Data Needs for Evolving Motor Vehicle Emission Modeling Approaches

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Reprint
UCTC No. 74

The University of California Transportation Center

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Berkeley, CA 94720

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Reprinted from
Transportation Planning and Air Quality II
Paul Benson, ed., American Society of Civil Engineers (1993)

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DATA NEEDS FOR EVOLVING MOTOR VEHICLE EMISSION MODELING APPROACHES

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ABSTRACT

After describing the current emission modeling regime, the paper identifies and discusses the major problems with the existing emission modeling approaches. The current short-term modeling improvement programs of the US Environmental Protection Agency and the California Air Resources Board are discussed. The paper then outlines the three long-term modeling improvement approaches that are currently being investigated by regulatory agencies: a multiple-cycle method, an engine map approach, and a modal modeling technique. Finally, the vehicle activity and emission rate data needs for each modeling approach (both for model development and implementation) are described.

INTRODUCTION

Transportation and air quality analysts recognize that hydrocarbon and carbon monoxide emissions from motor vehicles are significantly underestimated (National Research Council, 1991; Gertler and Pierson, 1991; Newell, 1991; Ingalls, 1989), although the amount of underestimation is hotly debated. In response, a large amount of recent research in the emission modeling field has focused upon identifying possible causes of emissions underestimation. Recent research and literature indicate that there are a number of problems with existing modeling approaches. These problems generally include: 1) neglecting a number of important emission-producing activities, 2) drawing inappropriate statistical inferences based upon collected data, 3) under-representing the contribution of high-emitting vehicles to average emission rates (i.e. failing to collect data from a representative sample fleet), and 4) linking already uncertain emission rate estimates with uncertain vehicle activity estimates. However, some of the studies reported in the literature appear "designed" to increase motor vehicle emissions estimates, a preconception that can be

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problematic. In cases where analysis of data is cursory, researchers may 'correct' a component of the emission inventory that is perceived to underestimate emissions, even when these conclusions do not appear supported by statistical analysis.

In general, the emission behavior of individual vehicles appears to significantly deviate from expected behavior. Thus, analysts are currently attempting to develop new emissions models that will better characterize the emissions from individual vehicles. To properly address uncertainty issues in vehicle emissions behavior, a great deal of additional data need to be collected, disseminated, and analyzed.

The goals of this paper are to: 1) identify and discuss the major problems with the existing emissions modeling regime, 2) to discuss the three major modeling improvement approaches currently being investigated, and 3) to identify the data needed to develop and implement each of the three proposed modeling improvement programs. To accomplish these goals, emission producing vehicle activities and the factors that affect the magnitude of activity-specific emission rates are reviewed, and the areas suspected of contributing the greatest amount of uncertainty in emission estimation are summarized. The three proposed general approaches to improving emission models are then discussed: a multiple-cycle method, an engine map approach, and a modal modeling technique. Finally, the vehicle activity and emission rate data needed to develop the models and to implement the models on an ongoing basis are summarized.

EMISSION INVENTORY MODELING

Motor vehicle emissions are estimated by quantifying emission-producing vehicle activities and coupling these activities with activity-specific emission rates. For example, vehicle miles of travel and engine idling are activities known to produce emissions, and gram/mile and gram/hour emission rates can be developed for these vehicle activities under various operating and environmental conditions. The text and tables that follow describe the current emission modeling regime (Guensler, 1993).

Emission-Producing Vehicle Activities

Motor vehicles pollute, whether operating on expressways or parked in driveways. For the purposes of estimating emissions, the action being performed by the vehicle (or inaction) at the time the emissions occur is an emission-producing vehicle activity. Table 1 contains the general vehicle activities known to produce vehicle emissions that are often included in the emission inventory modeling process, as well as the type of emissions that are produced:

The elevated emissions of CO, NOx, PM_{10}, and SOx, noted in Table 1 generally result from engine conditions that exacerbate incomplete combustion and from catalytic converter temperatures too low to facilitate efficient control of exhaust gas emissions (Jacobs, et al., 1990; Heywood, 1988; Joy, 1992; Stone, et al., 1990; Pozniak, 1980).

TABLE 1. Emission-Producing Vehicle Activities and Emissions Produced

Emission-Producing Vehicle Activity	Type of Emissions Produced
Vehicle Miles Traveled	• Running Exhaust (CO, VOC, NOx, PM_{10}, SOx) • Running Evaporative Emissions (VOC)
Cold Engine Starts	• Elevated Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOx)
Warm or Hot Engine Starts	• Elevated Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOx)
Engine "Hot Soaks" (shut-downs)	• Evaporative Emissions (VOC)
Engine Idling	• Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOx) • Elevated Evaporative Emissions (VOC)
Exposure to Diurnal and Multi-Day Diurnal Temperature Fluctuation	• Evaporative Emissions (VOC)
Vehicle Refueling	• Evaporative Emissions (VOC)
Modal Behavior (e.g. High Power Demand, Heavy Engine Loads, or Engine Motoring)	• Elevated Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOx)

CO = Carbon Monoxide; VOC = Volatile Organic Compounds; NOx = Oxides of Nitrogen; PM_{10} = Fine Particulate Matter (less than 10 microns in diameter) ; SOx = Oxides of Sulfur
Source: Guensler, 1993

Two modeling approaches can be used to address elevated emission rates: 1) the cause can be modeled as a discrete emission-producing activity (e.g. an engine start), and the emissions treated as a discrete "puff;" or 2) the emission rate for the parent activity (e.g. the running exhaust emissions that are elevated by the cold start) can be adjusted upward when the conditions that cause elevated emission rates are noted. The California Air Resources Board's (CARB's) emission rate model (EMFAC7F), for example, treats the elevated engine start emissions as a single "puff" (i.e. separate from running exhaust) and multiplies the number of engine starts by a cold start emission rate. The US Environmental Protection Agency's (USEPA's) emission rate model (MOBILE5.0), on the other hand, increases the calculated running exhaust emission rate for vehicles, based upon an assumed fraction of vehicles operating in cold start, hot start, and hot stabilized modes.

High power and load conditions, such as rapid acceleration or high speed activities, also produce significant emissions (CARB, 1991; Benson, 1989; Groblicki, 1990; Calspan Corp., 1973a; Calspan Corp., 1973b; Kunselman, et al., 1974). Recent laboratory testing indicates that high acceleration rates contribute significantly to instantaneous emission rates, and that one sharp acceleration may cause as much pollution as does the entire remaining trip (Carlock, 1992). In addition, unloaded vehicle deceleration events appear to be capable of producing significant emissions (Darlington, et al., 1992). In contrast to cold start emissions that occur over a period of minutes, acceleration and deceleration related emissions occur over a period of seconds. Like engine starts, however, acceleration and deceleration activities can be treated as discrete emission-producing events and modeled as emission puffs, provided that emission rates for these activities (as well as any potential factors that may influence the magnitude of the puff) can be determined. Specific modal activities that produce elevated emission rates are not currently modeled in the emission inventory process, and are likely to contribute to emission inventory underestimation.

Activity Specific Emission Rates

The motor vehicle emission rates associated with each of the emission-producing vehicle activities (i.e. grams of emissions per unit of emission-producing vehicle activity) are functions of vehicle parameters, fuel parameters, vehicle operating conditions, and the vehicle operating environment. Table 2 illustrates some of the important variables that can be taken into consideration in developing emission rate estimates:

The Emission Inventory Process

The on-road motor vehicle emission modeling process consists of: 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 emissions for all activities. Ideally, these emissions estimates must be temporally and spatially resolved for the purposes of air quality modeling. Developing an accurate emission inventory for motor vehicles is tremendously complex. As with most modeling approaches, various modeling assumptions and data aggregation techniques have been developed to simplify the emission inventory preparation and minimize labor and data requirements. However, simplifications often tend to yield uncertain emissions estimates.

The first item to keep in mind, from an emission inventory standpoint, is that estimation of vehicle activity must necessarily be a secondary process. That is, emission-producing vehicle activities must first be identified, and emission rates associated with those activities must be quantified. Only then should vehicle activity be quantified. Without the knowledge of the emission cause-effect relationships at work, analysts are likely to quantify the wrong activities. Currently, four-step transportation planning models (UTPS-type models), often with post-processing, are used to estimate vehicle activity for emission inventories (Quint, et al., 1993; Bruckman, et al., 1992; Guensler and Geraghty, 1991).

TABLE 2. Vehicle Parameters, Fuel Parameters, Vehicle Operating Conditions, and Environmental Conditions Known to Affect Motor Vehicle Emission Rates

Vehicle Parameters:	Fuel Parameters:
• Vehicle class [weight, engine size, HP, etc.]*	• Fuel type
• Model year	• Oxygen content
• Accrued vehicle mileage	• Fuel volatility
• Fuel delivery system (e.g. carbureted or fuel injected)	• Sulfur content (SOx precursor)
• Emission control system	• Benzene content
• Onboard computer control system	• Olefin and aromatic content
• Control system tampering	• Lead and metals content
• Inspection and maintenance history	• Trace sulfur (catalyst effects)*

Vehicle Operating Conditions:	Vehicle Operating Environment:
• Cold or hot start mode (unless treated separately)	• Altitude
• Average vehicle speed	• Humidity
• Modal activities that cause enrichment*	• Ambient temperature
• Load (e.g. A/C, heavy loads, or towing)	• Diurnal temperature sweep
• Trip length and trips/day*	• Road grade*
• Influence of driver behavior*	

* These components are not explicitly included in the USEPA or CARB emission rate models.
Source: Guensler, 1993

SUSPECTED PROBLEMS WITH THE EXISTING MODELING APPROACH

Without detailed re-analysis of the data used to develop the algorithms in existing emission rate models, practitioners cannot accurately identify the individual model components that contribute the greatest uncertainty to emission estimates. Confidence interval analysis (based upon re-analysis of the original data) can reveal how representative each of the model algorithms really are (Guensler, et al., 1993). Because confidence intervals for model algorithms have not been reported in the literature, assessments of modeling uncertainty are currently based upon professional judgment and sensitivity analysis (i.e. the degree to which a change in an independent variable affects the magnitude of the predicted, or dependent variable). While sensitivity analysis does provide a good feel for which algorithms are likely to cause significant model output uncertainty, based upon variation in the model input values provided, sensitivity analysis cannot reflect the modeling problems associated with poor statistical representation of the actual cause-effect

relationships being modeled. Thus, it is not surprising that emission modeling practitioners identify and rank uncertainty problems in their own order of importance, depending upon their unique experiences. The relative importance of the modeling issues identified in this section are subject to debate. Further discussion of these issues and of proposals to reduce uncertainty in the emissions models can be found in TRB (1992), Bruckman and Dickson (1992), USEPA (1992), Guensler and Geraghty (1991), Gertler and Pierson (1991), Wilson and Ripberger (1991); and Systems Applications International (1991).

Off-Cycle and Modal Emissions

Research at the University of California at Davis indicates that speed-related emission factors currently used in emission modeling techniques are highly uncertain (Guensler, et al., 1993). These emission correction factors, by the nature of their statistical derivation, yield uncertain results with high standard errors. Even a shift to a gram/hour modeling regime, suggested by some analysts to reduce the non-linearity of the relationship between speed and emission rates, will not solve the estimation problems (Guensler, 1993). The empirical models used to develop the speed correction factors for motor vehicle emission rates do not explicitly account for modal operations such as acceleration and deceleration (Guensler, et al., 1993; EEA, 1991; Guensler and Geraghty, 1991).

Analysts speculate that a significant cause of motor vehicle emission underestimation may be related to unrepresentative driving cycle tests used in measuring vehicle emissions and to develop existing emission models (Carlock, 1992; Darlington, 1992; CARB, 1992). Thus, on-road emission behavior may differ significantly from the baseline exhaust emission rates developed in the laboratory on a dynamometer under the codified federal test procedure (FTP). The FTP test does not include speeds over 57 mph nor sharp accelerations (i.e. greater than 3.3 mph/sec), and some of these 'off-cycle' conditions are likely to result in enrichment (higher than stoichiometric fuel/air ratios), which yields high carbon monoxide and hydrocarbon emission rates.

It is interesting to note that combustion enrichment, causing high carbon monoxide and hydrocarbon emission rates, occurs by design. Vehicle manufacturers use enrichment to provide necessary instantaneous power output, to control cylinder detonation, and to protect cylinders, valves, and catalysts from high temperature damage during high RPM activity (USEPA, 1993a). If these enrichment episodes are not being represented in the FTP, these events are likely to contribute to emission underestimation.

The effectiveness of the motor vehicle emission control system is related to whether the vehicle is running in open-loop or closed-loop mode. An oxygen sensor monitors the oxygen concentration in the vehicle exhaust, sending a descriptive voltage to the onboard computer system (if oxygen concentration is too low, incomplete combustion is indicated). To maintain stoichiometric combustion, the onboard computer continually adjusts the air-fuel ratio and other combustion parameters based upon oxygen sensor readings. This is known as operating in closed loop mode. However, during the first few minutes of engine start, or when the engine load deviates from a pre-determined range of values, the vehicle runs in open-loop mode. Under open-loop conditions, inefficient or high temperature combustion can occur and pollutant emissions can increase. Ideally, an emission model would be capable of accounting for open and closed-loop operating conditions. However,

the factors that affect the control mode are the engine technologies employed and the pre-programmed range of operations contained in the onboard computer, which are different for individual manufacturers. Certain engine parameters that affect fuel consumption rates may also affect emission rates, such as manifold pressure or throttle position (Ross, 1993). Thus, vehicles of different make, model, and model year can differ significantly in open- vs. closed-loop response to engine operating conditions imposed by environmental demands (temperature, speed, acceleration, deceleration, etc.).

Emission rates from those off-cycle operations that cause enrichment appear to be much greater than the emission rates noted under FTP testing (Carlock, 1992). However, the data upon which these preliminary conclusions are based (23 vehicles operating under high acceleration rates) can be questioned because there were a number of significant problems associated with the data collected. Problems noted in previous data collection efforts (Long, 1992) must be avoided in future data collection efforts by ensuring that: 1) many vehicles are tested; 2) the vehicle test population better represents a cross-section of the existing vehicle fleet; 3) testing cycles better represent onroad activity; 4) analytical equipment is capable of accurately measuring a wide range of emission concentrations (i.e. within calibration); 5) the response time of analytical equipment and analytical systems is fast enough to properly integrate the mass emission estimates over one or two second intervals; 6) background ambient air concentrations are measured if they have the potential to vary greatly (i.e. in a laboratory that is testing multiple vehicles concurrently or has open solvent containers) and are monitored on a second-by-second basis; 7) exhaust gas flowrates do not exceed the constant volume sampling pump capacity; and 8) actual vehicle speed vs. time traces are retained, rather than the speed time trace that each vehicle was supposed to follow.

As mentioned above, vehicle acceleration rates may not be adequately accounted for in the test procedures used to develop emission rates and correction factors. Recently, concern has been expressed that road grade is not adequately accounted for in the emission inventory modeling process, because emission testing cycles were developed to simulate level grades. Grade can be considered an acceleration that the vehicle must undertake (an acceleration against gravity), so it seems possible that emissions due to vehicle accelerations and due to grade could be similarly modeled. Yet, acceleration due to grade can take place without a change in throttle position. The response of the engine computer and combustion parameters to road grade deserves further investigation.

Given the poor state of understanding with respect to the actual cause-effect relationships between vehicle activity and emission rates, especially where modal vehicle activities are concerned, it is impossible to determine in a definitive manner the overall emission impact of many strategies such as transportation control measures and intelligent vehicle and highway systems (Washington, et al., 1993).

To solve the off-cycle emission rate dilemma and speed correction factor uncertainty, researchers are currently suggesting that vehicle emission behavior could be better modeled by examining the second-by-second emission outputs from the vehicle, rather than using average speed assumptions. Second-by-second data for potentially important influencing factors would be collected simultaneously during emission testing.

Characterization of the Fleet

If modeled emission rate estimates are to be representative of the current vehicle fleet, then vehicles used to derive the emissions models should also be representative. While this seems a common-sense assertion, implementing a representative testing program is not simple.

Analysts are relying on the "law of large numbers," where the larger the size of a representative homogenous sample, the better the sample average and standard deviation represents the total population (Cohen, 1986). For a representative sample of vehicles to be drawn, the factors that effect emissions behavior must be conceived before sampling begins. If an important factor in the population is ignored, the sample collected may not be homogenous and results may be misleading. As an example, Cohen cites a study of average vehicle length where a random sample ignores the controlling factor of vehicle class; the resulting average length is not likely to be representative of either trucks or autos (Cohen, 1986). If motor vehicle emission rates had not been developed separately for automobiles and trucks, the resulting average values would be representative of neither autos nor trucks. Other factors that affect emissions within the automobile class may be overlooked under the current emission testing system. For example, are high performance vehicles or vehicles with eight-cylinder engines adequately represented in the vehicle sample fleet for baseline emission rates and correction factor analyses?

The general problem of failing to control for significant factors is compounded by the likelihood that a small fraction of the vehicle fleet are currently responsible for a large percentage of vehicle emissions. For example, if one out of every hundred vehicles in a theoretical vehicle fleet emitted 10 grams/mile, and the remaining 99 vehicles emitted 0.1 grams/mile, a random sample of one hundred vehicles that failed to include one of these high-emitting vehicles would be problematic. The odds of excluding this vehicle from a one hundred vehicle test population are roughly 37%, and there is still a 13% chance that a sample of 200 vehicles will fail to include any of these hypothetical high emitters. Analysts clearly need to rethink current experimental sampling design. Test sample sizes must be large enough to encompass all of the important factors. Once the factors are better understood, statistical over-sampling of under-represented vehicle groups can be undertaken (Ross, 1993). Replicate testing should also be undertaken to examine the variance between emission test responses of the same vehicle in the same lab and across labs, as this turned out to be an important issue in the review of the emission inventory models for heavy-duty trucks (Guensler, et al., 1991).

As noted above, the current presumption that vehicle emission rates are normally distributed, and that random sampling will adequately represent the fleet, may be invalid. Vehicle attributes may affect emission rates more than currently modeled, meaning that we are not controlling for potentially significant factors in our sampling design. Furthermore, the mechanisms by which governmental agencies select candidate vehicles for testing may introduce significant bias (e.g. in California, vehicles are randomly selected for testing, but owners must consent to the test and give-up their vehicle in exchange for a rental car during the interim). If, for example, owners of tampered vehicles are less likely to consent to the use of their vehicles in the testing program, this type of sample self-selection can lead to bias in emission rate estimates (USEPA, 1992). Additional studies should be conducted to

ascertain how much variation exists in the factors (tampering, misfueling, malmaintenance, etc.) that lead to high emissions (Loudon, 1993).

While remote sensing technologies are making it easier to identify high-emitting vehicles on the road, getting these vehicles into the test fleet for emission factor development is still not a simple task. For more information on the problems of reconciling modeled and measured emission rates, as well as the potential contribution of high-emitting vehicles, see Ashbaugh, et al. (1992), Lawson et al. (1990), Pollack, et al. (1992), and Gertler and Pierson (1991). Problems with test fleet selection beget problems in estimates for baseline exhaust emission, emission control system deterioration, malmaintenance, and tampering rates included in the models.

Cold and Hot Start Emissions

Once the engine reaches a 'hot-stabilized' mode, combustion stabilizes, lubricant viscosity decreases, engine computers listen to oxygen sensors and move into closed loop control, and the emission control catalyst reaches light-off temperature. Hence, emissions are significantly elevated during the warm-up periods, and hot and cold start emissions become important contributors to the on-road emissions inventory. Typically, 3-way catalyst systems require about 2 minutes to reach catalyst light-off temperature, at which point exhaust gas emissions are significantly reduced (Joy, 1992). In 1987, cold and hot start operations were estimated to contribute about 27% of hydrocarbon emissions, 35% of CO emissions, and 19% of NOx emissions from automobiles in the Los Angeles basin (CARB, 1990). The operation of the vehicle during warm-up affects the rate at which the catalyst heats and the time it will take to reach catalyst light-off temperature (Austin, et al., 1992).

The hot and cold start emission factors employed in current emission factor models are based upon FTP testing. The cold start component of the FTP (Bag 1) employs an overnight soak. The hot start component of the FTP (Bag 3) employs a ten minute soak. Each engine start in the test procedure begins with 20 seconds of idle. The length of soak time affects the magnitude of emissions elevation based upon changes in catalyst and engine coolant temperature (also important are factors such as wind speed and low ambient temperatures that can tend to lower catalyst temperature more rapidly). The FTP sends vehicle activity into heavy load operation fairly quickly, and extended initial idling may delay the time before the emission control catalyst reaches light-off temperature (Austin, et al., 1992). The extent to which these effects are significant is currently being investigated.

All of the other test cycles employed in data collection (i.e. for speed correction factor analysis and running loss analysis) are conducted in hot-stabilized mode. That is, the vehicles are pre-conditioned so that elevated emission rates associated with engine warm-up are not included. The reliability of the hot and cold start emission estimates, under either the USEPA elevated emission rate approach or the CARB emission puff approach are questionable (especially when highly uncertain speed correction factors are employed in the derivation of the relative difference between hot stabilized baseline exhaust emission rates and hot start emission rates). The magnitude of emission effects for various modal activities under cold and hot starts has not been examined, nor have the relationships between modal

activity and time to reach catalyst light-off temperature. Based upon preliminary USEPA analyses, start emissions may be underestimated by as much as 35% (Markey, 1993).

Evaporative Emissions

The evaporative emission testing program has been undertaken separately from the emission testing programs designed to develop baseline exhaust emission rates and speed correction factors. There is reason to believe, however, that interaction occurs between vehicle activity and the evaporative emission rates. With modern fuel injected vehicles, fuel circulates through the fuel lines to the engine and if not needed for injection is returned to the fuel tank. Fuel recirculation appears to increase the temperature of the fuel in the fuel tank, resulting in increased fuel vaporization and tank pressure. Vapors are vented to a charcoal control canister, and canister vapors are occasionally purged to the engine for combustion (Jacobs, et al., 1990). The emissions from evaporative control systems while the vehicle is in motion constitute running losses. A lower frequency of canister purges at low speeds exacerbates the evaporative emissions problem. Hence, the vehicle activity undertaken (e.g. trip duration, trip frequency, and extended vehicle idling) may have a significant impact upon the temperature of fuel and evaporative emission rates. The USEPA in-use driving surveys indicate that short trips represent a larger fraction of trips than currently modeled, which may cause evaporative emissions to be underestimated (Markey, 1993).

Running evaporative emissions are already modeled as a function of vehicle speed, temperature, fuel volatility, and trip duration (based upon an assumed probability that elevated running loss emissions are more likely to occur for trips with long time duration). The emission factors in MOBILE4 were based upon the testing of 34 vehicles under the Federal Test Procedure, four of these vehicles under both the New York City Cycle and Highway Fuel Economy Test, at ambient temperatures of 80F and 95F, and for fuel volatility of 9.0 psi and 11.7 psi (USEPA, 1988). For MOBILE4.1, 78 vehicles were employed in testing, 32 that passed and 46 that failed functional evaporative control system purge and/or pressure checks (Newell, 1993). For MOBILE5.0, 126 vehicles (some overlapping the MOBILE4.1 effort) were tested on the FTP cycle at ambient temperatures of 80F, 95F, and 105F, and for fuel volatility of 7.0 psi, 9.0 psi, 10.4 psi, and 11.7 psi, with 39 passing and 87 failing the purge and/or pressure checks (Newell, 1993). Given the limited number of vehicles tested under the three average speed cycles, the relationship between speed and running loss emission rates are likely to be tenuous. Also, extrapolation of results beyond the test conditions would violate acceptable statistical procedures. The limited testing that has been undertaken should be supplemented to: 1) provide a better representation of fleet characteristics in the sample, 2) determine potential interactions between modal activities and existing correction factors with running and other evaporative losses, and 3) establish confidence intervals around the emission factor estimates.

Automobile fuel economy has been referred to as the forgotten hydrocarbon emission control strategy (DeLuchi, et al., 1992). The magnitude of refueling emissions (typically output as gram/mile factors by the MOBILE model) is dependent upon the frequency of refueling and volume of gas pumped, which are functions of vehicle fuel economy and fuel tank size. To the extent that vehicle activity affects fuel economy, the emission rates for refueling emissions are affected. The gram/mile MOBILE model refueling emission rates were based upon gram/gallon emission rate data, which were then

translated into gram/mile emission rates (Newell, 1993). Thus, conversion of gram/gallon emission rates into gram/mile emission rates is inherently uncertain, lacking the causal effect of duty cycles on fuel consumption rates. Because the MOBILE model is capable of providing gram/gallon emission rate estimates as well as gram/mile emission rates (Newell, 1993), it would seem prudent to approach the modeling of refueling evaporative emissions from a stationary source perspective rather than a mobile source perspective (i.e. allocating refueling emissions to the service station based upon fuel throughput and gram/gallon emission rates) as is recommended by the USEPA (Newell, 1993).

Interaction Between Various Correction Factors in Emission Models

As mentioned previously, the correction factors employed in the emissions models are typically assumed to be independent of each other. The one exception is the running loss emission calculation that takes into account average speed, temperature, and fuel volatility, albeit the significance of the modeled relationship is unsure at best. As Austin, et al. (1992) point out, all of the temperature correction factor algorithms in the emission models are based upon testing conducted on the FTP. It seems reasonable that the emission effects of temperature and vehicle load may be correlated in some manner; hence, correction factors for average speed and temperature are probably not independent. If temperature testing had been undertaken on the test cycles used to develop speed correction factors (Guensler, et al., 1993), the revealed relationships between relative emissions, average speed, and temperature would be more certain than the independent use of existing speed correction factors and temperature correction factors. The independence of all model algorithms can only be tested if sample selection and testing is undertaken specifically to control for the variety of potentially correlated variables. Other algorithms that should be tested for independence include: oxygenated fuel effects, tampering impacts, fuel volatility effects, and inspection and maintenance effectiveness. Factor levels can be varied while other factors are held constant, revealing the variation in emissions with varying factor levels. Replicate testing should also be undertaken. Solving the potential correlation problems will be neither cheap nor easy. For example, the CARB is currently in the process of contracting a pilot project that will investigate the synergistic effects of driving cycle, temperature, and fuel composition that will involve only ten vehicles and will cost $450,000 (Long, 1993).

Activity Quantification and Spatial Allocation

Typical uncertainty problems associated with the use of travel demand and other vehicle activity models are outlined in the literature (Harvey, 1993; Bruckman and Dickson, 1993; Purvis, 1992; Benson, 1992; Bruckman and Dickson, 1992; Guensler, et al., 1991; Ismart, 1991; Guensler and Geraghty, 1991; Atkins, 1986; and many others). As previously mentioned, the first problem associated with vehicle activity estimation is the basic premise of applicability ... that vehicle activities being estimated are the activities that actually produce vehicle emissions. For example, quantification of VMT and average speeds along roadway links do not yield an adequate picture of emissions under the current modeling regime. Activity model development must follow, or ideally parallel, emission rate investigation.

The additional factor to consider in developing activity modeling approaches is that air quality models must employ spatially allocated emission estimates and meteorological assumptions to predict ambient air quality. Thus, inherent assumptions that are employed in spatial allocation of emissions can cause inaccurate assessments. The typical problem currently encountered is questionable accuracy and poor resolution of vehicle activity models employed in the emission inventory estimates. In those areas that employ travel demand models, model outputs of hourly traffic flow and average vehicle speeds can often be inaccurate, especially if various model algorithms are modified simply to obtain agreement with certain required screenline counts (FHWA, 1990). Changes to modeling procedures that provide analysts better spatially allocated emission estimates will improve overall modeling results.

Recent activity modeling improvement efforts (Quint, et al., 1993; Harvey, 1993; jhk & Associates and Dowling Associates, 1992; Bruckman, et al., 1991; etc.) have focused on improving the quality of vehicle activity model outputs, primarily disaggregating the activity both temporally and spatially to improve emission quantification and resolution. Emission impact estimates cannot help but be enhanced by the recent improvements in vehicle activity estimates. However, the important long term question that must be addressed is whether these activity outputs are the important emission-producing activities. As new emission-producing activities are identified and emission rate models evolve, travel demand models will either have to be refined to provide estimates of the pertinent activity, or new vehicle activity modeling approaches will be needed.

THE USEPA FTP IMPROVEMENT EFFORT

The CAA amendments required the USEPA to undertake research designed to ensure that vehicles are tested under circumstances which reflect the actual current driving conditions under which motor vehicles are used (USEPA, 1992; USEPA, 1993a; USEPA, 1993b). The current mandate provides for an assessment of driving behavior by the USEPA, an assessment of emissions and vehicle testing, published notices of proposed rulemaking, and final rulemaking by December 1994. It should be noted that the efforts of the FTP improvement project are focused on potential regulatory action in the vehicle certification arena, and not on the improvement of the emission inventory (Markey, 1993).

Field studies of driving behavior were carried out by Radian Corporation and Sierra Research in Spokane, WA, and Baltimore, MD, this year. In accordance with a court ordered timeline (Markey, 1993), the USEPA produced the 'Federal Test Procedure Review Project: Preliminary Technical Report in May 1993 (USEPA, 1993c). The USEPA is undertaking the emission testing effort with the California Air Resources Board and auto manufacturers (Markey, 1993), and testing is to be completed in August 1993. Analytical results from the emission testing program will be a critical component of the notice of proposed rulemaking which must be published by March 31, 1994 (Markey, 1993). The emission assessment and testing process is open, with data freely shared by the USEPA.

To undertake the assessment of driver behavior, a chase vehicle program and an instrumented vehicle program were implemented. Sierra Research equipped one chase vehicle with a laser rangefinder so that it could follow onroad vehicles without alerting

drivers that their driving patterns were being monitored (DiGenova, 1992). The laser system allows second-by-second monitoring of speed and acceleration profiles for onroad vehicles. The laser-equipped vehicle has been employed extensively in Spokane and Baltimore, with more than 1500 vehicles chased and 100 hours of driving time monitored. Instrumented vehicles, equipped to monitor time of day, speed, manifold vacuum (load), and RPM were also implemented as a separate study (102 in Spokane and 113 in Baltimore) by Radian Corporation. Drivers for the Radian vehicles were recruited through the inspection and maintenance (I&M) program. Seventy nine vehicles instrumented to record throttle position, oxygen sensor voltage (to detect enrichment conditions), and coolant temperature were also put in service by private industry (USEPA, 1993b). An additional 101 privately-owned vehicles were instrumented by Georgia Tech. under a cooperative agreement with USEPA's Office of Research and Development (Markey, 1993). In sum, instrumented vehicles collected data from more than 10,000 separate trips and 6 million seconds of operation.

As mentioned previously, the FTP is limited to a maximum acceleration rate of 3.3 mph/second and a maximum speed of 57 mph (and even that speed is for a very short duration). Based upon the data collected during the FTP study, 8.5% of all speeds exceeded the FTP maximum rate (USEPA, 1993c) and more than 88% of the trips contained an acceleration activity that exceeded 4 mph/second (Markey, 1993). In fact, more than one third of the trips monitored included an acceleration rate at some point during the trip of more than 7 mph/second (USEPA, 1993b). The cumulative frequency plots for acceleration values prepared by Systems Applications International, based upon the Baltimore and Spokane instrumented vehicles, indicate that more than 15% of the total acceleration activity (in seconds) exceeded 3.5 mph/second (USEPA, 1993b). Similarly, more than 15% of the deceleration activity exceeded -3.5 mph/second. According to the FTP preliminary technical report (USEPA, 1993c), about 18% of the total driving time in Baltimore fell outside of the FTP speed and acceleration envelope.

Based upon the vehicle activity data being collected and analyzed, the possible options being assessed by the USEPA include: 1) revising the FTP based upon driving behavior studies, 2) adding a Bag 4 emission testing cycle to the FTP, and 3) developing new emission testing cycles and requirements. Manufacturers appear willing to undertake research efforts that will lead to the identification of vehicle activities that create elevated emission levels. However, during the FTP modeling improvement project public workshop, manufacturers also pointed out that some of the enrichment events that occur are designed to maintain the integrity of the catalytic converters and that any new emission certification program that might be developed through the FTP improvement research should take into account the added costs that may be generated by requiring increased efficiency of emission control systems under these conditions (USEPA, 1993b). Analyses of empirical evidence will be needed to resolve these issues.

In a parallel vehicle activity monitoring project undertaken for the California Air Resources Board, the Sierra laser-equipped vehicle was also employed to collect activity data from the greater Los Angeles area (DiGenova, 1992; Austin, et al., 1992). The CARB plans to develop a new in-use vehicle dynamometer cycle that is more representative of actual California driving conditions (CARB, 1991b). The new testing cycle (to be known as the LA92 cycle) is being developed by Sierra Research for the CARB, and will include high speed operations and acceleration profiles that are more typical of California highway and local road traffic. Data collected on the new cycle are expected to improve the accuracy of

emission inventories generated from bulk activity estimates. However, much of the same aggregation bias and uncertainty in application to individual corridor specific emission impact analysis will still remain. Plus, vehicle-to-vehicle variability will still not be explicitly addressed.

THE 25-BIN MODELING APPROACH

The patterns of vehicle operation on surface streets under congested conditions are typically represented by low average speeds and stop-and-go conditions. Subsequently, higher emission rates result per vehicle mile of travel. However, current modeling methodologies were designed to predict emissions for regions. When the models were developed, they were never designed with the goal in mind of accurately reflecting emission rates at the corridor level. Data collection efforts did not sufficiently focus on congestion effects. Hence, applications of the models using the average speed modeling regime yield questionable results.

The modeling approach discussed here is currently being investigated by the CARB and USEPA (Larsen and Baker, 1993; USEPA, 1992). The 25-bin modeling approach would involve the development of 5 sets of 5 new emission testing cycles. Each set of cycles would be designed to better reflect typical vehicle activity on five roadway classifications (freeways, expressways, arterials, connectors, and local roads) under five congestion levels. It is likely that the congestion levels would be defined in terms of level of service (LOS), where LOS is based upon traffic density for freeways and expressways and upon percentage of free flow speed on arterials (TRB, 1985). Rather than developing baseline exhaust emission factors under a single test cycle (currently the FTP) and correcting these emission factors to estimate emissions at speeds other than the FTP average speed, vehicles would be tested on each of the 25 testing cycles and baseline exhaust emission rates would be developed for each roadway classification and level of service. Thus, fleet average emission rates would be pulled from one of the 25 "bins" and then applied to vehicle activity that occurred under the specified conditions.

To develop 25 'representative' cycles, the results of vehicle activity studies similar to those currently being undertaken by Sierra Research and Radian for the CARB and USEPA would be employed. Three-dimensional Watson plots (named after H.C. Watson who developed the Melbourne Peak Cycle), illustrate the frequency of vehicle operation at all combinations of speed and acceleration (speed vs. acceleration vs. frequency). Watson plots are being developed from collected vehicle activity data (Austin, 1992). The 25 cycles would be constructed to typify trips undertaken on these roadway classes under specified levels of service, so that the Watson plot of representative new test cycle would yield frequencies of acceleration and speed combinations similar to those in the Watson plots of observed activity.

Vehicle-hours of delay (VHD) for each roadway link is a function of the traffic volume, link length, link capacity, number of lanes, and difference between modeled speed and free flow speed. The outputs from travel demand models, which are used in conventional emissions impact assessment, include traffic volumes and average vehicle operating speeds by time of day. However, these models can be configured to provide level

of service as a descriptive parameter for each link in the network, and each link in the network is readily allocated into roadway classification. This approach eliminates the need for demand models to precisely estimate average vehicle speeds for freeways and expressways and would eliminate the problems associated with the accuracy of current speed correction factor algorithms.

As with freeways and expressways, level of service is a function of roadway capacity on arterials and at intersections. Yet, recent studies (Suhrbier, 1993) indicate that arterial and intersection capacity is a function of time-of-day and day-per-week, probably due to driver familiarity with the local roadway network for peak period commute travelers (increasing capacity) and unfamiliarity with the local roadway network for off-peak shopping and recreational travelers (reducing capacity). This fluctuation of capacity and level of service will complicate the implementation of the 25-bin modeling approach on local networks. However, we should keep in mind that actual observation of traffic flows (using instrumented vehicles or stationary monitoring systems) can be used to determine which speed bin the emission rates should be pulled from.

Of course, the 25-bin approach to modeling would still employ aggregated data sets. The typical cycle would represent a large variation in speed profiles, and the emissions from vehicles operating on the cycle will still exhibit a great deal of variation. Emissions data collected on these cycles would then be averaged into fleet emission rates. Traffic data would also be aggregated into one of the 5 level of service classifications. Emission rates would be applied to average vehicle flows during an hourly period. Aggregation itself is not a problem, and the proposed modeling approach would likely yield a significant improvement in modeling accuracy. In developing future emission modeling approaches, effort should be taken at the outset to establish the uncertainty impacts of data aggregation.

The 25-bin modeling approach is not without the drawback of significant added data and analytical cost over the existing approaches, however (Newell, 1993). For example, if 25 cycles were developed, 500 vehicles were tested on each cycle, and the amortized cost per test were roughly $800.00, the new program would cost somewhere in the neighborhood of $10 million. The testing to develop 25 baseline emission rates, coupled with testing required to address independence of correction factors, "would require data collection and analysis efforts beyond those ever likely to be attempted (Newell, 1993)."

The CARB Alternative to the 25-Bin Approach (Larsen, 1993)

The high cost of emission testing has resulted in the CARB's proposal to develop a scaled-down version of the 25-bin modeling approach; a 10-bin modeling approach. Seven emission testing cycles are being developed for freeways and three cycles for arterials.

To develop the new freeway cycles, the Sierra Research chase car activity data for Los Angeles (described earlier) were revisited. Each time the observer in the chase vehicle perceived a significant change in traffic density, the end of a vehicle activity snippet and the beginning of a new vehicle activity snippet were defined. Cluster analysis was employed to separate more than 70,000 seconds of vehicle activity snippets into bins of similar vehicle activity. The standard deviation of speed, coefficient of speed variation, total absolute deviation of speed, and percent of activity at idle were the variables used to cluster the

snippets. The seven freeway bins that were created have average speeds of 9, 17, 25, 32, 40, 53, and 61 mph respectively. The snippets in each bin were dissected to yield a library of acceleration, deceleration and cruise events of between 1 and 20 seconds in duration that could be drawn from to create a new emission testing cycle. A Monte Carlo procedure was employed to create 500 potential test cycles for each bin. To determine the best cycle for each bin, the mean speed, standard deviation of speed, total absolute speed deviation, average positive kinetic energy (PKE/mile), and percent idle characteristics of the random test cycles were compared with the same average characteristics of the total bin (i.e. as if a single test cycle were composed of all snippets in the bin). The best match to the average bin characteristics that also achieved 80% or better 'similarity' to the bin speed (in 5mph increments) and acceleration (in 0.5 mph/sec increments) matrix was deemed the best cycle.

The development of three arterial cycles was not as straightforward as the development of the freeway cycles. Traffic flow on arterials is dependent upon architecture, traffic light placement and light timing (i.e. likelihood of being stopped), congestion levels, and possibly even driver familiarity with the local network. From the chase car data, vehicle activity snippets were created from transportation network node to node (i.e. conforming with the links of the Southern California Association of Government's travel demand model). Ideally, a matrix would be used to break snippets into bins based upon free-flow speed and traffic flow/congestion level for each arterial link in the network for the hour of the day in which it was traveled. However, these data were not available for the arterials in question (nor could they be easily obtained). Thus, activity snippets were sorted into bins based upon average speed alone, and the snippets in the bins exhibit average speeds of 14, 24, and 34 mph. Because the arterial nodes in travel demand models are often separated by a great distance, each arterial snippet was dissected into segments between traffic control points (i.e. stop signs and signals), with each segment called a TCP event. Random cycles were created by linking events with similar end points of speed (i.e. the end point speed of snippet 1 closely matched the start point speed of snippet 2). The best cycle was determined in a fashion similar to the selection for freeways. Cycles were compared to the bin average based upon average speed, standard deviation of speed, total absolute speed deviation, and average positive kinetic energy, as well as percent idle and number of queues encountered per mile. The best match to the average bin characteristics that also achieved 80% or better 'similarity' to the bin speed (in 5mph increments) and acceleration (in 0.5 mph/sec increments) matrix was deemed the best cycle.

THE ENGINE MAP APPROACH

An engine map approach is fairly straightforward and has been employed since the 1970s for some fuel economy models. The conceptual approach is to translate real-time speed and route information into instantaneous vehicle rpm and load parameters, use an engine map to look-up the instantaneous emission rates for the specific rpm and load conditions, and continuously integrate the instantaneous emission rates to estimate the total emissions from any given set of vehicle activities (USEPA, 1993a; USEPA, 1993b). The engine map is based upon steady-state testing of the engine and control system. That is, the engine is placed at specific RPM and load conditions and the emission result is recorded, creating a 3-dimensional graph of engine RPM, load, and emission rates.

Two models are employed in the engine map regime, VEHSIM and VEMISS. The VEHSIM (vehicle performance simulation) model was originally developed by the Transportation Systems Center of the US Department of Transportation to support vehicle energy efficiency studies (Zub, 1981). The VEHSIM program translates vehicle activity (instantaneous speed and acceleration) into horsepower requirements, after losses, in the form of RPM and torque (Zub, 1981). The translation of vehicle activity into RPM and load parameters requires that vehicle-specific part libraries be maintained for each vehicle (i.e. the relationship between vehicle speed, engine speed, and vehicle efficiency parameters), and numerous interpolations are required within the model (Zub, 1981). The second computer model is VEMISS, a program that translates RPM and load parameters into instantaneous emission rates (USEPA, 1993b), where engine maps list power output (brake horsepower) as the engine load parameter.

Power is required to do work against such forces as internal engine friction, drivetrain friction, road friction, wind resistance, gravity, and to provide linear acceleration. Keep in mind that power is work per unit time, work is a force through a distance, and force is mass times acceleration. The shorter period of time in which the work is performed, the higher the power requirement. Drivetrain information, gear ratios, tire diameter, etc., must be known to develop RPM profiles from instantaneous speed, and engine/drivetrain efficiency parameters are needed to translate instantaneous operating mode into engine load. Due to significant differences between vehicles (i.e. model to model and model year to model year), in terms of internal and external frictional forces that must be overcome, the VEHSIM model must be specifically calibrated for each engine, drivetrain, exhaust system, and vehicle configuration.

The USEPA is currently evaluating the potential of VEHSIM and VEMISS for application to general emissions modeling. Both models are in the public domain. The preliminary evaluation of VEMISS is complete. The prediction results for engine-out emissions appear encouraging (however, not enough information was presented in the USEPA (1993b) documentation to make an informed judgment as to model confidence). Additional work at the USEPA is ongoing. For example, Systems Applications International has been contracted by the USEPA to develop a cold start component for VEMISS (Markey, 1993). Variations in catalyst efficiency and dynamic response to changes in pollutant loading, however, may cause problems in engine map model development.

The evaluation of VEHSIM is still in progress today and results have yet to be reported. The main questions that still remain to be answered for the general modeling approach are: 1) will VEHSIM be capable of accurately translating time-speed and route information into engine load and RPM parameters, 2) will engine maps remain stable over time as vehicles accumulate mileage, and 3) will emissions that occur under transient conditions (e.g. response of cylinder volumetric efficiency and air fuel ratio to an acceleration followed quickly by a deceleration) be adequately represented by the emissions map that is derived under steady-state conditions?

An interesting approach for introducing operating mode information into an emission modeling regime might be to test computer control chips in the laboratory (Long, 1992). Engine loads and combustion conditions could be simulated electronically and analysts could monitor the signal that changes the system from closed loop operation to open loop operation. This approach is less intensive than the engine map approach, but may

capture those vehicle operating conditions that tend to cause enrichment events for specific vehicle models. Hence, existing models could be supplemented with results from computer control chip studies. Due to the vehicle to vehicle variability in control system response to load conditions, and the lack of disaggregate data that include open/closed control monitoring, it is not possible at this time to incorporate this aspect of emission monitoring into an existing emission modeling regime. But this approach warrants further exploration.

DISAGGREGATE MODAL MODELING WITH LINK PROFILING

Given the need for models that can better predict corridor emissions, research teams are proposing to use statistical analysis of new and existing data to ascertain the relationships between modal activities (acceleration, deceleration, constant-speed cruise, and idle activities) and emission rates (Guensler, et al., 1993; Barth and Norbeck, 1991). Presently, disaggregate second-by-second emission data are available for ten vehicles tested under a single high speed test cycle by the California Air Resources Board. Disaggregate data are now becoming available for instrumented vehicles; six General Motors vehicles in Atlanta (in an ongoing study being conducted by Georgia Tech.) and a Ford vehicle in Los Angeles (at the University of California, Los Angeles). Laboratory testing has recently begun at the California Air Resources Board in El Monte, and second-by-second emissions are being collected for a limited number (10-20) of vehicles. Plus, 29 vehicles are currently being tested in a modal approach by the USEPA office of mobile sources. In addition, testing by the Auto Oil/Air Quality Improvement Group has yielded a number of "cycle-subset" test results, where emissions associated with components of the Federal Test Procedure were collected in separate sample bags and analyzed. The Auto Oil group has also collected second-by-second data for a number of older vehicles with accumulated VMT, but the data are currently archived and have not yet been released for analysis. Given the lack of comprehensive second-by-second emission data currently available and expected to become available over the next few years, it is not likely that comprehensive disaggregate modal emission models that meet "microscopic, discrete-continuous, and stochastic" modeling criteria can be rapidly developed. Understanding the physical phenomena at work will be fundamental to model development, and new data and analyses are needed before this understanding can be achieved.

The primary limitations associated with using existing second-by-second data to develop a modal model directly are associated with the limited number and types of test vehicles used to collect data. Analysis of modal emission attributes, based upon the results from a single vehicle being used to collect on-road second-by-second emission data, will yield a fairly narrow result. Remember, significant vehicle to vehicle differences are noted in the engine map approach. But, these results will be important from the standpoint of identifying factors that must be controlled in future sampling programs. A framework of analysis into which new second-by-second emission data can be incorporated can be developed. Research in this area of modal emission rates is ongoing. Thus, as new data and analyses become available from vehicle manufacturers, agencies, consulting firms, and academia, the tools for analyzing the emission rate impacts of modal activities will continue to evolve.

Once emission rate information as a function of vehicle operating mode is developed, modal vehicle activity estimates must also be developed. To accomplish this task, a link profiling approach could be implemented. Link profiling would involve the development of vehicle speed-time traces along specific roadway classifications under specific levels of service. These relationships could be derived from observation, paralleling the 25-bin approach. Or, statistical techniques could be employed to develop relationships between speed profiles and highway capacity manual concepts. Potential independent variables could include average flow rates (vehicles/lane/hour) and roadway capacity (as a function of shoulder width, lane width, presence of abutments, sight distances, weather conditions, weaving section characteristics, etc.). Statistical representations of "typical" speed-time profiles could be developed from speed and acceleration frequencies. The relationships between vehicle flow and highway capacity manual concepts could even be integrated into existing freeway simulation models currently used to predict vehicle flows on freeway corridors. If computing power is unlimited, simulation models could actually retain estimated speed-time traces for individual vehicles. Perhaps an alternative or supplemental approach, given that some modal activities may be rare events that cause significant emission rate increases (or "puffs"), would be Monte Carlo simulation of the various speed-time traces that are encountered. These activity profiles could then be coupled with the modal emission rate models to better assess the emissions that result. Thus, a number of alternative approaches could be explored simultaneously.

Essentially, link profiling is the next step beyond the 25-bin modeling approach, moving from a stochastic model to a simulation model. Rather than developing an emission testing cycle for each roadway classification and level of service, emission rates would be developed for specific modal activities (acceleration, deceleration, idling, and constant speed cruise). However, it is difficult to know at this time whether a significant improvement in emission estimation would result from a shift to link profiling.

DATA REQUIREMENTS FOR NEW MODELING APPROACHES

The most sensible short-term approach to improving the emissions models is simply to revisit all of the data used to derive the emissions and activity algorithms in the current emission rate and vehicle activity models. Once quantified, uncertainties can be incorporated into policy analyses. This short-term approach could be implemented over a period of 1-2 years. Although this approach does nothing to reduce uncertainty in the models, it will serve to reduce uncertainty in the application of these models. That is, emission estimates based upon current models would be used with the level of confidence appropriate to their accuracy, making transportation policies reflective of the current level of uncertainty.

There are two medium-term approaches that can be developed and implemented over a period of 2-5 years. The USEPA is taking the first tack of simply improving the FTP cycle to make it more representative of on-road vehicle activity. The USEPA may ultimately develop a new testing cycle, and the new cycle may ultimately result in the implementation of a FTP Bag 4, representing some of the activities not currently incorporated in the FTP testing procedures, which will indirectly require manufacturers to improve onboard computer control systems. On the other hand, implementing a 25-bin approach (or the

CARB 10-bin approach) will help to disaggregate the current modeling approach to a much greater extent (by developing emission testing cycles for roadway classifications and level of service parameters and then applying these test results only to vehicle activity that occur under these conditions). Neither of these medium-term approaches would explicitly employ second-by-second emission modeling.

Probably the greatest complaint of policy analysts attempting to undertake evaluation of proposed emission reduction strategies is that models are not sensitive enough to evaluate policies that affect fleet composition or the characteristics of vehicle activity. The long range modeling improvements that will be discussed in this section are designed to move away from aggregate modeling techniques, and move toward modeling methodologies designed to better predict emissions from individual vehicles on the road.

Two long-term approaches that are currently being investigated are the engine map approach and the modal activity modeling approach. Given the data required to develop models that are representative of the vehicle fleet, it is not likely that either modeling approach could be implemented sooner than 5-10 years. Both of these emissions modeling approaches will require a detailed understanding of the cause-effect relationships at work in the vehicle engine and emission control system, and then the interactions between the vehicle operating environment and vehicle parameters.

None of the modeling approaches discussed in this paper would necessarily solve emission modeling problems associated with fleet characterization, hot/cold starts, evaporative emissions, interaction of emission model correction factors (except to the extent that correction factors can be eliminated), and spatial allocation of emissions issues, unless these issues are specifically addressed in future data collection efforts.

Data Requirements to Establish Uncertainty in Existing Models

Uncertainty associated with the use of the existing emission model algorithms can be quantified by revisiting the original data. No new data are required to implement the short-term uncertainty assessment for vehicle emission rates and activity. However, all emission testing data will need to be de-archived for analysis. Given the difficulty in obtaining the parent emissions database for speed correction factors, this will undoubtedly be an onerous task. The task of quantifying vehicle activity uncertainty is not as straightforward. The methods used to develop and calibrate vehicle activity models, coupled with the fact that variance of individual data sources in activity modeling is rarely known, may make quantification of activity uncertainty next to impossible (Loudon, 1993).

All of the new medium and long range modeling approaches require *extensive* collection of vehicle emission data if we are to adequately assess emissions from the vehicle fleet. The existing database is too scant even for today's modeling approach. Once the emission rate information is obtained, to implement these proposed modeling improvements new and appropriate vehicle activity data must be collected.

Data Requirements for the USEPA FTP Improvement Approach

The vehicle activity data necessary to improve the FTP and develop alternative testing cycles have already been collected and are currently being analyzed. As mentioned earlier, the three possible options being assessed by the USEPA include revising the existing FTP, adding a Bag 4 emission testing cycle to the FTP, and developing entirely new emission testing cycles and requirements (i.e. for high speed/acceleration activity). Once the FTP improvement solution is selected, data collection for representative fleet samples must then be undertaken to better characterize the baseline exhaust emission rates for the fleet.

If high speeds and acceleration activities are incorporated into the testing cycles used to develop baseline exhaust emission factors, some improvement in representation of modal activity will result. For any of the three FTP improvement scenarios, only one new and different testing cycle would be developed, meaning that the data collected would not significantly improve the average speed modeling regime. Without additional modal testing, or at least incorporation of new speed and acceleration profiles into the other cycles used to develop speed correction factors, the extent of the improvement is speculative. The emission testing data collected as a part of the FTP improvement project and the CARB emission testing project may contain up to 40% of the data on a second-by-second basis (Larsen, 1993). Thus, the project will yield much worthwhile data for future emission inventory modeling efforts.

Data Requirements for the 25-Bin Modeling Approach

In developing the 25-bin modeling approach, the first task is to develop 25 emission testing cycles representative of the types of vehicle operations that tend to occur on the five different roadway classifications under the five levels of service. Typifying vehicle activity under these conditions will not be simple. One speed vs. time trace will be selected to represent the individual vehicle profiles that occur. In essence, the cycles will need to represent the expected values of average speed and percent operation by mode (i.e. percent of activity at idle and at various speed/acceleration and speed/deceleration combinations). Data are already being collected to accomplish this task.

Once the cycles are developed, emission rate data will need to be collected from a representative sample of the vehicle fleet upon each testing cycle. The number of vehicles that must be tested is still an unknown at this point, and will remain unknown until studies are conducted to determine the "factors" that must be controlled for in the sample. Clearly, vehicle class (light-duty auto, light-duty truck, etc.), model year, fuel type (diesel vs. gasoline), accrued vehicle mileage, fuel delivery system (carbeureted, throttle body injected, and fuel injected), emission control system, presence of air conditioning, and perhaps even various tampering scenarios are variables that must be controlled in the sample selection. These variables have already been identified as being important factors that affect emission rates. However, current modeling methodologies essentially assume that these factors operate independently. Because the assumption of factor independence appears to be incorrect, future emission data collection efforts cannot afford to make this assumption. Samples must be sufficiently large to represent various combinations of factors so that independent and covarying effects can be gleaned from statistical analysis. Even so, the above mentioned factors may not be the only factors that need to be controlled. Preliminary

analyses of the speed correction factor emission rate database indicates that eight-cylinder engines appear to behave differently than four cylinder engines. Engine size, curb weight, horsepower, and other vehicle parameters probably need to be controlled as contributing factors in vehicle fleet sample selection. This implies that a great many vehicles need to be tested on each of the twenty-five testing cycles.

The 25-bin modeling approach is likely to make great strides in better representing modal activity in the emission inventory process by developing numerous new and more representative testing cycles. The 25-bin project could also be used to solve the emission modeling problems associated with hot/cold starts if data are collected in hot stabilized, cold start and hot start modes. Spatial allocation of emissions are likely to improve. As discussed previously, the development of future models would be greatly enhanced if data collected for the 25-bin approach were collected on a second-by-second basis. In fact, two of the five emission testing bays at the CARB are to be equipped with instrumentation capable of monitoring emissions on a second-by-second basis, meaning that about 40% of the data collected in the CARB effort may be useful for modal model development (Larsen, 1993).

Data Requirements for an Engine Map Approach

The emission rate data that must be collected to undertake an engine map approach are the instantaneous emission rates associated with specific engine RPM and engine load characteristics. Engine maps must be developed for individual engine models, and then assembled for the onroad vehicle fleet of engines in a multi-dimensional computer matrix. The engine map approach may help to solve the emission modeling problems associated with hot/cold starts if maps are developed under these conditions as well. The engine maps must represent the fleet, so a great deal of effort must be put into ensuring that the engine maps are consistent across vehicle models, model years, technology content, etc. Engine maps are likely to be dependent upon a number of additional factors that will also need to be controlled in sample selection. The first variable that comes to mind is the actual computer control chip that is employed to drive the air/fuel ratio and other combustion parameters.

Once engine maps are available for emission estimation, vehicle activity data need to be translated into engine map parameters (RPM and load). Translating vehicle activity into RPM and load does not appear to be a simple task. Parts lists and performance relationships must be developed for each model and model year that behaves differently. This task will not be accomplished easily, given the amount of information that must currently be known for each vehicle, but it can be undertaken. It may be that this modeling approach will stretch data needs too far and yield models that are too data intensive and unwieldy.

Data Requirements for Disaggregate Modal Modeling

In a modal modeling approach, emission rates would be developed as a function of modal activity (idle, constant speed cruise, acceleration, and deceleration). Emission testing data would be investigated to ascertain whether transient activities (e.g. specific speed, acceleration, and deceleration combinations) cause elevated emission rates. The average speed modeling regime could be eliminated in favor of a modal model that predicts

emissions on a second-by-second basis from vehicle activity traces. If, after detailed investigation of vehicle emissions data, analysts find that the average speed modeling techniques are valid for certain types of operations (e.g. perhaps for smooth traffic flow with relatively minor acceleration fluctuations) but invalid for other types of activity (e.g. high acceleration rates, acceleration/deceleration combinations, high speeds, or other high power operations), an average speed emissions modeling regime might be supplemented with emission factors for significant emission-producing modal activities.

Current activity monitoring efforts focus on the individual vehicle. The laser-equipped vehicle follows one target vehicle at a time through a given set of roadway and traffic conditions. Similarly, the instrumented vehicle approach, as currently implemented, follows the speed time trace of only one vehicle at a time on a roadway segment. The limited focus of the existing data collection efforts will not enable analysts to determine the variability of traffic flow on a roadway segment under specific congestion conditions. General roadway parameters such as average speed, traffic density, and flow rate, are empirically determined from average observations. The actual traffic flow that occurs under any roadway condition can be highly variable. Consider the slinky effect that is noted when vehicles approach congested areas. Individual driver response to instantaneous speeds, the gap between vehicles, relative acceleration and speed of proximal vehicles, lane width, etc., is highly variable. Hence, the modal patterns that occur are also highly variable.

There are a number of approaches that could be taken to better characterize the driving patterns that occur under congested conditions. First, instrumented vehicles could be dispatched as a subfleet along congested routes so that the differences in individual vehicle behavior among the mass could be discerned. Second, automatic vehicle identification systems (associated with automated toll collection systems such as currently used on the North Dallas tollway) could be implemented and speed/acceleration profiles could be monitored through a high density monitoring network along specific routes. Third, remote sensing or satellite technologies could be employed to physically monitor vehicle speed traces along congested routes. As discussed previously, once the speed traces are available for analysis, statistical analysis could be used to develop theoretical relationships for defining the speed profiles as a function of highway capacity manual concepts or to develop Monte Carlo techniques. This approach would also require assembly of link parameters that are found to significantly affect modal vehicle behavior.

INSTITUTIONAL BARRIERS TO DATA ACCESS AND COOPERATIVE RESEARCH

A lack of available data is a significant hindrance facing emission modelers today (although my evidence for this is anecdotal and based purely upon personal experience). In seeking data for my research, I encountered: 1) government agencies hesitant to release data that they considered to be in "preliminary draft" form; 2) private companies unwilling to release data that they considered to be proprietary (although some were willing to release their test result data of other manufacturers vehicles); 3) consultants unwilling to release data unless they were compensated (with the distinct exception of the Coordinating Research Council, which was very helpful); and 4) multiple parties, including academics, that were hesitant to release data from which they wanted to be the first to publish analytical results.

To resolve the data shortfall and develop rational solutions to current emission modeling problems, given that annual resource allocations in government and industry are limited, research must be pooled, staged, and prioritized (Long, 1993; Guensler, et al., 1992; Guensler and Geraghty, 1991). Most would argue that efficient sharing of data and findings will move us quickly toward modeling solutions that make sense. The majority of the working groups at the 1992 biennial summer meeting of the Transportation Research Board's Committee on Transportation and Air Quality indicated that broad-based research consortiums and a peer review process should be established on a nationwide basis to pursue research in the air quality arena (TRB, 1992). The primary goal of cooperative research is to provide access to knowledge and to encourage dialogue between experts, thereby improving our ability to make rational decisions regarding future transportation and air quality policies.

The development of a workable consortium process, focused on scientific understanding of the technical issues at hand is a key priority. The need for cooperative research is clear. Currently, none of the participants in the advocacy arena fully understand the depth and breadth of the complex issues, nor do they have access to all of the information necessary to optimize policy decisions. Hence, some advocates may push for regulations that are not completely rational or cost-effective, and other advocates may oppose regulations that would have been more rational and cost-effective than the final compromise solutions achieved in the regulatory arena.

It is easy for academics (who, in theory, have no financial stake in the outcome of research, only in performing the research) and government agencies (which face severe budgetary constraints that preclude comprehensive testing programs) to call for cooperation and pooling of funds in research efforts. The automotive and fuels industries are currently cooperating with each other on emissions research through the Coordinating Research Council and have released a variety of useful studies (CRC, 1989). However, private industry has yet to directly undertake cooperative emissions research with government agencies. Given that significant emission reductions must still be obtained from mobile sources, an efficiency argument can be made ... the additional costs of air pollution control that will be borne by the automotive and fuels industries and passed on to consumers will be lower on the average (and at the margin) if rational regulatory and policy decisions are made based upon the results of comprehensive and cooperative research, than if they are continually made in the inefficient, ad-hoc process that currently exists.

In the interim, while a consortium process is developed, data collection efforts funded by regulatory agencies should be organized and contracted in such a manner that all data are collected in standard formats and that these data are distributed electronically to any interested party free of charge. Of course, written descriptions of how the data were collected and what quality assurance and quality control procedures were employed should also be provided. To safeguard industry from overzealous publication of inaccurate analyses, a contractual peer review process could be established within the data dissemination framework. The ability to prepare detailed analyses in a timely fashion and to undertake adequate peer review of data collection and analyses depends upon the open dissemination of data and results.

CONCLUSIONS

The existing emission databases are insufficient to adequately characterize emissions from the vehicle fleet. There is a clear consensus in the research community that additional data are required for any emissions modeling approach, existing or future. New modeling approaches that are likely to improve emission modeling efforts have been proposed. Although, additional research will still be required to solve emission modeling problems associated with fleet characterization, hot/cold starts, evaporative emissions, interaction of emission model correction factors (except to the extent that correction factors can be eliminated), and spatial allocation of emissions.

The FTP improvement effort will clearly improve baseline exhaust emission rates, but will likely do little to reduce the uncertainty currently associated with employing the myriad of correction factors in the current modeling regime. The 25-bin approach is probably the most likely approach to gain a short-term as well as long-term benefit. The development of multiple driving cycles will better characterize onroad emissions and can remove the problematic speed correction algorithms from the models. The 25-bin approach can be implemented in concert with a second-by-second emission testing program, and long-term modal emission models can be developed based upon the data collected during the 25-bin modeling effort. The engine map and modal emission modeling approaches are clearly long-term efforts that will be very data and analysis intensive, and both programs should be vigorously and continuously investigated. Major emission testing programs need to be undertaken (at substantial cost) if we are to properly characterize emissions from the fleet.

As with emission modeling, major vehicle activity testing and model development programs need to be undertaken (at substantial cost) if we are to properly characterize emissions from the vehicle fleet. It is important to note that new approaches for modeling emission rates must be developed in concert with new vehicle activity models. Activity-specific emission rates must be coupled with their parent activities. Once significant emission-producing activities are identified, we must undertake efforts to model and quantify these activities (Guensler, et al., 1992). The efforts must be parallel, so that models yield compatible output. During the research efforts, conclusions can be drawn as to whether a single modeling solution can be developed for regional emission inventory analysis, project-level emission impact analysis, regulatory policy analysis, etc., or whether modeling limitations and conditions of model application require more than one modeling approach. The problems are complex. Logical approaches to model development must include multi-disciplinary education of analysts, increased communication between the emission and activity modeling disciplines, and open exchange of data and research findings.

APPENDIX II. ACKNOWLEDGMENTS

I would like to thank the following individuals for their constructive comments on the draft version of this paper: Paul Benson (Caltrans), James Markey, Ted Ripberger, Terry Newell, and Gene Lin (USEPA), Jeff Long and Larry Larsen (CARB), William Loudon (jhk & Associates), John Suhrbier (Cambridge Systematics), Dan Sperling and Simon Washington (Institute of Transportation Studies, UC Davis), Mark Ross (Lawrence Livermore Laboratory), Charles Crevo, Ph.D. (Vanasse Hangen Brustlin, Inc.), Bradley Keazer and Gary Hamby (USDOT), and Amulakh Parikh (New Jersey DOT).

APPENDIX II. REFERENCES

Ashbaugh, Lowell L., Douglas R. Lawson, Gary A. Bishop, Paul L. Guenther, Donald H. Stedman, Donald R. Stephenson, Peter J. Groblicki, Jayendra S. Parikh, Brian R. Johnson, and Steve C. Huang (1992); On-Road Remote Sensing of Carbon Monoxide and Hydrocarbon Emissions During Several Vehicle Operating Conditions; Draft Paper Prepared for Publication in the Journal of the Air and Waste Management Association; 1992.

Atkins, Stephen T. (1986); Transportation Planning Models - What the Papers Say; Traffic Engineering + Control; September 1986.

Austin, Thomas C., Thomas R. Carlson, Francis J. DiGenova, John M. Lee, and Mark Carlock (1992); An Analysis of Driving Patterns in Los Angeles During 1992; A Paper Presented at the Third Annual CRC-APRAC On Road Vehicle Emissions Workshop; Coordinating Research Council; Atlanta, GA; September 1992.

Barth, Matthew, and Joseph Norbeck (1991); The Development of an Enhanced Transportation Model using Dynamic Vehicle Emissions Data to Predict Mobile Source Emissions; University of California, Riverside; College of Engineering; Riverside, CA; December 1991.

Benson, Paul (1989); CALINE4 - A Dispersion Model for Predicting Pollutant Concentrations Near Roadways (FHWA/CA/TL-84/15); State of California Department of Transportation, Division of New Technology and Research; Sacramento, CA; November 1984, Revised June 1989.

Benson, Paul (1992); Data Requirements for Micro-Scale Modeling of Mobile Sources; Transportation Modeling Tips and Trip-Ups Proceedings, an Air and Waste Management Association Specialty Conference; Pittsburgh, PA; March 1992.

Bruckman, Leonard, Edmund L. Dickson, and Paula K. Brooks (1991); Description of a New Motor Vehicle Emissions Model (MoVEM); Emission Inventory Issues in the 1990's Proceedings, an Air and Waste Management Association Specialty Conference; Pittsburgh, PA; September 1991.

Bruckman, Leonard and Edmund L. Dickson (1992); Case Study - South Coast On-Road Motor Vehicle Emission Inventory Process; Transportation Modeling Tips and Trip-Ups Proceedings, an Air and Waste Management Association Specialty Conference; Pittsburgh, PA; March 1992.

Bruckman, Leonard and Edmund L. Dickson (1993); Preparation of Transportation Data for Use in Emissions Models (930333); A Paper Presented at the 72nd Annual Meeting of the Transportation Research Board; Washington, D.C.; January 1993.

Calspan Corporation (1973a); A Study of Emissions from Light-Duty Vehicles in Six Cities; Buffalo, NY; Prepared for the Environmental Protection Agency (Document #APTD-1497), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; March 1973.

Calspan Corporation (1973b); Automobile Exhaust Emission Surveillance (PB-220 775); Buffalo, NY; Prepared for the Environmental Protection Agency (Document #APTD-1544), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; May 1973.

CARB (1990), California Air Resources Board; Emission Inventory 1987; Technical Support Division; Sacramento, CA; March 1990.

CARB (1991), California Air Resources Board; Modal Acceleration Testing; Mailout No. 91-12; Mobile Source Division; El Monte, CA; March 20, 1991.

CARB (1992), California Air Resources Board; Methodology to Calculate Emission Factors for On-Road Motor Vehicles; Technical Support Division; Sacramento, CA; 1992.

Carlock, Mark (1992); Overview of Exhaust Emission Factor Models; In: Proceedings, Transportation Modeling: Tips and Trip Ups; Air and Waste Management Association; Pittsburgh, PA; March 1992.

Darlington, Thomas L., Patricia E Korsog, and Robert Strassburger (1992); Real World and Engine Operation: Results of the MVMA/AIAM Instrumented Vehicle Pilot Study; Proceedings of the 85th Annual Meeting of the Air and Waste Management Association; AWMA; Pittsburgh, PA; June 1992.

DeLuchi, Mark, Quanlu Wang, and David L. Greene (1992); Motor Vehicle Fuel Economy, the Forgotten HC Control Strategy? (ORNL-6715); Oak Ridge National Laboratory; Oak Ridge, TN; June 1992.

DiGenova, Frank (1992); Use of a Chase Car to Characterize Driving Patterns; Transportation Modeling Tips and Trip-Ups Proceedings, an Air and Waste Management Association Specialty Conference; Pittsburgh, PA; March 1992.

FHWA (1990), Federal Highway Administration; Calibration and Adjustment of System Planning Models (FHWA-ED-90-015); Washington, D.C.; December 1990

Gertler, Alan W. and William R. Pierson (1991); Motor Vehicle Emissions Modeling Issues (91-88.8); Air and Waste Management Association, 84th Annual Meeting Proceedings; Pittsburgh, PA; June 1991.

Groblicki, Peter J. (1990); Presentation at the California Air Resources Board Public Meeting on the Emission Inventory Process; General Motors Research Laboratories; Warren, MI; November 5, 1990.

Guensler, Randall, and Anne B. Geraghty (1991); A Transportation/Air Quality Research Agenda for the 1990's (91-87.2); Air and Waste Management Association, 84th Annual Meeting Proceedings; Pittsburgh, PA; June 1991.

Guensler, Randall, Daniel Sperling, and Paul P. Jovanis (1991); Uncertainty in the Emission Inventory for Heavy-Duty Diesel-Powered Trucks (UCD-ITS-RR-91-02); Institute of Transportation Studies; University of California, Davis; Davis, CA; May 24, 1991.

Guensler, Randall, Daniel Sperling, and Paul P. Jovanis (1992); A Research Plan Designed to Reduce Uncertainty in the Emission Inventory for Heavy-Duty Diesel-Powered Trucks (UCD-ITS-RR-92-01); Institute of Transportation Studies; University of California, Davis; Davis, CA; January, 1992.

Guensler, Randall (1993); Vehicle Emission Rates and Average Vehicle Operating Speeds; Dissertation; submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Civil/Transportation Engineering; Department of Civil Engineering, University of California, Davis; Davis, CA; Forthcoming in September 1993.

Guensler, Randall, Simon Washington and Daniel Sperling (1993); A Weighted Disaggregate Approach to Modeling Speed Correction Factors (UCD-ITS-RR-93-6); Institute of Transportation Studies; University of California, Davis; Davis, CA; April 1993.

Harvey, Greig (1993); Manual of MPO Modeling Practice; National Association of Regional Councils; Washington, D.C.; 1993.

Heywood, John B. (1988); Internal Combustion Engine Fundamentals; McGraw-Hill Publishing Company; New York, NY; 1988.

Ingalls, Melvin N., Lawrence R. Smith, and Raymond E. Kirksey (1989); Measurement of On-Road Vehicle Emission Factors in the California South Coast Air Basin; Southwest Research Institute; San Antonio, TX; June 1989.

Ismart, Dane; Travel Demand Forecasting Limitations for Evaluating TCMs (1991); A Paper Presented at the 84th Annual Meeting of the Air and Waste Management Association; copies available from author at the Federal Highway Administration; Washington, D.C.; June 1991.

Jacobs, Paul, Donald J. Churnich, and Mark A. Burnitzki (1990); Motor Vehicle Emissions and their Controls; California Air Resources Board; Sacramento, CA; July, 1990.

jhk & Associates and Dowling Associates, Travel Forecasting Guidelines; Prepared for the California Department of Transportation (RFP 60Q951); Sacramento, CA; June 1992.

Joy, Richard W. (1992); Drive Thru Windows - A Case Study; Proceedings of the Transportation Modeling Tips and Trip-Ups Conference; Air and Waste Management Association; Pittsburgh, PA; March 11-12, 1992.

Kunselman, P., H.T. McAdams, C.J. Domke, and M.E. Williams (1974); Automobile Exhaust Emission Modal Analysis Model; Calspan Corporation; Buffalo, NY; Prepared for the Environmental Protection Agency (Document 460/3-74-005), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; January 1974.

Larsen, Larry, and Michael Baker (1993); Personal Communication; California Air Resources Board; Sacramento, CA; March, 1993.

Larsen, Larry (1993); Personal Communication; California Air Resources Board; Sacramento, CA; July, 1993.

Lawson, Douglas R., Peter J. Groblicki, Donald H. Stedman, Gary A. Bishop, and Paul R. Guenther (1990); Emissions from In-Use Vehicles in Los Angeles: A Pilot Study of Remote Sensing and the Inspection and Maintenance Program; Journal of the Air and Waste Management Association; Volume 40, Number 8; pp. 1096-1105; Pittsburgh, PA; August 1990.

Long, Jeff (1993); California Air Resources Board; Mobile Source Division; El Monte, CA; Correspondence to Randall Guensler (regarding the draft version of this paper); June 30, 1993.

Long, Jeff (1992); Personal Communication; California Air Resources Board; Mobile Source Division; El Monte, CA; April 1992.

Loudon, William (1993); jhk & Associates; Emeryville, CA; Correspondence to Randall Guensler (regarding the draft version of this paper); July 1, 1993.

Markey, James (1993); U.S. Environmental Protection Agency; Ann Arbor, MI; Correspondence to Randall Guensler (regarding the draft version of this paper); July 20, 1993.

National Research Council (1991); Rethinking the Ozone Problem in Urban and Regional Air Pollution; National Academy Press; Washington, D.C.; 1991.

Newell, Terry P. (1991); Emissions Planning and Strategies Division, Office of Mobile Sources, United States Environmental Protection Agency; Memorandum to Charles Gray, Jr., Director, USEPA Emission Control Technology Division; June August 22, 1991.

Newell, Terry P. (1993); Emissions Planning and Strategies Division, Office of Mobile Sources, United States Environmental Protection Agency; Ann Arbor, MI; Correspondence to Randall Guensler (regarding the draft version of this paper); June 9, 1993.

Pollack, Alison, Jeremy G. Heiken, and Robert A. Gorse (1992); Comparison of Remote Sensing Data and Vehicle Emission Models: The High Proportion of Emissions from High Emitting Vehicles; Proceedings of the 85th Annual Meeting of the Air and Waste Management Association; Pittsburgh, PA; June 1992.

Pozniak, Donald J. (1980); The Exhaust Emission and Fuel Characteristics of an Engine During Warmup A Vehicle Study (800396); Society of Automotive Engineers; Warrendale, PA; February 1980.

Purvis, Charles (1992); Sensitivity of Transportation Model Results to Uncertainty in Input Data; Transportation Modeling Tips and Trip-Ups Proceedings, an Air and Waste Management Association Specialty Conference; Pittsburgh, PA; March 1992.

Quint, Malcolm M., William R. Loudon, and Dennis Wade (1993); Transportation Activity Modeling for the San Joaquin Valley Emission Inventory (93-RP-149.04); Proceedings of the 86th Annual Meeting of the Air and Waste Management Association; Pittsburgh, PA; June 1993.

Ripberger, Carl T. (1993); Personal Communication; JEIOG Highway Vehicle Coordinator; Air and Energy Engineering Research Laboratory; USEPA; Research Triangle Park, NC; March 1993.

Ross, Marc (1993); Physics Department, University of Michigan; Ann Arbor, MI; Correspondence to Randall Guensler (regarding the draft version of this paper); July 9, 1993.

Seitz, Leonard E. (1989); California Methods for Estimating Air Pollutant Emissions from California Motor Vehicles (89-7.4); Proceedings of the 82nd Annual Meeting of the Air and Waste Management Association; Pittsburgh, PA; June 1989.

Stone, C.R., A.J. Sorrell, T.W. Biddulph, and R.A. Marshall (1990); Analysis of Spark-Ignition Engine Performance after Cold Start, with Thermal and Cyclic Measurements; Proceedings of the International Conference on Automotive Power Systems Environment and Conservation; Mechanical Engineering Publications, Ltd.; Suffolk, England; September 1990.

Suhrbier, John (1993); Cambridge Systematics; Cambridge, MA; Correspondence to Randall Guensler (regarding the draft version of this paper); June 28, 1993.

Systems Applications International (1991); Assessment of Computer Models for Estimating Vehicle Emission Factors, Volume III: Sensitivity Analyses of the MOBILE4 and EMFAC7E Emission Models (SYSAPP-91/091c); San Rafael, CA; July 1991.

Taylor, Charles F (1985); The Internal Combustion Engine in Theory and Practice, Volume 1; MIT Press; Cambridge, MA; 1985.

TRB (1985), Transportation Research Board; Highway Capacity Manual (Special Report 209); Washington, D.C.; 1985.

TRB (1992), Transportation Research Board; Environmental Research Needs in Transportation; Transportation Research Circular, Number 389; Washington, D.C.; March 1992.

USEPA (1988), US Environmental Protection Agency; MOBILE4 Workshop Materials; Office of Mobile Sources; Ann Arbor, MI; November 30, 1988.

USEPA (1992), U.S. Environmental Protection Agency; Highway Vehicle Emission Estimates; Office of Mobile Sources; June 1992.

USEPA (1993a), U.S. Environmental Protection Agency; Review of the Federal Test Procedure Modification Status Report; Office of Mobile Sources, Certification Division; Ann Arbor, MI; February 11, 1993.

USEPA (1993b), U.S. Environmental Protection Agency; Materials from the FTP Review Project Public Workshop; Office of Mobile Sources, Certification Division; Ann Arbor, MI; April 5, 1993.

USEPA (1993c), U.S. Environmental Protection Agency; Federal Test Procedure Review Project: Preliminary Technical Report (EPA-420-R-93-007); Office of Air and Radiation; Washington, DC; May 1993.

Washington, Simon, Randall Guensler, and Daniel Sperling (1993); Air Quality Impacts of Intelligent Vehicle Highway Systems; Proceedings: Transportation Planning and Air Quality II; American Society of Civil Engineers; New York, NY; Forthcoming in September 1993.

Wilson, James H., and Carl T. Ripberger (1991); Proceedings of Two Highway Vehicle Emissions Workshops; Air and Waste Management Association, 84th Annual Meeting Proceedings; Pittsburgh, PA; June 1991.

Zub, Russell W. (1981); A Computer Program (VEHSIM) for Vehicle Fuel Economy and Performance Simulation (Automobiles and Light Trucks); US Department of Transportation, National Highway Traffic Safety Administration; Washington, D.C.; October 1981.