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16. Abstract This report provides an overview of the current state of practice in evaluation of air quality impacts and also in emissions modeling. This report also describes the recent developments in emissions modeling. The air quality impacts of various ITS strategies and technology bundles are also described in detail. Reported air quality benefits of various ITS projects are also presented.		
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METHODOLOGIES FOR EVALUATING ENVIRONMENTAL BENEFITS OF INTELLIGENT TRANSPORTATION SYSTEMS

by
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Environmental Impacts of Intelligent Transportation Systems

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 – INTRODUCTION

Air pollution results from two major sources: stationary sources such as factories, industrial units, power plants and mobile sources such as cars, trucks, and buses. The major pollutants are ground-level ozone, commonly known as smog and carbon monoxide. These pollutants are serious health and environmental hazards. The mobile sources, or the transportation sector, have been a major source of air pollution, as can be seen from Table 1.1.

To address air quality concerns, Congress enacted the U.S. Clean Air Act in 1970. The act requires state and local governments to develop strategies to address the problem, and set minimum air quality standards called National Ambient Air Quality Standards (NAAQS). The Clean Air Act was amended in 1977 to emphasize the need for coordination of air quality planning with the transportation planning process of metropolitan planning organizations (1).

Table 1.1 Pollutants by Source

Pollutants	**Sources of Emissions**			
	Transportation	**Fuel Combustion**	**Industrial Processes**	**Miscellaneous**
CO	78.6%	6.0%	5.4%	10.0%
Lead	13.1%	12.7%	74.2%	-
NO_x	53.3%	41.7%	3.7%	1.3%
VOC	43.5%	5.0%	47.2%	4.4%
PM_{10}	25.4%	38.6%	36.0%	-
SO_2	7.1%	85.1%	7.7%	0.1%

Source: EPA Emissions Trends Report (2)

The transportation sector, being a major source of air pollution, can play a very important role in improving air quality. The Clean Air Act Amendments of 1990 provides a framework for developing air quality improvement plans. It has also placed an additional requirement that transportation plans, programs, and projects conform to the purpose of State Implementation Plans (SIPs) for the attainment of NAAQS. This expanded requirement has resulted in a greater role for transportation officials in the development of air quality plans. It has also resulted in increased interaction, both collaboration and conflict, between the transportation and environmental communities (3).

These developments over the past two decades have resulted in some positive results as indicated in Table 1.2.

Table 1.2 Emissions and Air Quality Trends (1990—1999)

Pollutant	**Change in Air Quality**	**Change in Emissions**
Carbon Dioxide	-36%	-7%
Lead	-60%	-23%
Nitrogen Dioxide	-10%	+2%
Ozone	-4% (1 hr) 0% (8 hr)	-15% (VOC)
Particulate Matter (PM_{10})	-18%	-16%
Sulphur Dioxide	-36%	-21%

Source: EPA Emissions Trends Report (2)

The challenge now lies in improving the quality of the air we breathe without adversely affecting the mobility of the nation. The demand for travel is expected to increase at about 30% in the next few years. Therefore, to simply maintain congestion at the current levels and without the introduction of productivity-enhancing technologies, the capacity of the transportation system would have to be increased by 30%. This would mean an addition of approximately 4,427 new miles (7,125 kilometers) of roadway every year, an unlikely event under current political and economic conditions. Alternatively, Intelligent Transportation System (ITS) technologies could lead to capacity improvements with the same physical infrastructure by enhancing the efficiency of the transportation system. A 20-

year life-cycle cost analysis for fifty major urban areas for the two options (capacity increase as compared to ITS) indicated that the ITS-based investment would “reduce the need for new roads while saving approximately 35% of the required investment in urban highways” (4, 5).

In the above context, it is important to explore transportation options that may result in potential air quality benefits. ITS are one such class of strategies that could have significant air quality benefits. Quantification of these benefits is therefore an important part of any ITS assessment effort. ITS evaluation provides a decision-making tool in the context of ITS deployment.

Evaluation of air quality, in general, is a complex process. Evaluation of air quality benefits of ITS is further compounded by the fact that deployment of most ITS strategies has been relatively recent, and is largely still underway; therefore, the long-term relationships between these strategies and the parameters that affect air quality are not very clear. This is discussed in greater detail in the subsequent chapters.

This report presents an overview of the challenges involved in designing a suitable framework for evaluating air quality benefits of ITS. The report also describes the current evaluation procedures, the limitations of these procedures, and the improvements that can be undertaken within these procedures. It also reviews some of the methodological developments that have taken place or are underway in air quality evaluation of ITS.

CHAPTER 2 – MOBILE SOURCE EMISSIONS AND ITS

Emissions from vehicles are generally referred to as mobile source emissions. The pollutants are classified as criteria pollutants and non-criteria pollutants. The criteria air pollutants are those for which National Ambient Air Quality Standards (NAAQS) have been adopted. All other air pollutants are considered non-criteria pollutants.

Criteria pollutants

- Carbon monoxide
- Lead
- Oxides of nitrogen
- Ozone
- Particulate matter
    - Total suspended particulates (TSP)
    - Inhalable particulate matter (PM_{10})
- Sulfur dioxide

Non-criteria pollutants

- Sulfates and nitrates

The U.S. Environmental Protection Agency (EPA) is required by the Clean Air Act, last amended in 1990, to set NAAQS for pollutants considered harmful to public health and the environment. The Clean Air Act established two types of national air quality standards. ***Primary standards*** set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. ***Secondary standards*** set limits to protect public welfare, including protection against decreased visibility, damage to animals, crops, vegetation, and buildings (6).

NAAQS for six principal pollutants are given in Table 2.1. Units of measure for the standards are parts per million (ppm), milligrams per cubic meter of air (mg/m^3), and micrograms per cubic meter of air ($\mu g/m^3$).

2.1 Emission-Producing Activities and Processes

As is discussed later in Chapter 3, one of the principal components in evaluating air quality benefits is identifying the vehicle activities that result in emissions of these pollutants from the motor vehicle systems. Two emission-producing processes, combustion products from the exhaust system and evaporation from the fuel storage and delivery system, are responsible for these emissions.

Exhaust emissions largely depend on the vehicle-operating modes. Consequently, most recent work in the area of emissions modeling has been directed toward developing modal emissions models. This is discussed in detail in the subsequent chapters. The vehicle-operating modes can be classified into start modes and hot stabilized modes.

The start modes refer to the first few minutes of operation after the engine has been started. A cold start and a hot start are differentiated by the duration between shutting off and restarting the engine. The hot stabilized mode includes all operation time except for the start mode period. The fuel-air mixture and the emission control equipment are two primary factors that cause the differences in emission amounts among operating modes. During cold start mode, the catalytic emission control systems do not provide full control until the appropriate operating temperature is reached. Moreover, a richer fuel-air mixture must be provided to start a “cold” engine. Therefore, volatile organic compounds (VOC) and particulate matter (PM) emissions are higher in the cold start mode than in the hot start mode and reach the lowest amounts in the hot stabilized mode (7).

Evaporative emissions are composed primarily of VOC and these emissions are highly dependent on temperature. The six categories of evaporative emissions along with the processes that cause these emissions are given in Table 2.2. These different types of emissions are illustrated in Figure 2.1.

Table 2.1 National Ambient Air Quality Standards

POLLUTANT	STANDARD VALUE		STANDARD TYPE
Carbon Monoxide (CO)			
8-hour Average	9 ppm	(10 mg/m^3)**	Primary
1-hour Average	35 ppm	(40 mg/m^3)**	Primary
Nitrogen Dioxide (NO_2)			
Annual Arithmetic Mean	0.053 ppm	(100 µg/m^3)**	Primary & Secondary
Ozone (O_3)			
1-hour Average*	0.12 ppm	(235 µg/m^3)**	Primary & Secondary
8-hour Average	0.08 ppm	(157 µg/m^3)**	Primary & Secondary
Lead (Pb)			
Quarterly Average		1.5 µg/m^3	Primary & Secondary
Particulate < 10 micrometers (PM-10)			
Annual Arithmetic Mean		50 µg/m^3	Primary & Secondary
24-hour Average		150 µg/m^3	Primary & Secondary
Particulate < 2.5 micrometers (PM-2.5)			
Annual Arithmetic Mean		15 µg/m^3	Primary & Secondary
24-hour Average		65 µg/m^3	Primary & Secondary
Sulfur Dioxide (SO_2)			
Annual Arithmetic Mean	0.03 ppm	(80 µg/m^3)**	Primary
24-hour Average	0.14 ppm	(365 µg/m^3)**	Primary
3-hour Average	0.50 ppm	(1300 µg/m^3)**	Secondary

* The ozone 1-hour standard applies only to areas that were designated non-attainment when the ozone 8-hour standard was adopted in July 1997. This provision allows a smooth, legal, and practical transition to the 8-hour standard.

** Parenthetical value is an approximately equivalent concentration.

Source: *The Green Book: Non-Attainment Area for Criteria Pollutants* (6)

Table 2.2: Types of Emissions and Emission-Producing Activities

Hot soak emissions:	Emissions from the carburetor or fuel injector when the engine is turned off.
Diurnal emissions:	Emissions from the "breathing" of the gasoline tank due to temperature fluctuations during a 24-hour day.
Running losses:	Emissions occurring while the vehicle is being operated. These emissions result when more fuel enters into the emission control canister than can be purged by it.
Resting losses:	Emissions that result from vapor permeating the evaporative emission control system or from the vehicle fuel tanks.
Refueling losses:	Emissions occurring while a vehicle is being refueled. There are two components: vapor space displacement and spillage. These emissions have been estimated for the area source —— gasoline service stations; they are not included in the mobile source emissions.
Crankcase emissions:	Emissions that result from defective crankcase ventilation valves. They are not true evaporative emissions.

Source: Scope Study for Expanding the Great Lakes Toxic Emission Regional Inventory to Include Estimated Emissions from Mobile Sources (7)

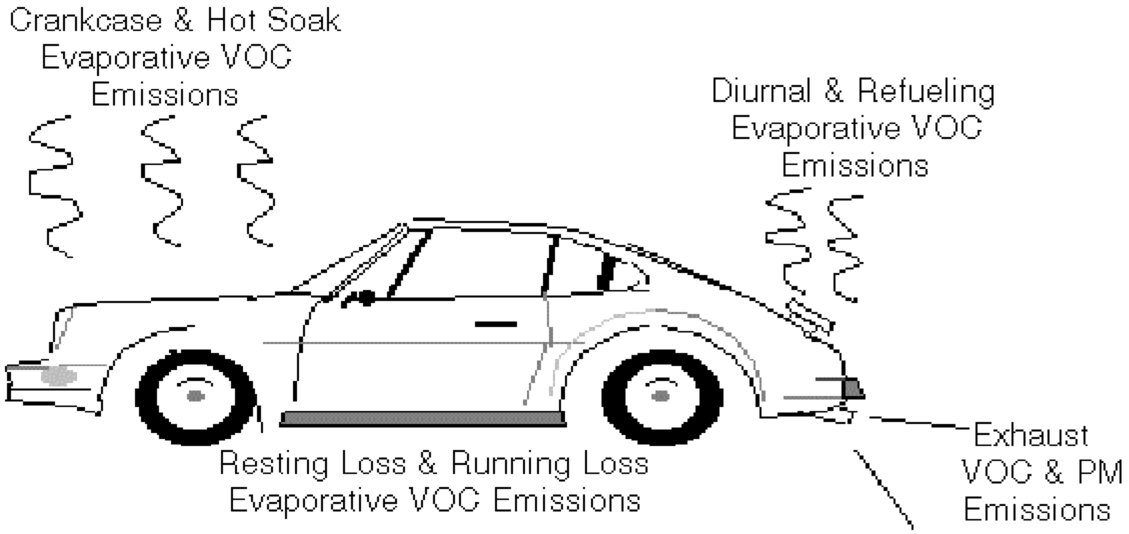

Figure 2.1: Different Types of Emissions

Source: Scope Study for Expanding the Great Lakes Toxic Emission Regional Inventory to Include Estimated Emissions from Mobile Sources (7), Figure 4-1

2.2 ITS and Air Quality

Deployment of ITS technologies may have significant air quality benefits. The underlying mechanism that is expected to realize these benefits is the smoothing of traffic flow, alleviation of congestion, and in general an overall improvement in traffic flow conditions. However, it is important to be able to associate expected air quality benefits, both qualitatively and quantitatively, with particular ITS strategies, taken individually and in combination with others as part of an ITS architecture. This necessitates an understanding of the logical relationships among various ITS technology bundles and the various emission-producing activities and processes discussed above.

Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS), and Emergency Vehicle Services (EVS) are technology bundles that have been identified early in the development and application of ITS technologies. Each of these functional areas has subsequently been specified in terms of “user services.” Washington et al. (8) provide a comprehensive qualitative assessment of the trip and travel characteristics that are most likely to be impacted by ITS technology bundles and the technology bundles that are most likely to impact these characteristics. Their assessment is summarized in the sections below (8).

2.2.1 Trip Characteristics Impacted by ITS

The following section summarizes the assessment by Washington et al. of the trip characteristics that are most likely to be impacted by ITS.

Vehicle Miles Traveled

The authors feel that the impact of information-related ITS technologies on vehicle miles traveled (VMT) are uncertain at best. They elaborate that better information may result in drivers making informed trip decisions in terms of route selection. Better information also makes the drivers less likely to get lost. This can result in a reduction in total VMT.

At the same time, better information may result in drivers selecting uncongested roads to reduce their total travel time. In addition, if the capacity and travel speeds increase, and congestion and travel times decrease, additional vehicle trips may be undertaken. These factors may result in an increase in the total VMT. The issue here is, therefore, the behavior of the driver to reduced congestion and travel time.

Engine Idling

ATMS are likely to reduce the waiting times at traffic intersections. In addition, better information and AVCS have the potential to reduce time spent caught in queues and congestion, and motoring in search of parking spots. All of this is most likely to reduce engine idling.

Vehicle Refueling

In parallel with the development of ITS strategies and systems, developments in automotive technologies are producing a new generation of more fuel-efficient vehicles. These vehicles will have smaller fuel tanks, will require less frequent fueling, and will generally emit less pollution per mile traveled. The important consideration is the fuel efficiency of the individual vehicles, and the rate at which these might replace older, less efficient vehicles in the present vehicle fleet.

Modal Activity

Many ITS technologies are targeted at reducing congestion. This is likely to result in reduced significant acceleration and deceleration events. This is even more so if the vehicles can be preprogrammed to avoid undertaking enrichment activities. The authors, however, point out that the relationships between the emission rates and modal activities are relatively uncertain.

2.2.2 Air Quality Benefits of ITS Technology Bundles

This section summarizes the assessment by Washington et al. of the ITS technology bundles that are most likely to affect air quality (8).

Advanced Traffic Management Systems

ATMS strategies can be broadly classified into strategies such as signal optimization and ramp metering, which are aimed at reducing recurrent congestion, and strategies like incident detection and rapid accident response, which are aimed at reducing nonrecurrent congestion. According to Washington et al. (8), the air quality benefits are less certain for the first type of strategies than for the latter type of strategies. There is little evidence for this claim.

Advanced Traveler Information Systems

ATIS strategies rely on acquisition and use of information by users, like onboard electronic maps, electronic route guidance, Variable/Changeable Message Signs (VMS, CMS), personal digital assistants, wireless devices, etc. These strategies are designed to provide users with information about routes and conditions of the system so as to provide a basis for travel-time minimizing strategies. An important consideration here is the impact of "perfect" information on route and mode choices.

The impact of information on route choice is likely to depend on whether the trip is being made during peak periods or otherwise. If the drivers are rerouted during peak periods, they are more likely to choose alternate routes that have shorter travel times even if it may mean traveling longer distances. If these alternate routes are congested as well, significant air quality benefits are not likely to result. If these routes are uncongested, then the resulting smoothed flow may reduce emissions.

The impact of information on mode choice is not very certain and therefore any associated air quality benefits of this are difficult to estimate.

Advanced Vehicle Control Systems

AVCS strategies are aimed at improving highway capacity by reducing headways at all speeds and by reducing the lateral space required between the vehicles. In theory highway capacity could be doubled or quadrupled with AVCS.

AVCS technologies are likely to reduce the inertial losses occurring during congested stop-and-go conditions. This may result in air quality benefits. However, it is important to note that AVCS can also result in high-speed operations. Current empirical data suggest that the emissions are lowest at average speeds of around 40—45 mph. High-speed operations are therefore likely to offset the benefits of AVCS.

Another serious consideration is the impact of congestion that occurs at the “ends” of automated segments. Because “automation” occurs in stages, with the primary candidates being heavily congested freeways and highways, the end of the automated segments can become serious bottlenecks. This potential for congestion may offset the benefits obtained by flow smoothing. Given that deployment of any AVCS technologies does not appear likely in the near- or medium-term future, the present study will not focus on their energy-reducing potential.

Washington et al. also discuss the air quality impacts of other ITS technology bundles like Commercial Vehicle Operations (CVO), APTS, and EVS but the impacts of these bundles are either not very certain or not significant. However, it would be wrong to dismiss any of these strategies offhand, because of the potential air quality improvements possible through CVO and APTS applications.

2.2.3 Critique

Washington et al. have listed a number of assumptions in their assessment of the air quality benefits of ITS technologies. The most important of these assumptions are (8):

- Commute distances and vehicle fleet will remain relatively unchanged in the long run.
- Travel behavior will not change significantly.
- ITS technologies will not significantly affect mode shares.

They also point out that the assessment is based on ITS technologies implemented in isolation. If these technologies were to be implemented simultaneously with some other strategies such as congestion-pricing and real-time signal optimization, the synergistic effect of these strategies may be very different.

CHAPTER 3 – AIR QUALITY EVALUATION OF ITS

This chapter describes the practices and methodologies that have been employed, or can be potentially employed, for evaluating air quality benefits of deployment of various Intelligent Transportation Systems (ITS) technology bundles. ITS could have significant potential air quality benefits and quantification of these benefits is a key component of any decision process in relation to ITS deployment.

The Clean Air Act Amendment of 1990 established a requirement that transportation plans, programs, and projects conform to the purpose of State Implementation Plans (SIP) for the attainment of National Ambient Air Quality Standards (NAAQS). In light of this expanded requirement, the evaluation of air quality benefits of ITS assumes particular significance.

The ITS Joint Program Office (JPO) of the United States Department of Transportation (USDOT) defines evaluation as "reasoned consideration of how well project goals and objectives are being achieved." The JPO has also issued an ITS Evaluation Resource Guide (9), which breaks down the evaluation process into six steps:

1. Form the evaluation team
2. Develop the evaluation strategy
3. Develop the evaluation plan
4. Develop one or more test plans
5. Collect and analyze data and information
6. Prepare the final report

The evaluation of air quality benefits is a complex problem. In theory, deployment of ITS technologies will increase the efficiency and capacity of the existing highway system, resulting in reduced congestion. This congestion mitigation will further result in "smoothed" traffic flows. Most of the air quality will presumably result from this smoothing of traffic flows. However, the air pollution, fuel consumption, and other traffic volume-related impacts of ITS do not vary in a straightforward way with the sum of individual user benefits from ITS. This lack of direct relationship necessitates a use of a somewhat different causal framework than the conventional planning model. The features of such a framework are discussed in detail by Brand (10).

The difficulty in evaluating the air quality benefits of ITS is further compounded by external factors such as weather conditions, contributions from nonmobile sources or other regions, and the time-evolving nature of ozone pollution.

As a result of the difficulties outlined above, direct field measurements are not practical and analysis and simulation remain the most appropriate methods for evaluation in most cases.

The Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR) researchers have conducted a study of the evaluation methods of ITS benefits and documented various frameworks for evaluating the benefits of ITS in a research report (11). The findings indicate that several techniques have been used for evaluation of ITS benefits. Many of these techniques, however, closely parallel the goal-oriented evaluation approach suggested by the USDOT.

The National ITS Program Plan (12) jointly developed by the USDOT and ITS America presented six goals for the national ITS program. The relevant goal with regard to air quality evaluation is shown here with further objectives:

- Reduce energy and environmental costs associated with traffic congestion
    - Reduce harmful emissions per unit of travel
    - Reduce energy consumption per unit of travel

The ITS JPO of the USDOT advocates the use of what is termed “a few good measures,” consisting of a “few measures robust enough to represent the goals and objectives of the entire ITS program, yet are few enough to be affordable in tracking the ITS program on a yearly basis” (4). These “few good measures” are as follows:

- Crashes
- Fatalities
- Travel time

- Throughput
- User satisfaction or acceptance
- Cost

3.1 Overview of the Current Emission Estimation Procedure

As mentioned earlier, most current evaluation procedures are simulation based. Washington et al. (8) have described the current emission estimation practice in the following five steps:

1. Quantifying emission-producing vehicle activities through a travel demand model or other means of estimation;
2. Providing data on vehicle, fuel, operating, and environmental characteristics to the computer model;
3. Running the emission rate model to predict activity-specific emission rates for the given vehicle, fuel, operating, and environmental characteristics;
4. Multiplying each activity estimate by its appropriate activity-specific emission rate; and
5. Summing the estimated emission for all the activities.

3.1.1 Estimation of Emission-Producing Vehicle Activities

The quantification of the emission-producing activities, like number of trips, VMT, and speeds, are estimated by using the transportation demand models such as the Urban Transportation Planning System (UTPS) generation of models. The components of the widely used UTPS are trip generation, trip distribution, and mode choice and trip assignment. Once all of these components are in place, the traffic could be simulated on a transportation network usually composed of links and nodes, though such simulation is not typically undertaken as a routine element of transportation planning studies. The computer simulation models used for this purpose can be either microscopic models like TRAF-NETSIM, CORSIM, Texas Model, or macroscopic models like FREFLO and TRANSYT-7F.

Newer simulation models like THOREAU, INTEGRATION, Smartpath, Smartlink, DYNAMIT, and DYNASMART are better suited for simulating various ITS scenarios because they have a greater level of detail and flexibility that is required for simulating new technologies.

After the vehicle activities that cause emissions have been estimated using the process outlined above, the next stage is determining a set of activity-specific emission factors that specify the rate at which the emissions are generated for each of the emissions-producing activities.

3.1.2 Estimation of Emission Factors

The Great Lakes Commission Scope Study (7) has identified three potential approaches to estimating emissions factors:

- use toxic emission factors based on activity level;
- use toxic emission factors based on fuel usage; or
- combine total organic gases (TOG) and PM emissions with speciation profiles for each source category.

The third approach is more appropriate for ITS evaluation and the tools most widely used for the generation of emission factors are the MOBILE series of models developed by the EPA. The California Air Resources Board (CARB) estimates on-road motor vehicle emissions for use in California by using a series of models called the Motor Vehicle Emission Inventory (MVEI) models. Four computer models, which form the MVEI, are CALIMFAC, WEIGHT, EMFAC, and BURDEN.

The PART5 model developed by the EPA Office of Mobile Sources calculates particle emission factors, including exhaust particulate, brakewear, tirewear, and re-entrained road dust, for particle sizes of 1—10 mm. PART5 is consistent with MOBILE 5a in format and fleet characterization data.

The Great Lakes Commission Scope Study (7) provides a concise overview of the structure and core components of the MOBILE 5a model, which is the most widely used model for estimation of emissions inventory outside California. The study identifies the following core components of the MOBILE 5a model:

- Basic Emission Rates (BER): The basic emission rates are idealized rates based on standardized vehicles.

- Fleet Characteristics: The BERs characterize emissions for each specific model year in the vehicle fleet. Based on the VMT fraction for each model year, emission factors for eight categories of vehicles are produced.
- Correction factors: In calculating emissions factors, BERs are multiplied by a series of correction factors to represent the varying speed, temperature, and operating mode profiles.
- Fuel Characteristics: Evaporative emissions and exhaust emissions (to a lesser extent) vary with fuel volatility. BERs are developed based on gasoline with volatility of 9.0 psi as measured by Reid vapor pressure (RVP). MOBILE 5a adjusts the emission factors by using RVP correction factors for the fuel with volatilities other than 9.0 psi RVP.
- Emission Control Program: BERs are developed for vehicles that are not affected by the vehicle control programs. Various inspection and maintenance (I/M) programs and antitempering programs are taken into account when estimating emissions factors.

MOBILE 6, which is currently under development, is to include many additional features over MOBILE 5 such as facility-based emission factor estimates (different average emissions for different roadway types, even at similar average speeds), needed for transportation conformity determinations and more sophisticated application of results (e.g., photochemical air quality modeling, versus simple inventory tabulation); “real-time” diurnal emission factors; updates on effects of oxygenated fuels on carbon monoxide (CO) emissions and effects of in-use fuel sulfur content on all emissions; separation of “start” and “running” emissions to permit more precise temporal and spatial allocation of emissions; and updates to many other areas on the basis of new data (13).

The Great Lakes Commission Scope Study (7) further indicates that the basic structure of MOBILE 5a and CARB’s EMFAC 7F is very similar. A significant difference is the way that each model allocates emissions associated with a vehicle trip. EMFAC 7F produces separate emission factors for cold starts and hot starts in units of grams per trip and for hot stabilized vehicle operation in units of grams per mile. On the other hand, MOBILE

5a spreads the emissions from vehicle starts over the entire trip so it provides a single emission factor in units of grams per mile for both starts and stabilized vehicle operation. These differences affect the travel-related data requirements of the models.

A research project at the University of California has generalized the methods for determining emission factors. The research report (14) states that these methods are typically based on laboratory-established emissions profiles for a wide range of vehicles with different types of emission control technologies. The emission factors are produced based on average driving characteristics embodied in a predetermined driving cycle, known as the Federal Test Procedure (FTP). Emissions of CO, oxides of nitrogen (NO_X), and hydrocarbons (HC) are integrated and collected for three sections of the cycle (called bags) and are used as base emission rates. Adjustments are made to the base emission rates through a set of correction factors. There are correction factors for each bag, which are used to adjust the basic emission rates to reflect the observed differences among the different modes of operation. There are also temperature correction factors and speed correction factors derived from limited off-cycle testing (speeds greater that 57mi/h, accelerations greater than 3.3 mi/h-s). Once the activity-specific emission factors have been determined, the emission inventory is calculated by multiplying the activity to its corresponding emissions factor and summing up the emissions for each activity.

The process outlined above is illustrated in Figure 3.1.

This methodology, though the most widely used in practice for quantifying air quality benefits of ITS, has some very serious limitations and research is underway at various places to develop methodologies that can overcome these limitations and can analyze the air quality benefits more accurately. An overview of the main features of some of these developments is presented in the next chapter.

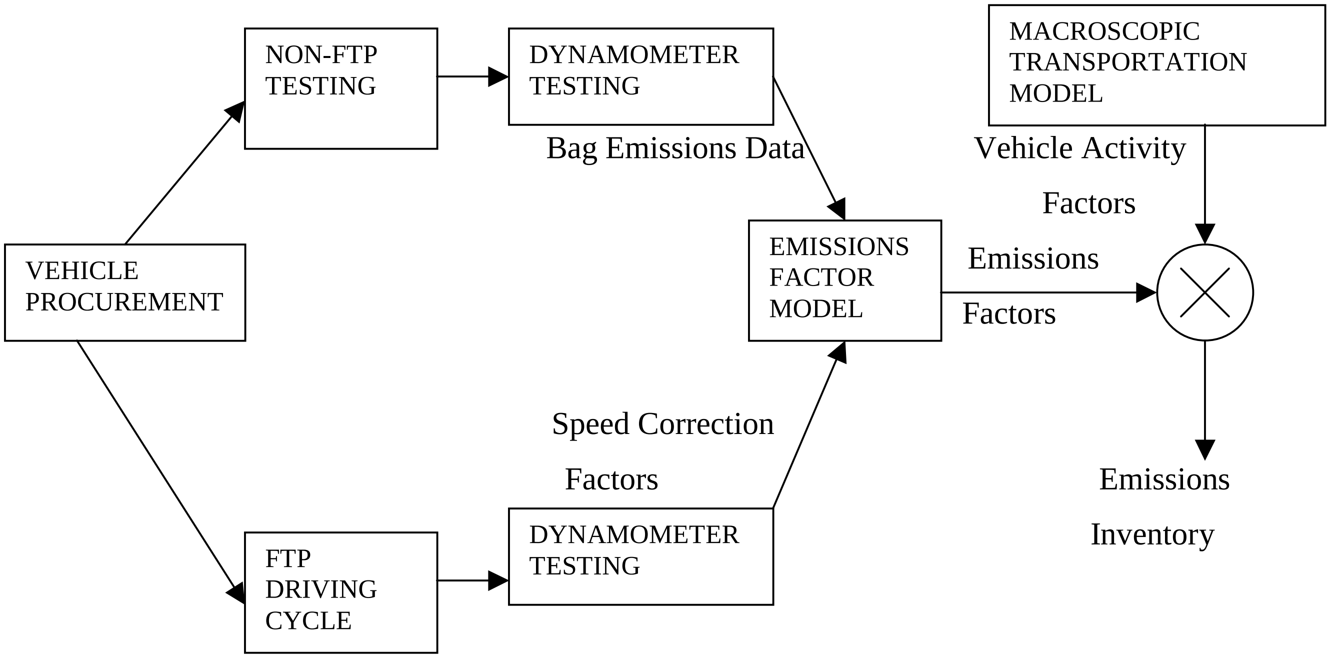

Figure 3.1 Current Emissions Inventory Process

Source: Transportation Modeling for the Environment: Final Report, University of California, Riverside (14), Figure 2.1

3.2 Analytic Approach to Quantify Air Quality Benefits of ITS

Though simulation remains the most widely used and, in most cases, the most appropriate method for evaluating air quality benefits of ITS, analytic approaches can also be employed in some cases**.** Al-Deek et al. (15) presents an analytical method for evaluating ATIS impacts on air quality.

The method is applied to a simple road network composed of two routes with one of the routes experiencing incident congestion. The impacts of rerouting traffic guided with Advanced Traveler Information Systems (ATIS) on total emissions of three air pollutants: CO, VOC, and NOx on the two routes are evaluated. The evaluation is done for three time periods: 1993-1998,1998-2003, and beyond 2003.

Analysis Methodology

A deterministic queuing model of the simple two-route corridor is used to simulate occurrence of incidents. The queuing model was then used to analyze the emissions of the three pollutants with and without ATIS.

The corridor consisted of the two routes that connect points A and B. The first route is a freeway with capacity μ_1 and free flow travel time T_1 and the second is an alternate route with free flow travel time T_2 and capacity μ_2 where $\mu_2 < \mu_1$ as shown in Figure 3.2.

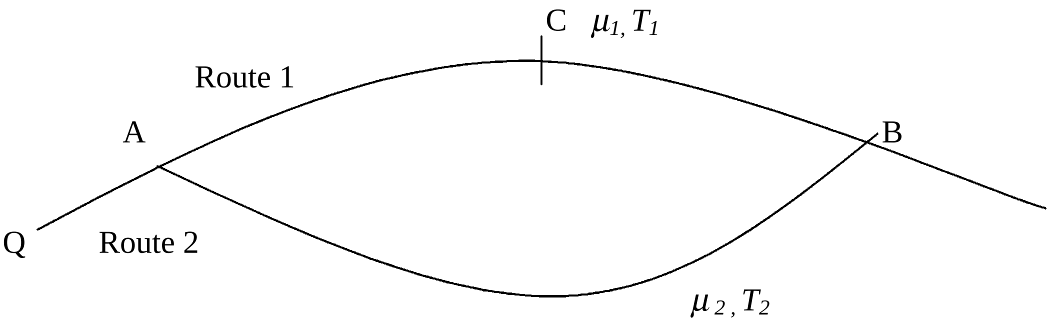

Figure 3.2 Corridor and Incident Parameters

Source: Al-Deek et al. *Evaluating ATIS Impacts on Air Quality* (15), Figure 1

The incident is assumed to occur at point C and the capacity of Route 1 is reduced as a result. For each route, cumulative queue evolution curves can be drawn with and without ITS. Total emissions for each of the three pollutants can then be estimated using the procedure outlined below.

Estimation of Vehicle Emissions on Routes

Vehicle Idling Emissions

Idling emissions for each of the three pollutants can be calculated by estimating the idling delay on the routes using the cumulative curves. Idling emissions for a certain pollutant can then be estimated by multiplying the idling delay by the corresponding emissions factor for that pollutant. Because there is no road closure on Route 2, there are no idling emissions on that route.

Vehicle Moving Emissions

The number of vehicles using a route can be estimated from the cumulative curves. Multiplying the number of vehicles using a route by the length of that route will give the VMT for that route. The total VMT can then be multiplied by the appropriate emission factors to get the estimate of vehicle emissions of each pollutant.

Estimation of Emission Factors

In the particular evaluation carried out by Al-Deek et al. (15), the emissions factors were estimated using the EPA-promulgated emission factor model MOBILE 4.1. The authors were not comfortable with the use of MOBILE 5.0 which did not contain idle emissions factors then.

Findings of the Evaluation

The emission estimates and the sensitivity analysis that followed indicated the following:

- Systemwide reduction of air pollutants can be achieved through the implementation of ATIS.
- More reductions in the emissions of CO and VOC can be achieved with higher ATIS market penetration levels. Reduction in emissions increases with market penetration of ATIS up to a critical market penetration level (fraction of guided traffic) beyond which no further improvement in air quality can be achieved. The critical fraction equals the ratio between the capacity of the alternate route to the corridor demand.
- Reduction in NOx emissions increases with higher market penetration rates up to the fraction of guided traffic that is associated with the network average speed of 40 mph. Reduction in NOx emissions decreases with larger fractions of guided traffic where the improved average network speed becomes larger than 40 mph.
- Air quality can be improved through the implementation of stricter emissions controls. Even with high market penetration rates, ATIS alone cannot compete with better emissions controls in reducing emissions.

3.3 Direct Field Measurement of Emissions

Although simulation and analysis have been the predominant methods for evaluating ITS technologies, direct field measurements can also be employed to measure the emissions from a vehicle. Booz, Allen & Hamilton Inc. performed a study of three field operational tests (FOTs) that evaluated the use of emerging technologies to help authorities measure emissions and develop strategies to help control them. The research report (16) of this study summarizes the test procedure and the results of the FOTs. The following are the three FOTs that evaluated the emerging technologies:

Evaluating Environmental Impacts of Intelligent Vehicle Highway Systems (IVHS) Using Light Detection and Ranging (LIDAR) Technology —— conducted during summer 1994 in the Minneapolis-Saint Paul metropolitan area.

Travel Demand Management/Emissions Detection (TDM/ED) —— conducted during spring 1995 in Ada County (Boise), Idaho.

Real-Time Vehicle Emissions Detection (R-TED) —— conducted during 1996 in Denver, Colorado.

CHAPTER 4 - RECENT DEVELOPMENTS IN ESTIMATING MOBILE SOURCE EMISSIONS

The current state of practice described in the previous chapter has some very significant limitations that limit the effectiveness of these methodologies when used for evaluation of air quality benefits of ITS. This chapter is a review of the improvements that could be incorporated within the framework of the current emission estimation methodology, and the developments in this direction. As mentioned earlier, the current emission estimation methodology has two main components:

1. Quantifying emission-producing vehicle activities through a travel demand model or other means of estimation.
2. Running the emission rate model to predict activity–specific emission rates for the given vehicle, fuel, operating, and environmental characteristics.

The emission-producing activities form the input for the emission rate-producing model, and therefore quantifying these activities as accurately as possible can significantly improve the estimation of air quality benefits. The transportation demand models such as the Urban Transportation Planning System (UTPS) generation of models have limited capability of producing accurate estimates of the desired transportation variables.

Suhrbier et al. (17) have expressed serious reservations concerning transportation models that are developed to support the design and construction of new and expanded infrastructure, serving as the underlying basis for spatially and temporally distributed emissions inventories. This may undermine the accuracy of these results, the robustness of the underlying data, and the ability of these systems representing current practice to capture the correct set of variables. They also identify and enumerate the type of data that is required to analyze air quality control strategies. The researchers point out that research is being done to improve analytical approaches, produce better data, and take advantage of better computational environments. However, this research is neither coordinated nor driven by integrated air quality analysis considerations.

The next stage in estimating the emission-producing activities is simulating the traffic movements in a network. As mentioned earlier, a number of microscale and macroscale simulation models are being used for this purpose. Many of these models are not suitable for evaluation of ITS strategies. Many older simulation models lack the level of detail that is typically required to accurately represent the impacts on ITS strategies.

Hawas et al. (18) enumerate the capabilities that a simulation-assignment framework should typically possess to effectively evaluate network performance under ITS strategies. These capabilities are: 1) a traffic flow simulator; 2) a trip maker behavior component that would determine an appropriate path selected by the trip maker on the basis of received in-vehicle information regarding congestion or other network problems; and 3) a network path processing component that takes the link level information received from the simulator and combines it with the path level information that assigns drivers to particular paths.

Koeppen (19) has identified additional functional capabilities, including: 1) ability to react to the time-varying changes in demand and link capacities because of disruptions in normal traffic flow (caused by lane closures, incidents, etc.) and owing to traffic control measures such as stop signs, signal coordination, and ramp metering; 2) ability to differentiate between vehicles that are equipped to receive enroute information and those that are not equipped to receive such information; 3) and the ability of the equipped vehicle to represent two-way communication between the vehicle and the information source. For nonequipped vehicles, it could simulate prespecified paths.

Koeppen analyzed the capabilities and features of various simulation models in the context of their suitability for use in evaluating ITS strategies. The models she studied were: 1) SATURN, 2) CONTRAM, 3) AIMSUM, 4) INTEGRATION, and 5) DYNASMART. She reports that while each of the first four models are an improvement over the simulation models used earlier, their effectiveness as evaluation tools for ITS is reduced because of lack of some of the key capabilities required for this purpose. She further reports that DYNASMART is one descriptive analysis tool that has managed to successfully incorporate drivers' responses to information, traffic flow behavior, and the resulting changes in the characteristics of the network paths into an integrated simulation framework.

After the emissions-producing activities have been estimated using a simulation model, the emissions factors for each of these activities have to be estimated using an emission factor model. The emission factor models used in current practice have several shortcomings.

The University of California research report on transportation modeling for the environment (14) has mentioned some of the shortcomings of the emissions factor approach:

- The federal test procedure (FTP) used in the estimation of the emissions factors did not include "off-cycle" vehicle operation, which consists of speeds in excess of 57 mi/h and acceleration rates above 3.3 mi/h-s, common in today's traffic operation. It has also been shown that the FTP does not accurately characterize today's actual driving behavior.
- The emissions model statistically smoothes the effect of acceleration and deceleration. Two vehicle trips can have the same average speed, but may have different speed profiles that consist of drastically different modal characteristics (acceleration, deceleration, idle, etc.) and thus drastically different emissions outputs, which may not be accurately represented by the emission models.
- The speed correction factors used as the model input are derived from transient tests, including the light-duty vehicle (LDV) FTP. The tests span a series of average speeds up to 65 mi/h. Real-world conditions may in some cases exceed the valid range of the test cycles. Also, emissions at a given speed depend on the engine load and this will greatly influence the emissions accompanying the average speed.
- The models underestimate the importance of acceleration/deceleration.
- The inherent emissions and vehicle operations "averaging" that takes place in the conventional emission models offers little help for evaluating traffic improvements that are microscale in nature.

The limitations of the current emission estimation methodology, both during the estimation of the emissions-causing activities and also during the emissions factors estimating stage, have prompted a lot of research in developing a methodology that can overcome these limitations.

4.1 Development of Modal Emissions Models

Most of the recent research in the area of emission modeling is in the direction of estimation of a modal emissions model. There is clear recognition of the fact the current approach based on average speed is not adequate and the vehicle-operating modes, like cruising, idling, acceleration, and deceleration, have to be explicitly represented in any modeling approach. The focus is therefore on developing modal emissions models.

The Comprehensive Modal Emissions Model (CMEM) user's guide (20) describes three approaches to developing a modal emissions model:

- **Statistical Approach**: This is a descriptive approach that involves characterizing vehicle-operating modes by developing a speed/acceleration matrix, by which the emissions associated with each "bin" or mode can be measured. A similar matrix is set up that has the vehicle activity broken down so that each bin contains the time spent in each driving mode. The product of these matrices will be the total amount of emissions produced for the specified vehicle activity with the associated emissions matrix. This approach cannot, however, properly handle other variables that can affect emissions such as road grade, use of accessories, etc.
- **Emissions Mapping:** This is also a descriptive approach. In this approach, second-by-second emission tests are performed at numerous engine-operating points, taking an average of steady-state parameters. The emissions inventory is created by deriving the vehicle-operating parameters, like engine power and speed form, on the second-by-second velocity profiles. Because this approach is based on engine power and speed, the effects of factors like grade, acceleration, and accessories are taken directly into account. Evidently, this approach is both time and cost intensive.
- **Power Demand Modal Emissions Modeling:** This approach is based on parameterized analytical representation of emissions production. In this approach, the entire emissions' process is broken down into different components that correspond to the physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These

parameters vary according to the vehicle type, engine, and emission technology. The majority of these parameters are stated as the specifications by the vehicle manufacturers and are readily available. Other key parameters relating to vehicle operation and emission production must be deduced from a comprehensive testing program. The testing involved is, however, much less extensive than creating emission maps for a wide range of vehicle-operating points.

Modal emissions models represent the effect of the vehicle-operating modes on emissions better than the emissions factor approach. The problem with the modal emissions models is current regional modeling practices; there are no tools for forecasting vehicle activity modes that are needed as inputs to this new generation of models. Alternative forecasting options are not sensitive to changes in traffic conditions brought about by current and emerging transportation planning alternatives. To address this issue, researchers at Georgia Institute of Technology, University of California at Davis, San Jose University, and California Polytechnic University in San Luis Obispo are developing a method to forecast modes of vehicle activity (21).

The paper by Washington et al. (21) describes a research effort to define the data needs, collect the data with a variety of available instrumentation, postprocess the data from differing instrumentation into a compatible database, estimate models to answer research questions, and address problems regarding the forecasting of vehicle modes of operation on freeways.

4.2 Overview of Modal Emissions Models

The Technical University of Graz research report (22) on methodologies for estimating air pollutant emissions from transport (MEET) discusses in detail a number of modal emissions models developed in Europe. It also provides an overview of the issues, such as data required and test procedures, associated with developing such emissions models. A number of such models have been developed or are being developed in the United States as well. Few of these models found in the literature are discussed here.

Georgia Tech Research Partnership is developing a modal emissions model within a Geographic Information System (GIS) framework. The model is called Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE). Guensler et al. (23) have provided an overview of the structure of MEASURE.

MEASURE is divided into several modules: vehicle technology modules, vehicle activity modules, vehicle emissions modules, and the reporting module. The vehicle technology module takes regional vehicle registration data and outputs time specific emission technology group distributions. The vehicle activity module takes regional planning model results and joins them with the appropriate speed and acceleration lookup tables to produce location and time-specific estimates and emission-specific modes of vehicle activity. The emission components of the model are weighted least squares regression models developed from large databases of vehicle emissions tests.

Ramachandran (24), in a study conducted at The University of Texas at Austin, developed similar modal emissions models using a database of fuel consumption and emissions for post-1980 vehicles. The database was generated as a result of “The Vehicle Testing Project” at the Oak Ridge National Laboratories (ORNL), sponsored by the Federal Highway Administration (FHWA). He also performed a preliminary evaluation of air quality impacts of providing traveler information by using these emissions models in conjunction with DYNASMART, a simulation-assignment tool developed at The University of Texas at Austin.

Both models described above are descriptive and based on the statistical approach described earlier. In August 1995, the College of Engineering-Center for Environmental Research and Technology (CE-CERT) at the University of California-Riverside, along with the researchers from the University of Michigan and Lawrence Berkeley National Laboratory, began a 4-year research project to develop a CMEM. The CMEM is a power demand modal emissions model. The principal features of such a model were described earlier. The project was sponsored by the National Cooperative Highway Research Program.

The overall objective of this research project was to develop and verify a modal emissions model that accurately reflects LDV (i.e., cars and small trucks) emissions produced as a function of the vehicle’s operating mode. The model is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., poorly functioning, deteriorated, or malfunctioning).

Barth et al. (14) calibrated the modal emissions model to a single vehicle, a 1991 Ford Taurus and addressed the direct relation between vehicle emissions and ITS traffic operations. Specifically, vehicle operations associated with two services were involved: Automated Highway Systems (AHS) and ramp metering. They have indicated that the power-demand model has certain key features that make this approach attractive for ITS evaluation:

- Factors in the vehicle-operating environment that affect emissions, such as vehicle technology and operating modes, are inherently handled in the model.
- It is applicable to all vehicle and technology types.
- It can be used with both microscale and macroscale characteristics.
- It is easily validated and calibrated.
- It does not require extensive testing.
- It is not restricted to pure steady-state emissions events.
- It identifies explicitly the sources of errors. The majority of these errors are related directly to the inaccuracy or uncertainty of key parameters. In other words, the accuracy level of the model is largely dependent on how accurately these parameters can be determined.
- Functional relationships among the models are well defined.
- The model is transparent. Results are easily dissected for evaluation. It is based on physical science, so that data tested against physical laws and measurement errors can be identified in the model establishment phase.

CHAPTER 5 - BENEFITS OF INTELLIGENT TRANSPORTATION SYSTEMS

The Intelligent Transportation System (ITS) Joint Program Office (JPO) of the U.S. Department of Transportation (USDOT) has been keeping track of the impacts of various ITS programs deployed at various places since December 1994. A series of reports (4, 27, 28) have been published that document the results of a large number of ITS evaluation projects. The first benefits report sponsored by the JPO was published in August 1995. The ITS JPO also maintains an online ITS benefits database (25).

Most of the ITS benefits reports have delay savings and travel times data but very little data on the impact of ITS on mobile source emissions. It has been noted that the environmental concerns such as fuel efficiency and emissions are rated lowest in terms of their importance as measures for evaluation (26).

The ongoing ITS benefits reports from the ITS JPO recognize the following three types of benefits estimates (4):

Measured —— outcome results from field measurements of benefits through studies, which are the most compelling.

Anecdotal —— estimates made by people directly involved in field projects, which are also compelling but less reliable than measured outcomes in terms of quantitative benefits assessments.

Predicted —— results from analysis and simulation, which can be useful tools to estimate impact of an ITS deployment when field experience is not available or when projects are not of sufficient scope to determine system impact.

5.1 Reported Benefits of Intelligent Transportation Systems (ITS)

Researchers at the Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR) conducted a study on the reported benefits of ITS. Their research report (11) contains a comprehensive summary of ITS benefits. Many of the benefits documented in the TTI report (11) have been obtained from the JPO reports from August 1995 to January 1998. The authors of this report have cited the lack of specific details in the

JPO reports and unavailability to the public of original source documents as the main obstacles in performing a critical review of the evaluation methods and assumptions used to derive the reported ITS benefits in the JPO reports.

The air quality benefits taken from the TTI report, along with the 1999 update report from the ITS JPO, are presented here. The benefits are organized in terms of the ITS component or technology bundle deployed.

Table 5.1 Air Quality Benefits of Traffic Signal Control Systems

Project	**Benefits**	**Comments**
Automated Traffic Signal Control (ATSAC) (27) Los Angeles, CA	13% reduction in fuel consumption 14% reduction in emissions	
Automated Traffic Signal Control (27) Abilene, TX	6% reduction in fuel consumption 10% reduction in HC emissions 13% reduction in CO emissions 4% increase in NOx emissions	
Adaptive Traffic Signal Control (SCOOT) (4) Toronto, Canada	6% reduction in fuel consumption 5% reduction in CO emission 4% reduction in HC emissions	Emissions estimated compared to the “best effort” fixed-timing plan.
Five Points Area (27) Las Vegas, CA	9.8% - 15.8% reduction in CO emissions	Estimates based on no changes in the vehicle miles traveled.

Table 5.2 Air Quality Benefits of Pre-Trip information

Project	Benefits	Comments
SmarTraveler (28) Boston, MA	Predicted emissions reductions: VOC, 25%; NOx, 1.5%; CO, 33%.	Benefits estimated using MOBILE 5a Model
Trav Trek (4) Orlando, FL	Predicted emissions: HC, 16% reduction; CO, 7% reduction; NOx, 5% increase	Assumed 100% Market Penetration

Table 5.3 Air Quality Benefits of Incident Management

Project	Benefits	Comments
San Francisco Freeway Service Patrol (4)	32 kg/day reduction in HC emissions 322 kg/day reduction in CO emissions 798 kg/day reduction in NOx emissions	
Transtar (4) Houston, TX (Incident management component of multifunction traffic management system.)	91 kg/day reduction in HC emissions	
Early deployment Study (4) Detroit, MI	42% reduction in fuel consumption 122,000 ton reduction in CO emissions 1,400 ton reduction in HC emissions 1,200 ton reduction in NOx emissions	Estimates based on no changes in the vehicle miles traveled.
Transguide (4) San Antonio, TX (Incident management component of multifunction traffic management system.)	Predicted savings of 2,243 gallons (9,880 liters) for a major incident.	Estimated using the FREEFLO simulation model.

Table 5.4 Air Quality Benefits of Electronic Toll Collection Systems (ETCS)

Project	**Benefits**	**Comments**
Electronic Pike Pass System (27) Asbury Plaza, NJ Western Plaza, MA	Average emissions reductions: CO, 72%; HC, 83%; NOx, 45%	Estimates based on a 260-day commuter case and 0.55 miles are used as the distance involved in the average barrier toll transaction.

Several studies (29, 30) have reported that 60% of the mobile source pollution arises from “gross polluters” comprising only 10% of the vehicles. The travel Demand Management Emissions Detection Project in Ada County (Boise), Idaho, examined the feasibility of using remote sensing technology to monitor vehicle emissions. The system could provide enough data to potentially eliminate the need for 90% of clean vehicles to undergo idle emissions testing. State cost savings could potentially range from $ 0.28 to $ 2.19 per registered vehicle over idle emissions testing procedures (31).

5.2 Critique

The above compilation of the reported air quality benefits of ITS strategies and technology bundles in various parts of the country over the years indicates that ITS technologies certainly have the potential to improve air quality. The early results are encouraging. At the same time energy and environmental concerns do not seem important evaluation criteria in most evaluation efforts. The ITS JPO series of reports, though an important reference source, do not give sufficient details on the evaluation methodologies and a critical analysis of these evaluation methodologies could not be performed.

CHAPTER 6 - CONCLUSIONS

This report has presented an overview of the current state of practice for measuring and evaluating the impacts on air quality of Intelligent Transportation Systems (ITS). The report focuses on the relationship between the various ITS technologies and air quality. The report also describes the developments that have taken place and the developments that are underway at various places in the area of emissions modeling. The reported air quality benefits that are found in literature are also presented. The following observations can be made about the current state of practice of air quality evaluation of ITS technologies:

- ITS technologies have potential to play a significant role in improving the quality of air that we breathe.
- The current state of practice of evaluating air quality impacts is based on emissions factors, which fails to adequately capture the effects of vehicle-operating modes on mobile source emissions.
- Developing modal emissions models, which explicitly incorporate vehicle- operating modes, like cruise, idle, acceleration, and deceleration, is becoming a priority for researchers in the field of emissions modeling.
- The current travel demand models and traffic flow simulation models are not sufficiently detailed for purposes of ITS evaluation.
- Travel demand models also fail to provide the kind of inputs needed for use in modal emissions modeling.
- Considering the scope of ITS technologies and the potential for improving air quality, greater emphasis has to be placed on including energy and environment as major evaluation criteria in future ITS evaluation efforts.
- The transportation planning community and the environmental community have to work together in a coordinated effort to identify the improvements that can be undertaken in both transportation-modeling framework as well as emissions-modeling framework to develop a suitable methodology for air quality impact assessment of transportation measures.

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