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CHARACTERIZING THE EFFECTS OF DRIVER VARIABILITY ON REAL-WORLD VEHICLE EMISSIONS

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Abstract—Recent studies on real-world automobile emissions measurements have not adequately addressed the question of whether driving style affects emission levels. In this study, we hypothesized that given the same experimental conditions and a random selection of drivers, the variability associated with individual driving styles (e.g. intensity or duration of acceleration events) would produce statistically significant differences in measured emissions. To test this driver variability hypothesis, we conducted a field study on 24 drivers in a single vehicle on a specified route under low traffic conditions using on-board exhaust emission and engine operating data analyzers and tested for statistically significant differences in CO and NOx emissions between drivers. Our data show significant (95% level) variations in carbon monoxide (CO) and oxides of nitrogen (NOx) emissions among the 24 drivers under driving conditions where we have controlled for driving route, traffic density and vehicle type. Since the ANOVA tests showed significant differences in emissions between drivers but the frequency of driving modes were very similar, this suggests that the intensity of vehicle operation within a give mode, not the modal frequency, explains the emissions variability between drivers.

Keywords: vehicle/mobile emissions, driver variability, CO, NO_x,

1. INTRODUCTION

1.1. Quantifying real-world automobile emissions

Traditionally, automobile emissions have been measured with dynamometer tests using representative driving cycles in order to meet EPA pre-production and assembly line emissions requirements. These results do not lend themselves to real-world applicability since (1) they are performed on new, well-tuned models; and (2) the standardized testing does not mimic today's driving styles (Pierson *et al*., 1990; Black, 1991; Ross, 1994; Joumard *et al*., 1995; Sjodin and Lenner, 1995). Nevertheless, the availability of this data has led to widespread use of these laboratory results to predict real-world pollutant levels using emission factor models such as EMFAC (California Air Resources Board) and MOBILE (U.S. EPA). Recent field studies of actual emissions via tunnel studies (Pierson *et al*., 1990; McLaren *et al*., 1996), roadside point sampling, across-the-road remote sensing (Lawson *et al*., 1990; Bishop *et al*., 1993; Stephens, 1994; Stedman, 1996; Woods, 1996; Zhang *et al*., 1996), and instrumented vehicles (Schurmann and Staab, 1990; Kelly and Groblicki, 1993; Guenther *et al*., 1996) have noted the inadequacies of using laboratory data to estimate real-world pollutant levels. These inadequacies are generally attributed to factors such as the limitations of the test driving cycle, vehicle tampering, poor vehicle maintenance, and the high frequency of 'off-cycle' driving events under actual driving conditions (Black, 1991; Ross, 1994).

Data from some of the field techniques, however, are also inadequate for describing and ultimately predicting real-world emission factors. For example, the on-road infrared analyzers (Lawson *et al*., 1990; Bishop *et al*., 1993; Stephens, 1994; Woods, 1996; Zhang *et al*., 1996), while important for identifying gross polluters, take a single 0.5 s analysis of an automobile's exhaust and may not be indicative of emission levels under all driving modes (acceleration, deceleration, idle, cruise, highway speeds). Inspection/maintenance program smog-check inspections provide data on in-use vehicles, but are inadequate indicators of on-road emissions since the tests are performed over only two no-load engine operating conditions (2500 rpm and idle). While more recent research has focused on correlating driving mode with emissions (Hansen *et al.*, 1995; Jensen, 1995; Joumard *et al.*, 1995; Sjodin and Lenner, 1995; Barth *et al.*, 1997; Washington *et al.*, 1997; Young *et al.*, 1997), emissions were usually estimated from emission models rather than measured directly in the field. The few studies that have used on-board gas analyzers (Schurmann and Staab, 1990; Kelly and Groblicki, 1993; Guenther *et al.*, 1996) demonstrated the capabilities of these instruments to measure second-by-second emission levels to aid in repair of malfunctioning emission systems, but made no effort to correlate driving style and emission levels.

1.2. Driver variability and 'Off-Cycle' emissions

'Driver variability' describes the differences in vehicle operating behavior between drivers. These differences may include variations in the *duration*, *frequency* or *intensity* of different driving modes such as cruise, acceleration and deceleration. Since the operation of a vehicle directly affects its exhaust gas concentrations, identifying an independent surrogate measure of driver variability could lead to: (1) development of error estimates for current mobile source emission inventories, (2) new methods to forecast future fleet emission factors as the technological variability between new vehicles declines with time, and (3) improved accuracy in emissions estimates relative to real-world driving conditions and behavior. For example, while it is generally recognized that operating at wide-open throttle results in elevated exhaust concentrations (Black, 1991; Ross, 1994; Ross *et al.*, 1995), only recently have a few studies begun to quantify the fraction of time such operating conditions occur in real-world driving conditions (St. Denis *et al.*, 1994). Lacking such data, current emission factor models use only two driver activity factors, the number of trips undertaken and the vehicle-miles-traveled (to estimate vehicle model year mileage accrual rates), in addition to speed and ambient temperature to quantify mobile source emission factors, a practice that may explain why measured and predicted emission levels often significantly disagree (Lawson *et al.*, 1990; Pierson *et al.*, 1990; Ross, 1994; McLaren *et al.*, 1996).

Driver variability is distinguished from 'off-cycle' or 'open-loop' vehicle operation due to the fact that exhaust emissions can vary between drivers even when the vehicle's emissions are under 'closed-loop' computer control [i.e. if catalyst temperature or speed or rate-of-change of vehicle operating modes vary (Pidgeon and Dobie, 1991; Ross *et al.*, 1995)]. This is because drivers may operate primarily in different regions of the broad 'closed-loop' operating envelope and thus, net emissions can differ. In the 'closed-loop' envelope, real-world emission levels will be affected by driver variability due to differences in: (1) the amount of time different drivers spend in different operating modes (idle, acceleration, cruise), (2) the average speed of travel among drivers, (3) vehicle type (which determines the limits of 'closed' vs 'open' operation), and (4) driver aggressiveness and maneuverability.

Thus, while driver variability encompasses all vehicle operating modes, 'off-cycle' operation generally occurs only during high power or high load conditions (i.e. hard accelerations, heavy loads on steep hills) for well-tuned vehicles, but may occur transiently for malfunctioning vehicles (Black, 1991; Ross, 1994; Ross *et al.*, 1995). A malfunction of either a feedback component or the catalyst causes extremely high emissions that are driver-independent and beyond the scope of this study, but malfunctions have been shown to be an important component in real-world vehicles (Lawson *et al.*, 1990; Bishop *et al.*, 1993; Calvert *et al.*, 1993; Hickman, 1994; Stephens, 1994; Beaton *et al.*, 1995; Bishop *et al.*, 1996; McLaren *et al.*, 1996; Stedman, 1996; Zhang *et al.*, 1996).

Vehicle operating parameters have historically been described by driving 'cycles' that were intended to replicate 'typical' urban driver behavior. Unfortunately, the most widely used driving cycle, the LA-4 or its shortened version, the urban dynamometer driving schedule (UDDS), which is used in the federal test procedure (FTP), is based on the commuting behavior of a single Los Angeles woman (Austin *et al.*, 1993; St. Denis *et al.*, 1994; Ross *et al.*, 1995). New driving cycles are currently being proposed since it has recently become apparent that the FTP cycle is too limited to account for today's real-world driver behavior (Ross *et al.*, 1995; Barth *et al.*, 1997; Washington *et al.*, 1997), but adoption of a new cycle awaits widespread field data collection and analysis. Key to adoption of a new cycle is demonstration that it adequately represents today's real-world driving. Thus, driving cycle development is also linked to understanding how driver variability contributes to overall emission levels.

1.3. Previous work on driving style

A few previous studies have directly discussed the issue of driver variability. Austin *et al.* (1993) compared driving characteristics of 10 drivers in a study on driving patterns, but the drivers were not selected randomly and vehicle emissions were not measured. Comparison of six mean driving parameters using a generalized linear model indicated significant differences between drivers, but since vehicle emissions were not measured and the correlation between driving parameters such as speed or acceleration and emissions is not straightforward, the authors could not extrapolate to vehicle emissions. This study also indicated differences in individual driver performance as a function of vehicle type. Di Genova and Austin (1994) later used an on-board data acquisition system and portable gas analyzer to monitor emissions as a function of vehicle operating conditions, but only two drivers were compared in terms of emissions. Despite the small sample, the authors concluded that "driver behavior can alter average per-mile emissions by more than an order of magnitude".

St. Denis *et al.* (1994) monitored engine operating parameters on a single vehicle under freeway and urban driving conditions in order to quantify the frequency of 'open-loop' operation under different driving modes. This study is important because 'open-loop' operation is, in general, not incorporated into the FTP and therefore is unregulated (Ross, 1994). Since the enriched fuel/air ratio of 'open-loop' operation leads to high CO and HC tailpipe emissions, understanding the frequency of 'open-loop' driving occurrences provides important information for modeling real-world vehicle emission factors. However, this study only used two drivers, the drivers were instructed how to drive (i.e. travel in center lane; maintain velocity of preceding car), and vehicle emissions were not measured. Thus, while relative comparisons of driving modes are possible from this study, the driver sample size was too small and too constrained to be useful for predicting whether driver variability can produce significantly different real-world vehicle emissions.

1.4. Study objectives

Since meeting ambient air quality objectives depends on accurate determination of emission rates, a thorough understanding of the relationship between vehicle operation and emission levels is highly desirable. We propose that one of the important variables controlling automobile emissions is driving style since it directly determines the fraction of driving time that is spent under conditions where the exhaust control system is not operating within the designed emissions control envelope. Thus, our objectives are twofold: (1) evaluate the hypothesis that different drivers, driving the same vehicle under similar road conditions on a single route, will produce significantly different exhaust gas emission factors, and (2) identify and quantify the driving parameters that contribute to this variability.

2. EXPERIMENTAL METHODS

2.1. Continuous field measurement of emissions and engine parameters

We examined the emissions from a single well-maintained vehicle, driven by 24 individuals during the month of September 1996, over a 3.2 mile driving route in Davis, CA. A 1991 automatic transmission Chevrolet Lumina at 70,000 miles, obtained from University Fleet Services, passed a standard smog test before and after the study (one month of operation later). The driving route encompassed four legs: a 25 mph semi-residential street, 35 mph and 30 mph collector streets, and a short freeway section with a 4% grade off-ramp. Exhaust and engine measurements were made under light traffic conditions, either early in the morning (prior to 8 am) or on weekends. Exhaust gas concentrations of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxides of nitrogen (NOx) were measured using an on-board continuous emission analyzer (OTC 5-gas monitor, SPX–OTC Corp., Owatonna, MN) with simultaneous measurement of the engine operating parameters (e.g. speed, rpm) from the vehicle's on-board diagnostics PROM using a scanner (Snap-On® Tools Corp., Kenosha, WI). Both instruments were interfaced to laptop computers via serial ports to collect emissions data every second and engine parameter data every 3 s.

All tests were conducted after the vehicle and the 5-gas monitor had been warmed up for at least 30 min and all non-essential electrical equipment on the vehicle was turned off (heat, air conditioner, radio). The gas analyzer was calibrated with Scotty® Calibration Gas before and after the study and showed essentially no instrument drift (worst case: $<7\%$ for NOx) over the testing period. Regular unleaded gasoline (87 octane) was obtained from one local gas station during the month of testing. Twenty-four drivers were randomly selected from the university population and each driver completed the route two times in succession. Use of a single vehicle, constant traffic conditions and a single driving route allowed us to examine how individual driving style affects exhaust emissions.

2.2. *Driving events descriptive statistics*

Statistical analysis of the exhaust emission factors and the vehicle speed and acceleration data was performed after dividing the entire driving route into six separate driving events or modes. These events account for the fact that individual runs of the entire driving route are not directly comparable due to differences in factors that are beyond the driver's control such as the frequency of stops (traffic signals) and the behavior of other drivers on the road. The events included: low speed cruise, high speed cruise, accelerations, decelerations, freeway travel, and an aggregate of all moving events (Table 1).

2.3. *Emissions factors calculations*

Since this study utilizes a sizable data set for field second-by-second emissions measurements of a well-maintained vehicle, it is important to examine how the $\mathrm{g\,mi^{-1}}$ emission rates compare to federal I/M standards. Measured gas concentrations in ppm or vol% were converted to $\mathrm{g\,mi^{-1}}$ for comparison with inspection/maintenance program standards. The conversion factors (Denver Research Institute, 1997) assumed a propane equivalency factor of 0.493 for our gas analyzer HC measurements and a fuel consumption factor of 22 miles per gallon (MPG):

$$CO(g/mi) = \frac{5479(\%CO)/(\%CO_2)}{\left(1 + \frac{\%CO}{\%CO_2} + \frac{3(ppmHC)}{0.493*10{,}000(\%CO_2)}\right) * MPG} \tag{1}$$

$$HC(g/mi) = \frac{8219(ppmHC)/10{,}000*0.493(\%CO_2)}{\left(1 + \frac{\%CO}{\%CO_2} + \frac{3(ppmHC)}{0.493*10{,}000(\%CO_2)}\right) * MPG} \tag{2}$$

$$NO_x(g/mi) = \frac{5900(ppmNO_x)/10{,}000(\%CO_2)}{\left(1 + \frac{\%CO}{\%CO_2} + \frac{3(ppmHC)}{0.493*10{,}000(\%CO_2)}\right) * MPG} \tag{3}$$

The driving route data generally show low mean emission rates relative to the standard values of $3.4\,\mathrm{g\,mi^{-1}}$, $0.41\,\mathrm{g\,mi^{-1}}$ and $1.0\,\mathrm{g\,mi^{-1}}$ for CO, HC and NOx, respectively (Ross, 1994). Over the entire driving route, mean values for all drivers were 0.8, 0.07, and 0.25 for CO, HC and NOx, respectively (Table 2). While the *mean* $\mathrm{g\,mi^{-1}}$ values for individual drivers met the national standards for every driver, the maximum emission limits were exceeded by the majority of drivers at

Table 1. Driving route events description

Event	Description	Number of observations	
		Run 1	Run 2
1 Low speed cruise	$0<v\leqslant 25$, $-0.05\leqslant a\leqslant 0.05$	493	489
2 High speed cruise	$v\geqslant 40$, $-0.05\leqslant a\leqslant 0.05$	429	381
3 Acceleration	$a>0.05$	517	467
4 Deceleration	$a<-0.05$	451	444
5 Freeway	$v\geqslant 40$, $10{,}000\leqslant d\leqslant 12{,}513$	292	262
6 Entire moving route	$v>0$	2950	2614

v = speed in mph; a = acceleration in $\mathrm{ft\,s^{-1}}$; d = distance along route in ft.

Table 2. Emission rates ($g\,mi^{-1}$) for three regulated gases for all 24 drivers over the driving route*

	HC			CO			NOx		
Driver no.	Max	Mean	σ	Max	Mean	σ	Max	Mean	σ
1	0.66	0.06	0.09	91.33	1.39	9.51	0.73	0.20	0.18
2	2.40	0.14	0.38	24.91	1.60	3.48	1.61	0.27	0.29
3	1.37	0.05	0.16	5.72	0.27	0.78	1.37	0.24	0.24
4	0.92	0.06	0.14	5.97	0.40	1.00	1.18	0.27	0.24
5	0.37	0.03	0.06	24.49	1.20	3.82	1.19	0.27	0.22
6	1.02	0.05	0.11	17.25	1.10	2.43	1.61	0.24	0.29
7	0.94	0.05	0.08	10.22	0.40	1.20	0.65	0.17	0.16
8	2.26	0.10	0.25	25.96	1.03	3.26	0.79	−0.03	0.30
9	0.05	0.03	0.01	1.68	0.12	0.34	0.87	0.19	0.18
10	0.80	0.08	0.14	39.27	2.86	6.91	0.57	0.20	0.15
11	0.27	0.06	0.03	14.57	0.85	2.09	0.92	0.24	0.19
12	0.82	0.07	0.12	9.57	0.48	1.38	1.08	0.16	0.29
13	0.63	0.08	0.07	8.31	0.62	1.39	0.88	0.12	0.22
14	0.56	0.06	0.08	5.34	0.34	0.89	2.34	0.35	0.36
15	2.20	0.11	0.26	27.79	1.32	3.66	1.07	0.22	0.23
16	2.65	0.11	0.37	16.71	0.73	2.22	1.16	0.27	0.27
17	0.33	0.05	0.05	9.52	0.90	1.89	0.95	0.24	0.23
18	0.35	0.03	0.05	18.33	0.82	2.13	1.17	0.27	0.26
19	0.28	0.02	0.03	13.68	0.37	1.47	2.66	0.26	0.37
20	3.44	0.12	0.37	22.36	0.96	2.69	1.12	0.23	0.23
21	1.48	0.08	0.20	10.17	0.83	1.72	2.07	0.32	0.39
22	0.91	0.05	0.10	17.10	0.32	1.61	1.84	0.22	0.33
23	1.82	0.10	0.19	81.04	2.18	9.06	1.81	0.26	0.29
24	1.68	0.08	0.17	14.15	0.63	1.76	1.33	0.21	0.23

*Federal standards for 1991 vehicles are 0.41 $g\,mi^{-1}$ HC, 3.4 $g\,mi^{-1}$ CO and 1.0 $g\,mi^{-1}$ NOx.

some point during the run. Eighteen (out of 24) drivers exceeded the HC limits, 16 for NOx, and 23 of 24 drivers exceeded the CO standard over some portion of the driving route.

2.4. *Analysis of variance (ANOVA) model*

We hypothesized that there was a significant difference in exhaust gas emissions generated by various drivers (i.e. different drivers have different driving styles that significantly affect the corresponding emissions). Thus, the persons driving the vehicles themselves are not of intrinsic interest but rather are assumed to be a random sample from the entire population of drivers. The driver is therefore considered a random factor with each run of the driving route considered a fixed factor.

To statistically test whether the emissions produced by individual drivers differ, we can specify an analysis of variance (ANOVA) mixed random and fixed factor model as,

$$Y_{ijn} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijn}, \quad i = 1, ..., 24; \quad j = 1, ..., 2; \quad n = 1, ..., N \tag{4}$$

where Y_{ijn} is the observed grams per mile gas emission rate, speed or acceleration; μ is the overall mean, α_i represents the random effects due to individual driving styles (i = driver), β_j represents the fixed effects for the specified driving route (j = *run*), $(\alpha\beta)_{ij}$ represents a random interaction effect between the run and driver effects, and ε_{ijn} is the random error (n = number of observations); the standard assumptions for mixed linear models apply. Under our hypothesis, we would expect that the driver means would be statistically significantly (at 95% level) different from one another.

3. RESULTS

3.1. *Driver variability ANOVA tests*

The driving route used in this study generally encompasses the same uncongested driving conditions one might encounter in any U.S. city: stop-and-go traffic with non-freeway speeds up to 45 mph, the majority of accelerations between −0.5 and 0.5 $ft\,s^{-2}$ and a short highway segment

(Fig. 1). Other researchers have shown an increase in emissions during hard acceleration events (Ross, 1994; Hansen *et al.*, 1995; Joumard *et al.*, 1995; Sjodin and Lenner, 1995). Consistent with this observation, the highest acceleration events in our study had concurrent high HC and CO values, but these hard accelerations were restricted to the very beginning of the driving route. We suspected that these high accelerations were attributable to driver unfamiliarity with the car at the beginning of the run, therefore the initial 700 foot portion of the route was omitted from our analysis.

Initially *t*-tests were performed to compare speed and acceleration means between duplicate runs for each driver. The results indicated that, on average, speed and acceleration over the entire route were not statistically different between the two runs for most drivers and most events (Fig. 1).

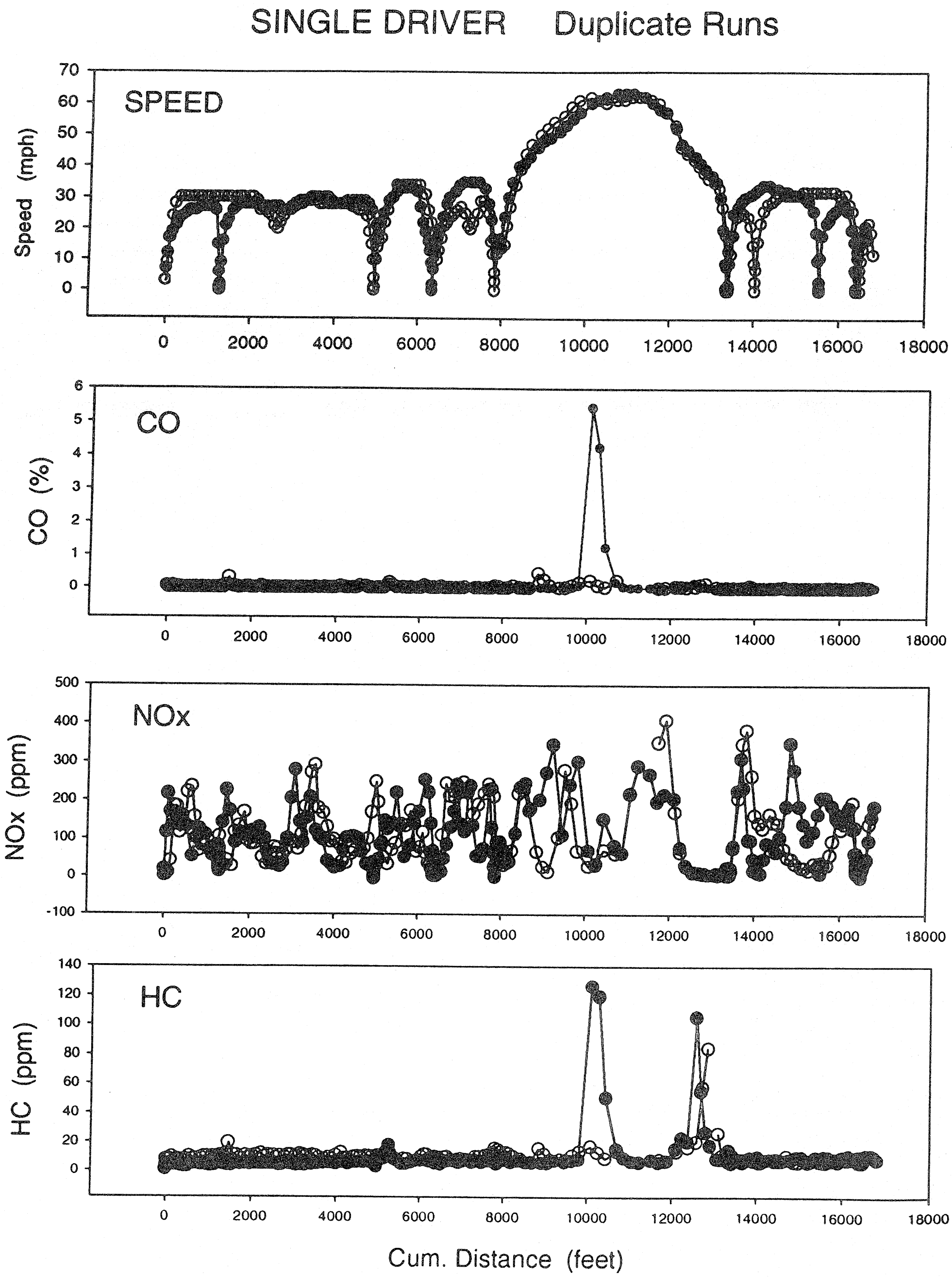

Fig. 1. Speed, CO and NOx concentrations as a function of driving distance along the driving route for a single driver. Duplicate runs are shown as different symbols. The CO data for this driver show some differences between duplicate runs (i.e. at 10,000 ft) but this variability was not significant for most drivers. Missing gas concentration data were due to automatic gas analyzer zeroing during the run.

Only the acceleration events (events 3 and 4) showed substantial differences in means between runs for a few drivers. This may have been due to two factors: (a) greater driver confidence with an unfamiliar vehicle and route on the second run, and/or (b) less awareness by the driver of being tested on the second run. The importance of these factors would be highly driver-dependent, in agreement with our results that a few drivers showed significant differences between runs, but most drivers did not. Thus, the *t*-tests generally indicated that in terms of mean vehicle operating parameters, individual drivers drove consistently from run to run.

The results of the ANOVA analysis for CO and NOx (Table 3) were computed for each of the individual driving events defined above using a log transformation to meet the normality assumption. The raw HC data did not fit the normality assumption with any of the transformations examined thus precluding statistical analysis. Further examination of the HC data showed numerous outlier values at high HC concentrations [Fig. 2(a)], suggesting that HC's may follow a gamma distribution as observed by others for on-road analyses of many different vehicles (Zhang *et al*., 1996). It should be noted that the relationship between HC and CO was approximately log linear over all driving events [Fig. 2(b)].

The ANOVA confirms that there was significant ($p < 0.05$; Table 3) driver variability in CO emissions for all driving events. This variability in CO emission rates between drivers under low speed cruise conditions is readily apparent in Fig. 3. Likewise, NOx emissions varied significantly between drivers for all driving events except the freeway portion of the route, event 5, where the mean emissions between drivers were not significantly different (Table 3). The main effects of run-to-run variability were insignificant for both gases. However, in some of the analyses, a driver-run interaction was observed. The presence of an interaction between driver and run ($\alpha\beta$) complicates interpretation of the run effects. This implies, for example, that the emissions for some drivers may have increased from run 1 to run 2 while others decreased, mathematically canceling out the run-to-run effects. A larger study is required to help resolve this question.

In general, the NOx data were more variable than the CO and HC data, possibly due to intrinsic variability in the NOx electrochemical sensor in the OTC 5-gas monitor, or the fact that the vehicle's three-way catalyst is more efficient in removing CO and HC than NOx from the exhaust stream. Higher variability in the NOx data may also explain why the freeway event NOx data were not significantly different between drivers.

In summary, the ANOVA results indicate that, as hypothesized, there was significant variability in CO and NOx emission levels between drivers. Thus, despite the within-driver variability (Table 2), the between-driver variability is greater and significantly different for all but the freeway event NOx data. The drivers in our small exploratory sample ($n = 24$) accounted for between approximately 7 and 14% of the total random emissions variability modeled with our data. The speed and acceleration ANOVA results (Table 3) also indicate that, on average, speed and acceleration were significantly different between drivers during both low and high speed cruise events. During acceleration events (events 3 and 4) and the freeway event (event 5), speeds differed significantly between drivers. Finally, it is important to note that over all driving modes (event 6) only speed differed significantly between drivers, suggesting that using acceleration as an aggregate route measure of driving style may not be useful. In addition, whereas the gas emissions data showed interactions between driver and run, the speed and acceleration data indicated that the driver–run interactions for most events were insignificant. That is, all drivers tended to operate similarly from run to run.

Table 3. Tests of significance for driver variability

Event	Statistical significance of driver (run-to-run) variability*			
	CO	NO_x	Speed	Acceleration
Low cruise	+(−)	+(−)	+(−)	+(−)
High cruise	+(−)	+(−)	+(−)	+(−)
Acceleration	+(−)	+(−)	+(−)	+(−)
Deceleration	+(−)	+(−)	+(−)	−(−)
Freeway	+(−)	−(−)	+(−)	−(−)
Entire moving route	+(+)	+(−)	+(−)	−(+)

*A positive sign (+) denotes statistical significance; a minus (−) sign indicates non-significant finding at the 95% level. All results are exploratory since significant driver-run interactions were seen in some cases.

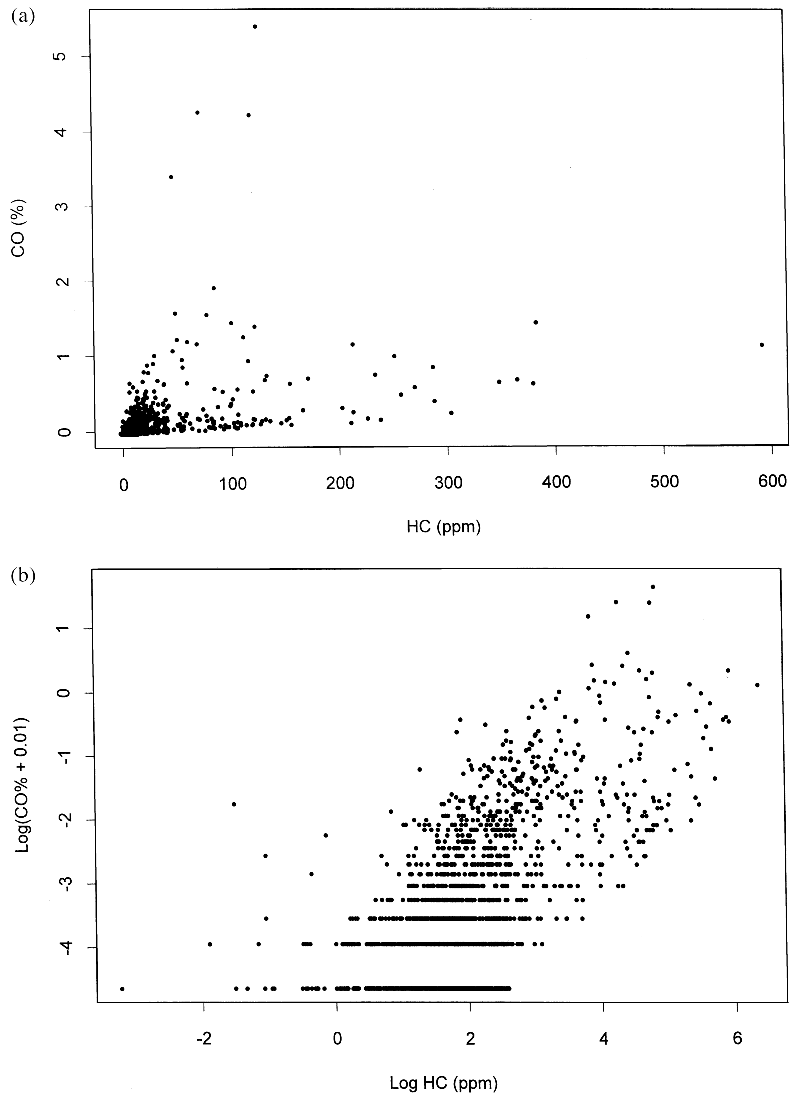

Fig. 2. (a) Carbon monoxide [CO(%)] and hydrocarbon [HC(ppm)] data for all drivers, all events. (b) Log–log plot of the data in (a) where log signifies natural logarithm.

3.2. Elevated exhaust emissions frequency

In contrast to previous research using dynamometer tests with non-catalyst and platinum catalyst vehicles (Hansen *et al.*, 1995; Jensen, 1995; Joumard *et al.*, 1995; Sjodin and Lenner, 1995), correlations between emission levels and driving parameters such as speed and acceleration were not obvious in our data. This suggests that a complex combination of factors affect emission levels for well-maintained automobiles with three-way catalyst systems. A more detailed analysis of the engine and emissions data dependencies for the extreme high emission factor values (Table 2) showed that outlier emission rates occurred either on the freeway portion of the route (34% of values exceeding the standard) or while decelerating to a stop light at the end of the uphill freeway exit ramp (23%). The low speed sections of the route with stop-and-go traffic accounted for 25% of the exceedances, 12% occurred during approach to a traffic signal after a moderately long cruise on the posted 25 mph link, and the remaining 5% occurred during the initial acceleration at the start of the route. Thus, entering and exiting the freeway accounted for ~60% of the violations of the federal standards.

This result agrees with observations by others that acceleration events and operation on hills (the exit ramp has a 4% grade) lead to elevated emissions. While the freeway acceleration and deceleration events generally occurred at high speeds, the magnitude of the accelerations was not

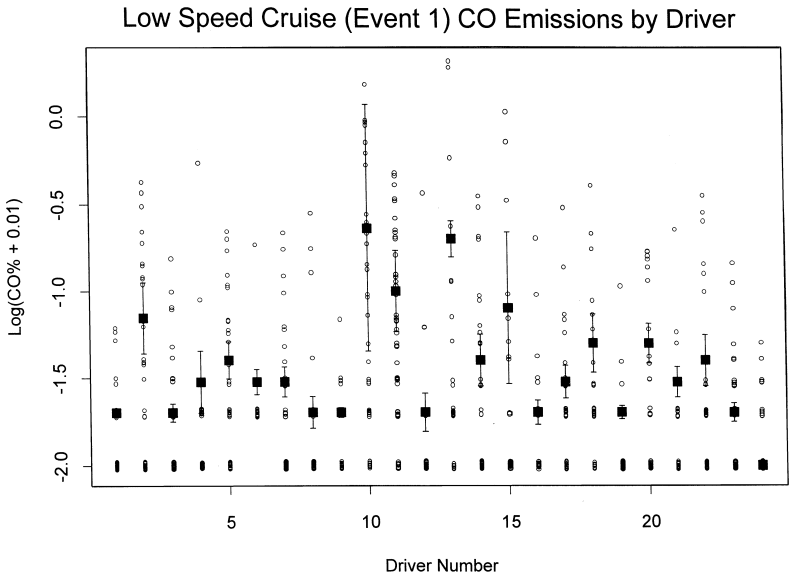

Fig. 3. Individual driver CO data for event 1 (open symbols), mean CO (filled square) and two standard deviation error bars around the mean indicate significant driver variability in CO emissions. Random noise has been added to jitter points to assist in visualization of overlapping data points.

great ($-0.05 < a < 0.05\,\mathrm{ft\,s^{-2}}$). In other words, the violations did *not* occur during what might typically be called 'hard' accelerations. We therefore suspect that the elevated emissions are associated with highly transient throttle operation, but operation that is of low intensity (i.e., "soft" acceleration. The frequency of these events should be highly driver-dependent. In fact, the percent of CO violations varied from zero to 17.6% among the 24 drivers with a mean value of 6.3% (4.3 σ). For both HC and NOx, the standards were exceeded less often: 2.8% (2.3 σ) and 1.5% (1.5 σ), respectively.

3.3. *Frequency of operating modes*

The engine PROM scanner data was used to evaluate the percentage of time each driver spent in each driving event or 'mode'. These data, while not necessarily directly correlated to exhaust emissions in three-way catalyst vehicles for reasons of transient operation mentioned above, nevertheless are useful for understanding urban driving patterns. We calculated the fraction of time each driver spent in a given operating mode (Table 4, top) and the average gas emission factors for all drivers over each type of event (Table 4, bottom). The event frequency results are very similar among all 24 drivers. This agreement among drivers indicates that the modal frequencies predominantly reflect the route conditions rather than capturing individual differences in driving style.

Since the ANOVA tests showed significant differences in emissions between drivers, this suggests that the intensity of vehicle operation within a give mode, rather than the frequency of the different driving modes, could explain the emissions variability between drivers. The average gas emission rates (Table 4, Fig. 4) indicate differences in mean emissions by event. A more interesting observation, however, is suggested by the large standard deviations associated with each operating mode, particularly high speed cruise and idle. These results suggest that *driving style within each type of event, rather than the frequency of each event, is key to understanding and quantifying driver variability*. That the highest mean emission rates occur during high speed (> 40 mph) cruise and freeway driving indicate that these are important driving modes for future driver variability research. Interestingly, these are the least-represented driving modes in current driving cycles.

4. IMPLICATIONS

This study has three major implications for understanding the variability associated with vehicle emissions. First, the modal frequency of vehicle operation is a less important determinant of emissions than the character of the driving style within a given driving mode. In other words, the

Table 4. Percent of time each driver spends in each operating mode on single run of route and mean emission rates for different driving modes

Driver no.	High cruise	Low cruise	Medium cruise	Acceleration	Deceleration	Idle	Freeway*
1	8.38	36.22	25.41	7.03	5.68	17.3	7.3
2	10.57	26.29	25.71	11.14	7.14	19.14	8.29
3	12.72	18.34	26.63	13.02	9.17	20.12	8.88
4	13.95	14.29	39.53	9.63	5.65	16.94	8.97
5	13.07	14.84	38.52	10.95	5.30	17.31	8.83
6	8.38	34.77	12.69	14.21	9.14	20.81	6.60
7	0.00	28.36	26.41	19.56	7.82	17.85	10.02
8	7.34	38.73	15.44	11.14	6.58	20.76	6.84
9	14.05	18.39	40.13	5.35	5.35	16.72	9.03
10	12.97	17.75	31.06	10.92	10.24	17.06	9.56
11	13.40	17.65	29.74	10.13	11.11	17.97	9.80
12	3.83	18.21	32.91	10.86	9.58	24.60	18.53
13	13.28	28.81	26.55	9.89	7.06	14.41	7.91
14	8.73	29.22	23.80	13.25	10.24	14.76	7.83
15	13.98	19.15	17.33	14.29	12.46	22.80	8.51
16	12.88	25.15	19.33	15.34	11.35	15.95	8.28
17	14.12	22.65	30.00	10.29	6.18	16.76	8.82
18	11.89	11.89	20.67	6.98	7.24	41.34	7.75
19	6.58	31.35	16.61	14.42	10.34	20.69	7.21
20	14.33	26.79	24.92	10.28	8.10	15.58	8.41
21	12.73	31.82	23.94	8.79	6.97	15.76	8.18
22	9.60	22.52	33.44	8.61	7.28	18.54	8.28
23	9.09	28.69	25.57	10.80	7.67	18.18	7.95
24	7.99	32.73	18.56	11.34	8.76	20.62	6.70
Mean	10.58	24.78	26.04	11.18	8.18	19.25	8.69
SD	3.68	7.50	7.49	3.04	2.04	5.33	2.29

Mean g mi^{-1} emission rates for all drivers by operating mode

	HC		CO		NOx	
Event	Mean	σ	Mean	σ	Mean	σ
Low cruise	0.06	0.02	0.75	1.39	0.12	0.09
Medium cruise	0.04	0.02	0.49	0.61	0.24	0.08
High cruise	0.16	0.11	2.62	4.12	0.34	0.21
Acceleration	0.05	0.02	0.67	0.69	0.24	0.07
Deceleration	0.10	0.08	1.10	0.92	0.25	0.13
Idle	0.06	0.08	1.82	5.85	0.08	0.11
Freeway*	0.18	0.18	2.85	3.32	0.45	0.26

*Note that the freeway event overlaps with other operating modes.

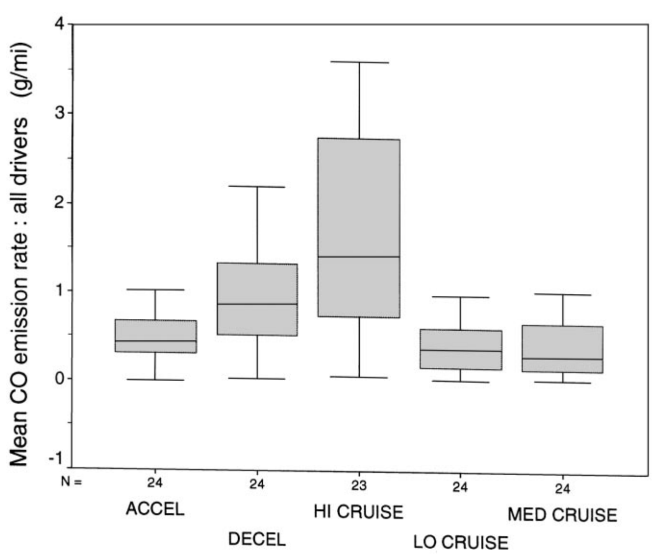

Fig. 4. Box plot of CO emission rates (g mi^{-1}) for all drivers by event. Shaded area represents the interquartile range with the median indicated by the horizontal bar.

percent time spent accelerating may not be as important as either the duration or the intensity of the individual acceleration events. Thus, quantifying the percentage of 'open-loop' driving time (Kelly and Groblicki, 1993; St. Denis *et al.*, 1994) may not be as important for predicting real-world emission levels as determining the intensity of these 'open-loop' events.

Second, the variability we found in individual driving styles may also have important implications on how vehicle fleet emissions testing is performed. For example, a well-moderated driver will produce different emission levels when driving the FTP cycle than a less-experienced driver. One possibility for reducing the discrepancies between real-world emissions and those estimated by emission factor calculations is to incorporated driver variability directly into vehicle emission control systems. That is, create a larger 'closed-loop' operating envelope in order to encompass more real-world driving styles.

Finally, the significance of driver variability on emissions suggests two areas for future effort. One is to identify the particular aspects of real-world driving habits that lead to high pollutant levels. This type of analysis will involve acquiring larger real-world data sets than used here and the use of highly sophisticated statistical analysis techniques. Many questions need to be addressed to improve emissions estimates. For example, are high speed accelerations more detrimental to air quality than high frequency, but slower speed and lower acceleration trips? When vehicles enter fuel enrichment ('off-cycle') operation, do the emission produced vary according to individual driving style? How should 'off-cycle' variations in emissions due to driving style be accounted for in emission factors?

5. CONCLUSIONS

Since three-way catalyst, electronically controlled emission vehicles will make up an increasing proportion of the vehicles on the roads in coming years, it is critical that we understand all of the variables that contribute to their exhaust emissions. We have evidence for significant (at 95% level) differences in driving style and associated emissions among the 24 drivers we tested. Our data indicate that the key operating parameter leading to elevated emissions from three-way catalyst vehicles is the intensity of operating within a mode rather than the frequency of different driving modes. We conclude that the intensity factor is highly driver-dependent and advocate the need for more real-world data on driver behavior and emissions in order to better quantify, model and verify new techniques for predictive modeling of air quality in urban areas. Future research should focus on developing statistically robust models that include this variability in addition to other currently used variables that contribute to urban air pollution episodes (i.e. meteorological variability). Questions, such as is vehicle miles travelled (VMT) more or less important than the driving style exhibited on those trips and how can changes in driving style, through public awareness campaigns, be used to achieve air quality standards in nonattainment areas, will also become increasingly important.

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