Alternative Operating Mode Fractions to Federal Test Procedure Mode Mix for Mobile Source Emissions Modeling

MOHAN VENIGALLA, TERRY MILLER, AND ARUN CHATTERJEE

An emission inventory is a key component of an air quality control program. The emission rates of carbon monoxide and hydrocarbons are sensitive to the variations in the inputs related to cold transient, hot transient, and hot stabilized operating mode fractions. Therefore it is important to provide realistic values for these parameters while modeling emissions using air quality models such as the MOBILE model. The objective of the research presented is to derive aggregate operating mode fractions as alternatives to the federal test procedure (FTP) mode mix on the basis of a detailed analysis of personal travel data. The data source used for the analysis of personal travel information is the 1990 Nationwide Personal Travel Survey. Issues related to data quality, screening, and aggregation are discussed. After determining of the percentages of start mode as cold starts and hot starts, the percentages of vehicle miles of travel (VMT) operating in different modes are derived by trip purpose and for different time periods. The VMT weighted operating mode fractions derived from these start mode fractions indicated a significant difference from the FTP operating mode mix. It is observed that the FTP operating mode mix generally underestimates the portion of travel in cold transient mode. Also, it is observed that the percentage of VMT in cold transient mode decreases with the increase in the size of the urban area.

Corridor-level and area-wide air quality studies require accurate information on the emissions of several pollutants with high spatial and temporal resolution so that the causes of air pollution can be understood and effective plans developed for future air quality improvement (*1*). Emission inventories for mobile sources are prepared mainly using computerized air quality models, such as MOBILE and, in some cases, EMFAC, which is mostly used in California. Embedded in these air quality models are several look-up tables, mathematical relationships, and analytical techniques that were developed through laboratory and empirical studies. The computer models estimate emission rates by using these embedded techniques and relationships with a given set of variables and parameters as inputs. Included among these inputs is information on operating modes of engines in the traffic stream.

The engine operating mode of a vehicle, which primarily refers to the operating temperature of the combustion chamber and catalytic converter if it exists, has a significant effect on emissions. Operating mode fractions of vehicles in transient and stabilized modes are among the key inputs to modeling vehicular emissions. The emission rates of carbon monoxide (CO) and hydrocarbons (HC) are sensitive to the variations in the inputs related to operating mode fractions. CO and HC emissions are the highest in the cold transient mode, when fuel mixtures are rich and catalytic converters are too cold to function effectively. Depending on the ambient temperature, CO and HC emissions can be twice as high during the cold start mode as during hot stable operation.

M. M. Venigalla, EG&G Dynatrend at Volpe Center, 55 Broadway, DTS 927, Cambridge, Mass. 02142. T. Miller and A. Chatterjee, Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, Tenn. 37996.

Therefore it is important to provide realistic values for the parameters related to operating mode fractions for emissions modeling using air quality models such as the MOBILE model. However, practitioners have traditionally been using an operating mode mix based on the federal test procedure (FTP), which is used to test emissions for new vehicles. The FTP mode mix was derived in the early 1970s based on a test driving cycle that may not be a true representation of the general driving patterns of the population. The purpose of this paper is to demonstrate an alternative approach to deriving operating mode fractions based on the analysis of one of the most widely used travel survey data bases, the Nationwide Personal Travel Survey (NPTS) data base.

The state of the practice in emission modeling with respect to operating mode fractions inputs is discussed in the next section. A brief discussion on the analysis of the NPTS data base is presented in the following section, which is followed by sections on trip length analysis and start mode analysis. The section on vehicle miles of travel (VMT) analysis explains the procedure used to derive alternative operating mode fractions to FTP mix and also compares the numbers derived from the NPTS data with the FTP values.

STATE OF THE PRACTICE

The Environmental Protection Agency (EPA) historically has defined a cold start to be any start that occurs 4 hrs or later following the end of the preceding trip for noncatalyst-equipped vehicles and 1 hr or later following the end of the preceding trip for catalyst-equipped vehicles. Hot starts are those starts that occur less than 4 hr after the end of the preceding trip for noncatalyst-equipped vehicles and less than 1 hr after the end of the preceding trip for catalyst-equipped vehicles (*2*). The time between the end of a trip and the engine restart for the following trip is called the cold-soak, or simply the soak, period.

Before attaining the hot stabilized operating mode, a vehicle will operate in a cold transient mode or hot transient mode, depending on the actual starting mode. The rate of emissions for stabilized mode is both uniform and significantly lower than the rate for any transient mode, especially the cold transient mode. The FTP is based on the assumption that in about 505 sec since the start of the engine, a vehicle's mode changes from a transient mode to hot stabilized mode.

The FTP involves determining the emissions of carbon monoxide, hydrocarbons, oxides of nitrogen, and carbon dioxide produced by a test vehicle during its operation through a standard driving schedule. Testing is performed on stationary vehicles using a dynamometer to simulate actual highway driving. The driving schedule, referred to as the EPA Urban Dynamometer Driving Schedule (UDDS), consists of three phases: cold transient, hot stabilized, and hot transient. On the basis of travel characteristics and conditions used for the FTP drive cycle, EPA derived operating mode fractions in the three phases of the UDDS.

In the absence of reliable field data or empirical studies of operating modes of vehicles, traditionally emission inventory studies have adopted an operating mode fraction mix specified in the MOBILE 5A user's manual, which were derived from the FTP drive cycle (*2*). The mode mix indicates that 20.6 percent and 27.3 of the vehicles in the fleet represent cold and hot transient modes of operation, respectively, and the remaining 52.1 percent of the vehicles are in hot stabilized modes of operation.

These operating mode fractions are being widely used in several corridor-level and area-wide emission studies at different levels of precision. The user manual states that EPA will accept for state implementation planning related modeling, the use of FTP operating mode values, except for small-scale scenarios where their use would clearly be inappropriate.

The research community and the practitioners have serious reservations in adopting the FTP operating mode mix for all cases. Ideally, the operating mode fraction values should be developed for varying situations. For example, these may be stratified by functional class of highways (freeways/expressways, principal arterials, etc.) and the geographic locations being modeled. (CBD, fringe, suburban, etc.). This concern is expressed in the following statement in the user guide to MOBILE 5A model (*2*).

> In the absence of supporting data for values other than those listed above (FTP mode mix), EPA believes that the values reflecting the conditions are appropriate in many cases. This is particularly true when the emission factors being modeled are intended to represent a broad geographic area (Metropolitan Statistical Area, entire state) and/or a wide time period (days, months).

Adding to this limitation, McIlvaine (*3*) states

> The FTP operating mode mix is only representative of conditions similar to those under which it was developed. These conditions include an urban setting (like Los Angeles), an average trip length of approximately 7.5 miles, and an average of 4.7 trips per day per vehicle. While the FTP was developed from a morning urban commute over a range of facility types, the FTP operating mode mix is not necessarily representative of the operating mode mix that occurs during a given hour, on a specific roadway facility type, and particularly not in non-urban areas.

One way to resolve the limitations associated with FTP's numbers is to use field observations and measurements. An accurate determination of the operating mode of a vehicle engine requires measurements of the engine temperature, and such measurements are difficult to implement on vehicles on roads under normal traffic conditions.

A study was done in New Jersey to determine the percentage of hot and cold transient trips for New Jersey roads (*4*). With the permission of the drivers, engine oil and coolant temperatures were measured, and engine run time estimates were obtained from the driver. The collected data were analyzed to determine the percentages of hot start, cold start, and hot stabilized modes of operation in the traffic.

There is also an indirect approach of estimating the operating modes of vehicles traveling on a roadway. This approach uses the travel time from a trip origin as an indicator of the operating mode. The travel time from trip origin can be estimated either by interviewing drivers (as in the case of New Jersey study) or by modeling. The interview technique is difficult to implement. Therefore, the modeling approach is more feasible.

Some studies have adopted the indirect modeling approach of estimating the operating mode of vehicles traveling on different road segments. Ellis et al. (*5*) attempted to develop procedures for estimating combined cold and hot transient operating fractions for light-duty vehicles from transportation planning data. Origin-destination survey data were used to determine area-wide operating mode fractions by trip purpose and by time-of-day.

An EPA study (*6*) focused on determining the percentages of vehicles operating in the cold transient mode for different functional classes of roads in two selected cities: Pittsburgh, Pennsylvania, and Providence, Rhode Island. This study estimated the percentage of VMT in the cold transient mode for the morning commuting hours, mid-day period, evening commuting hours, and early morning off-peak period for each of the 60 traffic streams analyzed. One important finding of the study indicates that the actual percentages of vehicles operating in the cold start mode are different from the percentages assumed in the FTP. The studies by Ellis et al. and EPA were conducted in the late 1970s. These studies were mostly localized and did not cover all classes of roads.

Another important issue related to the modeling approach for determining operating modes is the proportion of vehicles starting in cold and hot modes at trip origins. Several studies have assumed and recommended start modes for different trip purposes based on judgment. For example, 90 percent of home-based work (HBW) trips in the south Jersey area were assumed to have started as cold starts (*7*). The justification for this was based on the assumption that before the beginning of the trip, the engine would have been shut off for several hours, at work and at home.

When modeling emissions for different times of day, it is important to know these starting modes at the beginning of trips by time-of-day. Very few studies attempted to derive start modes at trip origins that would then be used to derive operating mode fractions on roadway facilities. Ellis et al. (*5*) and Venigalla et al., in another paper in this Record, have performed this analysis. Several limitations of the study by Ellis et al. were addressed in the study by Venigalla.

The network assignment techniques used by Venigalla (*7*) and COMSIS (*8*) required as input a detailed transportation network, trip matrices by purpose, and other transportation planning data appropriate to traffic assignment. When such planning data are unavailable or when the available resources are very limited, which renders the assignment analysis infeasible, an alternative to the FTP mode mix is desirable. The objective of the research presented in this paper is to derive aggregate operating mode fractions as an alternative to the FTP mode mix based on a detailed analysis of personal travel data. The data source used to analyze personal travel information is the Nationwide Personal Travel Survey (NPTS). The scope of the research presented in this paper, however, is limited to deriving aggregate operating mode fractions without specific detail on facility class and location.

ANALYSIS OF NPTS DATA

To compute the operating mode mix, it is important to have information on the travel characteristics, such as the travel time and trip length as well as the start modes at the trip origins. For deriving the start modes at trip origins, data pertaining to cold soak period and vehicle type are needed. Origin-destination data collected for comprehensive urban transportation planning purposes usually contain this information. However, these data sources are localized, tend to be outdated, and are some times inadequate for determining start modes.

A periodic survey on personal travel, NPTS, which is available for public use through the U.S. Department of Transportation, was examined for this purpose. The NPTS compiles national data on the nature and characteristics of personal travel. It addresses a broad range of travel in the United States, providing data on all personal trips for all purposes and by all modes of transportation (*9*).

For the 1990 NPTS, information on all trips made during a designated 24-hr period, called travel-day, was collected from a national household sample. Additional details were collected for trips of that were 120 km (75 mi) or longer and taken during the preceding 14-day period, or travel period, which included the 24-hr travel day. The information collected for each trip includes the purpose, mode, trip length, day-of-week, time-of-day, vehicle used, vehicle occupancy, and other information. For detailed information on this data source and other details, such as the sampling methods, data collection, and screening, the reader may consult the user's guide to the NPTS data base.

Available information in the 1990 NPTS data base pertinent to this study includes data on all trips that were made during a designated 24-hr period, including the time the trip began, the length of the trip, the mode of transportation, the purpose of the trip, and the vehicle used (if the travel was in a household vehicle). The data base contains information on 41,178 vehicles that were used for 149,546 trips taken during a 24-hr period.

The analysis of NPTS data for determining the operating modes at trip origins involved the following distinctive steps:

- Identify relevant variables in the data base,
- Identify vehicles with catalytic converters,
- Determine the cold-soak period for each trip,
- Screen data,
- Associate each trip end (origin and destination point) with a start mode (cold start or hot start) and an operating mode (transient or stabilized), and
- Analyze trip duration, operating modes at trip ends, percentage of VMT in different operating modes.

The four most important variables used to identify each chain of trips in the data base are the unique household identification number, the identification (within the same household) of the vehicle with which the trips were made, start time, and length of each trip. Variables such as the census region, the census division, the metropolitan statistical area (MSA), the size of the urban area, and the trip purpose were also used as stratification variables for this study.

Even though the NPTS data contain several items of information about the vehicles used for each of the travel-day trips, it is not obvious whether a vehicle is equipped with a catalytic converter. Because the emission standards from 1975 require using catalytic converters, all 1975 and later model vehicles were assumed to be equipped with catalytic converters (*7*). Because of a lack of sufficient information, it was assumed that about 25 percent of the vehicles manufactured and sold before 1975 were equipped with the converters. Vehicles with model year before 1975 were randomly identified as catalytic-converter equipped or noncatalytic-converter equipped in the proportion 25:75, respectively. Because the total number of vehicles with model years before 1975 was less than 8 percent of the total vehicles (41,178) in the data base, the possibility of errors occurring in the overall analysis as a result of this assumption is minimal. This procedure identifies 2191 (5.3 percent) vehicles in the data base as noncatalytic-converter equipped and 38,987 (94.7 percent) vehicles as catalytic-converter equipped.

The NPTS travel-day data file contains information on the characteristics of all the trips made by the respondents during the travel day (from 4:00 a.m. on the travel day to 3:59 a.m. the following day). Included among the available data items in this file are the time at which a trip started and the length of that trip (in minutes). This information was recorded for the chain of all trips made using each vehicle in the household.

By sorting and arranging the data base in a particular order, it was possible to identify the chain of trips made by each household vehicle. The time gap between the end time and the begin time of two successive trips, coupled with the characteristics of the vehicle used for that trip (i.e., catalytic-converter equipped or not), was used to determine the cold-soak period before each trip in a chain started. Following the determination of the cold soak period for each trip, each trip start is identified as a cold start or hot start according to the EPA's definitions.

Several consistency checks were performed to screen the data base so that only the error-free chains of trips would be used in the analysis. Chains of trips with information gaps and questionable data items were discarded. At the final stage of screening, there were 105,903 total trips in the data base that were eligible for final analysis. After the screening, the geographical distribution of the trips was found to be almost identical to that of the original data base.

Frequencies were obtained, by trip purpose and hour of day, for cold and hot start modes at the beginning of the trips. The analyses were conducted for all the trips in the data base, which means that the results should represent nationwide average values. The results of this analysis are presented in more detail in the work by Venigalla et al. in another paper in this Record. The results of this analysis indicated that the percentage of trips starting in cold mode decreases as the day progresses, a trend that would be expected.

An analysis of variance for the cold start percentages indicated that the time of day and the trip purpose significantly influence the variation in the percentage of cold starts. Among the geographic classification variables, individual MSAs exhibit different cold and hot start percentages, followed by the size of the urban area as the next best classification variable. These start modes based on NPTS data were used to derive the aggregate operating mode fractions presented in the next section.

TRIP LENGTH ANALYSIS

Regardless of the start mode at trip origin, the duration of an average trip indicates the operating modes on a road network. For example, when the average trip length associated with cold starts is less than 505 sec, the indication will be that most of these cold start trips end as cold transient trips. After the start mode is determined for each trip, the operating mode in which the trip ended was determined from the trip length analysis. Adopting the FTP transient mode duration of 8 min (closest approximation to 505 sec because the data indicate travel time only in increments of 1 min), the operating mode at the end of each trip was determined. As an example of this analysis, if the trip started in cold mode and ended before

8 min, the end of the trip was considered to be in a cold transient mode. The NPTS data were analyzed for trip duration (minutes) and length (miles).

When data on all trips are included, it was observed that the average trip duration and length were quite high [approximately 17 min and 16 km (10 mi)]. A few long trips [some as long as 1760 km (1,100 mi)] were found to be introducing a bias toward higher than usual average travel time and trip length estimates. To eliminate this bias, only the 48-km (30-mi) portion of these long trips was considered urban travel. In other words, the maximum length of the trips for the analysis was 48 km (30 mi).

Figures 1 and 2 illustrate the results of the trip length analysis. Travel time analysis (Figure 1) indicates a trend that would characterize the responses on travel time as approximations to the nearest 5-min intervals. Therefore, the results of any travel time analysis based on this data base should be used with caution, and adjustments are needed to counter the rounding of errors. The respondents do not appear to have rounded the trip length to the nearest 8-km (5-mi) interval as they did in the case of travel time responses (Figure 2). It can be seen that about 34 percent of all the trips have a duration of 8 to 9 min. This means that at least 34 percent of the trips would end in a cold or hot transient operating mode, depending on the operating mode at trip origin. It can be seen that an average trip is approximately 10.56 km (6.6 mi) long and is expected to last for about 13.5 min. The median (50th percentile) travel time and trip length are about 10 min and 7.2 km (4.5 mi), respectively.

ANALYSIS FOR VEHICLE MILES OF TRAVEL

As mentioned earlier, a key input to modeling the mobile source emissions using the MOBILE model is the percentage of VMT accumulated in each operating mode for each type of emission control equipment (or simply operating mode fractions). Whether a cold start or a hot start, each trip would operate in a transient mode for some length of time (defined as 505 sec per FTP) before operating in a hot stable mode. The distance traveled during the transient modes of operation can be assumed to be a portion of the total distance traveled, prorated for 8 min. For the remaining distance, the trip will be in a hot stabilized mode.

VMT Distribution in Different Modes

To study the distribution of the percentage of VMT operating in different modes, a VMT analysis was performed for different times of day and for different trip purposes. The trip-purpose categories used were HBW, trips, home-based other (HBO), trips and non–home-based (NHB) trips. Data pertaining to highway functional class used for NPTS trips are limited in the NPTS data base; hence, no attempts were made to classify the VMT by highway functional class or highway location. The percentages of VMT operating in each operating mode, stratified by trip purpose and hour of day, are presented in Table 1. (These numbers were derived for catalyst-equipped vehicles only.) The percentages of VMT numbers in cold transient, hot transient, and hot stabilized modes of operation in Table 1 are plotted in Figures 3 and 4, respectively.

The percentage of VMT operating in transient mode (Table 1 and Figure 3) indicates the following:

- Percentage of VMT operating in cold transient mode is higher during late hours in the night and early hours of the day,
- Peak for this operating mode occurs between 6:00 a.m. and 9:00 a.m.,
- NHB trips operate with low proportions of cold transient VMT between 6:00 a.m. and 9:00 a.m. The share of VMT in a cold transient mode due to NHB trips increases as the day progresses,
- In general, HBW trips have higher VMT operating in cold transient mode than the HBO trips.
- Percentage of VMT in hot transient mode is, in general, lower when compared with VMT operating in cold transient or hot stabilized modes,
- With the exception of NHB trips, hot transient mode VMT is lower in the morning hours and steadily increases as the day progresses,
- NHB trips exhibit higher percentages of hot transient VMT than home-based trips.

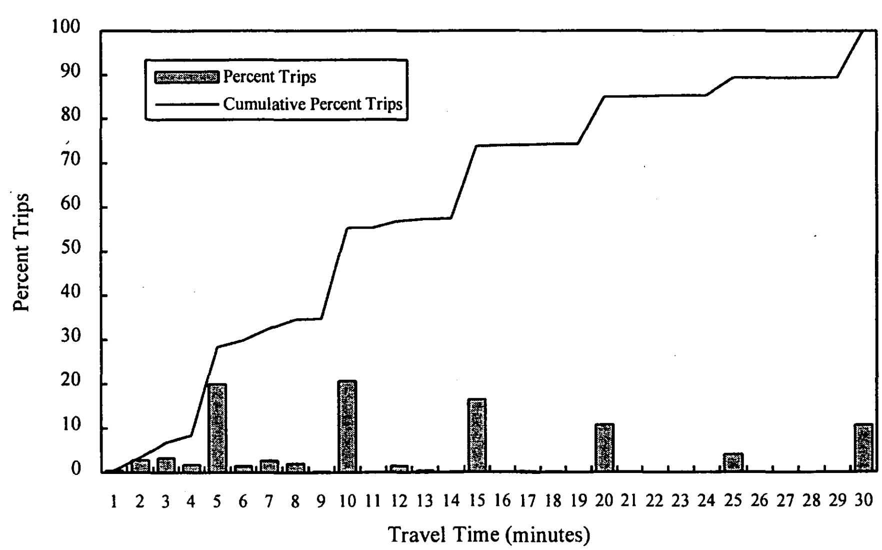

FIGURE 1 Distribution of trip duration for all trips.

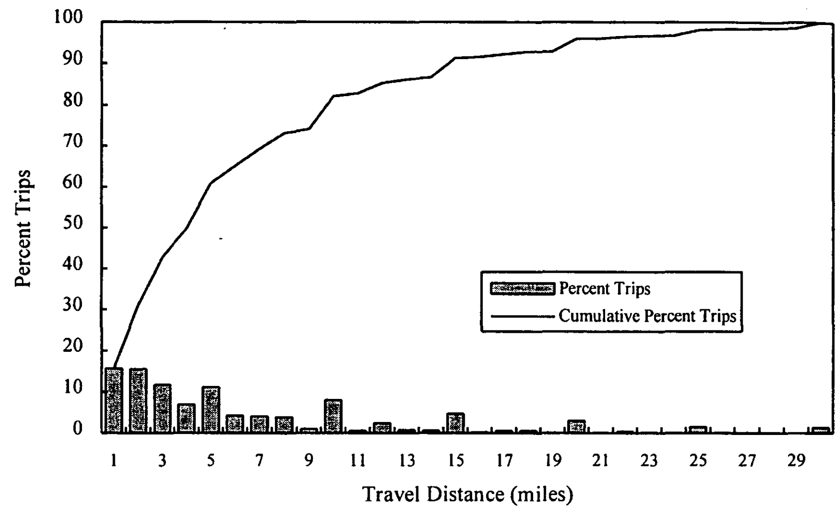

FIGURE 2 Trip length distribution of all trips (1 mi–1.61 km).

TABLE 1 Percentage of VMT Operating in Different Modes

Time Period	Home Based Work Trips			Home Based Other Trips		
	Cold Transient	Hot Transient	Hot Stabilized	Cold Transient	Hot Transient	Hot Stabilized
12 AM to 1 AM	41.1	3.7	55.3	36.5	14.3	49.2
1 AM to 2 AM	36.5	6.9	56.5	37.3	10.7	52.1
2 AM to 3 AM	46.6	1.0	52.3	36.6	13.3	50.1
3 AM to 4 AM	38.7	4.5	56.9	32.7	13.8	53.5
4 AM to 5 AM	42.0	3.7	54.3	49.1	5.2	45.7
5 AM to 6 AM	36.6	2.5	61.0	35.3	9.8	54.9
6 AM to 7 AM	36.2	2.5	61.3	38.0	11.4	50.6
7 AM to 8 AM	35.7	4.9	59.3	37.3	17.2	45.5
8 AM to 9 AM	36.0	7.6	56.4	35.9	21.3	42.8
9 AM to 10 AM	39.1	8.8	52.1	36.3	20.1	43.6
10 AM to 11 AM	37.4	9.2	53.4	35.7	20.1	44.2
11 AM to 12 PM	36.1	13.7	50.2	33.7	20.7	45.7
12 PM to 1 PM	33.4	16.5	50.1	31.4	21.0	47.5
1 PM to 2 PM	32.8	17.2	50.0	29.7	23.6	46.7
2 PM to 3 PM	35.2	10.8	54.0	29.5	24.1	46.4
3 PM to 4 PM	34.3	6.9	58.8	26.1	25.7	48.2
4 PM to 5 PM	34.1	8.0	57.9	25.0	27.3	47.6
5 PM to 6 PM	32.6	8.4	59.0	24.7	27.1	48.2
6 PM to 7 PM	33.7	9.6	56.7	29.0	24.1	46.9
7 PM to 8 PM	35.4	8.9	55.7	29.0	24.6	46.4
8 PM to 9 PM	37.8	6.6	55.6	28.6	23.6	47.8
9 PM to 10 PM	38.2	6.5	55.2	30.4	20.2	49.4
10 PM to 11 PM	37.5	6.8	55.7	30.4	15.7	53.9
11 PM to 12 AM	39.2	6.2	54.7	31.5	16.5	52.0
24 Hour Period	35.4	7.4	57.3	30.0	22.8	47.2

(continued on next page)

TABLE 1 *(continued)*

Time Period	Non Home Based Trips			All Purpose Trips		
	Cold Transient	Hot Transient	Hot Stabilized	Cold Transient	Hot Transient	Hot Stabilized
12 AM to 1 AM	37.0	11.2	51.8	38.0	10.4	51.6
1 AM to 2 AM	35.3	9.4	55.3	36.7	9.4	53.9
2 AM to 3 AM	37.4	9.1	53.5	40.5	8.0	51.5
3 AM to 4 AM	39.5	11.7	48.8	37.0	8.1	54.8
4 AM to 5 AM	44.3	16.2	39.5	43.0	4.3	52.7
5 AM to 6 AM	20.4	17.2	62.4	36.3	3.2	60.4
6 AM to 7 AM	10.0	46.8	43.1	36.0	4.3	59.7
7 AM to 8 AM	15.2	36.9	47.9	35.3	8.7	55.9
8 AM to 9 AM	11.0	45.7	43.3	34.1	15.4	50.5
9 AM to 10 AM	17.0	38.8	44.1	34.1	20.0	45.9
10 AM to 11 AM	17.9	38.2	43.9	32.0	22.4	45.5
11 AM to 12 PM	24.1	31.0	44.9	31.1	22.9	46.0
12 PM to 1 PM	25.9	29.9	44.2	29.9	23.4	46.8
1 PM to 2 PM	26.8	29.6	43.6	29.2	24.6	46.2
2 PM to 3 PM	25.3	26.1	48.5	29.3	22.3	48.4
3 PM to 4 PM	26.6	22.7	50.6	28.5	19.6	51.8
4 PM to 5 PM	27.1	21.6	51.3	28.8	19.0	52.2
5 PM to 6 PM	27.8	20.3	51.9	28.4	18.5	53.1
6 PM to 7 PM	23.7	27.6	48.8	29.2	20.9	49.9
7 PM to 8 PM	24.0	29.7	46.3	29.0	23.0	47.9
8 PM to 9 PM	26.3	28.0	45.7	29.5	22.0	48.5
9 PM to 10 PM	29.7	24.6	45.7	31.6	18.6	49.8
10 PM to 11 PM	34.7	17.8	47.5	32.7	13.8	53.5
11 PM to 12 AM	32.7	16.8	50.5	33.8	13.6	52.6
24 Hour Period	25.2	27.2	47.6	31.2	18.7	50.1

The percentage of VMT operating in hot stabilized mode (Table 1 and Figure 4) indicate the following:

- In general, VMT operating in hot stabilized mode are higher than that in the transient modes.
- During morning hours, the share of hot stabilized VMT in the total VMT is higher and decreases as the day progresses.
- Variation in the share of hot stabilized VMT is similar for home-based and NHB trips.

FTP Driving Cycle Versus NPTS Travel Patterns

The results of the VMT analysis for operating mode fractions are summarized in Table 2. It can be seen that average VMT per vehicle operating in transient modes (cold or hot) varies narrowly between 4.8 and 5.6 km (3 and 3.5 mi). The average VMT operating in hot stabilized mode is much higher for catalyst- and noncatalyst-equipped vehicles. Cold transient mode of operation accounts for 31 percent of the catalyst vehicles. The contribution by the hot transient mode (18.5 percent) of operation toward the total VMT is much lower than the FTP value of 27.3 percent for catalyst-equipped vehicles. The disagreement could be due to two reasons.

First, the composition of the catalyst and noncatalyst vehicles has changed dramatically since the FTP driving cycle was introduced in the early 1970s. The 1990 NPTS data indicated that about 95 percent of the vehicles surveyed could be catalyst equipped. By definition, with a cold-soak period of 1 hr or more, catalyst vehicles will start in the cold mode. It may be recalled that the cold-soak period for a noncatalyst vehicle is 4 hrs or more for a vehicle to start in cold mode. Therefore, the increase in catalyst vehicles in the overall vehicle composition would reduce the soak time required for cold starts. As a result, fewer engine starts are in hot start mode when compared with the vehicle composition in early 1970s.

Second, the NPTS data analysis indicated that the distance traveled following a hot start is significantly less when compared with the distance traveled following a cold start. These factors eventually contribute to the reduction of the VMT in the hot transient mode of operation.

This hypothesis is also supported by the fact that the VMT mode mix by noncatalyst vehicles (cold transient, 21.6 percent; hot transient, 28.8 percent; and hot stabilized, 49.6 percent) closely resem-

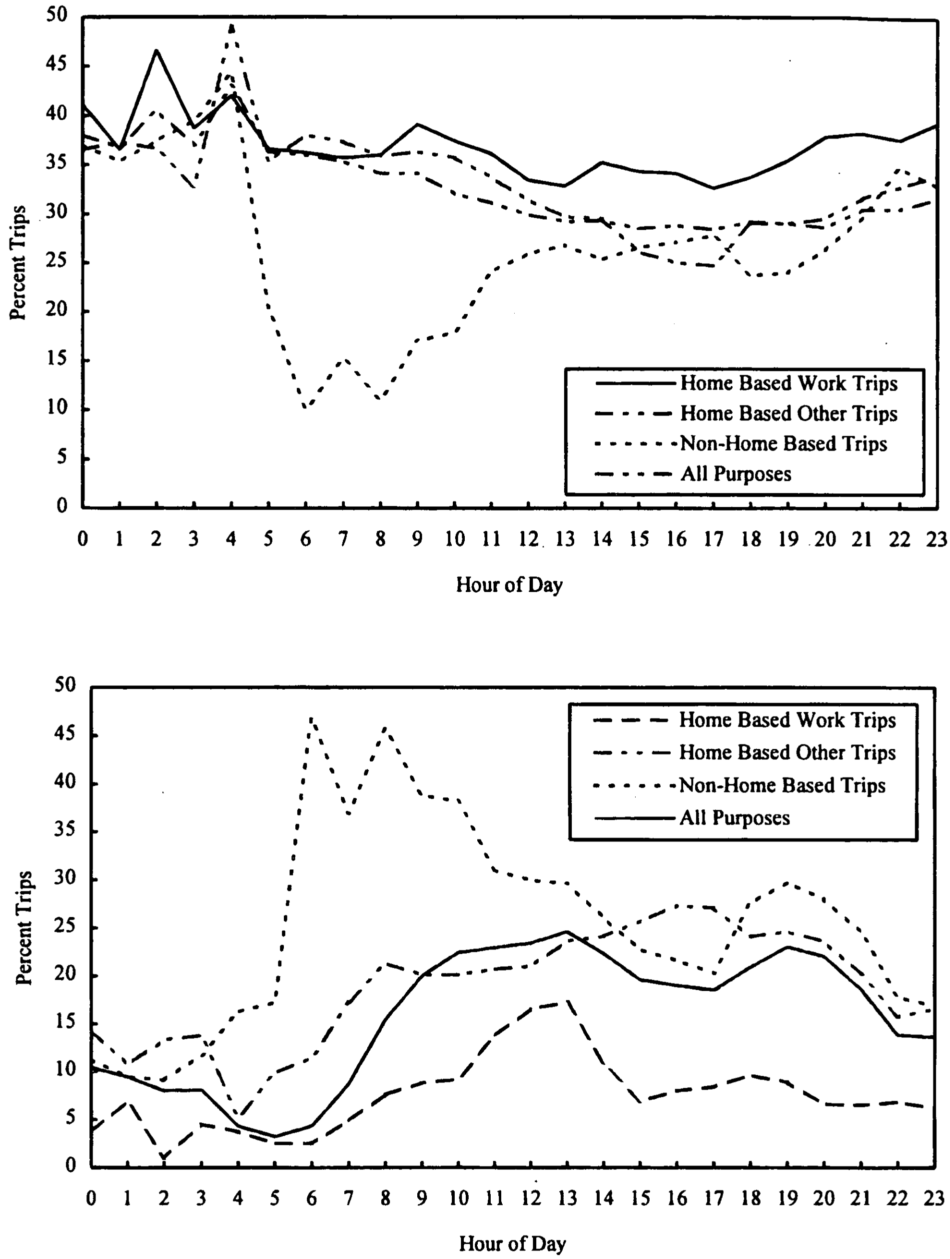

FIGURE 3 Distribution of transient mode VMT: (*top*) cold transient VMT; (*bottom*) hot transient VMT.

bles the FTP operating mode mix (cold transient, 20.6 percent; hot transient, 27.3 percent; and hot stabilized, 52.1 percent). As would be expected, in the morning peak period, cold starts are significantly higher than the cold starts for an average day (34.5 percent vs. 31.2 percent).

For a 24-hr period, total transient mode VMT are 49.9 percent, which is comparable to the FTP transient mode VMT of 47.9 percent. Most of the total VMT (over 50 percent) from the NPTS study, and over 52 percent for the FTP driving cycle), however, operates in hot stabilized mode. Because emission rates are sensitive to the share of VMT operating in cold transient mode, these findings could have a significant impact on overall emission estimation studies. Specifically, the mode fractions derived from the NPTS analysis may result in higher emission rates for CO and HC. However, it should be noted that these numbers are also sensitive to the length of the trip because the fraction of VMT in each operating mode was derived from a prorated basis of the total length of the trip.

Table 3 compares the trip characteristics and the operating modes of FTP driving cycle with the results from the NPTS data analysis. There are some noteworthy differences between the characteristics of FTP trips and the trips recorded for NPTS. An average NPTS trip is shorter than an FTP trip [10.56 versus 12 km (6.6 mi versus 7.5 mi) per vehicle trip for an average daily trip]. However, the number of cold and hot starts per household for an average day is comparable to the FTP driving cycle starts. According to NPTS data, on an average day, the number of cold and hot starts for a household is

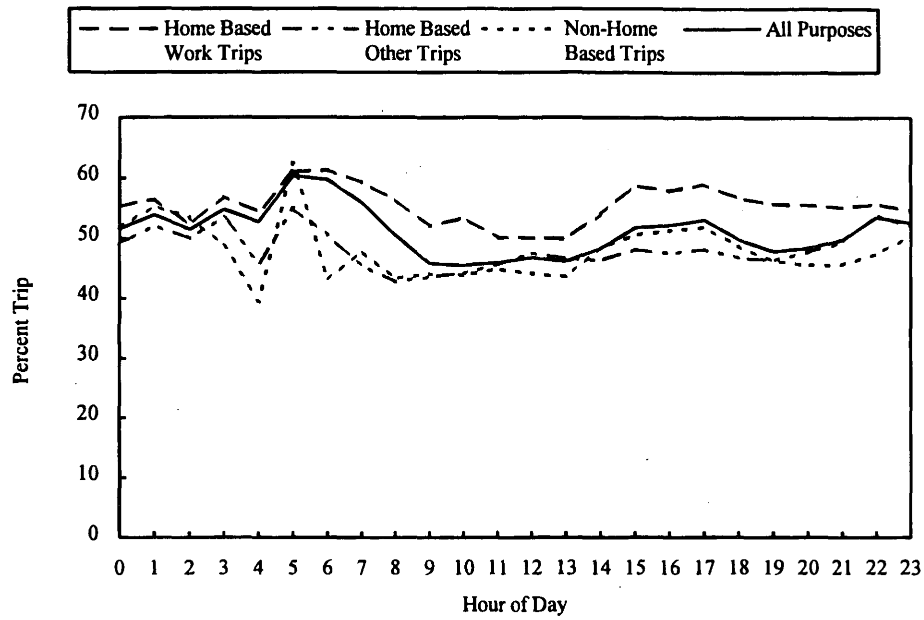

FIGURE 4 Distribution of hot stabilized mode VMT.

similar, 3.6 and 3.7, respectively. The data also indicate that, on a starts-per-vehicle basis, there are more hot starts than cold starts for an average day.

The FTP cycle, therefore, appears to be underestimating the cold transient mode VMT and overestimating the hot transient mode VMT. Also, FTP considers a longer trip duration (22.9 min) than the NPTS trip duration (13.5 min). It would appear that as the proportion of cold transient mode trips increases, the emissions would also increase. However, it is difficult to visualize the effect of these differences on the emission rates, which will be modeled using the MOBILE model. The relative significance of these differences can be analyzed by conducting a detailed sensitivity analysis of the emission factor model with FTP operating mode fractions and the NPTS operating mode fractions.

As mentioned earlier, an analysis of variance test indicated that the cold start fractions are different for individual MSAs. At a more aggregate level, the size of the urban area is found to explain variation in the start mode fractions. The geographic variation in transient and stabilized operating modes was also examined at an aggregate level for various urban areas based on the NPTS data. These numbers, presented in Table 4, do not indicate a clear trend. However, in general, the share of transient mode VMT is lower in larger urban areas. Because total VMT in larger urban areas are relatively higher, it would be natural to expect more stabilized mode VMT than the transient mode trips in these areas.

The use of the results presented in Table 4 can be demonstrated with a simple example. To conduct an areawide emission inventory analysis using MOBILE 5, if the urban area population is 300,000, an analyst will use cold transient, hot transient, and stabilized mode fractions of 35.9 percent, 23.7 percent, and 40.4 percent, respectively. The mode fractions for noncatalyst vehicles, however, can be used as specified by the FTP mode mix.

TABLE 2 VMT Accumulated in Each Operating Mode—NPTS Data

	Catalyst Equipped Vehicles[1]		Non-Catalyst Equipped Vehicles[2]		All types of vehicles	
Operating Mode	Mean VMT[3]	Percent VMT	Mean VMT[3]	Percent VMT	Mean VMT[3]	Percent VMT
Cold Transient	3.47	31.0	3.28	21.6	3.47	31.2
Hot Transient	3.00	18.5	3.11	28.8	3.00	18.7
Hot Stabilized	5.10	50.5	4.93	49.6	5.10	50.1

Notes:
[1]98.02 percent of total VMT is represented by catalyst equipped vehicles.
[2]1.98 percent of total VMT is represented by non-catalyst vehicles
[3]Average vehicle miles traveled in the indicated operating mode per vehicle

TABLE 3 FTP Driving Cycle Versus NPTS Data

Trip Characteristic	FTP (Av. Daily)	NPTS Data 7 - 9 AM	NPTS Data Daily
Number of trips made by household	n.a.	1.8	6.3
Number of trips made by each vehicle	4.7	1.5	4.5
Average trip length (miles/veh trip)	7.5	6.8	6.6
Average trip duration (min/veh trip)	22.9	14.0	13.5
Vehicle miles (for analysis period)	35.25	10.2	29.7
Number of cold starts (per household)	n.a.	1.3	3.6
Number of cold starts (per vehicle)	2	1.1	2.6
Number of hot starts (per household)	n.a.	1.8	3.7
Number of hot starts (per vehicles)	2.7	1.7	3.1
Cold transient travel (% of total VMT)	20.6[1]	34.5	31.2
Hot transient travel (% of total VMT)	27.3[1]	13.7	18.7
Hot stabilized travel (% of total VMT)	52.1[1]	51.8	50.1

n.a. - data not available for analysis or the characteristic is not applicable
[1] based on morning commute.

CONCLUSIONS AND RECOMMENDATIONS

The operating mode mix based on the FTP is only representative of the FTP drive cycle and does not necessarily apply to other conditions. Therefore, use of these operating mode fractions for deriving emission rates using the MOBILE model can produce incorrect results. An analysis of the NPTS data base indicates that, in most cases, the average VMT fraction of cold starts is more then 30 percent instead of the 20.6 percent as derived from the FTP drive cycle. Depending on the ambient temperature, this could yield a 20 to 40 percent increase in predicted CO and HC emissions using the MOBILE 5A model. Furthermore, during certain times of day, the cold transient mode travel may exceed 40 percent of the total VMT (Table 1). The greater the error in estimating the transient mode travel, especially the cold transient travel, the greater the error will be in emission estimate.

The methodology to deriving operating mode fractions presented in this paper as an alternative to the FTP mode mix is a step toward improving the inputs to emission estimation models. The numbers presented in Table 4 may be used in areawide emission inventory studies using the MOBILE model. The results of the methodology provide a basis for estimating vehicle operating mode mix for different times of day, by trip purpose and urban area size. However, for high-resolution emission inventory studies, it would be appropriate to derive operating mode fractions at even finer resolution, such as by functional class of roadways and geographic location.

It should be noted that the NPTS data do not contain information on the commercial trips. Correction factors are needed to modify the operating mode fractions presented in this paper to account for the commercial travel in the traffic flow. Also, it would be academically interesting to study the sensitivity of the emission estimation models to various sets of operating mode fractions presented in this paper. Such a study would likely draw attention to the degree of underestimation of CO and HC emissions when using the FTP operating mode fractions.

ACKNOWLEDGMENTS

The authors express their sincere thanks to Fred Wegmann and Bruce Ralston of the University of Tennessee at Knoxville and Mike Bronzini of the Oak Ridge National Laboratory for their helpful suggestions during the course of this study. The authors also extend their gratitude to Walter Gazda of Volpe National Transportation Systems Center and Krishna Jain of EG&G Dynatrend for thoroughly reviewing the manuscript for this paper.

TABLE 4 Operating Mode Fractions for Urbanized Areas (Daily)

Urban Area Population	Percent VMT in: Cold Transient Mode	Percent VMT in: Hot Transient Mode	Percent VMT in: Hot Stabilized Mode
50,000-199,999	32.9	21.9	45.2
200,000-499,999	35.9	23.7	40.4
500,000-999,999	31.0	18.6	50.4
Over 1,000,000 (No Subway)	29.8	18.1	52.1
Over 1,000,000 (With Subway)	30.0	18.8	50.5
Nationwide	31.2	18.7	50.1
FTP	20.6	27.3	52.1

Note: The urban area categories are according to the NPTS classification

REFERENCES

1. Miller, T. L., A. Chatterjee, J. Everett, and C. McIlvaine. Estimating Travel Related Inputs to Air Quality Models. *Transportation Planning and Air Quality, Proc. National Conference*, American Society of Civil Engineers, July 1991.
2. *User Guide to MOBILE 5A (Mobile Source Emission Factor Model.)*, U.S. Environmental Protection Agency, March 1993.
3. McIlvaine, C. M. *An Investigation of Vehicle Operating Mode Profiles for Use in Preparing a High-Resolution Emission Inventory.* M.S. thesis. University of Tennessee, May 1990.
4. Brodtmen, K. J., and T. A. Fuce. *Determination of Hot and Cold Start Percentages in New Jersey.* Report FHWA/NJ-84/001. New Jersey Department of Transportation, Trenton, July 1984.
5. Ellis, G. W., W. T. Camps, and A. Treadway. *The Determination of Vehicular Cold and Hot Operating Fractions for Estimating Highway Emissions.* State of Alabama Highway Department, Sept. 1978.
6. Midurski, T. P. *Determination of Percentages of Vehicles Operating in the Cold Start Mode.* Prepared for the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Aug. 1977.
7. Venigalla, M. M. *A Network Assignment Based Approach to Modeling Mobile Source Emissions.* Ph. D. dissertation. University of Tennessee, May 1994.
8. *MINUTP User's Guide.* COMSIS Corporation, 1992.
9. *User's Guide for the Public Use Tapes: 1990 Nationwide Personal Transportation Survey.* Research Triangle Institute. Prepared for the U.S. Department of Transportation, Dec. 1991.