Comparison of Vehicular Emissions in Free-Flow and Congestion Using MOBILE4 and Highway Performance Monitoring System

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Vehicular emissions in free-flow and congested traffic conditions are quantified and compared. The 1-hr volume/capacity ratio ranges that define free-flow and congested are 0 to 0.1 and 0.975 to 1.0, respectively. The MOBILE4 computer model was used to estimate the carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NO_x) speed correction factors and emission factors for a 1988 light-duty gasoline-powered vehicle (LDGV) executing a 10-mi trip from a cold-engine start. The Highway Performance Monitoring System analytical process (HPMS AP) was used to estimate average travel speeds and idling times in free-flow and congestion on urban surface streets and expressways. For the analytical conditions, emissions of CO are generally from 11 to 22 percent, depending on the facility type; they are greater in congestion than in free-flow. HC emissions are 3 to 8 percent greater in congestion. Congested NO_x emissions are 81 to 92 percent of free-flow emissions. Only CO and HC emissions increase as congestion worsens. One problem is that the HPMS AP is unable to simulate speeds lower than 13 mph. Another is that MOBILE4 was used to estimate single LDGV emissions rather than as a standard application to a vehicle fleet. Measurement of congestion with average speeds may oversimplify the true jammed driving aspects of accelerating, decelerating, and idling, each of which has a different emissions characteristic. The variable driving conditions of congested corridors, such as operating modes and the rate and amount of speed fluctuation, need more recognition in future model improvements.

The relationship between traffic congestion and vehicular emissions is unclear. A recent General Accounting Office (GAO) study stated that traffic congestion tends to increase the level of mobile source emissions of carbon monoxide (CO) and hydrocarbons (HC) (*1*). This is primarily because CO and HC emissions are greater when a vehicle is traveling at a slow speed, which increases the travel time and, thus, the running emissions (*2*). The emissions of CO and HC are also greater when a vehicle is accelerating, decelerating, or idling than during cruising at a steady, constant speed. The purpose of this paper is to quantify and compare mobile source emissions from light-duty gasoline-powered vehicles (LDGVs) in uncongested, free-flow travel conditions with those in congested conditions. From GAO's findings, it is expected that CO and HC emissions will be greater for an LDGV in congestion than for the same LDGV in free-flow travel. Emissions of nitrogen oxides (NO_x) will also be studied.

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MOBILE4 COMPUTER PROGRAM

MOBILE4 Method for Computing Emissions Factors

The MOBILE4 computer model calculates the grams of HC, CO, and NO_x emitted per vehicle mile for eight types of gasoline and diesel-fueled highway motor vehicles for low- and high-altitude regions of the United States (*3*). Among the eight individual vehicle types considered are LDGVs, light- and heavy-duty gasoline-powered trucks, light- and heavy-duty diesel-powered vehicles, and motorcycles. The emission factors can be used, when combined with estimates of vehicular travel, to estimate the total daily or annual mobile source emissions of a pollutant within an urbanized area or region.

MOBILE4 emission factors are dependent on a series of assumptions about ambient temperature, fuel volatility level, air conditioning use, loading and trailer towing, and vehicular operating mode, speed, age and mileage accumulation. Emission factors for LDGVs can be estimated for any year between 1960 and 2020, with the previous 20 model years presumed to be operating in any calendar year. The program estimates the mileage accumulation of each model year and the distribution of model years composing the fleet in each calendar year. The emission factors for any model year gradually increase with advancing calendar years because of mechanical deterioration resulting from mileage accrual.

MOBILE4 assumes that a vehicle of a given model year, in any chosen calendar year, accrues mileage and is affected by air conditioning, loading, towing, and environmental conditions to the same extent as all other vehicles of that model year in that calendar year. These are simplifying assumptions that eliminate consideration for different makes of LDGVs, the maintenance practices of individual owners, individual driving habits, different driving environments, or unusual mileage accrual rates.

Determination of Emission Rates and Use of Program

The mathematical form of a MOBILE4 emissions factor is a basic emission rate multiplied by a series of correction factors that account for the variables listed above. The values of the basic emission rates and the correction factors were determined from the results of the Federal Test Procedure (FTP).

The FTP for gasoline-fueled vehicles is a travel pattern, conducted under known driving and environmental conditions on city streets and highways, during which exhaust emissions are measured with a dynamometer (*4*). The major parts of the test are two 7.5-mi drives—one from a cold-engine start and one from a hot-engine start—into hot-stabilized mode. This provides cold-start, hot-start, and hot-stabilized emission estimates. During the FTP driving sequences, the vehicle accelerates and decelerates as in normal urban travel. The average overall speed of each drive is 19.6 mph. The maximum speed is 56.7 mph, while a total of 17.6 percent of the test time is spent idling.

The Environmental Protection Agency (EPA) provides suggestions and recommendations of the use of MOBILE4, particularly with respect to the determination of user-supplied values for variables. The EPA expects that many users of MOBILE4 will be developing regional mobile source emission inventories and projections for use in their State Implementation Plan processes. The program is periodically updated: MOBILE1, MOBILE2, and MOBILE3 successively preceded MOBILE4. MOBILE4.1, the most recent version, was introduced in November 1991 (the program's arrival post-dated much of the work for this paper); MOBILE5 is under development.

One of MOBILE4's useful features is its sensitivity to model years, environmental conditions, and operating modes when assessing LDGV emissions. For example, a 1988 LDGV traveling 10 mi at 25 mph from a cold-engine start in calendar year 1989 with a fuel volatility of 9 psi at low altitude would emit 3.3 g of CO/vehicle-mi at 75°F and 55.2 g CO at 0°F. The same vehicle under similar conditions but from a hot-engine start would emit 1.9 g CO at 75°F and 54.7 g at 0°F. At high altitude, these values would increase from 1 to 13 percent. With a fuel volatility of 11.7 psi, the emissions would increase by about 9 percent. In this example, the CO emissions from a 1988 LDGV traveling at 25 mph would vary by more than 1,000 percent under various environmental and operating conditions (*3*). Emissions of CO per mile would further increase with older model year LDGVs, shorter trip lengths from a cold-engine start (because the LDGV would be "cold" for a greater portion of the trip), and slower average travel speeds.

Application of MOBILE4

To simplify the calculation of speed correction and emission factors, several assumptions were made. First, only LDGVs were considered, because they make up the bulk of the traffic stream. Second, LDGV model year 1988 and calendar year 1989 were used for the computations. A 1988 LDGV in calendar year 1989 would have accrued 13,118 mi on the basis of MOBILE4's assumptions. Third, the LDGV begins its trip from a cold-engine start, then moves into hot-stabilized mode. From the FTP, the initial 505 sec of any trip would be the cold-start emissions phase. Fourth, a trip length of 10 mi was used. Figure 1 shows the amount of time spent in the cold-start and hot-stabilized modes as functions of average speed for a 10-mi trip. The cold-start period, at 505 sec, is constant; the hot-stabilized time increases as the speed decreases. Finally, the following assumptions were used: 75°F ambient temperature, humidity of 75 grains of water per pound of dry air, fuel volatility of 9 psi, and no effects of tampering, an inspection and maintenance program, air conditioning use, trailer towing, or loading.

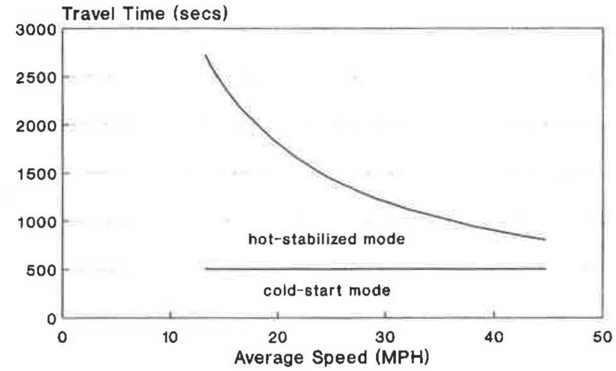

FIGURE 1 Cold-start and hot-stabilized fractions, 10-mi trip.

Speed Correction Factors

Equation 1 shows how MOBILE4 computes an LDGV emission factor. The basic emission rate for each model year in each calendar year is weighted by the fraction of total travel contributed by the model year. The composite correction factor, SALHCF, determined from Equation 2, accounts for speed, loading, and humidity variations as well as air conditioning usage and trailer towing. Variations in traffic conditions, as measured by a vehicle's average speed, are included in the speed component of the composite correction factor, SCF.

$$\mathrm{COMP}_{pn} = \sum_{i=n-19}^{n} \{\mathrm{TF}_{in} * [(\mathrm{BEF}_{pin} * \mathrm{SALHCF}_{ips} * \mathrm{RVPCF}) + \mathrm{REFUEL}_i + \mathrm{RNGLOS}_i + \mathrm{CCEVRT}_i]\} \quad (1)$$

$$\mathrm{SALHCF}_{ips} = \mathrm{SCF}_{ips} * \mathrm{ACCF}_i * \mathrm{XLCF}_i * \mathrm{TWCF}_i * \mathrm{HHH} \quad (2)$$

where

i = model year,
n = calendar year of analysis,
COMP_{pn} = composite emission factor for pollutant p,
TF_{in} = fraction of total miles driven by model year i by January 1 of calendar year n,
BEF_{pin} = basic exhaust pollutant p emission rate,
SALHCF_{ips} = composite correction factor, and
RVPCF, REFUEL_i, RNGLOS_i, CCEVRT_i = fuel volatility correction and the refueling, running loss, and crankcase and evaporative emissions factors, respectively.

The latter three are adjustments to HC emissions whereas RVPCF applies to HC and CO emissions from vehicles from model years 1971 through 1979. In Equation 2, SCF_{ips}, $ACCF_i$, $XLCF_i$, $TWCF_i$, and HHH are the speed, air conditioning, extra load, trailer towing, and humidity correction factors, respectively. HHH is used for NO_x emissions.

SCF is determined from Equations 3 through 6. For this paper it is assumed that, of all the emission correction factors, only the speed correction factor is affected by traffic conditions. Other emission correction factors may be affected by the additional miles driven to avoid congested situations; however, because traffic diversion is difficult to measure, this will be ignored.

$$SCF_{ips} = SF(s)/SF(sadj), \qquad (3)$$

where

$$SF_{ip}(s) = (A_{ips}/s) + B_{ips} \qquad (4)$$

or

$$= \exp(A_{ips} + B_{ips} * s + C_{ips} * s^2) \qquad (5)$$

where s is the average travel speed in miles per hour and A_{ips}, B_{ips}, and C_{ips} are constants that each vary with i, p, and s. Equation 4 is used for HC and CO, and Equation 5 is used for NO_x. These equations apply to all post-1976 model year LDGVs. Other equations, not shown here, apply to older LDGVs. The variable *sadj* is the FTP speed, 19.6 mph, adjusted for the fraction of cold-start and hot-start operation.

$$sadj = 1/\{[(w + x)/26] + [(1 - w - x)/16]\} \qquad (6)$$

where w and x are the fractions of vehicles in hot-start and cold-start modes, respectively. During the FTP, the test vehicle spends 27.3 percent of its operation in hot-start, 20.6 percent in cold-start, and the remaining 52.1 percent in hot-stabilized mode. In cold- or hot-start mode, for the first 505 sec of each of the 7.5-mi test trips, the average speed is 26 mph. In hot-stabilized mode, for the remaining times of both test trips, the average speed is 16 mph. The overall average speed for both test trips is 19.6 mph. When local data indicate a greater cold- or hot-start modal fraction than occurs during the FTP, the average test speed is adjusted from 19.6 toward 26 mph. When data indicate a hot-stabilized modal fraction that is greater than in the FTP, the average test speed is adjusted from 19.6 toward 16 mph.

Most of the speed correction factors were determined using tests that supplement the FTP. Seven additional tests had average speeds ranging from 2.5 to 47.9 mph. In each test, the amount of accelerating, decelerating, and idling varied. In MOBILE4, which uses the results of all seven test cycles, SCF applies to all speeds between 2.5 and 55 mph; values of SCF for speeds between 48 and 55 mph are estimated. Four new tests, the results of which are incorporated in MOBILE4.1, had average speeds of 48, 51, 58, and 64 mph, thereby allowing the accurate determination of SCF for speeds between 48 and 65 mph (*5*). Because of these revisions, MOBILE4's SCFs, for this paper, apply only to speeds between 2.5 and 47.9 mph.

HIGHWAY DESIGN TYPES AND DRIVING CHARACTERISTICS

HPMS Travel Speed Estimation

To compare vehicular emissions in free-flow and congested conditions, estimates of average speeds, accelerations, decelerations, and idling for different highway design types were made using the Highway Performance Monitoring System analytical process (HPMS AP). The HPMS AP computes average travel speeds in miles per hour for various vehicle types, classes of road, geographic areas, and other strata (*6*). The average speed is a function of initial running speed (IRS), pavement condition, roadway curves and gradients, speed change cycles (SCCs), stop cycles (STPs), and the fraction of time spent idling (IDL).

From HPMS, IRS is the initial speed in miles per hour at which vehicles tend to travel under a set of influential factors. These include the highway's location (i.e., urban or rural), functional class, design speed, speed limit, and peak-hour volume/capacity ratio (v/c). Initial running speed includes the cruising modes of a vehicle and excludes accelerations, decelerations, and stops. A speed change cycle consists of a deceleration to a final speed (FS), followed by an acceleration to IRS. A stop cycle is a speed change cycle with FS equal to zero. The percentage of travel time spent idling (at FS = 0) is IDL. Including only the effects of traffic conditions and ignoring pavement condition, curves, and gradients, an average travel speed (ATS) can be calculated from IRS, SCC, STP, and IDL, as follows:

$$\begin{aligned} ATS = 1/\Bigg[& \{[D_{SCC} * (SCC - STP)]/[(IRS + FS)/2]\} \\ & + [(D_{STP} * STP)/(IRS/2)] \\ & + \Big(\{1 - [D_{SCC} * (SCC - STP)] \\ & - (D_{STP} * STP)\}/IRS\Big) + \{IDL/[IRS * (1 - IDL)]\}\Bigg] \end{aligned} \qquad (7)$$

The numerator of Equation 7 is the unit distance of travel (1 mi), and the denominator is the time it takes to travel 1 mi, accounting for accelerations, decelerations, and idling. The variables in Equation 7 are calculated as follows:

$$SCC = 0.5 * (A - \log_{10} IRS + B) \qquad (8)$$

$$STP = 0.5 * 10^D * (2 * SCC)^C \qquad (9)$$

$$FS = [(1.0 + F) * IRS] - G \qquad (10)$$

$$D_{SCC} = (IRS^2 - FS^2)/RATE \qquad (11)$$

$$D_{STP} = IRS^2/RATE \qquad (12)$$

where

SCC, STP = number of speed change and stop cycles per vehicle mile, respectively;

FS = average final speed, or low point, of all speed change cycles;

A, B, C, D, F, and G = constants that depend on the facility type; and

D_{SCC}, D_{STP} = distances traveled during a speed change and a stop cycle, respectively.

Both equations assume constant acceleration and deceleration rates (RATE) of 2.5 ft/sec/sec for speeds above 30 mph and 5 ft/sec/sec for speeds below 30 mph (*7*). These rates are similar to those recorded by vehicles during the FTP and in supplemented test cycles.

The HPMS AP is primarily used to identify highway conditions, estimate capital investment needs, and measure changes in highway conditions over time (*8*). To identify highway conditions, the HPMS AP can be used to compute performance measures such as average travel speed. The HPMS AP average speed estimation procedure calculates ATS as a function of initial running speed and the number of speed change and stop cycles. IRS, which is associated with cruising rather than speed changes, is a function of v/c. The values of SCC and STP are the estimated numbers of deceleration-acceleration cycles; these two variables are functions of IRS. With this approach, the effects of the demand-supply relationship on ATS may be double-counted. That is, v/c, SCC, and STP, which are measures of roadway capacity usage, each reduce the initial running speed. The result is that average travel speeds may be slightly lower than they should be. This issue is to be examined in proposed research. For this paper, the HPMS AP speed estimation procedure has been used as is.

The speed estimation procedure considers idling in addition to running speed, accelerations, and decelerations. IDL is a constant based on the facility type and v/c. Assuming that the desired travel time is the time that would have been spent traveling at the initial running speed, the total travel time is the desired time plus the time spent idling. The time spent idling per mile traveled (T_{idle}) is therefore

$$T_{idle} = \mathrm{IDL}/[(1 - \mathrm{IDL}) * \mathrm{IRS}] \quad (13)$$

The HPMS AP uses values of IDL that, for v/c less than 0.9, range from 1.9 percent on freeways and expressways to 8.1 percent on multilane roads. For v/c greater than 0.9, IDL ranges from 6.5 percent on freeways and expressways to 31.4 percent on multilane roads. These are fairly similar to the idling times experienced by vehicles in the FTP and supplemented test cycles.

Highway Design Types

Equations 7 through 13 show that, in the HPMS AP, average speed estimation is related to the initial running speed and to some facility type constants. The facility types considered by the AP fall within four classes: freeways and expressways, multilane (nonfreeway) roads, two- or three-lane roads, and one-way roads. A different initial running speed is associated with each unique combination of functional class, speed limit, highway design speed, lanes, and v/c. Initial running and average travel speeds can be estimated for urban facilities for both free-flow (v/c = 0 to 0.1) and congested traffic conditions (v/c = 0.975 to 1.0). Considering only urban facilities with average speeds within the range that MOBILE4 is suitable for (2.5 to 47.9 mph) and excluding one-way roads, there are 27 facility types having unique sets of free-flow and congested IRS values. These 27 facility types, which include all urban nonfreeway roads (expressways, multilane, and two- or three-lane roads), have 15 free-flow and 11 congested IRS values. Tables 1 and 2 list these 26 values of IRS along with descriptions of the associated facility types. Then, employing Equations 7 through 13, the tables summarize the average travel speed associated with each initial running speed and facility

TABLE 1 Initial and Average Travel Speeds and Urban Highway Design Types: Midpoint of v/c Range = 0.05 (*6*)

IRS (mph)	Facility Type	Speed Limit (mph)	AHS (mph)	Lanes	ATS (mph)
48.8	multilane	≥ 45	≥ 40	≥ 4	32.3
48.5	2-3 lanes	≥ 45	any	2-3	29.4
47.9	expressway	≥ 45	≤ 55	any	44.7
46.0	expressway	40	any	any	42.8
44.0	multilane	40	≥ 40	≥ 4	28.8
43.6	2-3 lanes	40	any	2-3	26.4
41.0	expressway	35	any	any	38.0
39.0	multilane	≥ 35	≥ 30	≥ 4	29.7
38.7	2-3 lanes	30-35	any	2-3	23.7
35.0	expressway	30	any	any	32.2
33.0	multilane	30	any	≥ 4	25.3
29.0	expressway	≤ 25	any	any	27.4
28.0	multilane	≤ 25	any	≥ 4	21.7
25.0	multilane	any	< 30	≥ 4	19.6
24.8	2-3 lanes	≤ 25	any	2-3	19.4

Note: AHS = highway design speed.

TABLE 2 Initial and Average Travel Speeds and Urban Highway Design Types: Midpoint of v/c Range = 0.9875 (*6*)

IRS (mph)	Facility Type	Speed Limit (mph)	AHS (mph)	Lanes	ATS (mph)
29.0	expressway	≤ 25	> 65	≥ 4	26.2
28.7	expressway	≥ 30	60-65	any	25.9
28.5	expressway	≤ 25	60-65	any	25.7
27.3	expressway	any	≤ 55	any	24.6
22.8	multilane	any	≥ 40	≥ 4	16.4
22.1	multilane	any	30-40	≥ 4	15.9
21.1	multilane	any	< 30	≥ 4	15.3
19.7	2-3 lanes	≥ 45	any	2-3	14.2
19.4	2-3 lanes	≤ 40	any	2-3	14.0
19.2	2-3 lanes	30-35	any	2-3	13.9
18.2	2-3 lanes	≤ 25	any	2-3	13.2

Note: AHS = highway design speed.

type. The values of ATS range from 13.2 to 44.7 mph. From Figure 1, at 44.7 mph, the cold-start operating mode fraction is 62.7 percent; at 13.2 mph, the fraction is only 18.5 percent of the 10-mi trip travel time. Thus, any increased emissions that occur with slower speeds and longer travel times may be offset somewhat by the greater cold-start fraction that is present with high average speeds.

INTEGRATION OF MOBILE4 AND HPMS AP

Relationships Between Speed Correction and Emission Factors

An important assumption of this paper is that the speed correction factor is proportional to the composite emission factor for each pollutant. This relationship is shown in Equations 1 and 2. Figure 2 shows SCF versus the emission factors for CO, HC, and NO_x for a 10-mi trip by a 1988 LDGV at speeds ranging from 2.5 to 47.9 mph. The driving and environmental conditions assumed are as follows: calendar year 1989, low altitude, an ambient temperature of 75°F, humidity of 75 grains of water per pound of dry air, fuel volatility of 9 psi, a cold-engine start (with the initial 505 sec composing the cold-start phase), and no effects of tampering, an inspection and maintenance program, air conditioning use, trailer towing, or loading. Additionally, free-flow conditions are represented by a *v/c* of 0 to 0.1, whereas congestion has a *v/c* of 0.975 to 1.0. Both CO and HC emissions increase, nearly linearly, as SCF increases. The emissions of NO_x decrease, almost linearly, as SCF increases. The CO emissions factor ranges from 2.9 g/mi at 47.9 mph to 7.4 g/mi at 2.5 mph. The corresponding range of SCFs is from 3.17 to 0.45. The HC emissions factor increases from 1.0 to 2.1 g/mi, with corresponding SCFs between 6.72 and 0.45 for the same range of speeds. Hence, CO emissions are more sensitive to changes in speed than HC emissions are. Notably, based on MOBILE4.1, both the CO and HC emission factors would begin to increase at speeds greater than 48 mph (*9*). Both the SCFs and emission factors for NO_x increase between 2.5 and 47.9 mph.

Values of Speed Correction and Emission Factors

The next steps in the analysis integrated MOBILE4's method for computing SCF and emission factors with the HPMS AP

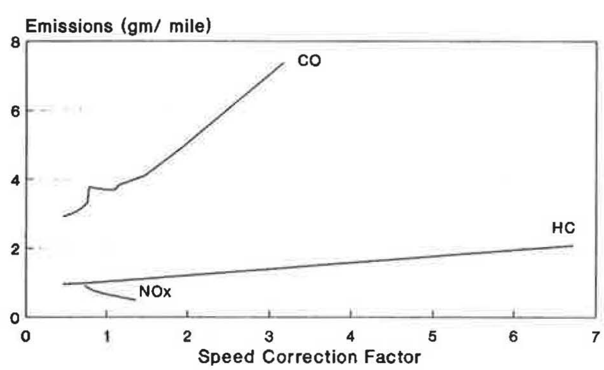

FIGURE 2 Speed correction and emission factors: 1988 LDGV, 10-mi trip, 2.5 to 47.9 mph, MOBILE4 estimates.

speed estimation procedures for free-flow and congested traffic conditions. Values of speed correction and emission factors were computed using the average speeds summarized in Tables 1 and 2. Table 3 summarizes free-flow and congested SCFs for CO, HC, and NO_x for a 10-mi trip on seven common urban facility types. The facilities are expressways with 45-mph speed limits, 55-mph design speeds, and six lanes; multilane (i.e., four-lane) roads with 45-, 40-, and 35-mph speed limits; and two- or three-lane roads with 30- and 25-mph speed limits. The associated values of SCF indicate how LDGV emissions would be expected to differ between free-flow and congested traffic conditions.

From Table 3, for CO emissions in free-flow conditions on urban facilities, SCF is lowest on an expressway (0.47) and greatest on a two- or three-lane road with a 25-mph speed limit (0.97). From Table 4 and Figure 3, the related CO emission factors are 2.93 and 3.77 g/mi, respectively. In congestion, SCF for CO emissions is lowest on an expressway (0.75) and greatest on a two- or three-lane street (1.12). The CO emission factors are 3.27 and 3.70 g/mi, respectively. The free-flow CO emission factor on a two- or three-lane road is slightly greater than in congestion. Table 4 and Figure 3 show that the CO emission factor increases as speed decreases from 44.7 to 19.4 mph, decreases as the speed falls to 13.9 mph, then increases as the speed drops to 13.2 mph. Hence, between 13.2 and 44.7 mph, for a 10-mi trip done under the assumed conditions, the CO emissions per mile are greatest in free-flow on a two- to three-lane road with a 25-mph speed limit. In congestion, CO emissions would be nearly equivalent on all urban surface streets. On a congested expressway, the CO emission factor would be about 12 percent less than on congested surface streets.

Table 3 shows that values of SCF for HC emissions are similar in magnitude to those for CO. In free-flow SCF is lowest on an expressway (0.47) and greatest on a two- or three-lane road with a 25-mph speed limit (0.92). From Table 4 and Figure 3, the corresponding HC emission factors are

TABLE 3 Speed Correction Factors for Some Common Urban Facility Types

Facility Type	Traffic Conditions	ATS (mph)	SCF CO	SCF HC	SCF NO_x
expressway (45/6)	free-flow	44.7	0.47	0.47	0.74
	congested	24.6	0.75	0.75	0.90
multilane (45/4)	free-flow	32.3	0.60	0.60	0.82
	congested	16.4	1.03	1.08	1.02
multilane (40/4)	free-flow	28.8	0.66	0.66	0.85
	congested	16.4	1.03	1.08	1.02
multilane (35/4)	free-flow	29.7	0.64	0.64	0.84
	congested	15.9	1.04	1.10	1.03
2 or 3 lane (30/2)	free-flow	23.7	0.77	0.77	0.91
	congested	13.9	1.09	1.26	1.07
2 or 3 lane (25/2)	free-flow	19.4	0.97	0.92	0.97
	congested	13.2	1.12	1.32	1.08

The numbers in ()'s following the facility type designation give the speed limit and the number of lanes.

SOURCE: HPMS AP, MOBILE4; Figure 2 and Tables 1 and 2.

TABLE 4 LDGV Emissions Estimates for Some Common Urban Facility Types

Facility Type	Traffic Conditions	ATS (mph)	Emissions (gm/ mile) CO	HC	NO_x
expressway (45/6)	free-flow	44.7	2.93	0.96	0.89
	congested	24.6	3.27	0.99	0.72
multilane (45/4)	free-flow	32.3	3.04	0.97	0.78
	congested	16.4	3.70	1.04	0.65
multilane (40/4)	free-flow	28.8	3.13	0.98	0.75
	congested	16.4	3.70	1.04	0.65
multilane (35/4)	free-flow	29.7	3.10	0.97	0.76
	congested	15.9	3.70	1.05	0.65
2 or 3 lane (30/2)	free-flow	23.7	3.31	0.99	0.71
	congested	13.9	3.69	1.07	0.63
2 or 3 lane (25/2)	free-flow	19.4	3.77	1.01	0.68
	congested	13.2	3.70	1.08	0.62

The numbers in ()'s following the facility type designation give the speed limit and the number of lanes.

See the text for the conditions assumed for the computation of emissions.

SOURCE: HPMS AP, MOBILE4 and Table 3.

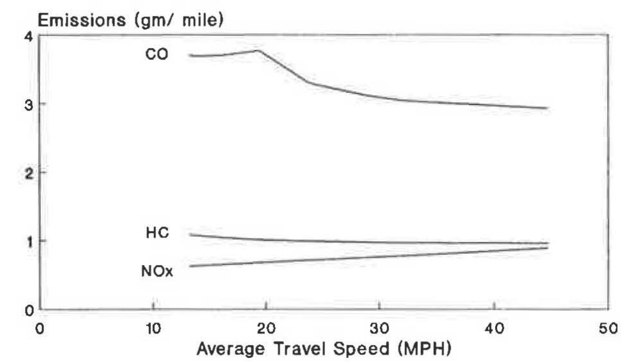

FIGURE 3 LDGV emissions at HPMS speeds: 1988 LDGV, 10-mi trip, cold-engine start, 1989 MOBILE4 estimates.

0.96 and 1.01 g/mi, respectively. In congestion, SCF is lowest on an expressway (0.75) and greatest on a two- or three-lane road (1.32). The corresponding emission factors are 0.99 and 1.08 g/mi, respectively. On all urban facilities studied, the HC emission factor is greater in congestion than in free-flow for a 10-mi trip executed under the assumed conditions.

From Table 3, SCF values for NO_x emissions in free-flow are lowest on an expressway (0.74) and greatest on a two- or three-lane road with a 25-mph speed limit (0.97). From Table 4 and Figure 3, the corresponding NO_x emission factors are 0.89 and 0.68 g/mi, respectively. In congestion, the SCF values for NO_x are lowest on an expressway (0.90) and greatest on a two- or three-lane road (1.08). The corresponding emission factors are 0.72 and 0.62 g/mi, respectively. On all urban facilities studied, the NO_x emission factors in congestion are lower than those for free-flow conditions for a 10-mi trip executed under the assumed conditions. The relationship between NO_x emissions and congestion is inverse to those of CO and HC emissions.

TABLE 5 Free-Flow and Congested LDGV Emissions

Facility Type	Free-Flow and Congested ATS (mph)	Ratio of Congested to Free-Flow Emissions CO	HC	NO_x
expressway (45/6)	44.7/ 24.6	1.12	1.03	0.81
multilane (45/4)	32.3/ 16.4	1.22	1.07	0.84
multilane (40/4)	28.8/ 16.4	1.19	1.07	0.87
multilane (35/4)	29.7/ 15.9	1.19	1.07	0.85
2 or 3 lane (30/2)	23.7/ 13.9	1.11	1.08	0.88
2 or 3 lane (25/2)	19.4/ 13.2	0.98	1.07	0.92

The numbers in ()'s following the facility type designation give the speed limit and the number of lanes.

See the text for the conditions assumed for the computation of emissions.

SOURCE: HPMS AP, MOBILE4 and Table 4.

Table 5 lists the ratios between the congested and free-flow CO, HC, and NO_x emission factors for six urban facility types. On five of the facilities, CO emissions would be 11 to 22 percent greater in congestion than in free-flow. For a two- or three-lane road with a 25-mph speed limit, CO emissions would be about 2 percent greater in free-flow than congestion. On all six facilities, HC emissions would be from 3 to 8 percent greater in congestion than free-flow. Both CO and HC emissions are generally greater in congested than in free-flow conditions, but CO is more sensitive to changes in average speeds than HC. On all six facilities, NO_x emissions in congestion would be from 81 to 92 percent of free-flow emissions. Hence, emissions of NO_x are lower in congestion than free-flow because of the lower average travel speeds. These results, of course, are applicable to the conditions assumed for the computations.

Other combinations of assumptions would likely yield results different from those reported here. For example, for the 10-mi trip used for the computations, the cold-start fraction ranged from 18.5 to 62.7 percent of the total trip for the speeds studied (13.2 to 44.7 mph), as shown in Figure 1. For a 20-mi trip, over the same range of speeds, the cold-start fraction would range from 9.3 to 31.4 percent of the trip time. The CO, HC, and NO_x emission factors would be lower for the longer trip because a reduced amount of driving would be conducted in cold-start mode. For a 1-mi trip, the cold-start fraction for the entire range of speeds would be 100 percent. For this trip, the emission factors would be greater than for a 10- or 20-mi trip. The emission factors of all three pollutants would also be greater for an LDGV older than 1988, at high altitude, at a higher fuel volatility, or with air conditioning use, trailer towing, or loading. A higher humidity would contribute to greater NO_x emissions, and a lower ambient temperature would lead to greater emissions of all three pollutants. A very high ambient temperature would propagate higher CO and HC emissions. The emission factors of all three pollutants would be lower with a hot-engine start or with an inspection and maintenance program in effect. The effect of variations in driving and environmental conditions presents many opportunities for further analysis of emissions in free-flow and congested travel.

Further examination of SCF reveals that its value increases sharply at speeds below 15 mph, particularly for CO and HC

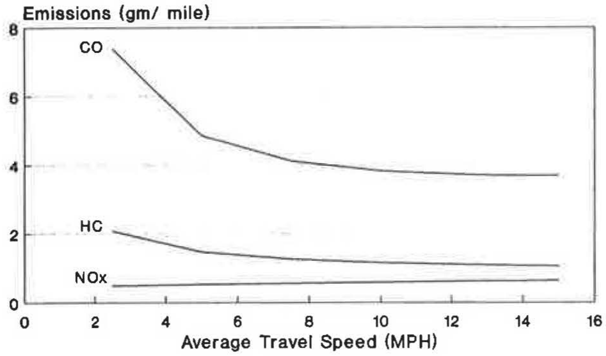

FIGURE 4 LDGV emissions at low speeds: 1988 LDGV, 10-mi trip, cold-engine start, 1989 MOBILE4 estimates.

(*3*). For example, for a 1988 LDGV traveling at 13.2 mph for a 10-mi trip from a cold-engine start, the SCFs for CO, HC, and NO_x would be 1.12, 1.32, and 1.08, respectively. From Figures 2 and 4, at 10 mph, the SCF values would be 1.27, 1.72, and 1.16 for CO, HC, and NO_x, respectively. At 5 mph, the values would be 1.90, 3.39, and 1.29; at 2.5 mph, they would be 3.17, 6.72, and 1.36. Between 13.2 and 2.5 mph, from Figure 4, the CO emissions factor would increase from 3.70 to 7.38 g/mi. Over this range of speeds, as shown in Figure 4, the HC emissions factor would increase from 1.08 to 2.08 g/mi, and the NO_x emissions factor would decrease from 0.62 to 0.49 g/mi. The HPMS AP does not calculate an average speed of less than 13.2 mph on any urban facility, even for congested surface streets experiencing a *v/c* of 0.975 to 1.0. Analysis of the severe congestion implied by such low speeds would require local speed, delay, and queueing data rather than the procedure used by the HPMS AP. It is also not clear that the MOBILE4 model would be appropriate for emissions analysis on the scale at which localized traffic data would be collected.

CONCLUSION AND RECOMMENDATIONS

It is evident that MOBILE4 calculates emissions assuming that the driving cycle values of the FTP and supplemental test cycles are typical for their speeds. The amounts of cruising, acceleration, deceleration, and idling during the tests are presumed to be applicable to all other driving situations. However, many combinations of the amount of time spent in each of the four driving cycle elements can produce the same average speed. The speed correction factor is an attempt to recognize this. For example, the emissions test procedure for very low driving speeds uses more accelerating, decelerating, and idling than the FTP does. However, here, too, the emission rates are specific to the driving cycle values of the test. This is a concern because the emission rates of the driving cycle elements may be very different. Sensitivity to the amount of cruising, accelerating, decelerating, and idling, and to the intensity of accelerations and decelerations, is not included in the test procedures and therefore does not exist in MOBILE4.

The ideal model for this paper would integrate estimation procedures for exhaust emissions with a driving simulation model that is sensitive to ambient traffic conditions. The simulator would quantify the amounts of driving in each of the cruising, accelerating, decelerating, and idling modes. Evans (*10*), for example, examined the relationship between the driving modes and emissions using the FTP and 12 automobiles from the 1975–1976 model year. Using the limited, and now old, data, Evans showed that HC emissions are strongly correlated with average travel speed. He also demonstrated a weak correlation between CO and NO_x emissions and average speed but a high correlation between the two pollutants and acceleration-deceleration measures. Similar research is needed on modern vehicles to determine the current relationships between traffic variables and emissions. One requirement of the 1990 Clean Air Act Amendments is the testing of "off-cycle" emissions at steeper acceleration and deceleration rates than have been used in past test procedures. The results may update earlier research findings with emission rates that are accurate for traffic conditions on surface streets and in congestion.

Further points are indicated by this study, even though there is a need for an improved approach at quantifying and comparing free-flow with congested emissions. First, for the assumed driving and environmental conditions, emissions of CO and HC are generally greater in congestion than in free-flow on urban surface streets and expressways. Second, for the assumed conditions, emissions of NO_x are lower in congestion than in free-flow on urban surface streets and expressways. Traffic conditions measured with local data could produce different results. That is, local data could exhibit higher average free-flow or lower congested speeds than those computed by HPMS for similar highway design types. The retrieval and analysis of such data are recommended to provide an alternative to the HPMS speed estimates.

To reduce urban area CO and HC emissions, the easing of congestion would be beneficial because travel speeds would increase and travel times would decrease. The emissions of NO_x, however, may increase with reduced congestion and greater speeds. This proposes a problem, since NO_x builds up in the atmosphere, potentially contributing to the greenhouse effect. Reducing trip ends, for the purposes of reducing motor vehicle travel as well as cold-engine starts and HC evaporation, would certainly ease emissions. Advances in vehicle technology should also continue to benefit the emissions-versus-speed relationship.

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