

APPLICATIONS OF MODAL EMISSION RATE MODELS IN TRANSPORTATION INFRASTRUCTURE DECISION MAKING

Randall Guensler, Ph.D., Georgia Institute of Technology, USA
Karen Dixon, Ph.D., Georgia Institute of Technology, USA
Matt Thornton, Ph.D., Georgia Institute of Technology, USA
Shauna Hallmark, Ph.D., Iowa State University, USA
William Bachman, Ph.D., Georgia Institute of Technology, USA

Abstract

In recent years, research has demonstrated that real-world vehicle emissions under typical onroad operating conditions can differ significantly from the emissions observed in the laboratory under standard test procedures. The occurrence of enrichment, when the air/fuel mixture becomes momentarily rich, results in orders of magnitude increases in CO and HC emissions rates for short periods. This paper presents a preliminary assessment of emission impacts from signal timing and ramp metering strategies evaluated in Atlanta. The analyses employ the average speed relationships in the current US EPA emission rate model (MOBILE5a) and the enhanced modal emissions relationships in the Georgia Tech model. Researchers conclude that the decision making process for air quality planning, infrastructure design, and traffic operations can benefit significantly from enhanced modal emission rate models.

Résumé

Les recherches menées dans les dernières années ont montré que les émissions des véhicules en circulation réelle et en conditions d'exploitation normales pouvaient différer sensiblement des émissions observées en laboratoire selon les protocoles expérimentaux standards. La présence de courtes périodes où le mélange air/carburant est considérablement enrichi conduit en particulier à une augmentation temporaire considérable des émissions de CO et HC. Cet article présente une première évaluation de l'impact de stratégies, testées à Atlanta, de réglages de feux et de contrôle d'accès sur voies rapides. Les analyses sont fondées d'une part sur un modèle d'émission classique aux États-Unis utilisant la vitesse moyenne (MOBILE5a) et d'autre part sur les équations d'émission modales avancées intégrées au modèle de Georgia Tech. Les conclusions montrent que les processus de décision en matière de qualité de l'air, de schémas d'infrastructure et d'exploitation du trafic pourraient tirer un bénéfice substantiel de l'utilisation de modèles d'émission avancés.

Keywords : Vehicle Emissions, Modal Emissions Modeling, Ramp Metering, Signal Timing, Traffic Flow

INTRODUCTION

The traffic flow and travel time benefits of ramp metering and signal timing improvements are well documented in the literature (Meyer, 1997; Piotrowicz and Robinson, 1995); Strong, 1984; Deakin et al., 1986), but the air quality benefits are not. The emissions impacts traffic flow smoothing activities have only been examined with conventional tools and modal emissions impacts are largely unexplored. This is an important question in light of the current urban air quality and traffic congestion problems and the fact the many cities are turning to traffic control measures to offset overall vehicle emissions (Guenster, 1998).

Kelly and Groblicki (1993) first reported indications that enrichment conditions were likely to be causing a significant portion of vehicle emissions not captured during standard laboratory tests. Carbon monoxide emission rates (grams/second) under enrichment conditions for the very cleanest of vehicles can soar as high as 2500 times the emission rate noted for stoichiometric conditions. "Although most vehicles spend less than 2% of their total driving time in severe enrichment, this can account for up to 40% of the total CO emissions (LeBlanc, et al., 1995)." Hydrocarbon emission rates can also rise by as much as a factor of 100 under enrichment conditions. Enrichment activity is usually associated with high power demand and engine load conditions, such as high-speed activity, hard accelerations, or moderate accelerations under moderate to high speeds. However, enrichment also occurs during hard deceleration events when the throttle plate snaps shut. The rapid decrease in intake manifold pressure vaporizes liquid fuel deposits causing the fuel mixture to become rich.

When enrichment episodes occur in the real world, but not in the laboratory under federal certification tests, real-world emissions are significantly higher than predicted. Similarly, if the causal relationships are improperly reflected in emission rate models, emission impacts associated with changes in transportation infrastructure design and operation will be poorly predicted. The USEPA model approved for use in the United States currently employs average vehicle operating speed as the sole variable for predicting the increased emissions that are typically associated with higher engine loads at higher average speeds. While the relationships in the model may be acceptable for predicting regional emissions, the relationships do not work well for predicting emissions from real-world activity on individual corridors.

For the past five years, the Georgia Tech Research Partnership has been developing a research-grade motor vehicle emissions model within a geographic information system (GIS) framework. The Georgia Tech model currently predicts emissions as a function of vehicle operating mode (including cruise, acceleration, deceleration, idle, and the power demand conditions that lead to enrichment). The model employs specific vehicle characteristics (model year, engine size, etc.) and speed/acceleration profiles in predicting emissions from the onroad operating modes. The USEPA MOBILE5b and MEASURE emission rate models were both developed from the same basic laboratory testing data (Fornumung, et al., 1999; Guenster, et al., 1998), but MEASURE developers employed significantly different analytical techniques and model functional forms. The models yield significant differences in predicted emissions for the strategies evaluated.

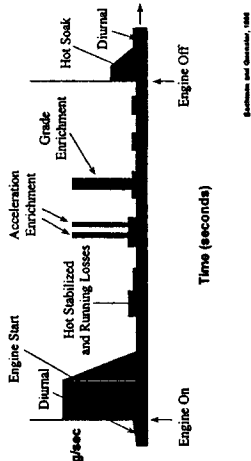
MODAL EMISSIONS MODELING

Engine-out emissions (into the exhaust manifold) and catalyst-out emissions (as emissions exit the tailpipe, after engine-out emissions have crossed the catalyst) are low and consistent when vehicles are operating under stable conditions. Modal emissions models predict emissions as a

function of the micro-cycle activities that tend to put vehicles into enrichment or leanment conditions. Figure 1 illustrates the hydrocarbon emissions from a hypothetical trip. Engine emissions are elevated during engine and catalyst warm-up and high again under specific onroad activities that lead to elevated emissions rates (such as hard acceleration or operation on grades).

Figure 1 - Hydrocarbon Emissions Rates from a Hypothetical Trip

Hydrocarbon Emission Rates for a Hypothetical Trip



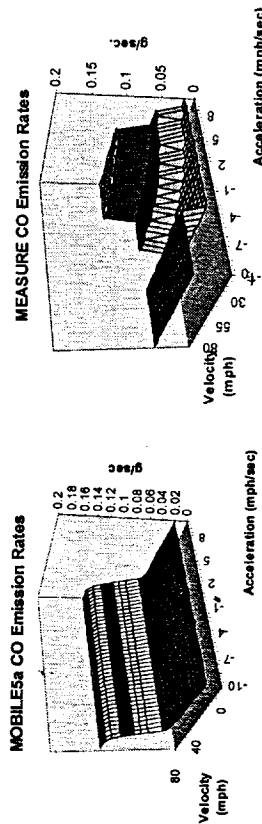
Conventional emission rate models predict emissions as a function of average speed. Because laboratory emissions testing cycles with higher average speeds also exhibit more frequent engine load conditions that elevate emission rates, such models predict higher g/second emissions at higher speeds. These models are highly dependent upon the aggregate characteristics of the cycles employed and previous studies have shown that the confidence bounds for such models are very large. When applied to onroad vehicle operations, the assumption is that the emissions are independent of the onroad acceleration characteristics (that is, that the average speed methods account for appropriate acceleration conditions in the test cycles).

The importance of modal emissions models comes in their application to traffic calming and flow smoothing scenarios. The emissions impact of traffic flow smoothing strategies have been difficult to estimate because the modeling regimes used to estimate vehicle emissions are not suited for the analysis of small scale traffic improvements. The USEPA's MOBILE emissions rate models are not sensitive to high-load activity encountered when vehicles accelerate from an intersection or ramp meter stop line. Such activities were never incorporated into laboratory testing nor explicitly accounted for in data analysis. Emerging disaggregate modal modeling regimes, such as the MEASURE modeling framework and UC Riverside's models (Barth et al., 1999) provide a basis for providing more accurate emissions estimate for ramp metering systems

Figure 2a illustrates the MOBILE5a average speed relations as independent of local acceleration conditions. However, the onroad acceleration and engine load conditions on an uncongested urban arterial are significantly different from the conditions on a forced flow freeway operating at the same average speed. Modal models are designed to differentiate between these two conditions and predict significant differences in onroad emissions as a function of the percentage of hard acceleration and other load-inducing activity in modal emissions models. The aggregate modal model employed within the MEASURE framework predicts emissions as a function of the fraction of high engine-load activity experienced by a vehicle. The model is based upon the

same data used to develop average speed models, but includes explanatory variables associated with power demand surrogates (Fonunung, et al., 1999) such as an the IPS inertial power surrogate (speed x acceleration). Figure 2b illustrates a generalized relationship between cycle speed and acceleration conditions employed in the MEASURE aggregate modal model.

Even more advanced modal algorithms, based upon analysis of second-by second data from instrumented vehicles and laboratory tests on modal cycles, predict emissions as a function of real-time driving cycle undertaken by modern vehicles (Barth, et al., 1999). This next generation of modal models also predicts the effects of modal transitions, such as the emissions burst that occurs for some vehicles when a hard deceleration follows a hard acceleration. These models can link to second-by-second vehicle trajectories rather than just the speed/acceleration profiles.



Figures 2a and 2b: Differences in CO Emissions Predictions Between an Average Speed and Aggregate Modal Model for one Vehicle Technology Group

SIGNALIZED INTERSECTIONS

Metropolitan areas in non-attainment for transportation-related air pollutants have relied on aggregate speed-based emission rate models to reduce emissions and meet clean air goals. Under this methodology, only emission reduction strategies, which either increase or decrease average vehicle speeds to ranges where emissions are lower, show reductions in air pollutant output. In recent years, transportation-related air quality analysis has shifted to a modal modeling approach which links emissions rates to specific vehicle operating modes. Certain ranges of activity (such as hard accelerations, high speeds, and decelerations), have the potential to yield elevated emissions (St. Denis & Winer, 1994; LeBlanc, et al 1995; Guensler, 1993; Cicero-Fernandez and Long, 1994; Yu, 1998; An et al, 1998). Hence, modal emission rate models allow the evaluation of the emission reduction potential of transportation strategies in terms of their ability to decrease fractions of total vehicle activity spent in these high-emitting operating modes.

Signal timing improvements are viable emission reduction activities since their implementation may lead to less interrupted traffic flow, decreased number of stops, and decreased idling time. During the energy crisis of the 1970's, improved signal timing proved to be effective and was widely used to decrease fuel consumption (Strong, 1984; Deakin et al, 1986; Cambridge Systematics, 1986). However, the ability of signal timing improvements to decrease emissions has not been as widely documented. Using a traditional emission rate modeling approach,

timing plans that significantly decrease stops and idling may only exhibit modest changes in average speed. Consequently, when coupled with emission rate models based on aggregate speeds, the benefits of improved signal timing may not be shown to be significant or cost effective.

Of particular interest in modal emission estimation is the engine load that vehicles experience as a function of deceleration at a red light and subsequent acceleration to cruise speed. As might be expected, the engine load for vehicles at the front of the traffic queue are significantly higher than those in the fourth and later queue positions and those that are able to cruise through the intersection without stopping. Figure 3 provides three measures of engine load (acceleration activity greater than 4.8 mph/sec, an inertial power surrogate (speed x acceleration), and accelerations greater than 9.7 mph/sec).

The use of a modal modeling approach shows more promise in identifying the emission reduction potential of signal timing improvements. With this method, specific ranges of vehicle activity associated with elevated emission production were identified and timing plan improvements were evaluated on their ability to reduce the time vehicles spend in those modes. With this methodology, signal timing improvements are expected to show much more promise in decreasing emissions as signalized intersections are characterized by a large proportion of activity in the high acceleration and deceleration ranges.

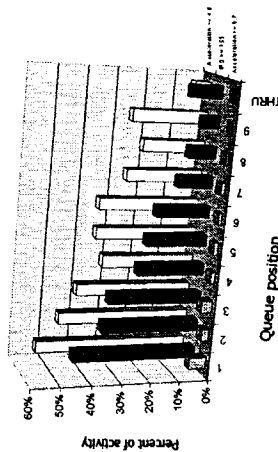


Figure 3: Percent of High-Load Activity by Intersection Queue Position

To demonstrate the potential emission reduction benefits of a modal approach for evaluation of signal timing improvements, Hallmark et al. (2000) describe comparison of a coordinated and uncoordinated timing plan for a study intersection. Hallmark developed and simulated two timing plans using the CORSIM simulation model to determine queue lengths and volumes. Field data were used to develop a distribution of second-by-second speed/acceleration profiles for individual vehicle traces, which determined fractions of activity spent in relevant emission-related operating modes. Hallmark, et al. (2000) provides a more detailed description of the field data studies. Both the EPA's aggregate speed model, MOBILE5a, and Georgia Tech's modal emission rate model MEASURE were used to evaluate the two timing plans. Carbon monoxide emissions were estimated using the technology group mix from the regional vehicle fleet for the Atlanta, Georgia area. Table 1 presents statistics for the coordinated versus uncoordinated plans. As shown, the percent of activity at the intersection where accelerations were ≥ 6 mph/s and \geq

3 mph/s were reduced roughly by half for the coordinated plan, yet the average speed only increased by 8 mph. The coordinated plan resulted in a substantial savings of 449 g/hour of CO using the MEASURE emission factors while a savings of only 138 grams per hour resulted from the improved coordination using MOBILE5a. Additionally, MEASURE overall predicted much higher emissions than MOBILE5a.

Table 1: Impacts of Coordinated Versus Uncoordinated Intersection Timing Plans on CO Emissions

Timing Plan	Average Speed (mph)	Activity >= 6 mph/s	Activity >= 3 mph/s	MEASURE CO Emissions, Peak Hour (g)	MOBILE5a CO Emissions, Peak Hour (g)
Uncoordinated	29	0.7%	11.4%	5,130	2,016
Coordinated	37	0.4%	5.4%	4,680	1,878
Change from Coordination	-8	0.3%	6.0%	449	138

A companion study compared the effects of different timing plan improvements. The timing plans for two intersections in Atlanta, Georgia were optimized using TRANSYT7F. Cycle length, splits, and phases were optimized and then simulated using CORSIM coupled with field data estimates as described above. Comparisons of intersection statistics for the unimproved and improved signal timing plans are provided in Table 2. Included in the table are total seconds of vehicle activity spent in those activity ranges where the MEASURE model indicated statistically relevant breakpoints for emission production potential.

Table 2: Improved Versus Unimproved Intersection Timing Plans

Intersection	Total Seconds of Activity for Intersection				Seconds of Delay per Vehicle	% Stops	Total Intersection Volume (vph)	Average Intersection Speed (mph)
	<= -2 mph/s	>= 3 mph/s	>= 6 mph/s	Idle				
Spring & 16 th Unimproved	12226	7131	469	56833	23	60	2411	14
Spring & 16 th Improved	9721	5676	476	22846	6	35	2411	21
Pleasant Hill & Satellite Unimproved	26358	15396	988	172027	78	99	3786	11
Pleasant Hill & Satellite Improved	23878	13513	1014	87335	21	67	3786	17

The average speed for Spring and 16th only increased by 7 mph, yet the number of hard decelerations decreased by 20%, hard accelerations decreased by 22%, total time spent idling decreased by 60%, and the percent of vehicles stopped by signalization decreased from 60% to only 35%. For Pleasant Hill and Satellite, average speeds only increased by 6 mph while hard decelerations decreased by 9%, hard accelerations decreased by 12%, and percent vehicles stopped by the traffic signals also dropped by 32%. Time spent idling also dropped by 49%.

Modal modeling better illustrates the emission reduction potential of timing improvements. With an average speed model, only modest increases in average speeds resulted, although a significant change in extremes in emission-producing modal activity occurred.

RAMP METERS

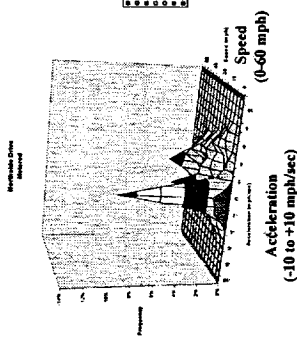
In a 1999 study of a continuous ramp-metered segment of Atlanta freeway, laser rangefinders (LRFs) captured the speed-acceleration profile of vehicles operating on on-ramps and mainline segments. The LRFs are set on tripods along the on-ramps and overpasses to record vehicle activity from the point of entry onto the on-ramp until merging with freeway traffic. Modal activity data for freeway traffic along merge areas, weave areas, and basic freeway sections were captured by locating LRFs from each overpass. The LRFs provide a measurement accuracy of 0.5 foot with a precision of 0.1 foot, sampling a vehicle's location at a rate of 238 times per second. Second-by-second vehicle trajectories were derived from these distance measurements. Probe vehicles equipped with distance measuring instruments (DMIs) collected supplemental data in areas where LRFs could not be employed (curved weaving sections and mainline areas between overpasses). Nu-Metrics NS-60 DMIs were used to record second-by-second vehicle distance, speed, and acceleration data when chasing onroad vehicles (500+ probe runs).

The core of this research is to verify if the "hard" accelerations and power demand operations at the on-ramp may significantly reduce the emissions benefit received by "smoothing" traffic along the mainline freeway section. Therefore, the focus of the LRF data collection effort was to record information as vehicles accelerate from the stop bar down the ramp to the merge area. For this reason, the data collection procedures and analyses separated vehicle on-ramp activity into two zones (a deceleration zone before the stop bar and acceleration zone after the stop bar).

Emissions analyses were conducted at two levels (ramp-related emissions rates and mass emissions under various operating and ramp metering conditions, and mainline emissions rates and mass emissions). This is important because the expected influences of metered flows can also impact mainline operating profiles (and change travel demand) resulting in different mass emissions levels. Changes in average speeds will also result in different mass emission levels even if the gram/second emissions rates remain the same because slower travel speeds yield longer travel times to traverse the segment.

Changes in traffic flow conditions were documented under metered and non-metered conditions for 14 days of ramp operation and 4 days of non-operation. Changes in speed acceleration profiles under these different conditions were summarized in Watson plots (see Figure 4) illustrating the joint probability distribution of speed and acceleration activity for use in average speed and modal modeling processes.

Ramp Meters On



Ramp Meters Off

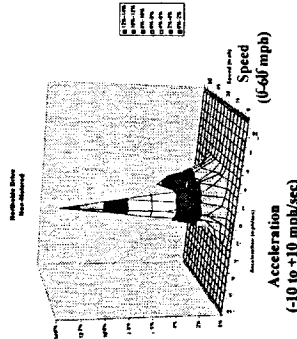


Figure 4: Northside Drive Metered versus Non-Metered Ramp Operating Profile

Emissions estimates from the USEPA MOBILE5b model were estimated and compared with the estimates from MEASURE. The MOBILE models area intended for application to vehicles in the aggregate over the course of a complete trip. This is one of the fundamental problems with using the MOBILE model for evaluating transportation improvements impacting only a portion of a trip. This notwithstanding, every effort was made to use the highest level of aggregation and averaging to produce the most appropriate estimates from MOBILE5b.

Statistically significant changes in onroad operating conditions resulted from the implementation of the ramp meters. As illustrated in Table 3, significant changes in average travel speeds and acceleration rates, as well as fractions of harder acceleration and deceleration occurred. The fraction of activity above a specific inertial power surrogate employed in the model also increased significantly. Table 4 illustrates emission rate changes, due to the changes in modal operations, for the modern Atlanta fleet operating along this ramp-metered corridor.

Although the ramp-related g/second emission rates under metered conditions decrease by 30% to 44% at the four ramps, the vehicle time spent in each metered zone also increases under metered conditions. Hence, the total onramp related NOx emissions under metered conditions decrease by only 14%. Note, however, that the improved traffic flow on the mainline results in a predicted increase in mainline emission rate by approximately 3%. Because onramp traffic volume is low, the emissions from the ramps are two orders of magnitude lower than the emissions from the mainline. Hence, the net emissions impact of the system change is almost exclusively experienced on the mainline segment. The NOx emissions reduction associated with onramp operation is completely overwhelmed by the increase in mainline emissions. The net increase in system NOx emissions along this corridor from ramp metering is approximately 4%.

Table 3: t-Test Results for Significance in Observed Differences in Modal Activity Changes for the Moores Mill Road On-Ramp

Modal Activity Variable	Metered Mean	Non-Metered Mean	t-Statistic	Critical t-Value (.05)	t-statistic Probability
Average Speed (mph)	34	45	21.48	1.98	.0000
Average Acceleration (mph/sec)	2.6	1.4	16.45	1.97	.0000
Percent of Cycle Acceleration > 3 (mph/sec)	16	3.0	16.765	1.97	.0000
Percent of Cycle with Accel. > 6 (mph/sec)	2.6	0.2	4.60	1.98	.0000
Percent of Cycle with Decel. > 2 (mph/sec)	5.2	8.4	4.39	1.98	.0000
Percent of Cycle with IPS > 90 (mph ² /sec)	10.5	5.9	5.21	1.98	.0000
Percent of Cycle with IPS > 120 (mph ² /sec)	5.1	3.0	3.03	1.97	.0028

Table 4: MEASURE Emissions Rates and Predicted Peak Period NOx Emissions

Location	NOx Emissions Rates (g/sec)		NOx Emissions Rates (g/sec)		Percent Change		Peak Period NOx Emissions (grams)		Peak Period NOx Emissions (grams)		Percent Change	
	Non-Metered	Metered	Non-Metered	Metered	Non-Metered	Metered	Non-Metered	Metered	Non-Metered	Metered	Non-Metered	Metered
Northside Drive	.01341	.00931	.01341	.00931	-31%	680	664	-2%				
Howell Mill Road	.01906	.01065	.01906	.01065	-44%	533	420	-21%				
Moores Mill Road	.01776	.01044	.01776	.01044	-41%	489	379	-22%				
West Paces Ferry	.01566	.01068	.01566	.01068	-32%	327	288	-12%				
All Ramps						2,029	1,751	-14%				
Mainline	.05642	.05839	.05642	.05839	3%	261,614	272,517	4%				

Figure 5a illustrates the differences in estimated mass emissions predicted by the MOBILE5b and MEASURE modal algorithms for the onramp locations under metered and non-metered conditions. This figure illustrates that while both models predict lower NOx emissions on the ramps associated with the observed metered ramp conditions versus the observed non-metered conditions, the MEASURE model predicts a significantly larger decrease in NOx. Given that the models were derived from the same basic data, the larger difference is attributed to the difference in the statistical methods used to develop the models. However, recent laboratory testing results in California (Sierra Research, 1997) indicate that modal emissions under ramp-cycle testing conditions may be higher than non-metered conditions (if the ramp cycles are representative of onroad operations). Hence, there is a discrepancy between the reported laboratory predictions and both the MOBILE5b and the MEASURE predictions. This discrepancy is currently being investigated to determine whether: 1) the ramp cycles observed in Atlanta differ significantly from those in the Sierra work, 2) the data from the four laboratory vehicles tested are sufficient to represent a trend, 3) the difference fleet composition (and response to the changes in onroad conditions) accounts for the differences noted, or 4) the laboratory emissions effects are induced by activities that lie outside the domain of the MEASURE model.

Figure 5b illustrates the differences in estimated mass emissions predicted by the MOBILE5b and MEASURE modal algorithms for the mainline segments under metered and non-metered conditions. The system emissions from ramps and mainlines are dominated by the mainline activity. The two figures taken together indicate that the main NOx emissions effect associated with the operation of ramp meters appears on the mainline segment. The predicted increase in mainline NOx emissions on this metered system overwhelms the predicted decrease in ramp-related NOx emissions. If, as recent laboratory tests indicate, the ramp NOx emissions actually increase under metered conditions, the net increase in NOx emissions for the metered system would be even greater than that predicted in this exercise.

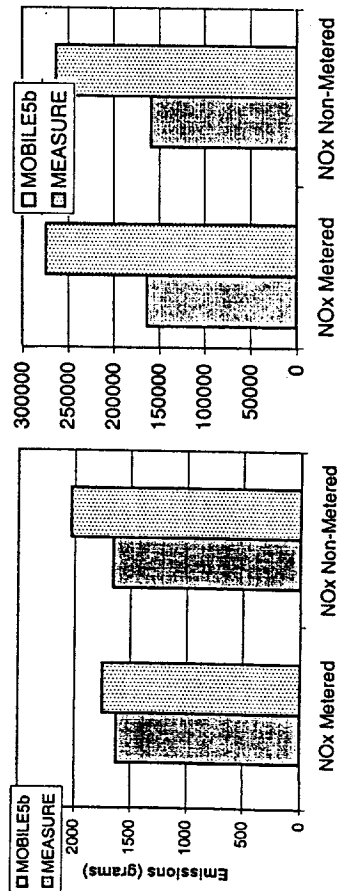


Figure 5: Comparison of MOBILE5b and MEASURE Emissions Estimates for the four Onramps (5a) and the Mainline Segments (5b) for Metered and Non-Metered Conditions.

It is important to note that the emissions results reported for the Atlanta metered system are for a series of freeway segments that seldom experience forced flow conditions. A bottleneck on the freeway system upstream from the ramp-metered section prevents the area at the meters from

reaching capacity during peak periods. While the metering of the onramp demand does improve mainline traffic flow, the mainline demand is never sufficient for the ramps to actually serve their intended function - preventing or delaying the onset of level of Service F conditions. The research team is currently performing simulation analyses to determine the expected emissions effects that would occur for the hidden bottleneck under conditions of increased entry volumes into the metered section. Given the emissions relationships described earlier, it is likely that under some conditions ramp metering can serve to reduce system emissions.

DISCUSSION

The modal algorithms employed in the studies reported in this paper employ speed-acceleration profiles rather than individual driving traces. The model is statistical in nature, predicting emissions as a function of deviation from load conditions employed in standard laboratory certification testing. However, the research teams collected second-by-second vehicle activity data in both the signalization and ramp metering studies. Hence, the two data sets serve as a means for testing a variety of modal emissions modeling approaches. The next step in modal analysis is to compare the test results that can be achieved by more advanced modal algorithms that predict emissions as a function of the real-time driving cycle (Barth, et al., 1997). The ability of these models to account for mode to mode transitions stands to significantly improve the modal modeling regime.

Policy decisions related to transportation infrastructure development and operations are currently made in the face of significant emissions modeling uncertainty, especially at the traffic flow improvement level. New emission rate modeling routines hold the promise of improving the accuracy of modeled emissions relationships, especially at the microscale modeling level. As new data, modeling methods, and models evolve, researchers need to be in a position to evaluate these models objectively. The data collected in Atlanta can serve as a base for model comparisons. That is, the predictions of different models can be compared against each other for observed traffic flow conditions. However, additional emissions studies are necessary if model verification studies are to be performed. Actual onroad fleet characteristics, individual vehicle operating profiles, meteorological conditions, and upwind downwind pollutant concentrations must be collected so that a variety of model modeling routines can be compared with field-measured emissions.

REFERENCES

- An, F., M. Barth, G. Scora, and M. Ross (1998), "Modeling Emission Emissions for Light-Duty Vehicles," Transportation Research Record 1641, National Research Council, Washington D.C., pp. 48-57.
- Barth, M., G. Scora, and T. Younglove, (1999), Estimating Emissions and Fuel Consumption for Different Levels of Freeway Congestion, Presented at the 78th Annual Meeting of the Transportation Research Board, Washington D.C., January 1999.
- M. Barth, M., T. Younglove, T. Wenzel, G. Scora, F. An, M. Ross, and J. Norbeck (1997), "Analysis of Modal Emission from Diverse In-Use Vehicle Fleet", Transportation Research Record 1587, Transportation Research Board, National Research Council, Washington D.C., 1997, pp. 73-84.
- Cambridge Systematics (1986), Improved Air Quality in Maricopa and Pima Counties - The Applicability of Transportation Measures, Prepared for the U.S. Environmental Protection Agency Office of Mobile Sources, Cambridge, Massachusetts, November 1986.

- Cicero-Fernandez, P., and J. Long (1994), "Modal Acceleration Testing on Current Technology Vehicles," The Emission Inventory: Perception and Reality, Air and Waste Management Association, Pittsburgh, Pennsylvania, pp. 506-522.
- Deakin, E., A. Skabardonis, and A. May (1986), "Traffic Signal Timing as a Transportation System Management Measure: The California Experience," Transportation Research Record 1081, Transportation Research Board, National Research Council, Washington, D.C. pp. 59-65.
- Fomunung, I., S. Washington, and R. Guensler (1999), "A Statistical Model for Estimating Oxides of Nitrogen Emissions from Light-Duty Motor Vehicles", Transportation Research D, Volume 4D, No. 5, pp. 333-352, September 1999.
- Guensler R. (1993), "Data Needs for Evolving Motor Vehicle Emission Modeling Approaches," Transportation Planning and Air Quality II, Paul Benson, Editor, American Society of Civil Engineers, New York, NY.
- Guensler, R. W. Bachman and S. Washington (1998), "An Overview of the MEASURE GIS-Based Modal Emissions Model", In: Transportation Planning and Air Quality III, Tom Wholley, Ed., American Society of Civil Engineers, New York, NY.
- Guensler R. (1998), "Increasing Vehicle Occupancy in the United States", L'Avenir Des Déplacements en Ville (The Future of Urban Travel), Laboratoire d'Economie des Transports, Lyon, France, December 1998.
- Hallmark, S.L., I. Fomunung, R. Guensler, and W. Bachman (2000), "Assessing the Impacts of Improved Signal Timing as a Transportation Control Measure Using an Activity-Specific Modeling Approach," Transportation Research Record, Transportation Research Board, National Research Council, Washington D.C. forthcoming.
- Kelly, N.A., and P. J. Grobicki (1993), "Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles", Journal of the Air and Waste Management Association: Pittsburgh, PA, Volume 43, October 1993, pp. 1351-1357.
- LeBlanc, D.C., M. Saunders, M. D. Meyer, and R. Guensler (1995), "Driving Pattern Variability and Impacts on Vehicle Carbon Monoxide Emissions," Transportation Research Record 1472, Transportation Research Board, National Research Council, Washington D.C., pp. 45-52.
- Meyer, M. (1997), A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility, Institute of Transportation Engineers, Washington, DC, 1997.
- Piotrowicz and Robinson (1995), Ramp Metering Status in North America, 1995 Update, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1995.
- Sierra Research (1997), Incorporating Freeway Ramp Speed Correction Factors in Emissions Models," NCHRP 8-33, Quantifying Air Quality and Other Benefits and Costs of Transportation Control Measures, National Research Council, Washington, DC, 1997.
- St. Denis, M., and A. M. Winer (1994), "Prediction of On-Road Emissions and Comparison of Modeled On-Road Emissions to Federal Test Procedure Emissions," The Emission Inventory: Perception and Reality, Air and Waste Management Association, Pittsburgh, Pennsylvania, pp. 495-504.
- Strong D. W. (1984), "Improved Urban Traffic Flow Through Signal Re-Timing -- California Experience," Innovative Strategies to Improve Urban Transportation Performance, American Society of Civil Engineers, pp. 213.
- Yu, L. (1998), "Remote Vehicle Exhaust Emission Sensing for Traffic Simulation and Optimization Models," Transportation Research D, Vol. 3, No. 5, pp. 337-347.