Corrections to Hot and Cold Start Vehicle Fractions for Microscale Air Quality Modeling

PAUL E. BENSON

A model is developed to correct hot and cold start vehicle fractions for input to conventional emission factor models. The method is appropriate for microscale air quality analyses of urban freeways and arterials. It is based on the propositions that hot and cold start transient emissions are highest at engine start-up and gradually diminish to zero as engine and catalyst reach a stable operating temperature and that the distribution of vehicles on urban freeways and arterials in the warm-up phase of operation is skewed such that more vehicles are near the end of the phase than the beginning. Use of the FTP-75 split 27 percent hot and 21 percent cold starts may result in significant overpredictions of air quality impacts for urban freeways. Corrected values of 1 and 5 percent, respectively, are predicted by the model.

Estimates of vehicle emission factors play a key role in evaluating microscale air quality impacts of proposed highway facilities. An important component of this estimation process is the determination of the fraction of vehicles in the warm-up phase of operation. During this phase, vehicles release excess quantities of carbon monoxide (CO) and hydrocarbons. These are referred to as transient emissions because their release occurs only during warm-up. After the engine and exhaust system reach a stable running temperature, called the hot stabilized mode, average CO and hydrocarbon emissions drop to much lower levels. Because the amounts of transient emissions are often quite large in comparison to those of hot stabilized emissions, their estimation is an important part of the overall emissions modeling process.

If the modeling of transient emissions is to be better understood, the operation of the internal combustion engine during warm-up must be considered. When an engine is cold, fuel fed to its cylinders is not readily vaporized. To achieve the ratio of air to fuel vapor needed for combustion, a fuel-rich mixture is used. The colder the air temperature, the more excess fuel needed. Much of this fuel leaves in the exhaust stream as unburned or partially burned carbon compounds. The suppression of combustion in the vicinity of the relatively cold cylinder walls further contributes to elevated levels of CO and hydrocarbons. For catalyst-equipped vehicles, the ability to deal with excess emissions during warm-up is controlled by the temperature of the catalyst.

The length of time required for warm-up of both engine and catalyst depends primarily on initial temperature of the components, engine size, and vehicle speed (*1*). A start is categorized as either hot or cold, depending on the length of time the engine has been off and whether or not the vehicle has a catalyst. For purposes of vehicle certification, the warm-up phase is defined by a standard driving cycle that is part of the 1975 Federal Test Procedure (FTP-75) (*2*). This cycle represents the first 3.59 mi of a typical urban trip, lasting 505 s at an average speed of 25.6 mph.

The MOBILE3 computer program (*3*) is used in most states to estimate vehicle emissions for proposed highway facilities. MOBILE3 was derived primarily from emissions data that were collected in accordance with FTP-75. Composite emission factors are reported by the program in grams per vehicle mile (g/vmi) as a function of ambient temperature, average vehicle speed, vehicle type distribution, calendar year, operating mode distribution, and several other variables. The model is extremely sensitive to the cold start portion of the operating mode distribution, especially at low temperatures.

Figure 1 shows MOBILE3 cold start and hot stabilized emission factors as a function of ambient temperature for a 1990 mix of light-duty gas vehicles (LDGVs) operating at an average speed of 20 mph. The cold start results represent the sum of both transient and hot stabilized emissions, and the difference between the curves represents the transient contribution. At 750°F, the average CO emissions of vehicles in cold start mode is three times that of hot stabilized vehicles. This increases to nearly six times at 0°. Hot start emission factors (not plotted) are similar to the hot stabilized factors. The figure shows that accurate estimation of the cold start vehicle fraction is critical to the accuracy of the overall composite emission factor estimate, especially at low temperatures. Estimation of the hot start fraction is much less important.

Because combustion efficiency increases with engine temperature (*4*), transient emissions from hot and cold starts will begin high and then gradually decrease to zero as the engine and catalyst approach stable operating temperatures. If the distribution of travel distances for vehicles in the warm-up phase is such that more vehicles are in the later stages of warm-up, the overall transient emissions on a particular highway segment may be lower than expected. This is frequently the case in urban corridors, where vehicles that have traveled longer distances are drawn from a larger area of potential trip origins. Previous efforts at characterizing the fractions of vehicles in hot and cold start operation make no correction for this factor (*5, 6*).

California Department of Transportation, Transportation Laboratory, 5900 Folsom Blvd., Sacramento, Calif. 95819.

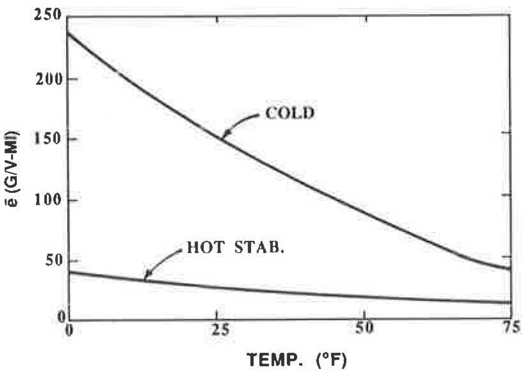

FIGURE 1 MOBILE3 composite emission factors for cold transient and hot stabilized operation (1990 LDGV mix at 20 mph).

TRANSIENT EMISSIONS MODEL

The conventional method of modeling transient emissions for microscale applications is to add an average transient emission rate, $\bar{e}_t$, to the baseline hot stabilized rate for the fraction of vehicles in the warm-up phase. This approach is applied to both hot and cold start fractions. The value of $\bar{e}_t$ is defined as

$$\bar{e}_t = \frac{E_t}{R} \tag{1}$$

where E_t equals the average transient emissions per vehicle trip and R equals the total distance traveled during warm-up (3.59 mi). A more comprehensive model for describing the distribution of transient emissions can be fashioned by establishing a set of boundary conditions consistent with the smooth, continuous nature of the warm-up process. A representation of this model is given in Figure 2. Note that either time or distance could be used as the abscissa in this model. Distance was chosen so that the model would be compatible with the travel distribution model discussed in the next section.

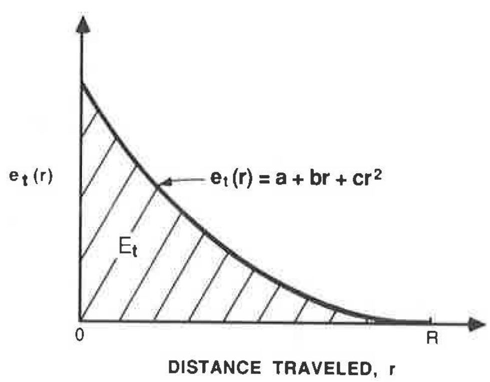

FIGURE 2 Transient emissions model.

By definition, transient emissions will dissipate to zero by the end of the warm-up phase so that

$$e_t(r)\big|^R = 0 \tag{2}$$

where $e_t(r)$ represents the rate of excess emissions (g/vmi) as a function of distance traveled, r. Furthermore, it is reasonable to assume that the rate of change of $e_t(r)$ will decrease during warm-up and will approach zero as a smooth function so that

$$\frac{de_t(r)}{dr}\bigg|^R = 0 \tag{3}$$

The quadratic equation

$$e_t(r) = a + br + cr^2 \tag{4}$$

is the simplest functional form that will satisfy the boundary conditions of Equations 2 and 3. The final boundary condition needed to evaluate the coefficients in Equation 4 is

$$E_t = \int_0^R e_t(r)\, dr \tag{5}$$

Simultaneous solution of Equations 2, 3, and 5, with substitution into Equation 4, yields

$$e_t(r) = 3\bar{e}_t\left[1 - 2\frac{r}{R} + \left(\frac{r}{R}\right)^2\right] \tag{6}$$

Equation 6 may also be cast as a function of the fraction of the warm-up phase completed, $f_r = r/R$. This form of the equation leads to a generalized relation between the fraction of transient emissions released, f_e, and f_r:

$$f_e = 3\int_0^{f_r}(1 - 2f_r + f_r^2)\, df_r \tag{7}$$

Performing the indicated integration and then simplifying gives

$$f_e = f_r^3 - 3f_r^2 + 3f_r \tag{8}$$

Equation 8 provides a simple way to calculate the cumulative amount of transient hot or cold start emissions up to any point in the 3.59-mi warm-up phase. Measured results of f_e, based on cold start CO emissions at 200°F for twenty-five 1967 to 1974 LDGVs (7), are compared to Equation 8 in Figure 3. The measurements were made at 137 and 343 s into the cold start portion of the FTP-75 test cycle. In terms of distance traveled, these times are equivalent to f_r = 0.19 and 0.73, respectively. The hot stabilized component was deducted so that the measurements could be compared directly to the transient emissions model. The mean and 95 percent confidence limits of the mean for the 25 vehicles are also plotted in Figure 3.

Clearly, the model falls short of accurately predicting f_e during the early phase of warm-up. The vehicles are emitting a greater proportion of their transient cold start emissions in the first 137 s than was predicted. Addition of a cubic term to Equation 4 would provide a better fit of the data but would require a fourth, somewhat arbitrary boundary condition. Because Equation 8 provides a conservative estimate of fe that is superior to the straight line estimate, $f_e = f_r$, and because it is based on acceptable boundary conditions, it will be used.

TRAVEL DISTRIBUTION MODEL

As long as vehicles operating in the warm-up phase are distributed equally by distance traveled, $\bar{e}_t$ adequately describes

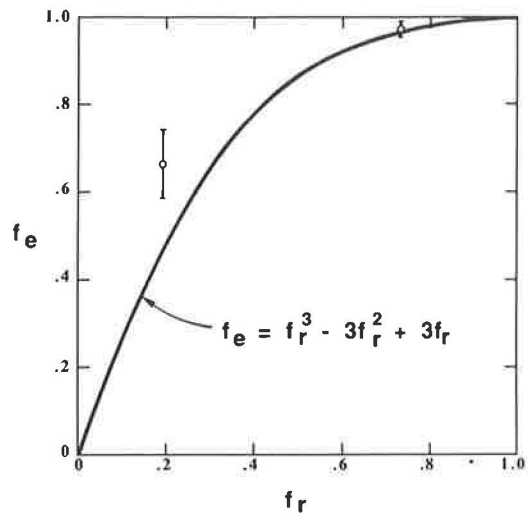

FIGURE 3 Verification of transient emissions model, illustrating the mean and 95-percent confidence limits for measured results from 25 LDGVs.

the transient emission rate. However, urban freeways and many urban arterials will attract vehicle trips at a more or less constant rate over distances approaching R. If evenly distributed trip generation can be assumed, vehicles that travel a longer distance will be drawn from a larger area of potential trip origins and will therefore be more numerous. Applying $\bar{e}_t$ to the overall fraction of vehicles in either hot or cold start mode without a correction for this factor will result in overestimates of the actual emissions.

To illustrate this point, consider the highway segment of length R presented in Figure 4*a*, with travel in one direction only, carrying an average traffic volume of V in vehicles per hour (vph) and drawing traffic from a corridor half-width W at a uniform rate v (vph/mi). Let the fraction of vehicles entering the highway in the warm-up phase be denoted as f_t, and let the travel distance from coordinates x, y to point P via the most direct route over a rectangular street grid be represented by r, such that

$$r = |x| + |y| \qquad (9)$$

To model the number of vehicles at P in the warm-up phase that have traveled a distance r, three assumptions must be made. First, assume that the production of trips passing point P is constant over the corridor half-width. Second, assume that V is constant over the highway segment. Third, assume that all vehicles exiting the highway are in hot stabilized mode. For major urban corridors in which microscale modeling results are most critical, these assumptions approximate actual conditions during peak commute hours.

All vehicles entering the highway upstream of the segment will be in the warm-up phase at P because their travel distance will exceed R. Similarly, vehicles beginning trips in the shaded area may enter the segment after traveling less than R, but they will have exceeded this travel distance by the time they reach P. Although these vehicles are included in the estimate of f_t, they will not be emitting transient emissions at P. Only

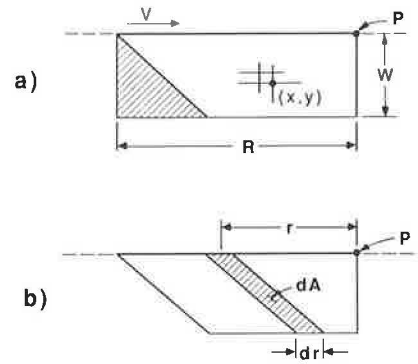

FIGURE 4 Illustration of the travel distribution model.

vehicles that started trips within the unshaded area will be in the warm-up phase at P. The total vph passing P in the warm-up phase is given by

$$N_t = f_t v \left(R - \frac{W}{2} \right) \quad W \leq R \qquad (10)$$

The distribution of hot or cold start vehicles by travel distance can be determined by applying the proportion of an infinitesimal element area, dA, shown in Figure 4*b*, to the total area from which the trips derive, $WR - (W^2/2)$. The resulting equation for the differential of n trips of distance r is

$$dn = \frac{f_t v}{W} r\, dr \quad 0 < r \leq W$$

$$dn = f_t v\, dr \quad W < r \leq R \qquad (11)$$

By integrating Equation 11, the fraction of vehicles that have traveled r or less at P, n_r/N_t, can be constructed. The resulting curves for $W = R/4$ and $W \geq R$ are presented in Figure 5. The greater fraction of trips in the later stages of warm-up is exhibited by the increasing slope of the curves as f_r

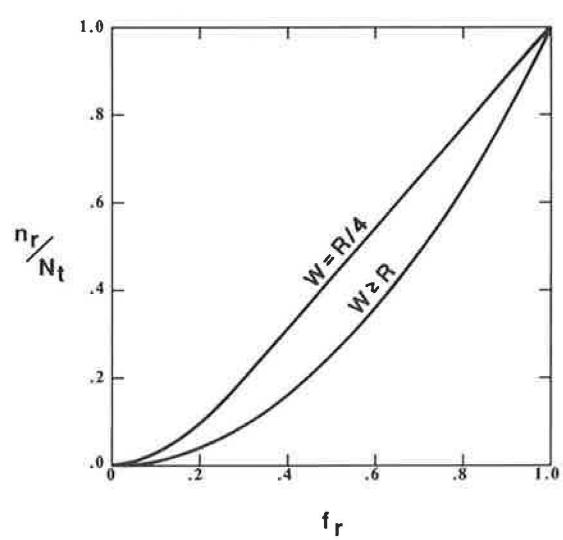

FIGURE 5 Fraction of vehicles that have traveled a distance *r* or less for two corridor half-widths.

approaches W/R. This effect is considerably more important as W becomes larger.

COMBINED MODEL

Gaussian line source dispersion models such as HIWAY2 (8) and CALINE4 (9) use a composite emission factor from MOBILE3 together with traffic volume to compute a lineal source strength term, q, in units of pollutant mass per length-time. The transient emissions and travel distribution models described in this paper can be combined to correct the transient component of q, q_t. Strictly speaking, the correction should be applied directly to q_t. However, the same result can be achieved by correcting the fraction of vehicles in hot or cold start mode. The corrected fraction can then be input directly to the MOBILE3 program without the need to isolate the transient emissions.

The correction must account for both the skewed distribution of travel distances for hot and cold start vehicles at P and the number of vehicles passing P in the hot stabilized mode. If it is assumed that the traffic volume and rate of entering vehicles are relatively constant over the section of highway being studied, the solution at P will be valid for all points. Even if this assumption is not entirely true, the solution will provide a good average value to use if it is calculated from average values of V, v, and f_t.

If the corrected fraction of vehicles in the warm-up phase at P is defined as ${}_cf_t$, q_t can be written as

$$q_t = {}_cf_t V \bar{e}_t \quad (12)$$

Another way of expressing q_t is as a summation of transient contributions from all vehicles passing P:

$$q_t = \int_0^{N_t} e_t(r)\,dn \quad (13)$$

Before this expression is evaluated, one further refinement needs to be made. For major arterials such as freeways, a minimum distance must be traveled by all vehicles before gaining access. In the model, this is represented as a trip length augmentation, r_a. Only vehicles that have traveled r_a or greater can be on the highway segment. Therefore, Equation 13 must be restated as

$$q_t = \int_0^{N_t} e_t(r + r_a)\,dn \quad (13')$$

This modification will mean that the area from which N_t is drawn will be smaller, with the highway segment reduced in length to $R-r_a$ and a further restriction, that $W \leq R-r_a$. However, the modification does not alter the travel distribution model described by Equation 11.

By including r_a in the model, the final solution will be applicable to a wider range of conditions. The inclusion of the factor not only adjusts for highway access but also can be used to account for inefficiencies in local street collector systems. In residential areas, most trips will start on local streets, not collectors or arterials. During travel to the nearest collector or arterial, it is not likely that a vehicle will always be able to travel directly toward P. An average value can be assigned to r_a to account for these detours.

Substitution of Equations 6 and 11 into Equation 13′ and assignment of the proper limits of integration gives

$$q_t = \bar{e}_t f_t v \left\{ \frac{3}{W} \int_0^W r \left[1 - \frac{2(r + r_a)}{R} + \frac{(r + r_a)^2}{R^2}\right] dr + 3 \int_W^{R-r_a} \left[1 - \frac{2(r + r_a)}{R} + \frac{(r + r_a)^2}{R^2}\right] dr \right\} \quad (14)$$

The final model is determined by integrating Equation 14, combining the result with Equation 12, and solving for ${}_cf_t$:

$${}_cf_t = \frac{f_t v}{V}\left[R - W\left(\frac{3}{2} - \frac{W}{R} + \frac{W^2}{4R^2}\right) - 3r_a\left(1 - \frac{W}{R} + \frac{W^2}{3R^2}\right) + 3r_a^2\left(\frac{1}{R} - \frac{W}{2R^2}\right) - \frac{r_a^3}{R^2}\right] \quad (15)$$

If we assume that $r_a = 0$ and $W = R$, Equation 15 simplifies to

$${}_cf_t = \frac{f_t v R}{4V} \quad (16)$$

The combined model assumes that the warm-up portion of FTP-75 typifies the actual driving pattern of all vehicles in the travel distribution model. This assumption is not true in all cases. The FTP-75 cycle, which has as its genesis a 12-mi test loop in downtown Los Angeles (10), represents both city street and freeway driving conditions. Vehicles entering a free-flowing freeway shortly after start-up will operate at higher average speeds than the FTP-75 average of 25.6 mph. Higher speeds favor a quicker warm-up of the engine and catalyst so that hot stabilized conditions may be achieved in less than 3.59 mi (1). Conversely, vehicles traveling on stop-and-go city streets exclusively may require more or less than 3.59 mi to reach hot stabilized operation. The exact distance will depend on the amount of time spent idling and the overall average speed.

To account for these differences, a further disaggregation of the travel distribution model might be possible on the basis of average speed or a breakdown of idle, acceleration, deceleration, and cruise modes. Such a refinement is worthwhile, however, only if the composite emission factors generated by MOBILE3 contain sufficient detail to make use of the disaggregation. This is not currently the case. MOBILE3's idle emission rates and speed correction coefficients are both derived from data that are valid only for hot stabilized vehicles (11, 12).

MODEL SENSITIVITY

To evaluate the sensitivity of the model described by Equation 15, realistic values for v/V and f_t were used. A recent study by the New Jersey Department of Transportation recommended values of f_t for a variety of facility types in both urban and rural settings (13). In that comprehensive study, vehicles in cold start mode were identified by using a relationship between oil temperature and elapsed time from start-up derived for 32 representative test vehicles. A driver survey was used to identify vehicles in hot start mode. Vehicles were sampled randomly during peak (7 to 9 a.m.) and off-peak (9 a.m. to noon) periods. More than 7,500 vehicles were tested at 49 sites. The summary of the percentages of vehicles in hot and cold start operation presented in Table 1 provides a basis for estimating f_t.

TABLE 1 SUMMARY OF COMBINED RESULTS FOR HOT AND COLD START PERCENTAGES (*13*)

Roadway Classification	Hot Transient Fraction (%) Peak	Hot Transient Fraction (%) Off-Peak	Cold Transient Fraction (%) Peak	Cold Transient Fraction (%) Off-Peak
Urban principal	6.5	21.1	46.8	29.9
Urban minor arterial and collector	10.6	29.1	46.4	29.7
Urban local	8.3	30.8	64.0	30.7
Rural principal arterial	3.0	8.6	36.9	23.2
Rural minor arterial and collector	5.6	14.3	44.8	27.8
Rural local	4.9	20.8	45.2	34.2

To quantify v/V for typical urban freeways, 10 representative sections were chosen from urban areas in California. For each section, the average daily traffic (ADT) and entering volumes in ADT per mile were obtained (*14, 15*). The ratios of these averaged daily results were used as an approximation of peak hour v/V. As can be observed in Table 2, the results were reasonably consistent from section to section.

Figure 6 shows values of ${}_cf_t/f_t$ as a function of corridor half-width for r_a equal to 0 and 0.25 mi. The curves were generated by using Equation 15 and assuming a value of 0.1 for v/V. The importance of W to the travel distribution and resulting correction to f_t is clearly illustrated. As W decreases, a smaller correction is necessary for f_t. As W approaches zero,

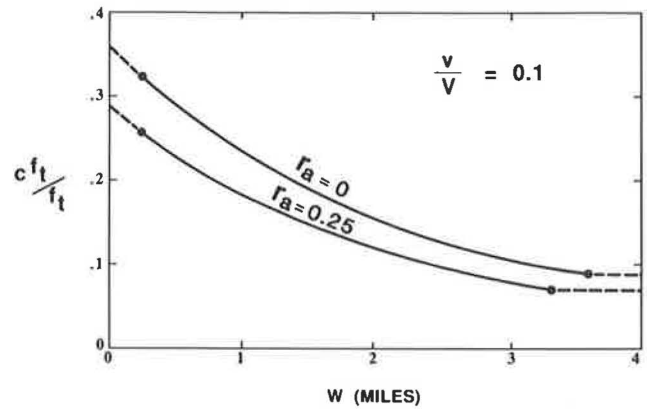

FIGURE 6 Sensitivity of the combined model to the corridor half-width and trip length augmentation variables.

the correction becomes a simple function of the dilution effect of hot stabilized through traffic characterized by v/V. Figure 6 also indicates that r_a assumes greater importance as W approaches zero, but that overall this factor appears to be less critical than either W or v/V.

As a realistic example, the information in Tables 1 and 2 can be combined with the simplified form of the model (Equation 16) to determine the corrected percentage of hot and cold start operation for a typical urban freeway. Because this example will be based on representative data, the results will demonstrate the importance of correcting hot and cold start fractions for travel distance distribution. Because freeway access is typically limited to arterials, approximate values for f_t from Table 1 of 10 percent hot and 50 percent cold starts will be used. When Equation 16 is applied and $v/V = 0.1$ (approximated from Table 2) is assumed, corrected fractions of 1 percent and 5 percent, respectively, are obtained.

The importance of this correction is best illustrated by comparing composite emission factors for the uncorrected values from Table 1, the hot/cold start split defined by FTP-75 (27/21 percent, respectively), and the corrected values of 1 and 5 percent from Equation 16. In Figure 7, MOBILE3 composite emission factors at 55 mph for each of these scenarios is

TABLE 2 RATIOS OF ON-RAMP VOLUMES TO ADT FOR URBAN CALIFORNIA FREEWAYS, 1982–1983

County	Route	Post Miles	ADT/Mile (v)	ADT (V)	v/V
Sacramento	US-50	1–16	8,900	83,000	0.11
Alameda	I-880	22–30	16,800	189,000	0.09
San Mateo	US-101	12–20	16,900	199,000	0.08
Santa Clara	I-280	4–10	25,400	154,000	0.16
Los Angeles	I-10	32–42	13,800	136,000	0.10
Los Angeles	I-110	10–20	20,300	212,000	0.10
Orange	I-405	11–20	21,500	192,000	0.11
Riverside	SH-91	9–22	9,900	98,000	0.10
San Diego	SH-94	5–10	10,700	93,000	0.12
San Diego	I-805	3–13	13,700	92,000	0.15
Average					0.11

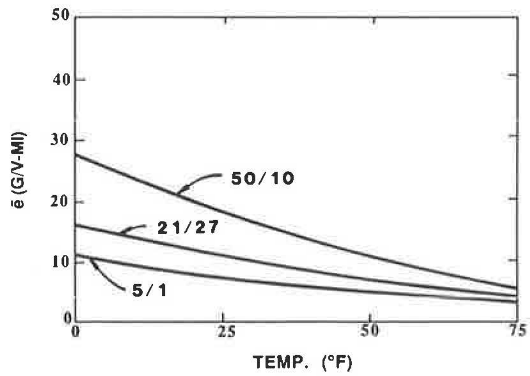

FIGURE 7 MOBILE3 composite emission factors as a fraction of ambient temperature for three cold/hot start fractions (1990 LDGV mix at 55 mph).

plotted against ambient temperature for a 1990 LDGV mix. The results indicate that using the 21/27 percent split can result in overpredictions of freeway emissions of 25 to 50 percent. Use of the uncorrected Table 1 values leads to even higher overpredictions.

SUMMARY AND CONCLUSIONS

The model described by Equation 15 provides a method to correct the fraction of vehicles in either hot or cold start operating mode for the type of travel distance distribution that is likely to be found on urban freeways and arterials. Reliance on the model is based on the acceptance of two concepts. First, transient emissions are high at the beginning of the FTP-75 hot and cold start cycles and gradually diminish to zero by the end of the cycles. Second, more vehicles on urban freeways and arterials in hot or cold start mode are likely to be near the end of the warm-up phase than the beginning.

The first of these concepts was tested against measured results from 25 LDGVs. The measured transient emissions dropped off even faster than the model predicted. The form of the model was retained, however, because it is conservative and avoids arbitrary boundary conditions. The second concept remains untested.

Measured traffic volumes and cold start percentages were used to develop a corrected cold start fraction of 5 percent for typical urban freeways during morning commute. This calculation assumed trip attraction at a uniform rate to a distance of at least 3.59 mi. In cases for which this assumption is valid, use of 21 percent cold start vehicles or higher will result in significant overpredictions of vehicle emissions.

More accurate estimates of cold start percentages can be obtained by using project-specific values for the variables in Equation 15 and applying the resulting correction factor to the cold start fractions given in Table 1 or derived from other sources. Although this approach is less important to the overall result, it can be applied to the fraction of vehicles in hot start mode.

Further work is certainly needed before the model can be used with complete confidence. However, all other methods for estimating microscale transient emissions are equally untested, and many lack coherent rationale. The method presented in this paper is based on well-defined concepts and is adaptable to unique situations. By specifying a corridor half-width, the model may be adjusted for parallel commute corridors or natural restrictions to development, such as coastlines or canyons. The trip length augmentation may be used to accommodate minimum access distances, detouring, or even ramp metering. Such flexibility offers a distinct improvement over the use of "average" values or tabulated ranges of values. More important, the model addresses the nonlinear nature of transient emissions release during warm-up, an aspect that was not considered by other published methods.

ACKNOWLEDGMENTS

This work was sponsored by the California Department of Transportation (Caltrans). Assistance was provided by Caltrans staff members Dick Wood and Bill Nokes.

REFERENCES

1. T. A. Fuca and O. J. Senyk. *Determination of Hot and Cold Starts in New Jersey: Phase I, Task 2—Vehicle Operating Experiment.* Division of Research and Development, New Jersey Department of Transportation, Trenton, 1978.
2. *Federal Register,* Vol. 42, No. 124, Part III, 1977.
3. *Compilation of Air Pollutant Emission Factors: Highway Mobile Sources.* Report EPA-460/3-84-005. Environmental Protection Agency, Ann Arbor, Mich., 1984.
4. T. C. Pearce and M. H. L. Waters. *Cold Start Fuel Consumption of a Diesel and a Petrol Car.* Supplementary Report 636. Transport and Road Research Laboratory, British Department of the Environment Department of Transport, Crowthorne, England, 1980.
5. T. P. Midurski and A. H. Castaline. *Determination of Percentages of Vehicles Operating in the Cold Start Mode.* Report EPA-450/3-77-023. Environmental Protection Agency, Research Triangle Park, N.C., 1977.
6. G. W. Ellis, W. T. Camps, and A. Treadway. *The Determination of Vehicular Cold and Hot Operating Fractions for Estimating Highway Emissions.* Report DOT-FH-11-9207. Alabama Highway Department, Montgomery, 1978.
7. B. H. Eccleston and R. W. Hurn. *Ambient Temperature and Vehicle Emissions.* Report EPA-460/3-74-028. Environmental Protection Agency, Ann Arbor, Mich., 1974.
8. W. B. Peterson. *User's Guide for HIWAY-2: A Highway Air Pollution Model.* Report EPA-600/8-80-018. Environmental Protection Agency, Research Triangle Park, N.C., 1980.
9. P. E. Benson. *CALINE4: A Dispersion Model for Predicting Air Pollutant Concentrations near Roadways.* Report FHWA/CA/TL-84/15. California Department of Transportation, Sacramento, 1984.
10. D. J. Simanaitis. Emission Test Cycles Around the World. *Automotive Engineering,* Vol. 85, No. 8, 1977.
11. P. Kunselman et al. *Automobile Exhaust Emission Modal Analysis Model.* Report EPA-460/3-74-005. Environmental Protection Agency, Ann Arbor, Mich., 1974.
12. M. Smith et al. *Development of Revised Light-Duty-Vehicle Emission—Average Speed Relationships.* Report EPA/460/3-77/011. Environmental Protection Agency, Ann Arbor, Mich., 1977.
13. K. J. Brodtman and T. A. Fuca. *Determination of Hot and Cold Start Percentages in New Jersey.* Report FHWA/NJ-84/001. New Jersey Department of Transportation, Trenton, 1984.
14. *Traffic Volumes on California State Highways.* California Department of Transportation, Sacramento, 1984.
15. *Ramp Volumes on the California State Freeway System.* California Department of Transportation, Sacramento, 1984.

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