Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment

DAVID C. LEBLANC, MICHAEL D. MEYER, F. MICHAEL SAUNDERS, AND JAMES A. MULHOLLAND

The Clean Air Act Amendments of 1990 place a great deal of importance on the use of transportation controls to meet air quality standards in nonattainment areas. Inherent in the approach to estimating the beneficial impacts of such transportation measures is an estimation of current levels of emissions (the emissions inventory) and then a determination of what changes in emissions would occur given changes in the operation and use of the transportation system. One aspect of vehicle emissions behavior, that is, emissions due to engine power enrichment, which is not well represented in existing models, is examined. A 46-instrumented vehicle data base was used to analyze the importance of enrichment emissions to overall vehicle trip emissions records while relating these emissions to velocity-acceleration characteristics. It is concluded that enrichment emissions can be a significant contributor to overall vehicle emissions. In addition policy implications of these results on current public policy and emissions model development are discussed.

The Clean Air Act Amendments of 1990 place a great deal of importance on the use of transportation controls to meet air quality standards in nonattainment areas. Inherent in the approach to estimating the beneficial impacts of such transportation measures is an estimation of current levels of emissions (the emissions inventory) and then a determination of what changes in emissions would occur given changes in the operation and use of the transportation system. For mobile source emissions (that is, those emissions originating from transportation sources), this estimate is usually based on an activity factor [for example, vehicle miles of travel (VMT) for specified vehicle categories] and then multiplying this by emission rates that are produced from emission rate models. These emission rates are average rates that reflect emissions generated from vehicle tests on typical driving cycles modified by external factors such as ambient temperature and elevation.

Recent studies, however, have suggested that the models currently used to produce estimates of mobile source emissions could possibly underestimate these emissions by a factor of two or three (*1,2*). The reasons offered for this underestimation include inappropriate specification of the emissions models to model insensitivity to emissions generation that occurs under driving conditions in an actual road network. In particular some have hypothesized that one of the major causes of the emissions underestimation is a phenomenon called *power enrichment*, a condition of engine operation that causes the engine management feedback control system (which ensures stoichiometric operation) to be overridden to provide extra power by applying excess fuel, and thus producing high levels of carbon monoxide (CO) and hydrocarbon (HC) emissions (*3–5*). The purpose of this paper is to identify the characteristics of vehicle emissions as they are found in actual roadway driving.

The data base used in the present study consisted of 50 1989 to 1991 model year vehicles instrumented for engine and emissions monitoring. The vehicles were driven in Spokane, Washington, and Baltimore, Maryland, as part of a Motor Vehicle Manufacturers Association (MVMA)-sponsored project that was associated with a larger study of driving behavior being conducted by the Environmental Protection Agency (EPA). One component of the vehicle instrumentation was a wide-range oxygen sensor (WRO_2) that was able to detect air/fuel ratios over a wide range of operating conditions, thus providing an indication of when the engine is in an enriched condition. For those vehicles in which mass air flow can be determined, CO throughput can be estimated. In addition to air/fuel ratio, vehicle speed, engine speed, throttle position, a flow parameter, and engine coolant temperature were also recorded for six parameters.

BACKGROUND

The transportation and air quality professional community has only in recent years begun to explore in some detail alternative concepts for estimating mobile source emissions. Guensler (*6*) provides an excellent overview of some of the more important efforts as they relate to mobile source emissions modeling. Before the empirical evidence from this data base is presented, it is important first to set the context for some of the issues associated with a desire for a different approach toward such modeling. By so doing the empirical evidence of vehicle emissions from the six-parameter data base can be placed in the context of current hypotheses of why there is an underestimation of mobile source emissions.

As noted by Guensler, "For the purposes of estimating emissions, the action being performed by the vehicle (or inaction) at the time emissions occur is an emission-producing vehicle activity" (*6*). During the past several years several researchers have argued that one of the vehicle-producing activities that must be better understood in the context of emissions modeling is engine load-induced power enrichment (*3,7–9*). Some preliminary laboratory data suggest that high acceleration rates (which put heavy loads on the engine) could in fact contribute higher-level emissions due to power enrichment. The results of these preliminary

---

School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga. 30332.

investigations suggest that emissions due to power enrichment could possibly be an important contributor to the overall level of emissions due to vehicular sources.

Ripberger and Markey (*10*) provided a more conceptual perspective on the need for a better method of estimating vehicle emissions. They described the results of discussions among a working group of air quality and emissions modeling professionals and identified several elements of a new highway vehicle emissions estimation methodology that needed to be considered during the development of such a methodology. Those elements that relate directly to the character of vehicle emissions include the following:

> - *Modal Testing*—Vehicle emissions are not constant over the range of operating conditions. Certain operating conditions or modes can produce higher emissions and may contribute to a significant portion of the inventory. . . . Modal testing would need to cover the range of modes experienced by in-use vehicles: idle, cruise, acceleration, and deceleration. . . .
> - *Output In Grams Per Hour*—. . . grams per hour is feasible because emissions are linear and nearly constant during all vehicle operating modes (except cold start). . . .
> - *Vehicle Operation Data*—Vehicle in-use models would focus on estimating the number of vehicles and time spent in specified modes (e.g., idle, acceleration, or cruise). (*10*)

The paper by Ripberger and Markey (*10*) has served as a starting point for research efforts at the Georgia Institute of Technology (Georgia Tech) and elsewhere to provide a better understanding of the significance of these modal emissions to overall emissions levels.

Although some researchers and modelers have suggested that emissions due to power enrichment could be an important contributor to vehicular emissions, and in some limited cases laboratory experiments have been conducted, very few emissions data have been collected from real-world driving. The value of the six-parameter data base is that the emissions and engine behavior data represent driving conditions and road network topography that are typical in everyday driving. As will be described the results of the six-parameter study reinforce the concepts already presented by the authors.

METHODOLOGY AND DATA BASE

In February and March 1992, 79 vehicles were equipped with instrumentation that recorded time of day, day of year, vehicle speed in miles per hour (mph), engine speed in revolutions/min (RPM), throttle position as percentage of full throttle, coolant temperature in degrees Celsius, and either manifold absolute pressure (MAP) in kilopascals, mass air flow (MAF) in kilograms/hour, or LV8. LV8 is a proprietary measure used by General Motors (GM); it appears to be a composite of MAP and MAF. LV8 also varies in implementation from one engine family to another. Without a means of calculating mass air flow from LV8, the analysis of overall emissions presented here omits these vehicles. Each vehicle also was equipped with a WRO_2, and the output voltage from this sensor was mapped into an equivalence ratio to represent the air/fuel ratio. Values of all monitored parameters were recorded once per second. Data were recorded for approximately 1 week of driving for each vehicle by a randomly selected population of owner-drivers. Equivalence ratio (ϕ) is defined as:

$$\phi = \frac{(A/F)_{\text{Stoich}}}{(A/F)_{\text{Actual}}}$$

where A/F is air/fuel ratio.

Of the 79 originally instrumented vehicles, 50 data sets were initially judged by the contractor to have recorded acceptable data and were transmitted by EPA's Office of Mobile Sources to Georgia Tech for analysis. On closer examination four anomalous data sets were excluded from further analysis: one data set was missing four of six data channels, and the other three displayed badly skewed ϕ profiles and were excluded because it was not possible to tell whether the vehicle or the instrumentation was malfunctioning. Because of instrumentation requirements, the vehicles used in the study were relatively new (1989 to 1991 model years), and only vehicles manufactured by Chrysler, Ford, GM, Mazda, Mitsubishi, Nissan, and Toyota were represented. The median mileage on these vehicles at the time of instrumentation was 47,266 km (29,370 mi), with a maximum of 165,965 km (103,126 mi) and a minimum of 10,798 km (6710 mi). Young drivers (25 years and younger) were poorly represented, with only one sample taken from that age group. The results of this bias could be significant because the lone young driver was among the most aggressive and also had one of the highest incidences of power enrichment activity. Instrumentation requirements may have produced a biased sample. Manual transmission vehicles may have been underrepresented, as were vehicles with large engines and sports cars. As a result this sample may be somewhat more conservative than the overall population. A much larger sample would better extrapolate this analysis to the overall population.

ESTIMATION OF POLLUTANT THROUGHPUT

CO concentration was estimated by using either directly measured mass air flow or an estimated mass air flow derived from RPM and MAP and an estimate of the CO concentration based on the measured equivalence ratio. HC emissions tend to be a complex function of engine design parameters, engine speed, and state of maintenance of the engine (piston rings, spark plugs, etc.) and are not addressed directly in this paper. Nitrogen oxide (NO_x) emissions have not been modeled at this time. Mass air flow was determined by using the RPM and MAP signals along with engine displacement for vehicles equipped with MAP sensors by using the following equation:

$$\text{MAF} = \left(\frac{1\text{ intake stroke}}{2\text{ revolutions}}\right)\left(\frac{\text{RPM}}{60\text{ sec/min}}\right)$$
$$\left(\frac{\text{MAP}}{100\text{ kPa}}\right)(1.2\text{ g/L})\ (\text{Displacement, } L)$$

The density of air was assumed to be constant (1.2 g/L) when evaluated at standard pressure and temperature (1 atm and 20°C, respectively). Variations owing to altitude and daily temperature were not included since external air temperature and pressure were not recorded. Temperature variations could induce up to 8 percent error. Altitude variations should not be a problem in Baltimore, but Spokane drivers could experience significant changes in pressure because of altitude. Mass air flow sensor-equipped vehicle data were converted to grams per second, and LV8-equipped vehicles were not used because the exact relationship between LV8 and flow is unavailable. The contribution of fuel to overall mass flow is taken into account by

$$\left(1 + \frac{\phi}{14.56}\right)$$

where 14.56 was taken to be the stoichiometric air/fuel ratio on a mass basis.

Thermodynamic CO concentrations were determined as a function of ϕ by using Sandia Chemical Equilibrium Code [Stanjan (Stanford-JANAF) thermodynamic data tables]. A combustion temperature of 2500 K and pressure of 68 atm were assumed on the basis of typical values *(11)*. From the same text the hydrogen-to-carbon ratio in a typical gasoline was assumed to be 13:7. The combustion temperature is a maximum at ϕ of approximately 1 and will drop on either side of that value; variation in combustion temperatures over the range of ϕ values observed was estimated to result in less than a 1 percent change in CO concentration in this model. More than 50 chemical species were used for the thermodynamic calculations. Under fuel-rich conditions the carbon monoxide/carbon dioxide (CO/CO_2) ratio is controlled by the water-gas shift equilibrium expressed as

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The thermodynamic equilibrium equations are not easily reduced to an explicit equation for CO concentration in terms of ϕ. CO concentration on a mass basis (wet) was calculated for 13 points over the span of $0.76 \leq \phi \leq 1.42$. These datum points were then fit by using a cubic splines method to interpolate between points. Catalyst efficiency was estimated by mapping points from a published curve, and the cubic spline method was then used to model the curve. The resulting equation is

$$CO = MAF\left(1 + \frac{\phi}{14.56}\right)(X_{CO})(1 - \eta)$$

where X_{CO} is the mass fraction for CO and η is the catalyst efficiency. It is also possible to explicitly calculate the CO mass fraction by using the water-gas shift equilibrium and mass balance requirements under severe enrichment conditions. Under these conditions one can assume the carbon as CO and CO_2, hydrogen as H_2 and H_2O, and oxygen as CO, CO_2, and H_2O. The solution of these equations yields a quadratic equation with ϕ, pressure, and temperature setting X_{CO}. This solution breaks down when the assumption that none of the oxygen is in the form of O_2 is no longer valid. Because this method is valid only for a segment of the range of ϕ, it was not applied in calculating the results presented here.

Laboratory data reported by Patterson and Henein *(11)* were compared with these results as well as with data obtained in a related on-road experiment conducted in Atlanta with an MVMA pilot study vehicle and a remote sensing system. A Buick Park Avenue used as part of the MVMA pilot study *(4)*, which was outfitted with WRO_2 sensors from the same batch as those used in the full-scale study, was driven past a remote sensing unit. The clock on the vehicle data logger was compared with the clock used by the remote sensing computer, and over 50 passes were matched. As can be seen in Figure 1 the resulting CO concentration derived from ϕ as measured by the WRO_2 and the thermodynamic model (with catalyst efficiency included) is very close to that measured by the remote sensing unit *(12)*. A typical catalyst

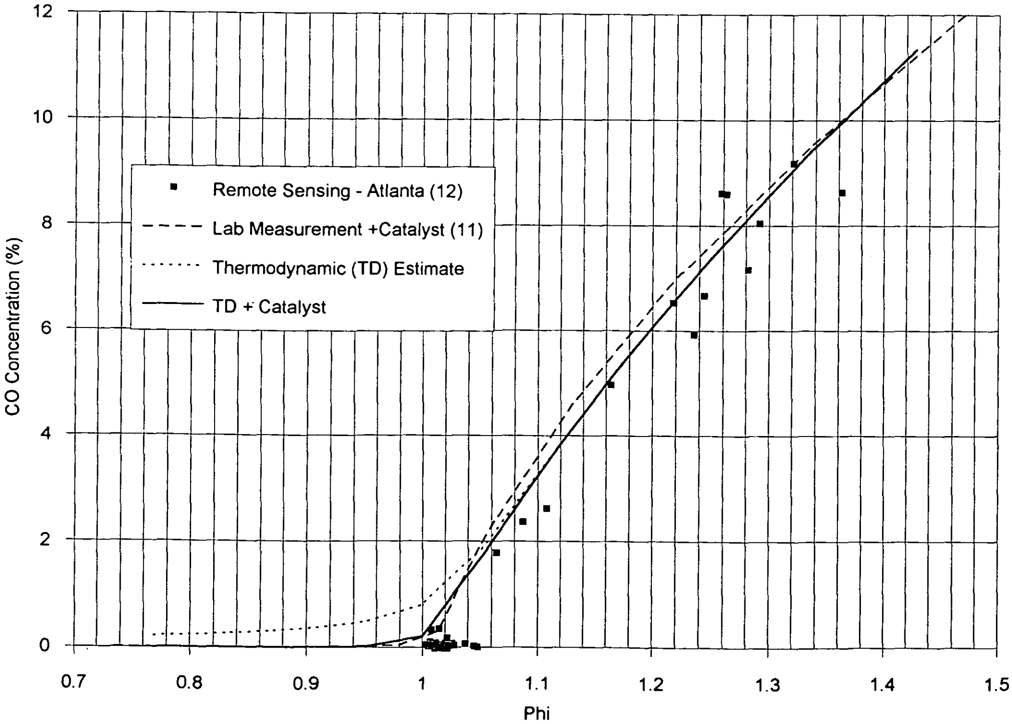

FIGURE 1 Comparison of thermodynamic model with remote sensing by WRO_2.

efficiency curve (*11*) was applied to the laboratory data and the thermodynamic model. The catalyst efficiency curve is taken as a function of ϕ only; however, this may be an oversimplification. Catalytic converters have some capability to buffer short-duration spikes; however, it is not clear how this effect should be modeled. The catalyst efficiency curve does not reflect that different manufacturers may have larger or smaller volumes with respect to flow, and residency time in the catalyst may have an effect on efficiency. A new catalyst coupled with a state-of-the-art engine management system can achieve a higher conversion efficiency than this model, but the model used is appropriate to the vehicle years studied. There is close agreement among remote sensing, laboratory data (with catalyst efficiency included), and the composite thermodynamic estimate-catalyst efficiency curve (Figure 1).

Data from an instrumented car that had an on-board exhaust gas analyzer and a WRO_2 sensor from the same batch as those used in the MVMA study and that used the same voltage to ϕ conversion as that in the present data set showed that there was excellent agreement between calculated values and measured values. The approximation of ϕ from the WRO_2 response for the six-parameter data set is considered to be within 10 percent for air/fuel ratios of $\geq$11.5:1 ($\phi \leq 1.27$) (P. J. Groblicki, unpublished data). Because recorded values of ϕ range higher than 1.27, there will be some error resulting from the curve fit for values beyond 11.5:1 that would result in the overestimation of ϕ. To compensate for extremely high values, any air/fuel ratio of less than 10:1 ($\phi = 1.46$) was limited to 10:1 in the calculations. Extremely high values of ϕ ($\phi \geq 1.27$) were rare (0.2 percent of all enrichment events), and this solution is intended to minimize the impact of overestimating ϕ from WRO_2 response because it effectively caps the CO concentration at 10 percent by weight.

ANALYSIS OF INSTRUMENTED VEHICLE DATA BASE

The analysis of the instrumented vehicle data base focused on the driving modes in which power enrichment occurred and the resulting overall effect of this enrichment. For the purposes of the present study mild enrichment is defined as $\phi \geq 1.03$ (air/fuel ≤ 14.1) and $\phi < 1.12$ (air/fuel > 13.0). Severe enrichment is defined as $\phi \geq 1.12$. By using these definitions mild enrichment represents an exhaust CO concentration of between 1 and 4 percent by weight, and severe enrichment can range as high as 10 percent.

Enrichment events were examined by treating each excursion past ϕ of 1.03 as a whole event. Peak and average values of ϕ and acceleration were calculated for each event as well as duration, peak throttle position, average speed, and CO emissions. An offset of 1 sec was applied to correlate each exhaust pulse to the engine and vehicle parameters, taking into account the time for the pulse to reach the WRO_2 sensor as well as the response time of the sensor. A careful inspection of the time offset shows that 1.5 sec would be ideal, with 1 sec being best at high mass air flows; however, the data were sampled once per second, making fractional-second offsets impractical. The data were then sorted into 16 bins of 5 mph each for speed and 16 bins of 1 mph/sec for acceleration. All acceleration data were obtained by using a 2-sec running average (central differencing) to reduce noise resulting from the limited resolution of the speed data. All data presented are for engine coolant temperatures of greater than 70°C, thus eliminating cold-start conditions. Under those conditions the catalytic converter should be at full operating temperature.

Mild enrichment tends to be a function of a momentary inability of the engine management system to respond to changes in driver input and operating conditions, whereas severe enrichment frequently results from a commanded enrichment by the engine management system. Many modern electronic engine management systems command either a stoichiometric ratio ($\phi = 1$) or enrichment. Inspection of data taken by using vehicles with the ability to monitor commanded air/fuel ratio and measured exhaust composition shows that variations in CO concentration occur when stoichiometric operation is commanded; however, these fluctuations are not as severe as those resulting from commanded enrichment and do not typically reach the levels found in commanded enrichment. Commanded enrichment occurs at high throttle (*13*) to provide peak demand power and to protect engine components. It can also occur during idle to provide extra power for accessories such as an air conditioner. Enrichment can also occur if the throttle is opened rapidly; a burst of fuel is needed to prevent a momentary stall and ensure drivability. Closing the throttle quickly can also result in enrichment in some engine configurations. Recent analyses have shown that rapid changes in throttle of relatively small magnitude can result in enrichment in some engine management systems.

Figure 2 gives a composite of the speed-acceleration profiles for all vehicles that were analyzed in the study. The three peaks correspond to idle, arterial driving, and highway driving. Severe enrichment events comprise only 15.7 percent of all enrichment events, but result in 58.4 percent of all estimated CO because of enrichment in this data set. Because mild enrichment events tend to occur in less well defined regions of operation and have less of an impact compared with severe enrichment events, the remainder of this analysis will concentrate on severe enrichment events. Severe enrichment events are plotted by using the same technique in Figures 3(*a*) and 3(*b*). The current federal test procedure (FTP) cycle contains no accelerations greater than 1.48 m/s^2 (3.3 mph/sec) and no speeds higher than 91.7 km/hr (57 mph). Much of the severe enrichment seen in the present study lies outside the bounds of the FTP cycle, and the further outside these bounds an event occurs the more likely it is to have extremely high pollutant throughput. During normal stoichiometric operation, the median sample from this data set is estimated to have a CO throughput of approximately 0.05 g/sec. Severe enrichment events at high speeds and high accelerations can easily range as high as 8 g/sec, with peak values in some of the larger-engine vehicles exceeding 15 g/sec.

It is also of interest to examine these events by duration. One-sec-duration events tend to occur at lower speeds or accelerations. It is likely that many of these events are in response to rapid changes in throttle position or are idle correction events. These events comprise 42.3 percent of all severe enrichment events, but account for only 14.8 percent of total severe enrichment CO emissions. Events from 2 to 5 sec duration show the effects of high speeds and accelerations much more strongly and account for 47.2 percent of the total number of events and 36.2 percent of total severe enrichment CO emissions. Events of 6 to 10 sec duration tend to occur at higher mass air flows and are relatively few in number (7.7 percent), but account for 20.8 percent of total severe enrichment CO emissions. Long-duration events (>10 sec) are rare

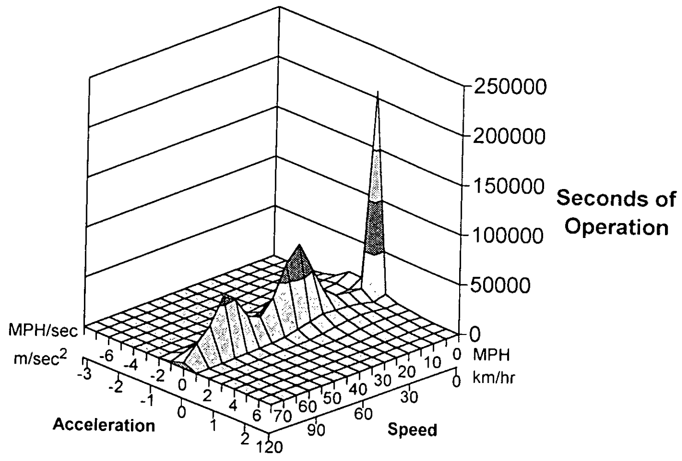

FIGURE 2 Driving mode distribution for all instrumented vehicles in Spokane and Baltimore (LV8 vehicles included).

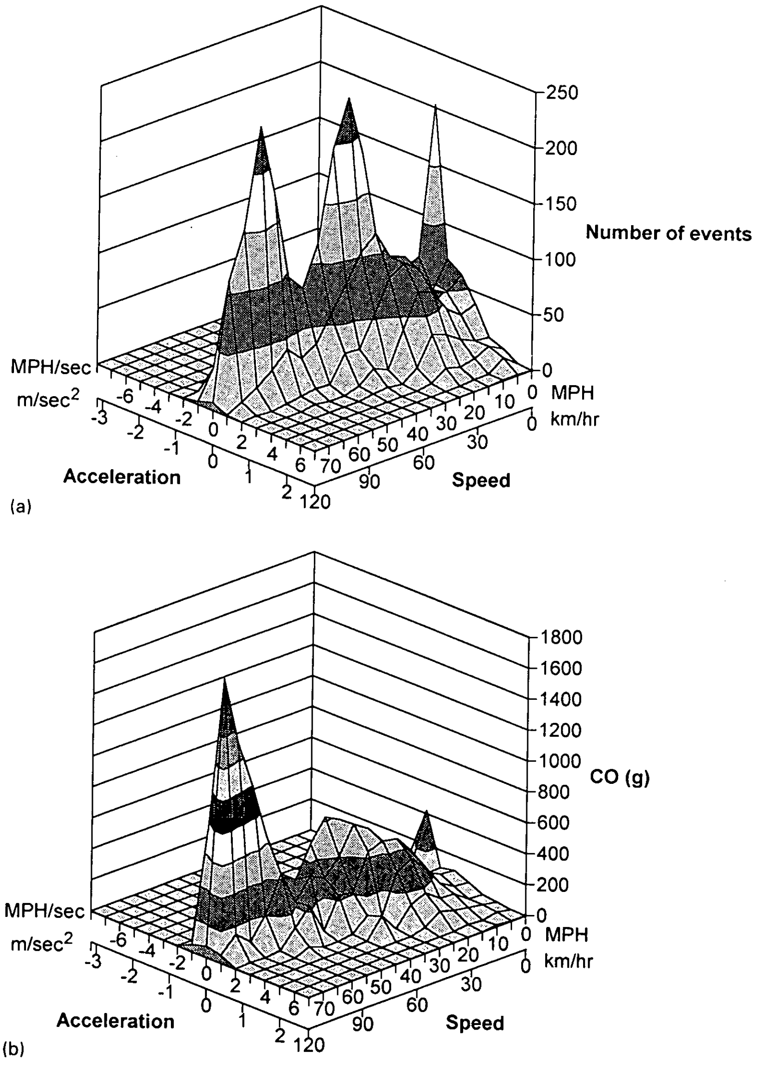

FIGURE 3 Distribution of severe enrichment events by (*a*) number and (*b*) total CO emissions.

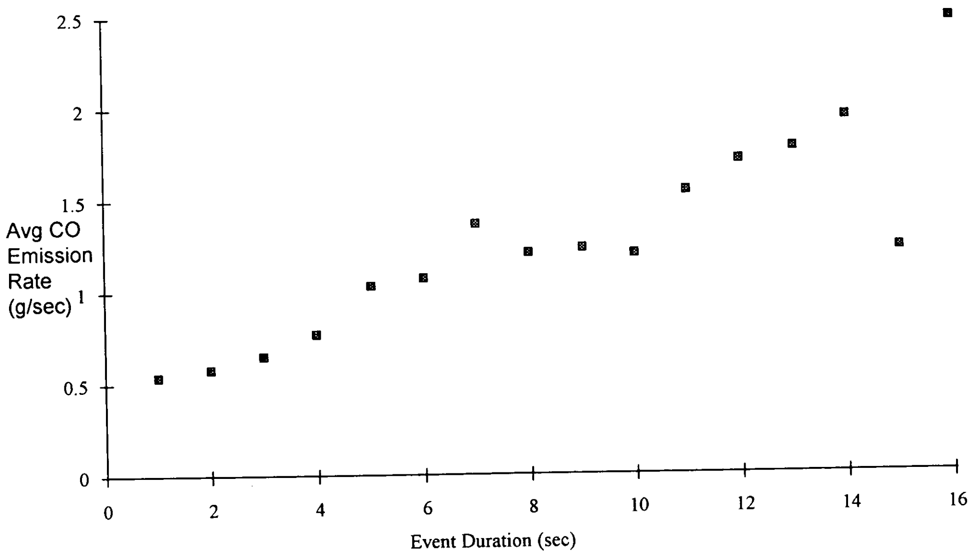

FIGURE 4 Average CO emissions rate versus event duration for data when more than 10 events were recorded.

(2.8 percent of all severe events), but tend to occur at very high speeds (≥112.7 km/hr or 70 mph) or at very high accelerations and account for 28.2 percent of all total severe enrichment CO emissions. A plot of average event intensity (Figure 4) shows that average CO throughput during each event increases rapidly as duration increases. A comparison of cumulative percent total severe enrichment CO emissions and cumulative number of events (Figure 5) shows that a control strategy based on a delay would decrease commanded enrichment CO emissions substantially. For example Figure 5 shows that just over 70 percent of total CO due to severe enrichment is created by events of less than 10 sec duration. A 10-sec delay would reduce emissions by much more than 70 percent since an 11-sec event would then become a 1-sec event. Some of these events may not have been commanded, so changes in control strategy would not achieve all of the reductions indicated.

The overall effects of severe enrichment are shown in Figure 6. Although most vehicles spend less than 2 percent of total driving time in severe enrichment, this can account for up to 40 percent of total CO emissions. Furthermore the few vehicles operated in severe enrichment a high percentage of the time (2 to 7 percent) contribute disproportionately to the total CO emissions of the fleet. A typical vehicle-driver combination will produce between 0.05 and 0.10 g of CO per sec overall, whereas the most aggressive drivers in this sample produced as much as 0.25 g of CO per sec. Some vehicles emitted as little as 0.2 g/sec, and a new vehicle

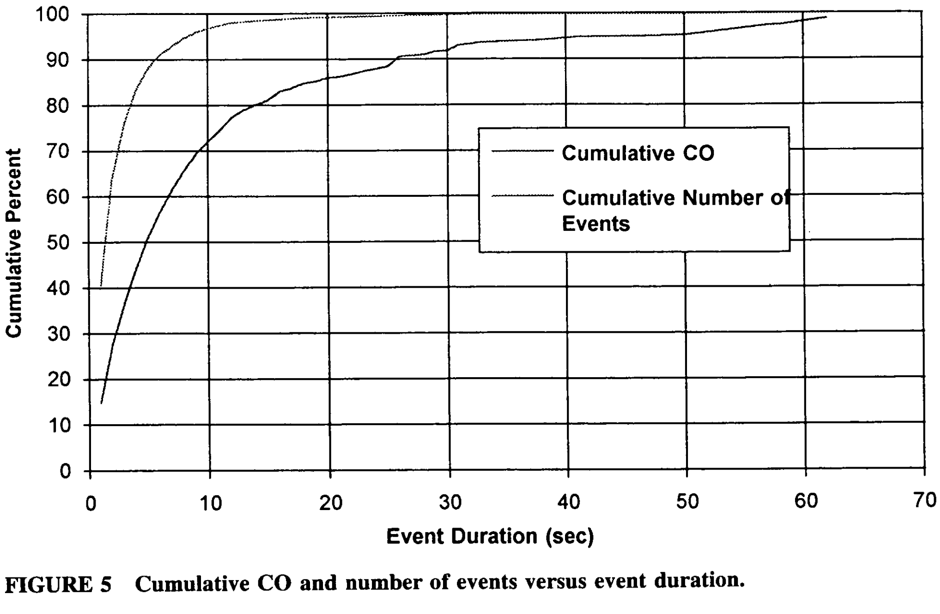

FIGURE 5 Cumulative CO and number of events versus event duration.

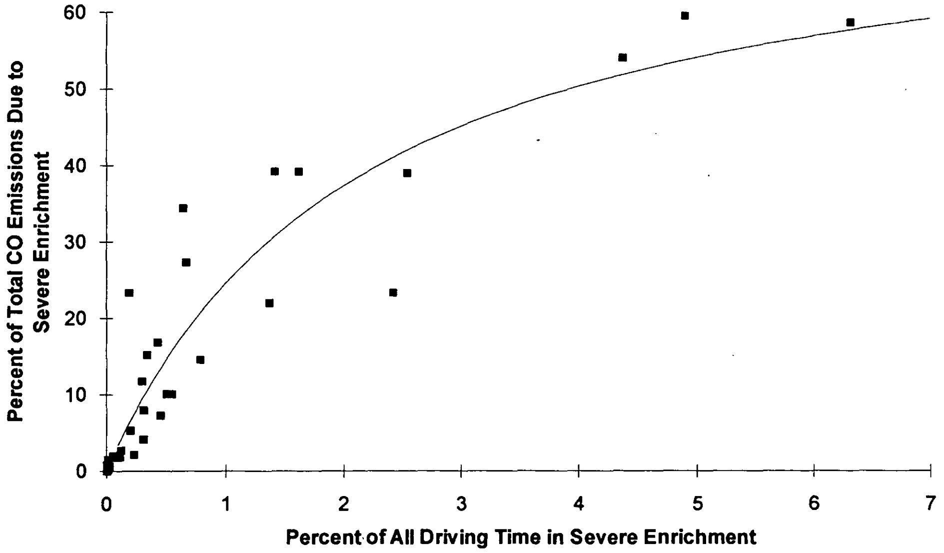

FIGURE 6 Contribution of severe enrichment to total CO emissions by vehicle.

with state-of-the-art engine management can be significantly cleaner. It is well documented that elevated HC emissions occur when CO emissions are elevated (*14,15*). However it has been estimated that although CO emissions during an enrichment event can be elevated by more than three orders of magnitude compared with stoichiometric emissions, HC emissions increase by a factor of 40 (*16*).

It is also of interest to analyze total CO emissions (enrichment and nonenrichment) by driving regime. Driving within the FTP cycle typically accounted for a smaller proportion of emissions than the proportion of all driving activity in that regime, suggesting that any estimate of warm engine running emissions based only on the FTP cycle would underestimate total emissions by a significant factor. The driving modes outside of the FTP cycle were divided into three zones: (a) accelerations higher than are present on the FTP, but speeds of less than 91.7 km/hr (57 mph), (b) decelerations outside the FTP at speeds of less than 91.7 km/hr (57 mph), and (c) all accelerations and decelerations at speeds greater than 91.7 km/hr (57 mph). High-speed driving outside the FTP cycle (>91.7 km/hr, or 57 mph) accounted for 28 percent of all CO produced by enrichment (mild and severe) and 15 percent of all enrichment events; however, the fraction of total CO versus total time spent in this region is only slightly elevated. Many drivers spend a significant amount of time in this region, resulting in slightly higher CO emission rates at significantly high mass air flows. When high-acceleration non-FTP driving at less than 91.7 km/hr (57 mph) is plotted comparing time spent in this driving mode with proportion of total CO produced (Figure 7), it is clear that driving in this region accounts for a disproportionate amount of the total CO emissions. On average the CO emission rate within the bounds of FTP cycle is 88 percent of the overall emission rate, at high speeds (>91.7 km/hr or 57 mph) it is 115 percent of the overall emission rate, and at high accelerations outside the FTP cycle it is 377 percent of the overall emission rate. The calculated emission rates found for these vehicles within the bounds of the FTP cycle may differ significantly from the emission rates obtained in an actual FTP test.

CONCLUSIONS AND POLICY IMPLICATIONS

As noted earlier in this paper several researchers have concluded that existing mobile source emissions models do not adequately estimate emissions as they occur in real-world driving. This paper has presented one of the earlier vehicle data bases that has been available for analysis. In particular this data base has been analyzed from the perspective of one possible cause of emissions underestimation: emissions due to power enrichment.

As shown in this data base severe enrichment events occur under speed-acceleration conditions typical of urban driving. Although severe enrichment conditions represented only a small fraction of overall driving, they contributed substantially to pollutant throughput. Important for public policy, some of the vehicle speed-acceleration regimes in which this enrichment occurred were outside of the speed-acceleration combinations found in FTP. A broader FTP cycle could potentially reduce these emissions significantly because the manufacturers would have to design vehicles to be tightly controlled over a more representative range of conditions. Some vehicles have already been designed so that severe enrichment does not occur except under very extreme conditions. To control for the severe enrichment conditions, which might very well be included in an updated FTP cycle or cycles, other vehicle manufacturers might do likewise. Innovative engine control strategies that use more sophisticated techniques such as "drive by wire" could also have a strong positive effect.

The analysis of the data base raises many important questions regarding the way that mobile source emissions are currently estimated. Many of these questions are the subject of further research, some of which is under way. Some of the more important issues that surface from this analysis include the following:

1. The contribution of severe enrichment emissions to the overall level of vehicle trip emissions could be very significant, given the right combination of conditions that add load to the vehicle engine. The most important parameters identified in this paper were speed and acceleration. However heavy engine loads can be

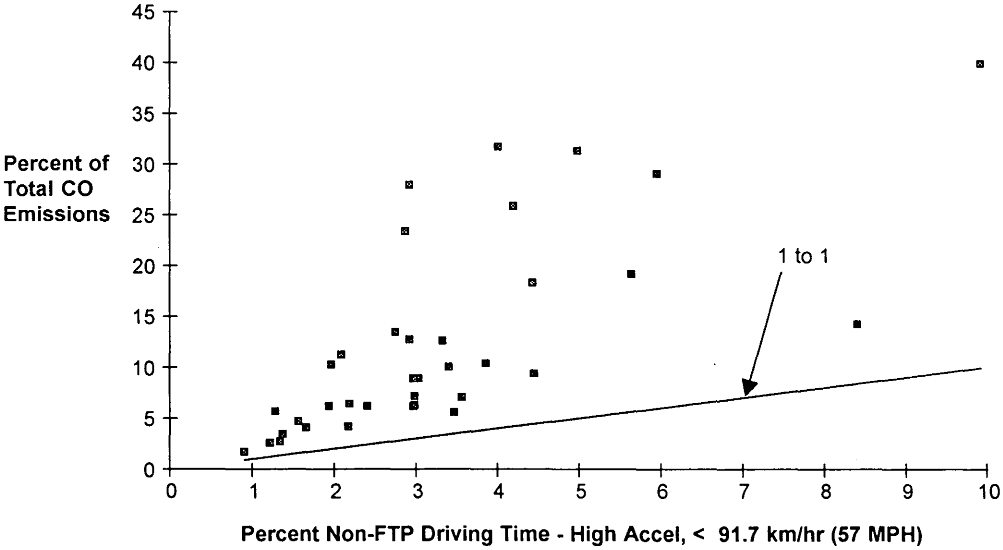

FIGURE 7 Comparison of time spent at higher accelerations than are present on FTP and <91.7 km/hr (57 mph) to proportion of total CO produced in this driving mode.

caused by engine power requirements because the vehicle is carrying a heavy weight (e.g., trailers or boat carriers in recreational areas) or vehicles with low power-to-weight ratio are traversing long, steep grades. Engine load because of an air conditioner can contribute to a higher incidence of enrichment, particularly at idle. The six-parameter data base does not include location or road characteristics when enrichment occurred. In fact low-speed or low-acceleration enrichment could be occurring (in the data base) on steep hills. There is no way of knowing what network or driver characteristics caused enrichment to occur. Therefore a significant need exists to better identify the elements of the transportation network that result in high-probability occurrences of severe enrichments (e.g., steep hills, intersections, and ramps where high levels of acceleration might occur or recreational sites with high numbers of vehicles towing trailers). These elements could very well become important activity factors that better define the contribution of enrichment emissions to the overall mobile source emissions inventory.

2. The emissions impact of some of the transportation management strategies adopted in many urban areas could very well be more severe than originally expected. For example some of the preliminary results of research conducted at Georgia Tech suggest that ramp merge areas are likely to show the highest incidence of severe enrichment events in a typical freeway network. In this case the contributing factors are primarily the heavy acceleration rates that are often used by drivers to merge with traffic flow. Efforts to provide an easier merge with such traffic flow, such as ramp meters, could very well cause the types of acceleration rates that lead to enriched conditions. Alternatively efforts under way to apply intelligent vehicle-highway system technologies to traffic systems whose primary intent is to smooth the flow of traffic (that is, reduce the likelihood of stop-and-go traffic) might very well have an important emissions benefit. As additional research is conducted on the types of vehicle behavior that seem most important for emissions, this research should be used in a broader context to better evaluate the likely impacts of the transportation control measures and other transportation management measures that are being proposed and implemented across the country.

3. The occurrence of enrichment at lower speeds and relatively lower acceleration rates raises serious questions about the current methodology for assessing emissions impacts at intersections. Current intersection models do not explicitly take into account the types of enrichment emissions that are shown to occur in this data base. Yet it is at intersections that one might see exactly the type of speed-acceleration combinations that could lead to enrichment emissions. The results of this research and of other projects using second-by-second emissions data should be used in assessing the overall validity of intersection-level emissions modeling.

4. An interesting observation that surfaced from this data base is that a small segment of the population tends to drive very aggressively and contribute an inordinate amount of the overall pollutants. The driver in the present study with the highest average CO emissions rate had approximately three times the median rate of CO emissions. An analysis of a broader data base to determine what portion of the population drives aggressively, and correlated with what types of vehicles they typically drive, should shed more light on this. Preliminary analysis of a larger data base shows significant differences in the driving habits present in Atlanta, Baltimore, and Spokane. Road network topology and climate may have an effect on the incidence of aggressive driving.

Most important, the results of this research indicate the value of second-by-second vehicle emissions and engine behavior data for better understanding the underlying phenomena that cause high levels of vehicle emissions. Only by undertaking such research efforts will investigators be able to better model the cause-and-effect relationships that determine overall levels of mobile source emissions.

ACKNOWLEDGMENTS

This paper is the result of research funded by EPA. The authors acknowledge the support and participation of Jim Markey and

John German of Office of Mobile Sources, EPA. Their assistance and insight have proved invaluable. The authors also thank Ted Ripberger of AEERL, EPA, for his continued assistance.

REFERENCES

1. Gertler, A., and W. Pierson. Motor Vehicle Emissions Modeling Issues. *Proc., 84th Annual Meeting of the Air and Waste Management Association*, Pittsburgh, Pa., June 1991.
2. *Rethinking the Ozone Problem in Urban and Regional Air Pollution.* National Academy Press, National Research Council, Washington, D.C., 1991.
3. Meyer, M., et al. A Study of Enrichment Activities in the Atlanta Road Network. *Proc., Air and Waste Management Conference on Emission Inventory Issues*, Durham, N.C., Oct. 1992.
4. Darlington, T. L., et al. Real World Engine Operation: Results of the MVMA/AIAM Instrumented Vehicle Pilot Study. *Proc., 85th Annual Meeting of the Air and Waste Management Association*, June 1992.
5. Ashbaugh, L. L., et al. On-Road Remote Sensing of Carbon Monoxide and Hydrocarbon Emissions During Several Vehicle Operating Conditions. *PM10 Standards and Non-Traditional Source Control.* Air and Waste Management Association, Pittsburgh, Pa., 1992.
6. Guensler, R. *Transportation Data Needs for Evolving Emission Inventory Models.* Paper presented at the ASCE Conference on Transportation and Air Quality, Boston, Mass., 1993.
7. Benson, P. *CALINE4—A Dispersion Model for Predicting Pollutant Concentrations Near Roadways.* California Department of Transportation, Sacramento, 1989.
8. Groblicki, P. Presentation at the California Air Resources Board Public Meeting on the Emissions Inventory Process, Sacramento, Nov. 5, 1990.
9. *Modal Acceleration Testing.* Mobile Source Division, California Air Resources Board, 1991.
10. Ripberger, T., and J. Markey. *Conceptual Design Issues: Developing a New Highway Vehicle Emissions Estimation Methodology.* Presentation at the AWMA Specialty Conference on Emission Inventory Issues in the 1990s, Durham, N.C., 1991.
11. Patterson, D. J., and N. A. Henein. Combustion Engine Economy, Emissions and Controls. Course notes. University of Michigan, Ann Arbor, July 8–12, 1991.
12. LeBlanc, D. C. *Comparison of WRO2 Output with Remote Sensing Data.* Technical Report 93-1. School of Civil Engineering, Georgia Institute of Technology, Atlanta, Feb. 14, 1993.
13. LeBlanc, D. C., et al. *Use of Wide Range Oxygen Sensors in Instrumented Vehicles—Preliminary Studies.* Presentation at Air and Waste Management Conference on Emission Inventory Issues, Durham, N.C., Oct. 1992.
14. Patterson, D. J., and N. A. Henein. *Emissions from Combustion Engines and Their Control.* Ann Arbor Science, Ann Arbor, Mich., 1972.
15. Obert, E. F. *Internal Combustion Engines and Air Pollution.* Harper & Row, New York, 1973.
16. Kelly, N. A., and P. J. Groblicki. *Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles.* General Motors Research Publication GMR-7858 EV-403, Dec. 1992.

Publication of this paper sponsored by Committee on Transportation and Air Quality.