driving cycles*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Speed (mph)</td>
</tr>
<tr>
<td>Metered</td>
<td>15.1</td>
</tr>
<tr>
<td>Non-Metered</td>
<td>40.8</td>
</tr>
</tbody>
</table>

*Based on driving data collected from a sample of ramps in Sacramento, California.
Figure 2.3 shows how the average emissions of four mid-to late-model vehicles varied by ramp type. To provide a perspective on how ramp emissions compare with more typical driving, average FTP emissions also are presented. The results show that freeway on-ramp emissions, on a grams-per-vehicle-mile basis, are much higher than emissions from general driving represented by the FTP, and emissions from metered ramps are higher than emissions from non-metered ramps (roughly double).

From a broader perspective, these results illustrate the problems that analysts face in evaluating the emission impacts of TCMs and similar strategies affecting capacity and traffic flow. The speed correction factors currently employed in the emission factor models used by the EPA and the CARB in the MOBILE and EMFAC emission factor models suggest that emissions for any speed and pollutant will vary between 0.5 and 3.0 times the FTP value. The results presented in Figure 2.3 indicate that CO and NOx emissions may vary by a much wider range, up to a factor of 9.5 for CO. These averages, however, mask a much wider range of variability that individual vehicles can experience depending on the mode of engine operation.

Qualitatively, these findings are not new to motor vehicle emission analysts. Instead, they are consistent with a growing recognition that the existing MOBILE and EMFAC emission factor models are inadequate for the analysis of the emission impacts of certain types of roadway improvements.

Effort was not made in Project 8-33 research to control for effects of grade, ramp geometry, or ramp length. However, preliminary dynamometer tests show that (simulated) upgrade on-ramps resulted in several-fold increases in hydrocarbon, carbon monoxide and carbon dioxide emissions as compared to driving the same cycles on level or down-grade ramps. This effect was most pronounced for metered ramps. NOx emissions had a mixed response to grade change. These preliminary results of emissions measurements with grades should be repeated using other cars and other grades, including more severe grades, particularly more severe up-grades.

In the short term, agencies can immediately improve the accuracy of TCM emission estimates by improving the quality of the transportation input data and by modifying the manner in which MOBILE and EMFAC are used. The improved versions of MOBILE and EMFAC being developed by EPA and CARB will further enhance analysis capabilities.

Modal Emission Models

Independent of these improvements to current emission factor models and analysis procedures, efforts are underway to develop an entirely different class of emission model referred to as “modal emission” models. The results of this modal emissions modeling research already are being introduced into MOBILE6 and TRANSIMS, and it is likely that modal emissions modeling will gradually be introduced into transportation practice over the coming years.

A major objective of these modal models is to overcome the assumptions embedded in the current regulatory MOBILE models.
and EMFAC models regarding the relationship between average speed and emissions. In a modal emissions model, analysis is performed to identify the modes of vehicle operation responsible for significant differences in emissions performance. Tests are then performed to measure emissions from these modes of operation for a sample of vehicles that represents the in-use fleet. The following different approaches are being used to characterize the range of in-use emissions performance:

- In-use driving data are analyzed to develop multiple driving cycles to characterize vehicle operation by facility type and level of congestion. Emission measurements are taken for a representative sample of vehicles tested on these alternative cycles. Travel activity is segregated by facility type and congestion level and combined with the appropriate emission factors to quantify emission estimates.
- Emission measurements are taken for each mode of speed and acceleration for a representative sample of vehicles. This approach is based on steady-rate measurements of emissions at fixed speed and acceleration points (i.e., the transitional impacts of acceleration or deceleration, which can be considerable, are ignored). To prepare emission estimates, travel activity for the entire vehicle fleet must be supplied in units of time at these modes of speed and acceleration.
- Emission measurements are taken for a representative set of engine speed and load points (commonly referred to as engine maps of emissions) to characterize the range of engine operation and related emissions performance for a representative sample of vehicles. A computer model is used to translate second-by-second driving activity into engine power demands. The power demands then are matched with related emissions estimates (in most cases, these estimates must be interpolated because test measurements are limited) to generate estimates of in-use emissions.

The result of this increased research on emissions models is that a wide spectrum of modeling approaches is becoming available to estimate motor vehicle fleet emissions, as illustrated in Figure 2.4. This spectrum ranges from highly aggregate regional models to highly disaggregate vehicle models. Models can range from the simple, employing very few highly aggregated emission rate and activity variables, to the extremely complex, employing a large number of disaggregate emission rate and activity variables. A variety of modeling assumptions and data aggregation techniques have been developed to simplify the emission inventory preparation and minimize labor and data requirements. However, these simplifications typically sacrifice the explanatory power of the models.

At one end of the spectrum, a very simple regional model can be employed using only two variables. On the emission rate side, one could simply develop an average gram per trip emission rate for the average fleet vehicle. On the vehicle activity side, one would simply estimate the average number of trips per vehicle per day. The regional model is highly aggregate in nature. Nevertheless, an accurate model of this type can provide very good regional estimates of daily emissions. That is, if the average trip/day values are correct, and the average emission rate values are correct, users will arrive at an accurate estimate of total emissions. The basic problem is that the model has limited value in policy evaluation. Users can really only change two values: (1) average fleet emission rates and (2) number of starts per day.

At the other end of the spectrum is a complex vehicle simulation modal emissions model. In this modeling regime, the second-by-second emissions rates for each vehicle are predicted as a function of the actual engine operating parameters. Numerous variables can be employed in predicting second-by-second emission rates, each variable contributing to stoichiometric emission rates and/or occurrence and magnitude of enrichment emissions.

Figure 2.4 provides examples along the emissions modeling spectrum between the two arrows for motor vehicles. As models evolve from the left to the right, additional explanatory variables are included in the model. Because the models employ additional variables, they become more complex and resource intensive. However, the overall explanatory power of the models is significantly improved. Spatial and temporal resolution of emissions predictions also improve along the spectrum. This means that the improvements in emission inventory resolution can also yield improvement in the accuracy of regional and microscale emissions impact assessment models.

As agencies implement these enhanced emissions modeling capabilities, it is recommended that particular emphasis be given to the following capabilities, as elaborated upon in Appendix B:

- Representing high-emitting vehicle activity and emissions,
- Representing the effects of engine enrichment and operating cycle,
- Separating engine start and running exhaust activity and emission rates,
- Allocating emissions on a spatial and temporal basis, and
- Drawing appropriate statistical inferences based on pre-analysis assumptions and available data.

### 2.6 AIR QUALITY

TCMs and other forms of mobile source air quality control strategies typically are evaluated in terms of the magnitude of their emissions reductions, with the location and timing of those emissions changes occasionally also being examined. The ultimate objective of implementing TCMs, though, is
Figure 2.4. Emissions modeling spectrum.

to improve ambient air quality levels. There is considerable
interest, therefore, on the part of state and local transporta-
tion officials in knowing the degree to which implemented
TCMs and other mobile source control strategies are actually
accomplishing this intended objective.

Existing Data on the Effects of Mobile Source
Air Quality Controls

Various researchers have employed statistical techniques
to analyze ambient measurement data to determine the effects
of oxygenated fuel, reformulated gasoline, and vehicle I/M
programs on ambient air pollution levels. Table C.1 in Appen-
dix C (which is not provided herein, but which is contained
on the accompanying CD-ROM) summarizes the technical
approaches and results for eight such investigations. A
review of this table indicates mixed results, despite carefully
thought out experimental and analytical approaches. From a
purely statistical perspective, most of these efforts were
inconclusive. Although the effects of larger emissions gen-
erally could be detected, the effects of smaller reductions in
emissions proved much more difficult to discern. Similarly,
changes in CO concentrations were easier to detect than
changes in other pollutants.

These studies demonstrate the difficulty in detecting an
emission-related effect through statistical analysis of moni-
tored air quality data. One reason for this difficulty is the sig-
nificant variation in pollutant concentrations that occurs nat-
urally because of the stochastic character of the atmosphere
and changes in meteorological variables. In situations where
a control measure has only a modest influence on emissions,
the resulting change in pollutant level is only one component
of the overall variability in ambient concentrations. Even
though there may be evidence that emissions are reduced, it
may not be possible to show the associated change in ambi-
ent air quality to the desired level of statistical confidence.

A second reason for problems in correlating emissions
and air concentration data is the influence of outside or un-
controlled events. Such events can have a significant effect
on the ambient concentrations, yet this may not be accounted
for by the statistical modeling techniques.

Similar difficulties will be encountered in efforts to detect
the effects of TCMs on ambient ozone data. Photochemical
modeling results indicate that small changes in precursor
emissions are likely to yield correspondingly small changes
in ozone concentrations. Evaluating the effects of transporta-
tion and other forms of mobile source air quality control mea-
sures by using ambient ozone measurements is a desirable
objective, but one which has proven especially challenging to
achieve in practice.

Although isolating the effects of particular emission changes
through the statistical analyses of monitored air quality data
is difficult, these approaches are nonetheless still appealing
because of their potential to directly address impacts on ambi-
ent air quality. The studies summarized in Appendix C (pro-
vided in the accompanying CD-ROM) indicate that statistical
approaches are likely to be most successful in discerning
effects on ambient air quality levels of control measures that
result in relatively large reductions in emissions; for example,
those greater than 10 percent. Control measures that have a
spatially diffuse effect on emissions, such as many forms of
TCMs, will be much more difficult to discern through the sta-
tistical analysis of monitored air quality data.

Similarly, these studies indicate that detecting the effects of
emission reductions on monitored levels of a secondary pollut-
ant such as ozone is considerably more difficult than detect-
ing changes in primary pollutants such as CO. As pointed out
in several of the analyses summarized in Appendix C, this
does not necessarily mean that these measures are not result-
ing in improved air quality, only that this determination is
difficult to demonstrate with the desired levels of statistical
confidence.

Achieving air quality goals is likely to require the imple-
mentation of several emission control measures. Although
each of these may have only a modest influence on emis-
sions, the combined influence of these measures may provide
the overall required emissions reduction needed to attain the
air quality standards. The difficulty in analytically isolating
the effects of one or more individual mobile source control
measures on monitored air pollutant concentrations should
not automatically lead to the conclusion that these measures
are not reducing emissions or are not beneficial.

Changes in Air Quality and
Transportation Associated with the
1996 Atlanta Summer Olympics

In an attempt to determine if changes in ambient air qual-
ity would result from regional changes in a transportation sys-
tem, transportation and air quality data collected in conjunc-
tion with the 1996 Olympic Games held in Atlanta, Georgia,
between July 19 and August 4, 1996, were analyzed. Major
changes were made during the Olympic Games to the high-
way, transit, and other transportation systems serving the
Atlanta region. Together with the Games themselves, these
resulted in major changes in virtually all aspects of travel
demand, including the time of travel, modal shares, traffic
volumes, transit ridership, and travel speeds.

Data from the Olympics indicate that the transportation
strategies implemented during the Olympics were largely suc-
cessful in reducing traffic, particularly during the morning
and evening rush hours when unusually low levels of congestion
were experienced. At the same time, average ozone levels
were between 10 and 20 percent lower than the summer 1996
average (Table 2.8 and Figure 2.5). One of the primary goals
of this analysis was to determine whether this improvement in
air quality can be attributed to transportation strategies imple-
mented for the Olympics, or whether other factors caused
lower ozone levels during this period.
TABLE 2.8 Change in maximum hourly ozone levels during Olympics

<table>
<thead>
<tr>
<th>Monitoring Site</th>
<th>Location Relative to Downtown Atlanta</th>
<th>Mean ppb (non-Olympics)</th>
<th>Mean ppb (Olympics)</th>
<th>Change During Olympics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conyers</td>
<td>20 miles SE</td>
<td>71</td>
<td>65</td>
<td>-10%</td>
</tr>
<tr>
<td>Decatur</td>
<td>8 miles SE</td>
<td>69</td>
<td>56</td>
<td>-19%</td>
</tr>
<tr>
<td>Tucker</td>
<td>11 miles NE</td>
<td>72</td>
<td>59</td>
<td>-19%</td>
</tr>
<tr>
<td>Yorkville</td>
<td>40 miles WNW</td>
<td>67</td>
<td>57</td>
<td>-15%</td>
</tr>
<tr>
<td>Confed. Ave.</td>
<td>2 miles SE</td>
<td>75</td>
<td>63</td>
<td>-16%</td>
</tr>
<tr>
<td>Gwinnett</td>
<td>18 miles NE</td>
<td>68</td>
<td>61</td>
<td>-11%</td>
</tr>
</tbody>
</table>

Four major components were included in this analysis:

- A historical background on ozone and traffic trends in Atlanta;
- An overview of transportation strategies implemented during the Olympics and indicators of the effectiveness of these strategies;
- An analysis of traffic data from the Summer 1996 period, including changes in total and peak-hour traffic during the Olympics; and
- An analysis of air quality data from the Summer 1996 period, including ozone, NO\textsubscript{x}, and CO from ambient monitors, as well as relevant meteorological data.

Establishing a direct link between individual transportation strategies and air quality is difficult for several reasons. First, comprehensive detailed quantitative evidence was not available on the travel impacts of individual strategies, so only aggregate traffic and transit volumes could be used as an indicator of the overall effectiveness of combined strategies. Second, a comparison of Olympics traffic data with normal traffic levels includes both the subtractive effects of transportation strategies and the additive effects of two million Olympic visitors to the metropolitan area. Given that the specific travel characteristics of the visitors are not known, assigning a “baseline” from which to gauge program effectiveness is difficult. Finally, strategies may have affected traffic patterns in different ways, including overall volumes, demand by time of day, the location of traffic, and the mix of vehicle types. Separating out the separate effects of these various impacts on emissions and monitored air quality is not possible given the aggregate characteristics of the available data.

**Effectiveness of Transportation Strategies**

Evidence on the effectiveness of the various transportation strategies implemented for the Olympics is largely consistent with the available traffic data. Surveys of employers suggest that shifted work hours, a compressed work week, transit ridership, and taking vacations were all fairly widespread. Shifted work hours, in particular, are consistent with an observed shift in peak-period traffic to other times of the day. Traffic at some locations decreased by up to 30 percent during the maximum a.m. hour and up to 25 percent during the maximum p.m. hour. Traffic impacts were most notable in the central Atlanta area and substantially reduced congestion.

Traffic outside of the peak periods showed little change or a slight increase from normal, and it appears that total daily traffic volumes decreased by 5 percent or less. This is remarkable when contrasted with the potential levels of travel given the number of visitors in Atlanta at the time. The traffic and transit data suggest that a large percentage of Olympics visitors used transit to access events, particularly in the Olympic Ring area. Overall, given the number of visitors to the Atlanta region in addition to the base level of travel by residents, the smooth operation of the transportation system was a considerable accomplishment.

**Air Quality Impacts**

Monitored levels of both secondary pollutants (ozone) and primary pollutants (CO and NO\textsubscript{x}) were analyzed to determine whether air quality changed significantly during the Olympics, and, if so, whether these changes could be attributed to changes in emissions due to changes in traffic patterns.

Raw ozone data from six Atlanta area monitoring sites indicated a 10- to 20-percent decrease in ozone during the Olympics. Statistical analysis based on meteorological variables also indicated an overall 18-percent decrease in maximum ozone levels among the six sites. A comparison of ozone levels at other sites in the southeastern United States, however, indicated a regionwide decrease during the same period (Figure 2.6). In particular, ozone decreased by roughly 25 percent in Birmingham, 150 mi west of Atlanta, while winds during
Figure 2.5. Summer 1996 ozone history (Decatur, Georgia).
this period were consistently from the west. This suggests that regional meteorological factors largely, if not fully, explain the decrease in ozone levels in Atlanta during the Olympics.

An analysis of NO\textsubscript{x} and CO data indicates a decrease in both pollutants during the morning peak period during the Olympics. CO and NO\textsubscript{x} also were positively correlated with nearby traffic volumes, suggesting that a decrease in pollutant levels would be expected based on decreased traffic volumes. The analysis was confounded by several factors, however, including limitations on monitoring and traffic data availability and the influences of local meteorological factors.

The results of the Atlanta analyses underscore the difficulty of observing changes in mobile source emissions through ambient monitoring of pollutants, particularly ozone. During the period of the Olympics, ozone levels were lower not just in Atlanta but over much of the southeastern United States. This regionwide improvement in air quality cannot be attributed primarily to Olympics-related control measures and appears to be largely due to regional meteorological conditions. Particularly given the short time period of impacts, the effects of meteorology confound attempts to relate monitored levels of ozone and primary pollutants to changes in traffic. Transportation measures related to the Olympics may have produced significant emissions benefits, but the related improvements in air quality cannot be quantified or demonstrated with any certainty given the data available for this analysis.

The Atlanta analyses also point to the importance of supplementing monitoring data with photochemical modeling efforts, particularly for secondary pollutants. This would help account for meteorological influences and for changes in the specific proportions of precursors in causing ozone formation. Given the uncertainties in current modeling capabilities, it
would be ideal to both model and monitor ozone in order to identify and verify expected changes due to changes in emission patterns.

Such a combination of modeling and monitoring was utilized by Davidson and Cassmassi in analyzing changes in ozone levels during the 1984 Los Angeles Summer Olympics (4). Observed ozone levels during the June 15 to June 30 Olympic period were compared with similar periods during 1982 and 1983 using a set of statistical relationships that empirically link ozone concentrations to the observed values of an array of meteorological predictor variables and persistence terms. In response to changes in traffic patterns that were similar to those that occurred in Atlanta, Davidson and Cassmassi’s conclusion was that ozone levels were 11.8 percent lower than those predicted based on similar meteorological conditions. In comparing the Los Angeles and Atlanta conclusions, however, it is important to note the differences that exist between the Los Angeles and Atlanta air basins, as well as in the analytical methodologies utilized.

Potential of Remote Sensing and Personal Exposure Monitors

Two alternatives to the use of traditional air quality monitoring techniques were assessed to determine their potential applicability for evaluating the air quality impacts of TCMs:

- Use of remote sensing techniques to directly measure changes in vehicle emissions and ambient air quality and
- Use of personal exposure monitors to measure changes in individual exposure to air pollutants.

In transportation studies, remote sensing currently is used to provide a direct measure of in-use vehicle “tailpipe” emissions. Other remote sensing techniques provide a measurement of ambient pollutant levels, either integrated over the line of sight of a laser beam or at discrete points (or bins) along the line of sight of the beam. When such devices operate in a scanning mode, it is possible to map out the spatial field of pollutant concentrations. The spatial aspect of the information provided by such devices is in contrast to the “point” observations provided by conventional measurement techniques.

A personal exposure monitor (PEM) is a small, portable air quality measurement device that provides a direct observation of the exposure of an individual to a pollutant, such as ozone. Given that people spend their day in various environments (at home sleeping, in a motor vehicle traveling to and from work and other destinations, indoors or outdoors working, etc.), personal air monitors provide an attractive alternative to the use of routine air monitoring for establishing the integrated exposure of an individual.

The most promising of these two technologies is the roadside remote monitoring system, similar to that currently being used or considered for supplementing vehicle inspection/maintenance programs. Although these systems measure vehicle emissions and not ambient air quality, they offer two important advantages over conventional monitoring approaches. First, it is possible to collect a large number of samples (i.e., measurements of emissions from individual vehicles) over a relatively short period of time. And second, measurements of tailpipe emissions are less influenced by variations in meteorological conditions and the need to accurately determine both upwind and downwind concentrations. Because these remote sensing devices provide an estimate of emissions per unit volume of fuel burned, it will be necessary to independently assess the possible effect of a TCM on fuel consumption of that portion of the vehicle fleet operating in the area of interest. The estimated cost to hire a contractor to deploy such a system for a month is approximately $50,000. Costs would be reduced if a system were already available and could be deployed and operated by agency personnel. Given that measurements must be conducted both before and after implementing the TCM, the total cost would be approximately $100,000 or less.

Personal exposure monitors are best suited for use in situations where there is an interest in relating the effects of a TCM to changes in individual exposure levels. Potential applications include characterizing the effects of a TCM implemented in a transportation corridor on motorist exposures or the effects on individuals that live or work near a roadway. The estimated cost to mount a study to assess the impacts of a TCM on vehicle occupants while driving along a prescribed transportation corridor would be approximately $300,000 to $400,000 (this includes measurements both before and after implementing the TCM).

As logical next steps, field studies could be undertaken as a national research effort to demonstrate the utility of these techniques for characterizing the effects of TCMs. To enable these approaches to be implemented, if desired, by state transportation agencies, guidance then should be developed concerning experimental design and the analysis and interpretation of the data.

Feasibility of Using Advanced Air Quality Monitoring Systems to Evaluate TCMs

Four aspects are critical in designing a monitoring-based air quality evaluation program to measure the effects of TCMs:

- Spatial scale,
- Experimental control,
- Conditions for maximizing the ratio of signal to noise, and
- Duration of the monitoring program.

The primary conclusion resulting from the feasibility assessment of using a research or advanced air quality monitoring system to evaluate TCMs is that such systems are technically feasible in appropriate situations. The expense associated with implementing such specialized monitoring programs, though,
may be relatively high, and, in many cases, may be comparable to or even greater than the costs of the TCMs themselves. Consequently, a careful assessment of the costs and benefits of such monitoring programs is necessary. The result is that such evaluation programs are likely to be undertaken only in highly specialized research situations.

Specific findings with respect to the feasibility and desirability of using air quality monitoring to characterize the effects of TCMs on ambient air quality are summarized as follows:

- **Air quality monitoring is technically feasible for primary pollutants.** To maximize the likelihood of seeing the effect of TCMs, measurements of primary pollutants (e.g., CO, VOC, and NOx) should be carried out in the immediate proximity of a roadway corridor. Measurements of upwind concentrations can be subtracted from the downwind values as a means for characterizing the contribution of the roadway to ambient downwind concentrations. Experiments should be conducted both prior to and subsequent to implementing the TCMs.

- **TCM effects on secondary pollutants require a combination of monitoring and modeling approaches.** For a secondary pollutant, such as ozone, the initial focus should be to characterize the effect of the TCM on the pertinent precursor species (e.g., VOC and NOx) through near-roadway measurements. A combination of modeling and data analysis should be used to investigate the effects on downwind ozone formation.

- **It is feasible to observe TCM effects only if they exceed a certain threshold value.** The results from a simple statistical model indicate that it should be feasible to observe the effect of a TCM on ambient air quality levels for primary pollutants so long as the effect is greater than, say, 2 percent. The duration of the monitoring program would be in the range of several weeks to a year, depending on the magnitude of the effect on emissions (the larger the effect, the shorter the duration of the monitoring program). Direct observation of TCM effects on secondary pollutants is considerably more difficult. A threshold at which a precursor emissions change would produce an observable change in downwind ambient ozone concentrations may be on the order of at least 10 percent.

- **Monitoring over a large geographic area to determine the effects of areawide TCM programs is inherently more difficult than monitoring on a location-specific basis.** For example, the impacts of TCM programs such as telecommuting may result in significant areawide impacts, yet may be difficult to detect statistically at the level of individual transportation facilities. The implication is that use of an air quality monitoring program to evaluate the synergistic impacts on ozone levels of a coordinated urban area program of TCMs is technically extremely difficult and is not likely to be financially feasible. Directly observing statistically reliable effects of TCM implementation on areawide air quality levels is not considered to be a worthwhile research objective, unless such impacts are both sufficiently large and it is possible to isolate the TCM effects from other factors contributing to changes in ambient air quality.

- **Specialized TCM air quality monitoring programs are costly.** Preliminary estimates indicate that the cost of two 3-month monitoring programs (one before and the other after implementation) to examine the effects of TCMs on peak-hour CO levels downwind of a congested intersection (assuming an impact on emissions of about 10 percent) would be on the order of $500,000. If the effect on emissions is smaller, say requiring two 1-year programs, then the cost would be on the order of $1,000,000. Two 3-month programs to study effects on ozone formation would cost on the order of $1,300,000. These cost figures, however, are preliminary; refined estimates could be developed for a more specific application. Because of these high costs, it probably is not practical for local transportation or air quality agencies to undertake such specialized monitoring programs. This kind of research-grade monitoring, though, could be undertaken as part of a national research program; for example, the development of general primary pollutant reduction factors for commonly implemented localized traffic operations measures.

- **Specialized TCM air quality monitoring programs would be beneficial.** The key benefit of a TCM monitoring program is the information it would provide to public- and private-sector decision-makers, transportation agencies, and the public concerning the actual effectiveness of TCM control programs. Such information may be useful in obtaining approval for emissions reduction credits claimed as part of a State Implementation Plan (SIP). In addition, a monitoring program can be used to assess the effectiveness of a limited or prototype version of a TCM program prior to a more widespread implementation of the program.
CHAPTER 3
INTERPRETATION, APPRAISAL, AND CONCLUSIONS

3.1 SUMMARY

The basic framework and associated methodologies for the analysis of air quality and other benefits and costs of air quality transportation control strategies are intentionally broad in scope. Numerous improvements to current analysis methodologies, however, can be immediately implemented that will improve the accuracy of estimated transportation and emissions impacts. Critical shortcomings, unfortunately, will still remain. Eliminating deficiencies in the variables used to link transportation emissions and air quality analyses is especially important if accurate estimates of spatially and temporally distributed emissions impacts are to be produced.

The long-term need is for essentially a new set of analytical capabilities, rather than just incremental improvements to current modeling approaches. These longer run improvements require a combination of improved analytical methodologies and better data. Equally important, this new generation of transportation air quality analytical capabilities should take advantage of emerging computational environments.

3.2 ADEQUACY OF EXISTING AND PROJECTED FUTURE ANALYSIS CAPABILITIES

Changes incorporated in the Clean Air Act Amendments of 1990 placed increased emphasis on transportation control measures and on the use of quantitative methods to estimate transportation-related emissions. An important question is whether the set of existing and projected future transportation, emissions, and air quality modeling capabilities are sufficient to satisfy these requirements for quantitative analysis.

A National Academy of Sciences Special Committee reported in Transportation Research Board Special Report 245 (5) that, “the analytical methods in use are inadequate for addressing (CAA) regulatory requirements.” Further, “The current (CAA) regulatory requirements demand a level of analytic precision beyond the current state of the art of modeling.” The findings of this research confirm that deficiencies in the existing state of the practice are at least as serious as reported in Special Report 245 and probably greater in terms of the ability to effectively link the sequence of transportation, emissions, and air quality models. The imprecision in existing models is larger than the impacts associated with transportation control measures; existing transportation, emissions, and air quality models have been developed independently of one another; and the variables used to link existing models do not fully capture all of the relevant data parameters.

TRB Special Report 245 also contains a minority opinion to the effect that “significant and steady improvements in operational regional models for evaluating the likely emission, system performance, travel behavior, and development impacts of changes in highway capacity, pricing, and policy is possible in both the short- and mid-term to meet current (CAA) regulatory requirements.” The minority opinion further asserts that metropolitan planning organizations “have made only slow progress in improving their analytical tools to respond to new policy requirements.”

The findings of this research indicate that, although selected MPOs have demonstrated important leadership with respect to the implementation of improved transportation air quality analysis capabilities, the overall state of the practice lags significantly behind the state of the art. Numerous data and modeling enhancements have been successfully developed and applied by one or more MPOs or state DOTs that could be immediately adopted by other transportation agencies. It may be unrealistic to expect all agencies to employ today’s best practices. It is within existing budget and personnel resources, though, for transportation agencies in the short term to move toward better practices.

Looking even a few years into the future, significantly improved transportation, emissions, and air quality analysis capabilities will be gradually introduced that will alleviate many of today’s most serious analytical deficiencies with respect to the evaluation of transportation air quality control strategies. There is no question of whether this will happen; capabilities such as activity-based travel demand models, modal emission models, and EPA’s Models-3 air quality system already are being deployed. The only question is the time that will be required for this new generation of analytical capabilities to be broadly introduced into practice. Although it is unlikely to happen within an immediate 2- or 3-year future, the state of the art of transportation air quality analyses 10 years from now almost certainly will be far superior to today’s best practices and dramatically different from today’s current practices.
The multiple dimensions of the recommended analytical framework are illustrated in Table 3.1. Improvements are required and are occurring in each of these four defined areas:

- Significant research and development activities are underway with respect to each of the core analysis activities: transportation, emissions, and air quality. Although these research efforts are not being undertaken in as coordinated a manner as ideally would be desired for TCM analysis purposes, they will result in the introduction of important new analytical capabilities. As demonstrated in the Portland testing, these advances will improve the ability to accurately predict the nature and magnitude of impacts that could realistically be expected from the implementation of TCM types of strategies.

- These methodological improvements involve the introduction of new types of analytical procedures, improved methods of data collection, and the use of coordinated programs of data monitoring and analysis. Their implementation will be facilitated by taking advantage of geographic information system (GIS) technologies and rapidly evolving network-based hardware and software computational power.

- There likely will be a movement from the use of simplified, aggregate transportation air quality analyses toward more detailed, disaggregate analyses. This trend will apply to emission as well as transportation modeling and will extend to the linking of transportation with air quality modeling. Further, this shift in the level of analytical detail will necessitate the development of a new generation of simplified “sketch planning” or screening methods that are sensitive to these more disaggregate relationships.

- We have become accustomed to using a relatively fixed and stable set of transportation air quality analysis capabilities. The techniques in use today do not differ that much from those employed 10 and even 20 years ago. Although changes in transportation air quality analysis practices will occur more rapidly than in the past, these changes will still be gradual. Rather than deploying a single new analytical capability, transportation and air quality agencies need to put in place relatively long-term, multi-year implementation programs through which transportation air quality analysis capabilities are incrementally enhanced over time.

3.3 WHERE ARE WE HEADING?

There is, unfortunately, no simple, single solution to making TCM-related transportation air quality analyses accurate, easy, and low-cost or that will entirely eliminate the potential for debate and differences of opinion over the results. The transportation air quality analysis process also is more than a set of quantitative models and their supporting data and

<table>
<thead>
<tr>
<th>TABLE 3.1 Multiple dimensions of the analytic framework</th>
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<tr>
<td>1. Core Activities</td>
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<tr>
<td>Transportation</td>
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<td>Emissions</td>
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<td>Air quality</td>
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<td>2. Methodological Activities</td>
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<td>Analysis</td>
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<td>Data collection and monitoring</td>
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<td>Computational environment</td>
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<td>3. Level of Analysis Detail</td>
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<td>Simplified or aggregate</td>
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<td>Detailed or disaggregate</td>
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<td>4. Timeframe</td>
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<td>Short-term</td>
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<td>Intermediate time horizon</td>
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<td>Mid- to long-range</td>
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assumptions. Equally important are the kinds of analyses that are undertaken using these models and data. Based on the research performed, the following are seven observations regarding the future direction of analyses related to transportation air quality control strategies.

1. Although traditional regulatory-based transportation control measures may receive less emphasis in the future as candidate strategies to include in an air quality State Implementation Plan, increased emphasis will be placed on the development of transportation plans, programs, and projects that simultaneously support state and regional objectives for improved accessibility, environmental quality, and economic growth. Transportation analyses will be conducted within a broader context of assessing the potential of transportation investment and management decisions to support sustainable communities. These decisions will be made on a regional as well as a site-specific basis and will require the support of rigorous, defensible transportation, emissions, and air quality analyses. The demand for strong analytical capabilities is not likely to lessen in the future and is not tied exclusively to the regulatory requirements of the Clean Air Act.

2. Mobile sources will continue to be an important element of national, state, regional, and local air quality analyses, with increased emphasis given to fine particles, PM$_{2.5}$, and the role of NO$_x$ in ozone formation. An examination of changes in vehicular emissions has been satisfactory in the past as the primary output of interest. In the future, increasing interest is likely to be placed on the relationship between changes in the transportation system and actual changes in ambient air quality levels. In addition, increased focus will be given to emissions associated with heavy duty vehicles and the movement of freight; for example, the concern about diesel particulate emissions as a toxic air contaminant. Transportation air quality analyses in the past have concentrated primarily on the movement of persons, and even person movement occurring within the peak weekday travel period. Increasingly, air quality is being incorporated into analyses of intermodal freight improvements. At the national and international scale, issues associated with global climate change and greenhouse gas emissions are increasing in importance. These will require supportive analytical modeling, including an understanding of vehicle activity patterns and travel behavior.

3. Emphasis in past TCM-related air quality analyses has been placed on the use of quantitative modeling techniques. In the research undertaken for the 8-33 project, the role of monitoring was examined as both a supplement to and a potential replacement for modeling. As demonstrated in the analysis of changes in air quality associated with the Atlanta Olympics, data monitoring programs can be undertaken for transportation and emissions activities as well as for ambient air quality. Given the advances taking place with respect to data collection technologies, systematically designed monitoring programs can be efficiently undertaken as part of the analytical process for designing and evaluating the effectiveness of mobile source air quality control strategies. The challenge is in developing a monitoring program that is statistically rigorous. Monitoring, though, should not be viewed as a replacement for modeling; the opportunity exists to use monitoring and modeling in combination to overcome the difficulties of using either approach independently of the other.

4. Increased attention will be given to examining the temporal and spatial distribution of transportation-related emissions and air pollution. This almost certainly will be accomplished through the use of GIS-based databases and analyses having the ability to integrate demographic, travel, emissions, and air quality information. Two factors are motivating this trend. The first is that air pollutant levels, particularly for secondary pollutants, are very much dependent on the temporal and spatial distribution of emissions. Thus, the pattern of mobile, stationary, and area sources of emissions needs to be understood to improve the accuracy of estimated changes in air quality resulting from the implementation of one or more air quality control strategies. Second, dramatically increased attention is being given to issues of environmental justice, including the distribution of both adverse air pollutant levels and implementation characteristics by income level and population. Conducting this type of analysis requires an examination of the spatial distribution of emissions and air quality and, again, is facilitated through the use of GIS analysis technologies. Thus, analysis approaches that rely either primarily or exclusively on areawide impact estimates no longer will be satisfactory. Instead, the emphasis will be on examining impacts by different combinations of individual household characteristics.

5. Air quality analyses increasingly are being conducted for multistate regions, reflecting the multistate regional formation and transport of secondary pollutants. Examples include the Lake Michigan Ozone Study, the Southern Oxidant Study, and the 37-state Ozone Transport Analysis Group (OTAG). This increase in the size of the analysis area represents a significant shift from the traditional focus on individual sites, urban areas, or even state-level analyses. This also means that a consistent set of transportation data must be developed on a multi-state regional basis. Network-based transportation air quality analyses will continue to be useful, but these results must be integrated with transportation and emissions data from areas where network analysis capabilities may not be present. This also means that transportation data need to be developed for multi-day episode periods, including weekend as well as weekday travel conditions. In
concert with these larger geographic-scale air quality analyses, there is a growing interest on the part of non-transportation professionals in the analysis of TCMs and other transportation-related air quality control strategies. This includes environmental organizations and industry associations interested in reducing emissions from within the transportation sector. Experience is demonstrating a desire on the part of these groups to use methods that mirror their own analytical framework, rather than relying on traditional transportation analysis approaches that they neither understand nor accept.

6. In addition to evaluating the air quality and other benefits and costs of transportation control measures, transportation air quality analyses also involve the development of base and future year emission inventories, project and program conformity analyses, environmental impact analyses, and the projection and monitoring of vehicle miles of travel. Too often, these analyses are conducted using different analysis methodologies, different databases, and different assumptions. There is, instead, a need for common analytical approaches, databases, and assumptions. Rather than being conducted relatively independently of one another, efforts directed toward environmental streamlining should include the development of integrated approaches to conducting the different types of required transportation air quality analyses. The use of network-based or distributed personal computer systems supported by a set of centrally maintained GIS and related databases is gradually being introduced into transportation and air quality organizations and will facilitate the introduction of this style of improved analysis framework.

7. Given the personnel, budget, and program demands existing on transportation and air quality agencies, there is an understandable desire for simplified styles of analysis techniques. Indeed, many such techniques have been developed in recent years in an attempt to meet these demands. Although some of these “sketch planning” techniques do a better job than others in satisfying the analysis criteria defined by this research, the examination of emerging transportation, emissions, and air quality analytical approaches indicates that future methodologies will be more complex and data intensive than existing techniques. This is a natural byproduct of introducing more of the important causal variables into the analysis. Examples include traffic operations effects, the use of a more detailed vehicle fleet distribution, and the desire to differentiate trip-based from running emissions. The result is that the data and technical needs required to support transportation air quality analyses will become more rather than less daunting. Simplifying assumptions still can be developed, but these new relationships need to evolve from a set of underlying analytical techniques and data that are more solidly grounded than those that are in use today.

### 3.4 Next Steps

This report describes a recommended analytical framework for use in evaluating the air quality and other benefits and costs of transportation control measures. It is anticipated that over the next 10 to 15 years, a fundamentally new set of transportation, emissions, and air quality analysis capabilities will be developed and implemented. Modeling and data enhancements implemented in the short run should be directed at facilitating the implementation of these longer term and more fundamental improvements.

In examining the recommended analytical improvements, it is important to also ask

- Are transportation and air quality agencies capable of implementing these new modeling and data capabilities?
- What steps can be taken to facilitate the successful implementation of a new generation of transportation air quality analytical capabilities?

The answer to the first question must be “yes.” As transportation professionals, we are being asked to improve the manner in which transportation management and investment decisions affecting accessibility are coordinated with society’s simultaneous desires to improve environmental quality and to maintain a strong economy. To move forward with desired transportation improvements, it will be necessary to develop an improved understanding of the full range of impacts potentially associated with these improvements. The immediate need is simply for better practices, and these are well within existing capabilities.

Over the longer term, it is recommended that attention be given to parallel deployment and research programs. Simultaneous testing and deployment of incremental changes will both accelerate the overall implementation process and improve the effectiveness of a long-term research program. For example, considerable research already has been completed with respect to both activity-based travel demand modeling and modal emissions modeling. Although continued research can be justified on each of these topics, there is a need to move existing research into implementation and application. These implementation activities should include selected testing and demonstration activities, technical assistance, training, and the convening of user forums to promote the exchange of information among users. Care should be taken to include development of less sophisticated analytical capabilities applicable to smaller and medium-sized areas having less access to technical resources, as well as more robust approaches for use by larger transportation and air quality agencies. The desire in each case, though, is to move toward leading-edge, state-of-the-art analytical practices.

Extensive transportation air quality research has been conducted over the past decade. The products of this research are helping to improve the existing state of the practice and also
providing the technical foundation for the next cycle of deployment activities. Continued research, however, is desirable in the following general areas:

- Development of data and procedures to improve the linkages between transportation, emissions, and air quality models with particular attention given to incorporation of improved information with respect to traffic and vehicle operations.
- Basic research in areas such as the contributions of transportation to fine particle pollution, and the air quality impacts associated with the movement of both inter- and intra-city freight.
- Development of an improved understanding of travel behavior, especially the linking of individual trips into chains of trips, and the effects on trip-based emissions.
- Development of procedures for incorporating transportation data into multi-state air quality analyses, including an improved understanding of the relationship between the spatial and temporal distribution of transportation emissions and ambient levels of ozone and PM$_{2.5}$. What level of data disaggregation is necessary to support large geographic scale air quality analyses?
- The classification of vehicles normally used in transportation planning continues to be different from the classification required to estimate vehicle emissions accurately. In the future, an even more detailed or disaggregate understanding of the vehicle fleet will be desired for purposes of accurately estimating emissions. As new vehicle and fuel technologies are introduced, the phase-in likely will vary by state and metropolitan area and these differences need to be reflected in transportation air quality analyses. An improved and more detailed understanding of vehicle ownership and usage decisions is desirable in order to predict which vehicles are being used for which trip chains.

The focus of this research has been on the development and testing of an improved analytical framework and associated quantitative methods for evaluating the air quality and other benefits and costs of transportation control measures. An important finding, though, that emerges from this research is that TCM analyses should not be unique or independent of the consideration of other forms of transportation investment and system operation, or even the analysis of vehicle and fuel technologies. Issues of vehicle type and operating condition, for example, are important in all types of transportation air quality analyses. The challenge is in determining the level of aggregation that is appropriate for site, corridor, metropolitan, statewide, and multistate regional analyses.

Significantly new analysis and monitoring capabilities are being introduced affecting the conduct of transportation, emissions, and air quality decision-making. The kinds of analysis methodologies and approaches that will be in use 10 years from now almost certainly will be dramatically different from those in use today. A coordinated program of deployment, testing, training, technical assistance, applied research, and basic research will support the successful introduction of these improved transportation air quality analysis procedures.
REFERENCES

The following appendixes are not published in this printed report:

- Appendix A, Portland Pilot Testing,
- Appendix B, Analytical Framework for the Evaluation of Air Quality Transportation Control Strategies, and

These appendixes are available on the accompanying CD-ROM.
The **Transportation Research Board** is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board’s mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board’s varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

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The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

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**Abbreviations used without definitions in TRB publications:**

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>AASHO</td>
<td>American Association of State Highway Officials</td>
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<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
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<td>ASCE</td>
<td>American Society of Civil Engineers</td>
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<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>FHWA</td>
<td>Federal Highway Administration</td>
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<td>FRA</td>
<td>Federal Railroad Administration</td>
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<td>FTA</td>
<td>Federal Transit Administration</td>
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<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>ITE</td>
<td>Institute of Transportation Engineers</td>
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<td>NCHRP</td>
<td>National Cooperative Highway Research Program</td>
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