Remote Sensing, Means, Medians, and Extreme Values: Some Implications for Reducing Automobile Emissions

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A remote sensing unit that measures exhaust percentages of carbon monoxide (CO) and hydrocarbons (HC) from vehicles passing through a single lane of roadway was used in this study. During a 4-day period, more than 24,000 valid motor vehicle CO and HC emission measurements were made in the Baton Rouge area. The results indicated that more than half of the CO was emitted by 6.9 percent of the vehicles—the "gross polluters." About half of the HC was emitted by 20 percent of the vehicles measured. The average emission for the measured fleet was 0.72 percent CO, which corresponds to approximately 70 grams CO per liter of gasoline consumed. The average emission was 0.09 percent HC, or 14 grams HC per liter of gasoline. Usually the impact of transportation control measures (TCMs) is estimated from the mean emissions levels. However, it is most likely that TCMs based on voluntary compliance will achieve reductions primarily by individuals best represented by the median emissions. On the other hand, if TCMs were aimed specifically at vehicles with extreme levels of CO and HC emissions (gross polluters), more significant emissions reductions may be achieved.

Passage of the Clean Air Act Amendments of 1990 (CAAA) has given transportation agencies new challenges to improve air quality in many urban areas that do not meet the federal air quality standards. The CAAA has also initiated a round of state implementation plans and the need for establishing emission inventories (*1*). Carbon monoxide (CO) standards are primarily violated as a result of direct automobile emissions. Violations of the ozone standard arise from photochemical transformation of oxides of nitrogen (NO_x) and hydrocarbons (HC). In this paper we will only discuss CO and HC since NO_x measurements by remote sensing were not possible at the time of this study.

Mobile sources are believed to contribute significantly to emissions of CO, HC, and NO_x. Various sources of CO, HC, and NO_x in the Baton Rouge nonattainment area (six parishes) are given in Table 1. Air pollution control measures taken to mitigate mobile source emissions in nonattainment areas include inspection and maintenance (I/M) programs, oxygenated fuel mandates, and transportation control measures (TCMs). Despite two decades of air pollution control efforts, 84 million Americans continue to live in areas where the air is unhealthful (*2*). On a national basis, vehicle miles traveled (VMT) increased an average of 4.4 percent annually during the 1980s while the population increased 2.5 percent (*3*). Cars and trucks in the United States now travel 2 trillion mi every year compared with 1 trillion mi in 1970. The car and truck VMT is expected to increase to 3.8 trillion by 2020 (*4*).

Usually the impact of TCMs is estimated from the mean emissions levels. However, it is most likely that TCMs based on voluntary compliance will achieve reductions primarily by individuals best represented by the median emissions. On the other hand, if TCMs were aimed specifically at vehicles with extreme levels of CO and HC emissions, referred to as gross polluters, more significant emissions reductions may be achieved. Such an approach is currently feasible through the use of remote sensing to obtain on-road measurements of vehicular pollutants.

The remote sensing instrument used in this study [Fuel Efficiency Automobile Test (FEAT)] was developed by the University of Denver. This instrument measures the CO and HC in the exhaust of any vehicle passing through an infrared (IR) light beam, which is transmitted across a single-lane of roadway. Figure 1 shows the instrument.

THE INSTRUMENT

FEAT was designed to emulate the results obtained using a conventional exhaust gas analyzer, for example, a tail pipe probe. FEAT can measure the CO and HC emissions in all vehicles, including gasoline- and diesel-powered vehicles, as long as the exhaust plume exits the vehicle within 1 m of the ground. Because of the current height of the sensing beam, FEAT will not register emissions from exhausts that exit from the top of vehicles, as in heavy-duty diesel vehicles. The CO and HC emissions from diesel vehicles are, in any case, relatively unimportant. FEAT analyzes the exhaust from a car that drives between an IR source and the detector. Each time the IR beam is blocked, an analysis for vehicle exhaust is initiated. The IR source sends a horizontal beam across a single traffic lane approximately 25 cm above the road surface. The beam is picked up by the detector on the opposite side and split into four wavelength channels: CO, CO_2, HC, and reference. Placed in front of the detector is an optical filter that transmits the IR light of a wavelength known to be uniquely absorbed by the molecule of interest. The absorption of light by the molecules of interest reduces the signal, causing a reduction in the output voltage. FEAT is effective across traffic lanes up to 12 m wide. However, it can only operate across a single lane of traffic if one wishes to identify positively and video-record each vehicle with its exhaust.

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TABLE 1 Sources of CO, HC, and NO_x in the Baton Rouge Nonattainment Area (Six Parishes) (Source: Baton Rouge Ozone Advisory Committee)

	Carbon Monoxide (Tonnes/Day)	Hydrocarbons (Tonnes/Day)	Nitrogen Oxides (Tonnes/Day)
Industry	244	65	209
Mobile	510	80	55
Biogenic	0	909	0
Miscellaneous	127	47	43
Total	881	1101	307

Although not used for the Baton Rouge area study, a radar system has also been developed that is capable of determining both the speed and acceleration of passing vehicles during the same fraction of a second in which the emissions are measured. The radar readings are stored in the data base with the emissions information.

The mechanism by which FEAT measures the exhaust percentages of CO and HC is explained by Bishop et al. (*5*). The system works by sampling in front of and behind the vehicle and registering the difference. Hence, the ambient air quality conditions do not affect the measurements. Also, there is no effect on measurements from the pollution plume left by a previous vehicle. For every vehicle that passes through the IR beam, the computer freezes a videotaped picture of the rear end of the vehicle showing the license plate number and a readout of the percentage of CO, CO_2 , and HC in the exhaust plume. The results are stored on a digital computer data base as well as on S-VHS videotapes. The computer writes the date, time, and the calculated exhaust CO, HC, and CO_2 percentage concentrations at the bottom of the image.

The measurements are independent of wind, temperature, and turbulence. FEAT operates most effectively on dry pavement. Rain, snow, and very wet pavement cause scattering of the IR beam. These interferences cause the frequency of invalid readings to increase, ultimately to the point that all data are contaminated by too much "noise." Error-checking routines in the FEAT computer eliminate invalid data caused by oversized vehicles, pedestrians, or other nonexhaust obstacles; when errors are detected, the measurement is rejected, and an invalid data flag is set in the data base. Two major criteria for rejection are not observing sufficient signal change to measure exhaust components accurately and observing too much scatter in the HC or CO to CO_2 correlations to derive the ratio from the slope of the best fit straight line. The calibration gases (mixtures of CO, propane, and CO_2) are used as a daily quality assurance check on the system. FEAT has been shown to give correct readings for CO and HC by means of double-blind studies of vehicles (*6–8*).

On the basis of combustion chemistry, the percentages of CO and HC can be used to determine many parameters of the vehicle's operating characteristics, including the instan-

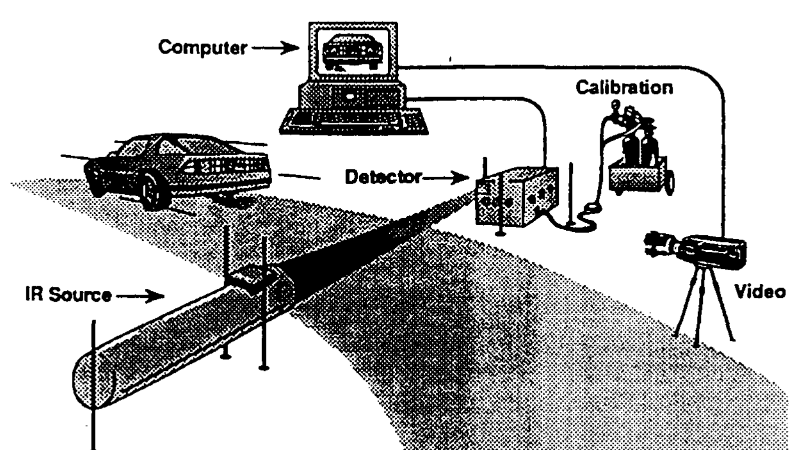

FIGURE 1 On-road emissions monitor used in the Baton Rouge study.

taneous air/fuel ratio, grams of CO emitted per liter of gasoline (gCO/L), and the percentage of CO. The measured emissions in percentages of CO and HC can be converted to mass emissions in grams per liter of gasoline burned using the following equations (*7*):

$$gCO/L = 4{,}180 * \%CO/(42 + 1.07 * \%CO) \quad (1)$$

and

$$gHC/L = 1.57 * gCO/L * (\%HC/\%CO) \quad (2)$$

CO AND HC EMISSIONS FROM AUTOMOBILES

The automobile CO and HC emissions in the exhaust manifold are a function of the air-to-fuel ratio at which the engine is operating. Figure 2 shows approximate engine-out emissions as a function of air-to-fuel ratio where 7.09 (14.7 percent air to fuel by weight) is the ratio at which there is exactly enough air to fully burn the fuel to CO_2 and water.

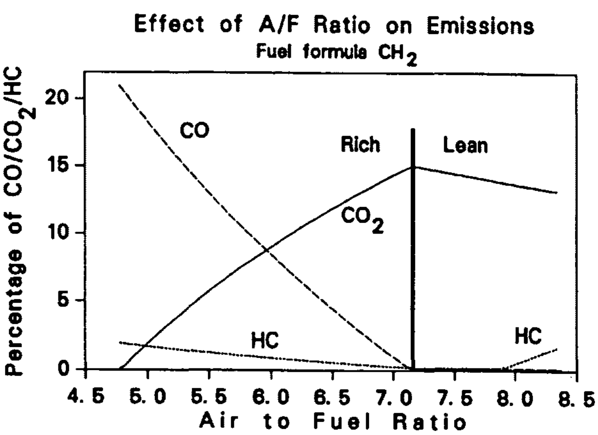

FIGURE 2 Approximate relative concentrations of CO and HC produced by a spark-ignited engine as a function of air/fuel ratio by moles.

CO emissions are caused solely by the lack of adequate air for complete combustion (*9*). Therefore, CO is likely to be produced if the mix is too rich or under stop-start conditions where the engine load keeps changing. Although a fuel-lean air/fuel ratio impairs driveability, it does not produce CO in the engine.

For HC the situation is more complex. In the main part of the combustion chamber away from the walls, essentially all the HC is burned. However, the flame front initiated by the spark plug cannot continue to propagate within about 1 mm of the relatively cold cylinder walls. This phenomenon causes a "quench layer" next to the walls made up of a thin layer of air/fuel mix against the cylinder wall. The opening exhaust valve and the rising piston scrape this layer off the walls and send it out of the exhaust manifold. As the mixture becomes richer, the quench layer contains more HC; thus, more HC is emitted when the vehicle is operating with rich mixtures. This production of HC is likely to be correlated with emission of CO.

A second peak in HC emissions is indicated on the right-hand (fuel-lean) side of the diagram. This phenomenon is known as "lean burn misfire" or "lean miss" and is the cause of the hesitation experienced at idle before a cold vehicle has fully warmed up. When this misfiring occurs, a whole cylinder full of unburned air/fuel mix is emitted into the exhaust manifold. Misfiring also occurs if a spark plug lead is missing or the ignition system to one cylinder is otherwise not working. Thus, the second peak HC emission occurs under conditions in which CO is not produced and is not correlated with CO emissions.

The "engine-out" emissions are further altered by any tail pipe emission controls that may be present. The catalytic converters are placed in the exhaust line to remove excess HC. Therefore, if the catalytic converter is present and functioning at correct operating temperature, most of the HC produced under the above conditions will be partially or totally converted to CO and CO_2. Thus, under the condition of lean miss, a high CO reading with low HC would be observed. If the catalytic converter is absent or nonfunctional, high HC will be observed in the exhaust without the presence of high CO. Table 2 gives a summary of various levels of CO and HC that may be expected under various engine operating conditions. In summary, this shows that a high HC reading cannot be obtained when the catalytic converter is fully func-

TABLE 2 Expected Levels of CO and HC Emissions from Automobiles

Engine Operating Condition	Working Catalytic Converter		Non-Working Catalytic Converter	
	CO	HC	CO	HC
Fuel-lean or Misfire	High	Low	Low	High
Normal	Low	Low	Low	Low
Fuel-rich	High	Low	High	High

tional, although an incorrect air/fuel ratio will generate high CO readings. If the catalytic converter is absent, faulty, or nonfunctioning, the state of operation of the vehicle engine is clearly defined by the exhaust composition. In addition, an absent, faulty, or nonfunctioning catalytic converter will result in emissions readings from an incorrect air/fuel ratio that are distinct from those produced when the catalytic converter is functional.

RESULTS AND DISCUSSION

In March 1992, 4 days of measurement were carried out, 2 days at the eastbound on-ramp to Interstate Route 10 in Baton Rouge at College Drive and 2 days at the southbound on-ramp to Interstate 110 in Baton Rouge at Harding Boulevard. The measurement sites are shown in Figure 3. There was no precipitation during the data collection period, and the average

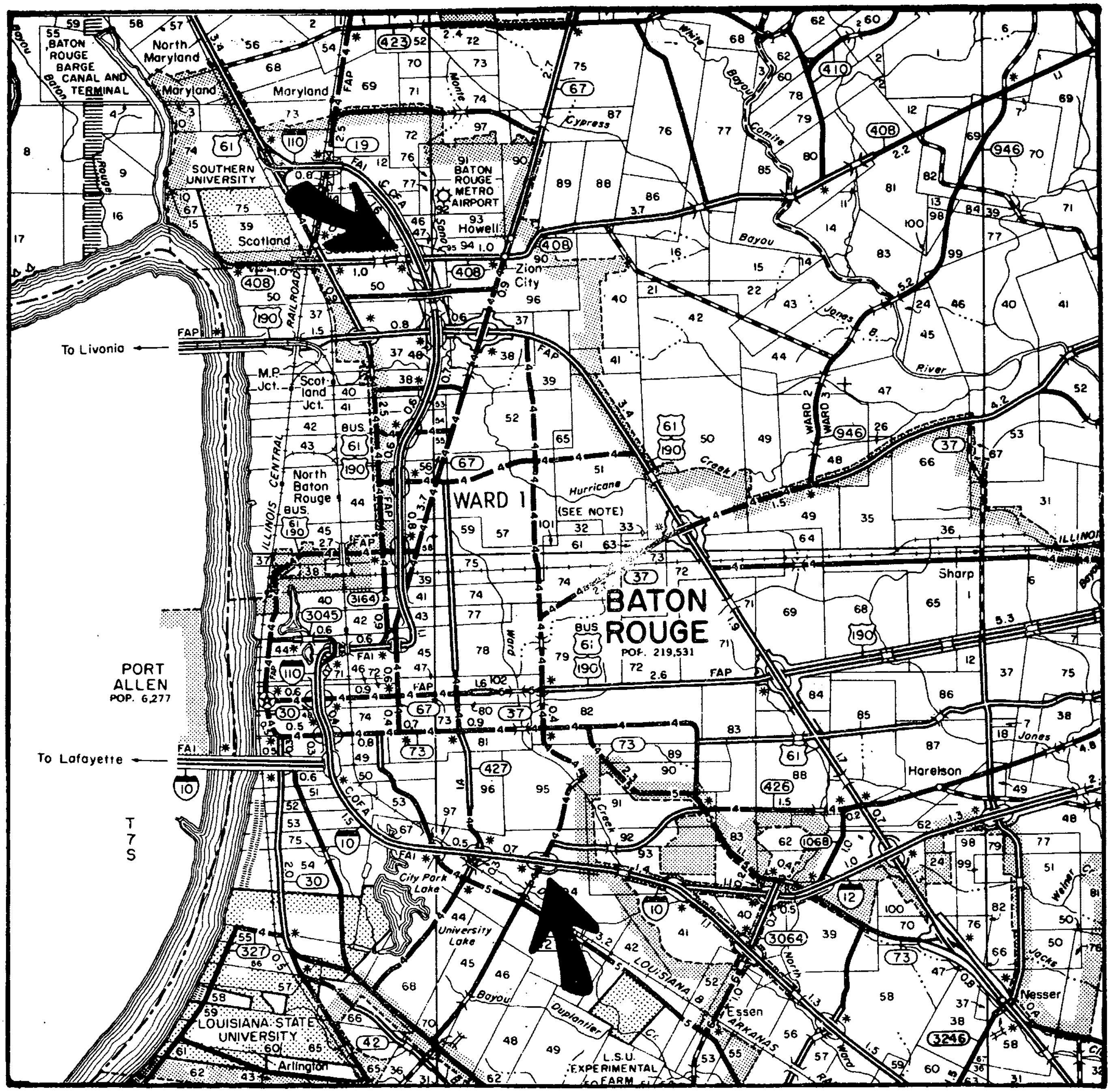

FIGURE 3 Location of remote sensing sites.

daily maximum temperature was 24°C. At the Harding Boulevard location, the vehicles were accelerating up a moderate slope and around a reverse loop to I-110. The vehicles at the College Drive location were accelerating on a relatively flat and straight approach ramp. The videotapes were read for license plate identification at both locations. A total of 24,133 vehicles with valid CO and HC readings were recorded. Of that total, 12,127 measurements were taken at College Drive and 12,006 at Harding Boulevard. The College Drive site is located in the southern part of Baton Rouge and is a mixed socioeconomic area, although it is fairly close to one of the high-income areas of Baton Rouge. On the average, we expected to get a large number of newer models in the vehicle fleet. Neighborhoods around Harding Boulevard are predominantly low income. This site is located between Southern University and some of the major refineries in the Baton Rouge area, and the interchange is also used heavily by airport traffic. As a result, it was expected that the fleet would more likely consist of older vehicles with the exception of the airport traffic. However, no analysis has been performed to correlate the emissions with the age of the vehicle fleet. Also, the data were not expanded and weighted; therefore, they may not be fully representative of the vehicle fleet in the Baton Rouge area. To develop reliable emissions inventories based on the collected data, we are currently conducting a study to expand and weight the data and to correlate the emissions with the age and make of the entire fleet in the Baton Rouge area.

The results are presented in Figures 4 through 8. Figure 4 shows the distribution of CO emissions by percent CO category for the 24,133 vehicles measured in Baton Rouge. The mean percent CO is 0.72, with a standard deviation of 1.429, whereas the median is only 0.18. The average emissions of 0.72 percent CO translates into 70 gCO/L. If mass emissions in grams per kilometer are required, then grams per liter must be converted to grams per kilometer by means of data on kilometers traveled per liter of gasoline. For the purpose of obtaining emissions inventories, it is likely that accurate data on liters of gasoline sold are more easily obtainable than accurate VMT data. The distribution of the data is such that more than half of the emissions come from 6.9 percent of the vehicles with emissions greater than 3.0 percent CO or 277 gCO/L of gasoline. Vehicles in this 6.9 percent category are referred to as gross CO polluters.

To convert these emission figures to total daily emissions, the daily gasoline use in the parish of East Baton Rouge is needed. Because this figure is not readily available, it was estimated by calculating an average per vehicle consumption of gasoline for Louisiana (2345 L/year/vehicle, or 6.42 L/vehicle/day) and multiplying this figure by the number of registered vehicles in the parish. This yields an estimate of 2.16 million L of gasoline used per day in the parish. Applying this figure to the mean CO emissions shows a total vehicular production of 152 tonnes (metric) of CO per day. Of that total, assuming that they consume gasoline at the average rate, the top 10 percent of polluters account for 85 tonnes, leaving 67 tonnes produced by the remaining 90 percent of vehicles. Whereas evidence suggests that a number of gross polluting vehicles are driven fewer miles than the clean vehicles, the gasoline consumption of these vehicles is usually above the average. Therefore, average gasoline figures are probably a good approximation.

Figure 5 shows the distribution of HC emissions by percent HC category for the Baton Rouge data. The average percent HC in propane equivalent is 0.09 with a median value of 0.06. The mean percent HC of 0.09 converts to 14 gHC/L. As with the CO emissions, the distribution is skewed such that more than half the emissions come from 20 percent of the vehicles with emissions greater than 0.16 percent HC or 14 gHC/L of gasoline (the HC gross polluters).

To convert HC emissions to total daily values, the same procedure can be used as was used to estimate CO emissions from the estimated daily gasoline consumption in the parish of East Baton Rouge (2.16 million L). Applying this figure to the mean HC emissions shows a total vehicular production of 29 tonnes of HC per day. Of that total, assuming that all vehicles consume gasoline at the average rate, the top 10

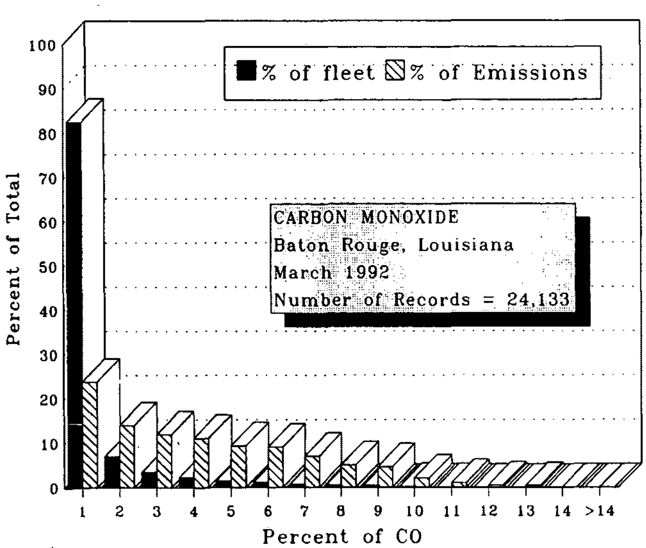

FIGURE 4 Distribution of CO emissions in Baton Rouge.

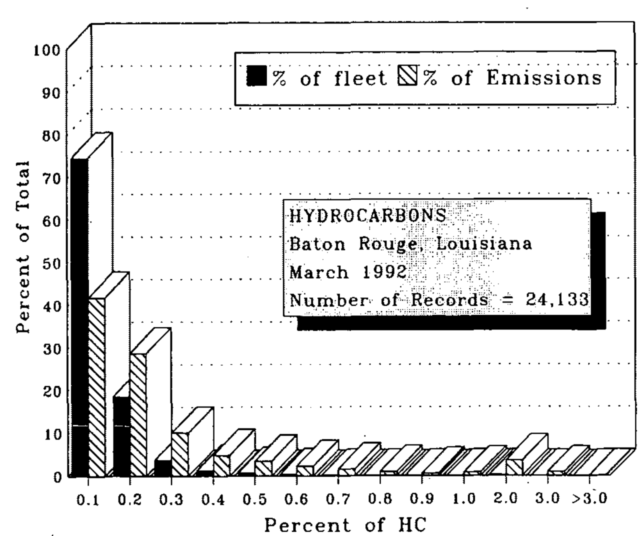

FIGURE 5 Distribution of HC emissions in Baton Rouge.

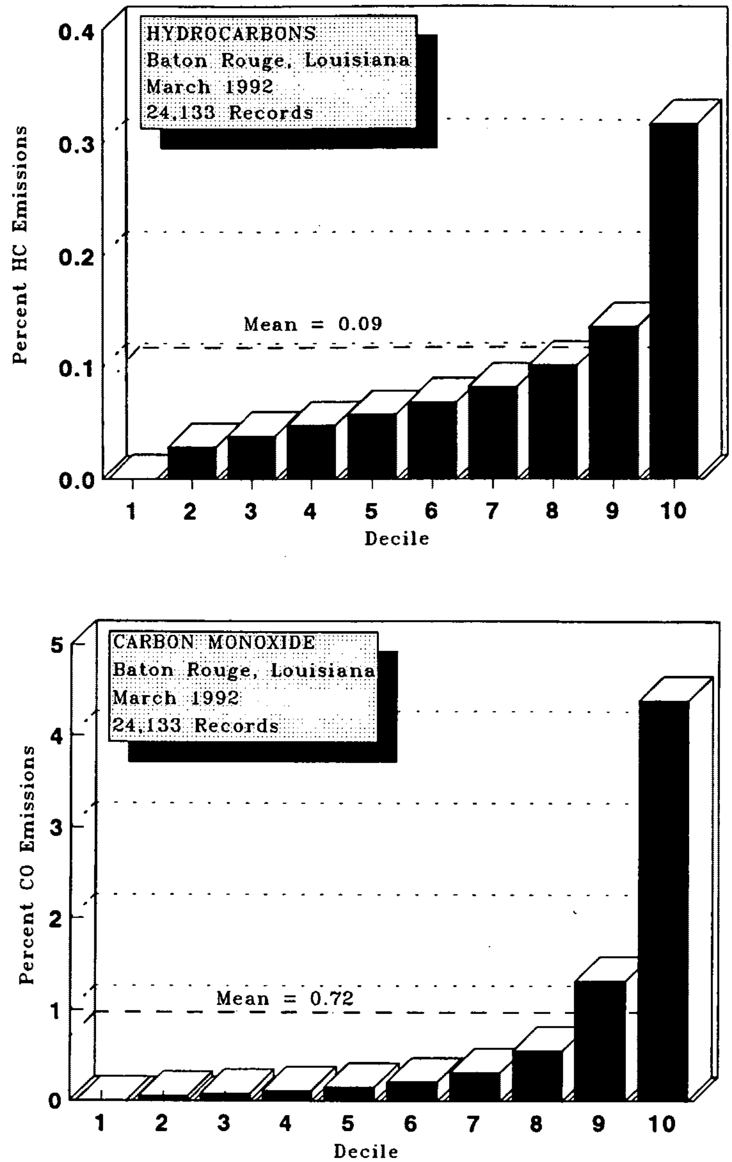

FIGURE 6 Percent CO and HC emissions in Baton Rouge organized into deciles.

percent of polluters account for 10 tonnes, leaving 19 tonnes produced by the remaining 90 percent of vehicles.

The estimated total vehicular production of each of CO and HC are based on on-road measurements that represent normal driving conditions. These figures, in reality, are expected to be higher because of higher emissions during other modes of engine operation, such as a typically fuel-rich acceleration mode. The estimated figures, however, seem to be in accordance with the modeled estimates of an analysis of air quality for the Baton Rouge urban area that was conducted jointly by the Louisiana Department of Transportation, Department of Environmental Quality, and the Capital Region Planning Commission, which is the metropolitan planning organization (*10*). Since the Baton Rouge area has been designated as a serious nonattainment area for ozone, this study only pertains to HC and NO_x. Using TRANPLAN estimates of VMT and MOBILE 4 emission factors, an estimate of total 1988 base year emissions for the Baton Rouge metropolitan area, which includes parts of the West Baton Rouge and Livingston parishes, are 31 tonnes per day of HC and 21 tonnes per day of NO_x. The 31 tonnes per day of HC compares very favorably with our estimate of 29 tonnes per day for almost the same geographical area.

Figure 6 shows, in a different way, the overall sample fleet shown in Figures 4 and 5. The sample has been subdivided into tenths, and the height of each bar represents the average emissions for that tenth of the sample fleet. The graphs show even more clearly the impact of the gross polluters representing the dirtiest 10 and 20 percent of vehicles. Clearly, vehicles in the two highest deciles (9 and 10) produce by far the largest

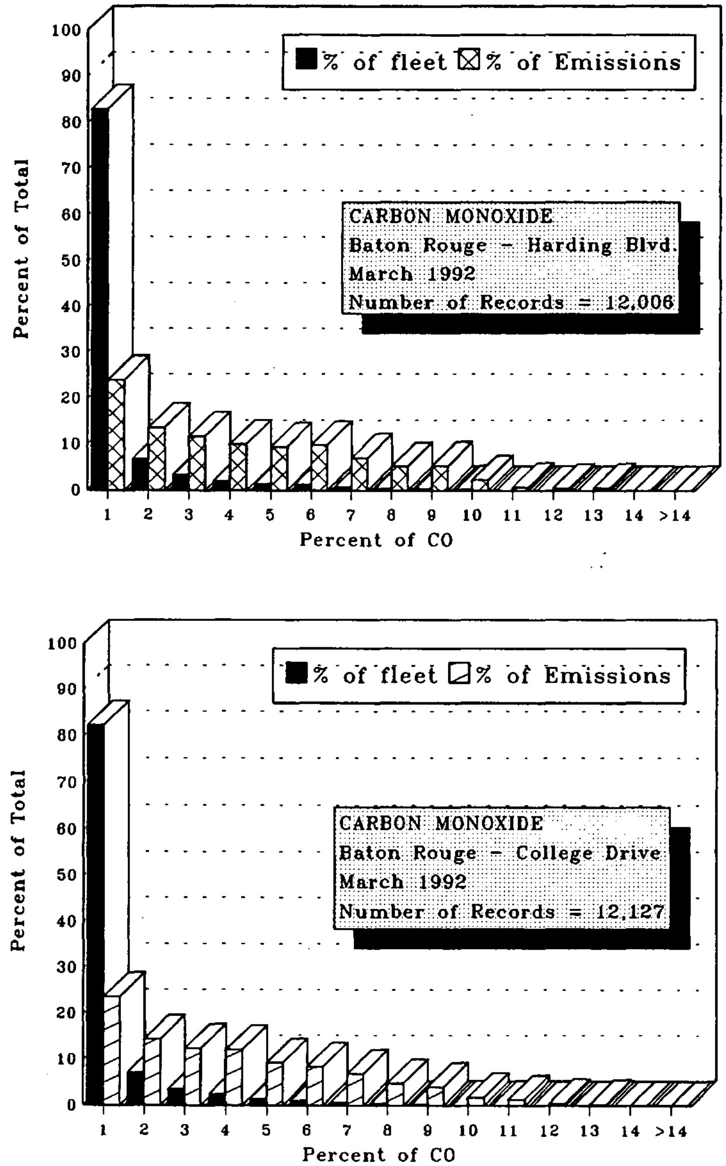

FIGURE 7 Percent CO emissions for Harding Boulevard and College Drive.

contribution to emissions. Removal or remediation of these vehicles would clearly provide considerable reductions in mobile emissions.

A comparison of the College Drive and Harding Boulevard data is shown in Figures 7 and 8. Figure 7 shows the percentage of vehicles in each CO category and the percentage of the total CO emissions for the College Drive and Harding Boulevard data. Most noteworthy are the similarities between the two sites; more than 80 percent of the vehicles are quite clean, emitting less than 1 percent CO and contributing only 24 percent of total emissions. The CO gross polluter cut-point (50 percent of emissions) is about 3 percent CO for both locations. However, for HC, the results are slightly different, as shown in Figure 8. The HC gross polluter cut-points are 0.10 and 0.15 percent for the College Drive and Harding Boulevard locations, respectively. These findings show that even though these two locations are from two demographically different areas, the CO and HC emissions are practically identical.

The impact on the effectiveness of any type of TCM because of the skew in both the HC and CO emissions frequency distributions is important. Usually, it is assumed that the impact of a TCM can be estimated from the mean. However, few vehicles are actually at the mean. In the case of CO emissions more than 80 percent of vehicles emit less than the mean, and in the case of HC emissions more than 70 percent of vehicles emit less than the mean. The effects of this can be illustrated best by the following scenarios. These scenarios are based on the estimated daily emissions for the parish of East Baton Rouge (152 tonnes of CO and 29 tonnes of HC).

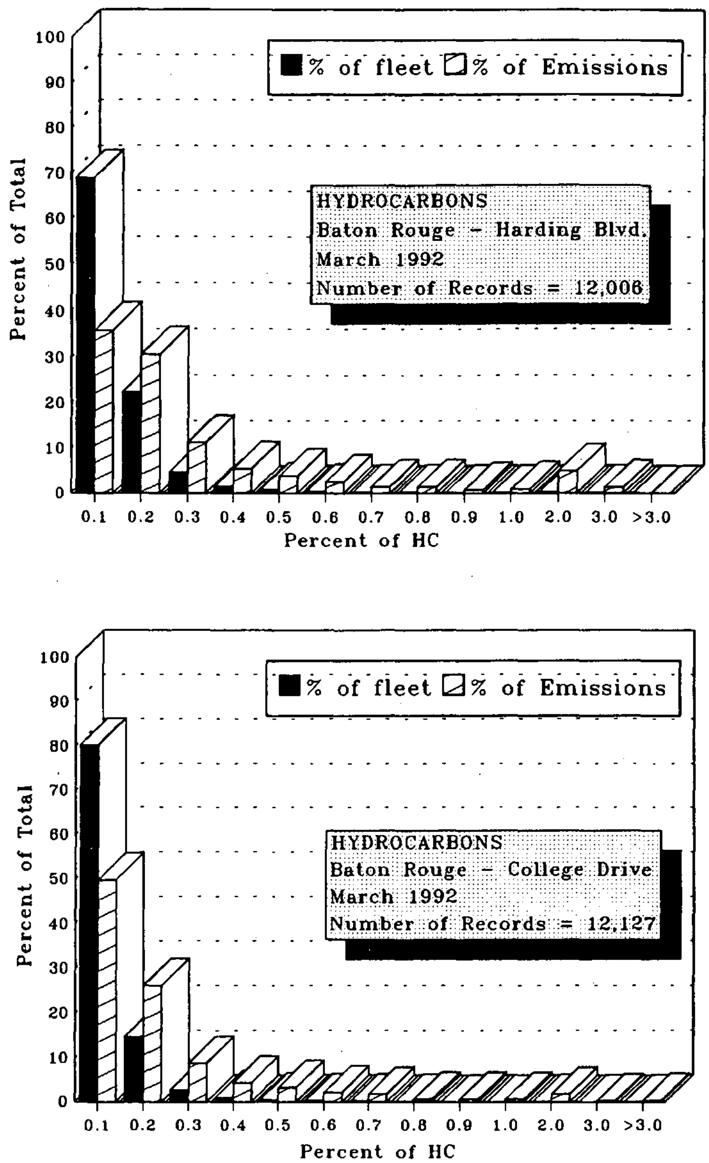

FIGURE 8 Percent HC emissions for Harding Boulevard and College Drive.

Suppose a TCM package were implemented in Baton Rouge that resulted in a 10 percent reduction in fuel use. If the strategies achieved a uniform reduction in fuel use across the entire vehicle fleet, the reductions in emissions would be 15 tonnes of CO per day and 3 tonnes of HC per day. This is a highly optimistic scenario, however, as has been shown by Fleet and DeCorla-Souza (*11*). It is most likely that TCMs based on voluntary compliance will achieve reductions primarily for those individuals who already maintain their vehicles, own newer, cleaner vehicles, and are best represented by the median emissions. In this case, the emissions reductions are more likely to be on the order of 4 tonnes of CO per day and 2 tonnes of HC per day (assuming that the 10 percent fuel reduction is achieved from 80 percent of the vehicles). On the other hand, if the TCMs were aimed at the gross polluters representing the dirtiest 10 percent of vehicles and these vehicles were brought down to the median emissions level, the emissions reductions would be 81 tonnes of CO and 8 tonnes of HC. These results are given in Table 3.

Each scenario results in impacts on 10 percent of the vehicle fleet. Scenario 2 is the most likely result of applying voluntary TCMs, whereas Scenario 1 is most likely to be the claimed result for voluntary TCMs before they are applied. Scenario 3 is clearly far more desirable than either the reality of Scenario 2 or the expectation of Scenario 1. However, Scenario 3 is possible only when remote sensing is used to identify the gross polluters and it is used in association with a follow-up to correct emissions problems of these vehicles. Such a strat-

TABLE 3 Summary of Emissions Reduction Scenarios

Scenario	CO (Tonnes/day)		HC (Tonnes/day)	
	Total Remained	Reduction Achieved	Total Remained	Reduction Achieved
1. Uniform Reduction	137	15 (10%)	26	3 (10%)
2. Reduction on Clean Vehicles Only	148	4 (3%)	27	2 (7%)
3. Targeted to 10% Dirtiest Vehicles	71	81 (53%)	21	8 (28%)

egy has the advantage of not inconveniencing vehicle owners who keep their vehicles in good condition and avoids wasting time on needless inspections of these vehicles.

CONCLUSIONS

The measurements of the 24,133 on-road vehicle emissions show that only a small percentage of vehicles contribute to more than half of the pollution from CO and HC. The average CO emissions for the measured fleet was 0.72 percent CO, which corresponds to approximately 70 g CO per liter of gasoline consumed. The average emission of hydrocarbons was 0.09 percent HC, or 14 g HC per liter of gasoline.

The results imply that on-road identification of gross polluters in conjunction with targeted repair programs may be the only strategy available currently that can have significant impacts on vehicle emissions. Remote sensing has the advantage of inconveniencing only a small fraction of the vehicle owners affected by routine I/M programs while producing potentially large reductions in emissions.

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