Trip-Based Approach To Estimate Emissions with Environmental Protection Agency's MOBILE Model

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The Environmental Protection Agency's (EPA's) MOBILE model outputs an emission rate per vehicle mile of travel (VMT). The rate is based on the federal test procedure (FTP), which represents typical driving conditions for an urban vehicle trip. In current practice, however, links instead of trips are used to estimate both VMT and many of the travel characteristics needed as inputs to MOBILE. For example average link speeds are provided as input to MOBILE in current practice, although trip speeds might be more appropriate, given the FTP basis of MOBILE emission factors. A different approach to application of emissions factors from MOBILE is presented. The approach is based on trips rather than on links and therefore more consistent with the trip basis used to develop MOBILE's emissions factors. The approach also allows development of data on travel characteristics from travel model output and travel survey data in a straightforward manner and does not require the special efforts to account for missing VMT needed in the link-based approach. However its most important advantage over the link-based approach is that it facilitates estimation of impacts of transportation control measures on non-VMT MOBILE inputs such as cold-start percentages, vehicle mix, and trip length distribution.

As a result of recent studies (*1,2*) there is a perception that hydrocarbon (HC) and carbon monoxide (CO) emissions from vehicles are underpredicted by both MOBILE and EMFAC. There are several reasons for the inaccuracies. For example the model algorithms are based on average estimates of responses to a particular variable made on the basis of vehicle test results, and emissions estimates may not be truly representative of the entire range represented by the average. Many weaknesses of the models are due to either limited data or faulty assumptions made by their users (*3*). Also travel forecasts or even base travel data inputs to the emissions models may have significant errors (*4*). The focus in this paper is on the inaccuracies that may result from the incompatibility of travel model outputs with emission model inputs and from inaccurate estimation of the non-vehicle miles of travel (non-VMT) transportation data inputs to MOBILE.

The MOBILE model outputs an emission rate per VMT. The rate is based on the federal test procedure (FTP), which represents typical driving conditions for an urban vehicle trip. The Environmental Protection Agency (EPA) has developed and is currently testing a remnant cycle to supplement FTP to provide for emission control under high-speed and high-acceleration events not currently represented in the FTP. However no changes to the basic structure of the model are proposed.

The standard procedure for estimating emissions by the MOBILE emissions model is as follows: emissions = emission factor × vehicle activity. For MOBILE travel activity is VMT. Emission factors vary depending on several characteristics of travel activity such as:

- Vehicle type and age mix,
- Vehicle speed,
- Time of day of travel, which determines ambient temperature,
- Operating mode (i.e., hot or cold start and hot stabilized operation), and
- Trip length distribution.

In current practice estimates of both travel activity and many of the travel characteristics are link based. However MOBILE emissions factors are based on FTP data, which represent trip travel characteristics rather than link-level travel characteristics. In FTP, which is the basis for development of baseline emissions factors, "bags" of pollutants are collected from entire trips about 20 min long. Therefore development of travel characteristics for limited segments of the highway network is inconsistent with the base from which MOBILE factors are developed, that is, entire trips. For example average speeds on which MOBILE factors are based represent speed cycles for an entire trip and not speed cycles on any specific link. This paper proposes a method to derive VMT on the basis of trips instead of links and investigates the magnitude of the possible differences in emissions estimates by using a case study analysis for a large urban area.

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ADVANTAGES OF THE TRIP-BASED APPROACH

Aside from the fact that a trip-based approach is more consistent with the way MOBILE emissions factors are developed, it has other advantages. Many transportation control measures (TCMs) affect not just VMT but also other important emission model variables. For example a TCM that shifts short vehicle trips to the bicycle or walk modes will not just affect impact VMT but also reduce the percentage of cold-start VMT. On the other hand a TCM that shifts single-occupant vehicle trips to transit or car pool modes will increase the percentage of cold-start VMT if the shifts involve park-and-ride access to transit stops or car pool staging areas. Shifts to bus transit affect vehicle mix and operating mode percentages. The current link-based method makes it difficult to estimate such changes. This is where the trip-based approach presented has an important advantage over the link-based approach: it facilitates estimation of non-VMT MOBILE inputs such as cold-start percentages, vehicle mix, and trip length distribution. Thus future estimates of the impacts of TCM policies on emissions will nevertheless improve in accuracy.

Another advantage of the trip-based approach is that it does not require special efforts to estimate VMT missing in link-based VMT estimates developed from model output, that is, local VMT and park-and-ride VMT. With a link-based approach special efforts are necessary to estimate local VMT because all streets in the urban area are not reflected in the model network, and therefore as much as 15 percent of regional VMT that occurs on local streets may not be accounted for. Also generally trips made by automobile to transit park-and-ride lots or to car pool staging areas are not assigned to the model network, and their effects on percentage of cold starts are ignored. With a trip-based approach park-and-ride VMT and its effects on cold-start percentages are easily estimated.

ESTIMATING VMT AND AVERAGE SPEED BY TRIP-BASED APPROACH

By the trip-based approach vehicle activity is calculated from trip tables instead of from network links, as follows:

- Zone-to-zone VMT = zone-to-zone trips × zone-to-zone distance. (Note that matrices of zone-to-zone distances are called *distance skims*. Zone-to-zone travel distances are computed from the shortest time path between zones and take into account detours caused by congestion by skimming distances from the loaded network.)
- Zone-to-zone average speed = zone-to-zone distance/zone-to-zone travel time. [Note that matrices of zone-to-zone travel times are called *travel time skims*. If realistic speeds are not output from assignment, link speeds may first need to be adjusted on the basis of the relationships of speed to highway volume-to-capacity ratios derived from the *Highway Capacity Manual* (*5*) and assigned traffic volumes on individual links.]
- VMT in a specific average speed category = sum of all zone-to-zone VMT for trips made at the specific average speed.

The trip-based approach will not overlook vehicle activity that is missing in the travel model output used in the link-based approach:

- Local VMT: intrazonal VMT is not excluded. To get intrazonal VMT vehicle trip tables, which provide the number of intrazonal trips by zone, are multiplied by distance skims in which intrazonal trip distance is based on:
  - –Intrazonal trip lengths (in minutes) output from the trip distribution model and
  - –Assumed average speeds for intrazonal trips (which will be slow speeds, since these trips are made on local streets).
- Park-and-ride VMT: park-and-ride VMT is estimated on the basis of the number of such trips from each zone (on the basis of the output from the mode choice model) and average distance to the zone in which the relevant park-and-ride lot is located (from distance skims).

However the main advantages of the trip-based approach do not relate to completeness of its VMT estimates. More important advantages are (a) its ability to provide average speed estimates more consistent with the average speed expected by the MOBILE model and (b) its ability to estimate the impacts of future TCMs on travel characteristics, which are discussed next.

ESTIMATING OTHER TRAVEL CHARACTERISTICS

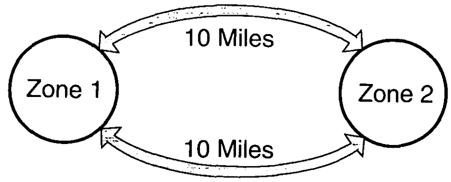
The trip-based approach allows development of base year as well as future year estimates of travel characteristics from travel model output and from travel survey data in a straightforward manner. Two types of data are needed to estimate vehicle travel characteristics: travel model and survey data.

Home interview travel survey data are useful primarily for developing distributions of base travel activity by time of day (for use with ambient temperature and to get average speed estimates by time of day) and to get estimates of base vehicle mix and operating mode. Shifts from these base characteristics that are induced by TCM policies (for example impacts of location-specific flextime or peak period pricing policies on VMT distribution by time of day or impacts of transit park-and-ride lots on percentage of cold-start VMT) are then estimated for future scenarios. In the link-based approach travel characteristics for the base year may be obtained from sample surveys of highway links, but estimating the impacts of TCMs on those characteristics for specific links (or aggregations of links) in future scenarios is difficult. The following types of data are obtained from home interviews:

- Time of trip, by trip purpose, from which appropriate temperature inputs to MOBILE can be developed.
- Operating mode of vehicle, derived from elapsed time between trips, from which shares of trips starting cold versus starting hot can be developed by trip purpose and time of day.
- Vehicle type use by trip purpose, from which estimates of vehicle mix by trip purpose and time of day can be developed. (A special type of travel survey called an *auto log survey* is needed to get this type of information from home interviews. Note that truck trips are often a separate trip purpose in travel demand models. Special surveys are needed to get truck travel data.)
- Travel time, which can be used to develop trip length (i.e., duration) distributions by trip purpose and to check network speeds and average trip lengths estimated by the models.

If home interview survey data are not available for a specific urban area, national data on personal travel can be obtained by urban area size category through analysis of Nationwide Personal Transportation Survey (NPTS) data. Research with NPTS data has recently been completed at the University of Tennessee (*6*). Alternatively individual urban areas that are planning to undertake a home interview survey for the purpose of updating their travel models could add questions relating to vehicle use and time of trip for a small increase in cost. Typically home interview surveys cost about $100 per interview.

Note that home interview survey data could also be used with the link-based approach to get regionwide shares of base (but not future scenario) VMT by operating mode, vehicle mix, and time of day (*7*). In other words the survey data can be used to estimate travel characteristics applicable to base regionwide VMT in an aggregate fashion. However the trip-based approach allows development of travel characteristics for base conditions as well as for future scenarios with TCM policies. The demonstration example that follows shows how estimates of the impacts of a future TCM policy on base travel characteristics may be obtained.



100	1500
1500	50

HB Work

600	2000
2000	300

HB Non-Work

300	1000
1000	150

NHB

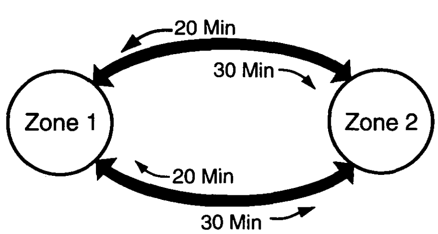
FIGURE 1 Demonstration example and vehicle trips.

DEMONSTRATION EXAMPLE

The demonstration example uses ETOWN, a small hypothetical urban area with two traffic analysis zones and a highway network, as shown in Figure 1. ETOWN has proposed express bus service with park-and-ride access for inclusion in its transportation plan and needs to develop transportation data inputs for an emissions analysis to determine conformity with its state implementation plan for air quality.

Future year vehicle trip tables by trip purpose [Home-Based (HB) Work, HB Nonwork, and Non–Home-Based (NHB)] have been developed for the peak period by using ETOWN's mode choice model, as presented in Figure 1. The vehicle trips made to park-and-ride lots do not appear in the vehicle trip table because the model considers them to be transit trips. The vehicle trip table has been assigned to ETOWN's highway network by using an equilibrium technique, and the resulting volume/capacity ratios have been used to compute adjusted travel times on the basis of congestion; the results are shown in Figure 2.

A home interview (automobile log) travel survey was also recently undertaken in ETOWN, from which it was determined that the percentages of vehicle trips starting cold during peak periods were as follows: HB Work, 90 percent; HB Nonwork, 50 percent; NHB, 30 percent.



10	30
20	10

Travel Time Skim

0	10
10	0

Distance Skim

FIGURE 2 Assignment results.

10	30
20	10

Times

0	10
10	0

Distances

12	20
30	12

Speeds

FIGURE 3 Speed calculation.

On the basis of home interview survey ETOWN planners were able to derive light-duty gasoline vehicle (LDGV) use for peak period trips by trip purpose, as follows: HB Work, 90 percent; HB Nonwork, 90 percent; NHB, 60 percent. The focus for this demonstration is on development of peak period transportation data for work trip purposes. Trips for other purposes are handled by simply repeating the steps for each trip purpose. Note that temperature to be used as input is determined by the time of day of the peak period being analyzed.

Step 1: Estimate VMT by Speed Class

Step 1(a): Speed Calculation

In Figure 3 skimmed times and distances are used to calculate average speed for each zone pair. For example speed between zone 1 and zone 2 = (10 miles/30 min) × 60 min/hr = 20 mph. For intrazonal trips a low speed of 12 mph is assumed because this travel occurs on local streets.

Note that the same average speed could result from very different speed cycles, as shown by recent research (*8*) done by the California Air Resources Board. For example an average speed of 35 mph when the majority of travel is on freeways is based on a very different cycle of stops, accelerations, and decelerations than an average speed of 35 mph when the majority of travel is on arterials. However the MOBILE model currently assumes the same speed cycle for all trips of the same speed. If the MOBILE model is enhanced to reflect the effects of varying shares of freeway versus arterial travel for trips with the same average speed, the path skimming process in travel models could be enhanced to keep track of shares of the path on freeways versus arterials.

Step 1(b): VMT Calculation

In Figure 4 the vehicle trip table input into traffic assignment and the distance skims are used to calculate VMT for each zone pair.

100	1,500
1,500	50

Trips

2	10
10	2

Distances

200	15,000
15,000	100

VMT

FIGURE 4 VMT calculation.

For example total number of trips between zone 1 and zone 2 is 1,500, and the vehicles travel a distance of 10 mi for each trip. Therefore VMT = 1,500 × 10 = 15,000. For intrazonal VMT one first needs to estimate an intrazonal average distance using the intrazonal travel time and average speed of 12 mph assumed previously. For example intrazonal distance for zone 1 = 12 mph × (10 min/60) = 2 mi.

The trip-based approach can be used to easily estimate the VMT impacts of trips to park-and-ride lots that were not included in the vehicle trip table used as input to ETOWN's traffic assignment. Figure 5 demonstrates the process for calculation of park-and-ride VMT. In ETOWN the park-and-ride lot is assumed to be in the zone from which park-and-ride trips are generated, and the park-and-ride VMT is obtained by multiplying the number of park-and-ride trips by intrazonal distance. (Note that bus VMT may be obtained from transit network data.)

Step 1(c): Classify VMT

All VMT in a specified speed range is aggregated (Figure 6). For example intrazonal VMT, for which the travel speed is 12 mph, falls in the speed range of 10 to 14 mph. Aggregating all VMT in the 10- to 14-mph speed range gives (220 + 120) = 340 VMT. (Caution: the speed ranges used in this example are too wide for use in practice.)

Speed Range	VMT
0-4	
5-9	
10-14	340
15-19	
20-24	15,000
25-29	
30-34	15,000

FIGURE 6 VMT classification.

Step 2: Estimate Distribution of Trip Lengths

In step 2 VMT is classified by trip length (i.e., duration) category to get the percentage distribution in each category (Figure 7). For example all intrazonal VMT falls in the range of 0 to 10 min.

Step 3: Estimate Regional VMT Mix by Vehicle Type

For the purpose of this demonstration estimates of LDGV VMT percentages are shown. The survey estimates of the percent trips by each vehicle type are used to represent the percent VMT by vehicle type. The percent VMT would be different from the percent trips only if survey data showed that trips by some vehicle types were longer (i.e., in distance) than those by other vehicle types.

Park-and-ride policies can have an impact on VMT mix. In ETOWN it was assumed that the future new trips to park-and-ride lots will be made 100 percent by LDGV, whereas all other trips reflect the vehicle mix from the base year survey. Figure 8 shows how the VMT mix resulting from such an assumption can be estimated.

Step 4: Percent Cold Start VMT

The proposed park-and-ride policies in ETOWN will affect operating mode shares. These impacts can be estimated by the trip-based approach. Estimation of percent cold-start VMT or percent hot-start VMT involves similar steps. Below the steps for estimating percent cold-start VMT, as shown in Figure 9(*a*), are described.

1. By using the work purpose's non–park-and-ride vehicle trip table and percent cold-start trips for the work purpose from survey data (i.e., 90 percent), a cold-start-trip table for the work purpose for non–park-and-ride trips was calculated. In ETOWN 100 per-

10	0
0	10

Trips (to P/R Lot)

2	10
10	2

Distances

20	0
0	20

VMT (P/R)

220	15,000
15,000	120

Total VMT (P/R + all other)

FIGURE 5 Park-and-ride (P/R) VMT.

220	15,000
15,000	120

VMT

10	30
20	10

Travel Time

Time Range (Minutes)	VMT
0-10	340
11-20	15,000
21-30	15,000
31-40	
41-50	
51-60	

FIGURE 7 Trip length distribution.

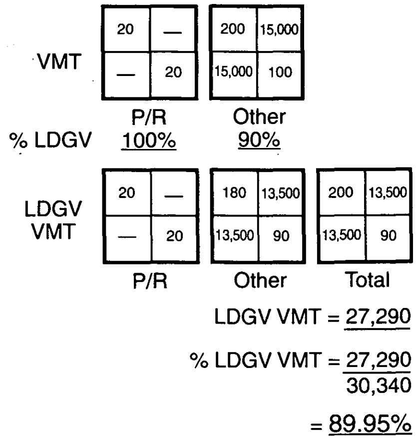


FIGURE 8 VMT mix by vehicle type.

cent cold starts were assumed for park-and-ride trips, and a cold-start-trip table for park-and-ride trips was likewise obtained.

2. Next trip lengths shorter than 3.6 mi were identified from the cold-start-trip table. These are trips that are made entirely in the cold-start mode. The 3.6-mi limit is based on the distance traveled in the FTP drive cycle during its start phase. (Note that alternatively 8.4 min can be used as the cutoff, with a slightly more complicated computation procedure. The cold-start VMT for these trips was obtained by multiplying the number of these trips by the appropriate zone-to-zone distance from the distance skim table. Caution: It may be more appropriate in practice to assume that trips shorter than 3.6 mi generate 3.6 cold-start VMT, because most excess emissions from cold starts actually occur in the first minute or about 0.5 mi (*9*). This is shown in Figure 9(*b*).

3. For trips longer than 3.6 mi (i.e., trips that operate only partly in the cold mode), one obtains cold-start VMT by multiplying total cold-start trips by 3.6 mi.

4. Percent cold-start VMT is then obtained by aggregating VMT from Substeps 2 and 3 and dividing by total VMT. [Caution: if trips shorter than 3.6 mi were assumed to be 3.6 mi in Substep 3, then appropriate adjustments must be made to total VMT to include the "excess" miles.]

These steps can similarly be used to estimate hot-start mode VMT (using 0 percent hot starts for park-and-ride trips and 10 percent hot starts for non-park-and-ride trips). The balance of VMT would be in the hot-stabilized mode.

REAL-WORLD EXAMPLE: COMPARISON OF ESTIMATES FROM TRIP-BASED APPROACH WITH ESTIMATES FROM LINK-BASED APPROACH

Table 1 gives a comparison of HC emissions estimates for the Baltimore, Maryland, urban area by the trip-based approach versus estimates obtained by the conventional link-based approach. The Baltimore travel models estimate trips for six trip purpose categories and for a 24-hr period (*10*). By using national survey data from NPTS (*11*), estimates of cold- and hot-start percents and vehicle mix for each trip purpose were derived for the trip-based approach. Trip length (i.e., duration) distributions were obtained for each trip purpose from the travel models on the basis of congested speeds after traffic assignment.

For the link-based approach link-based VMT was developed from the combined-purpose traffic assignment. To ensure consistency with travel characteristics developed for the trip-based approach, the cold- and hot-start percentages, vehicle mix, and trip length (i.e., duration) distribution used with the combined-purpose VMT from highway network assignment were obtained as weighted averages of the parameters used by trip purpose in the trip-based approach. Table 2 gives these MOBILE inputs. Note here that MOBILE defaults for technology parameters were used (i.e., the emissions factors used do not reflect inventory and main-

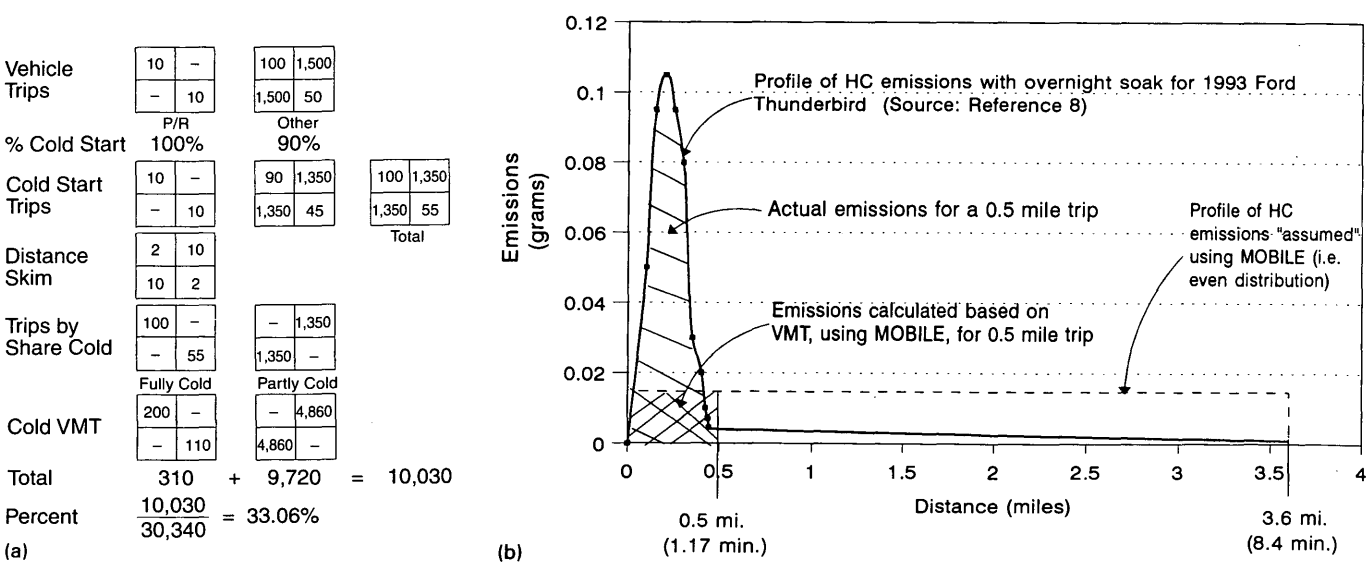


FIGURE 9 (*a*) Percent cold starts and (*b*) profiles of actual versus model cold-start emissions.

tenance programs, etc.), and therefore the emissions estimates in Table 1 cannot be expected to match those developed for Baltimore's 1990 base year inventory. Figure 10 shows the process used to conduct the analysis.

Table 1 indicates that the two approaches result in different total emissions estimates for this case study application. This analysis suggests that further investigation is necessary to determine the causes of these differences and to determine whether the differences are statistically significant or merely a chance occurrence. A comparison of the VMT distribution by speed category was developed for each approach; the comparison is shown in Figure 11. The VMT distributions suggest that a possible reason for the higher emissions with the link-based approach is the much larger share of VMT in the lower speed categories and the higher speed categories for which MOBILE generates higher emissions rates.

The particular procedures that were used to apply the link-based approach demonstrate that the two approaches are not necessarily mutually exclusive and can be used in tandem. Estimates of travel characteristics (vehicle mix, operating mode shares, and trip length distribution) used for the link-based approach were in fact obtained as an output from the trip-based approach. Thus urban areas wishing to continue to use the link-based approach could still use the trip-based approach to estimate the impacts of TCMs on travel characteristics other than speed.

TABLE 2 Travel Characteristics for Combined-Trip Purpose

Operating Mode (% VMT):		
Cold start	19.1%	
Hot start	12.0%	
Hot stabilized	68.9%	
TOTAL	100 %	
Vehicle Mix (% VMT):		
LDGV	Light duty gasoline vehicle	68.0%
LDGT1	Light duty gasoline truck 1	17.5%
LDGT2	Light duty gasoline truck 2	9.7%
HDGV	Heavy duty gasoline vehicle	0.8%
LDDV	Light duty diesel vehicle	0.8%
LDDT	Light duty diesel truck	0.5%
HDDV	Heavy duty diesel truck	2.2%
MC	Motorcycle	0.5%
		100.0%
Trip Length Distribution:		
0 - 10 min.	6%	
11 - 20 min.	24%	
21 - 30 min.	28%	
31 - 40 min.	20%	
41 - 50 min.	10%	
51 - 60 min.	12%	
TOTAL	100%	

SPECIAL APPLICATIONS OF THE APPROACH

This section discusses two special applications of the approach: (a) for base year emissions inventory development and (b) for developing gridded emissions estimates for input to dispersion models.

Use of highway performance monitoring system (HPMS) data is currently recommended by EPA for base year emissions inventory development. This recommendation can be satisfied by ensuring that model VMT output for the base year is made consistent with HPMS ground count-based VMT before any output from the model is used. For future year inventories the model can be run without adjustments to estimate future travel, and the ratio of base year HPMS to base year model VMT can be used to factor future model VMT uniformly for all trip purposes.

TABLE 1 Daily HC Emissions for Baltimore Study Area (1990)

	VMT	Emissions (grams)
Trip-based approach:		
HB Work	19,960,287	64,974,674
HB Non-work	13,140,846	43,782,673
Non-home based	6,816,524	23,718,698
Light truck	3,026,189	13,650,688
Heavy truck	723,762	4,038,273
External	3,833,984	11,594,334
TOTAL	47,501,592	161,759,340 (178 tons)
Link-based approach:		
Network links	45,519,179	174,233,476
Intrazonal	1,982,413	10,962,744
TOTAL	47,501,592	185,196,220 (204 tons)
Difference:		
Magnitude	0	26 tons
Percent	0	14.6 %

The trip-based approach produces regionwide emissions estimates. If emissions estimates are needed for smaller geographic areas (grid cells), regionwide estimates will need to be disaggregated. Three possible ways of doing this are outlined.

1. EPA's procedures (*12*) can be used to perform geographic disaggregation to grid cells.

2. Emissions can be disaggregated on the basis of relative emissions rates per VMT by volume/capacity (V/C) ratio for various facility classes and area types, and the VMT estimates by link output from the models. (Note: centroid connector and intrazonal VMT would be considered to be on local streets in the grid cell in which the zone centroid is located.) However development of appropriate emissions rates per VMT by V/C ratio for various facility class and area type categories is not easy and requires research, because as discussed earlier the MOBILE model is based on entire trips and not specific links. CARB is considering developing emissions rates by facility type and level of service (*8*).

3. Shares of total emissions in each grid cell developed from emissions calculated on the basis of the link-based approach to allocate total regional emissions calculated by the trip-based approach can be used.

With more sophisticated computer software emissions could be estimated by trip interchange (i.e., each cell of the trip table) and then assigned to the shortest time path between the two relevant zones. The assignment procedure would be similar to current traffic assignment procedures, with proration of zone-to-zone emissions to individual links on the basis of standard profiles of emissions by elapsed time or distance from origin.

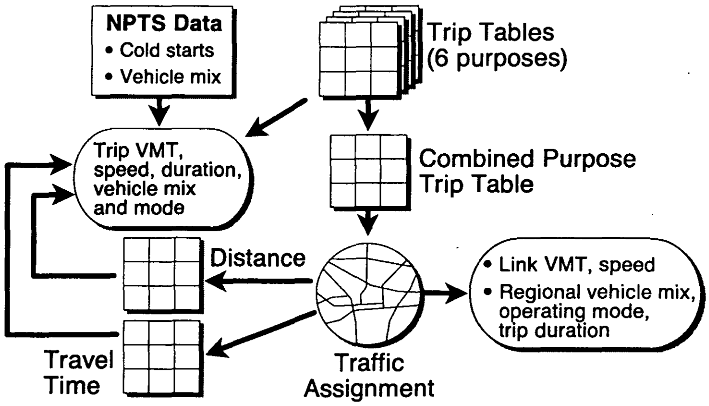


FIGURE 10 Analysis procedures using Baltimore models.

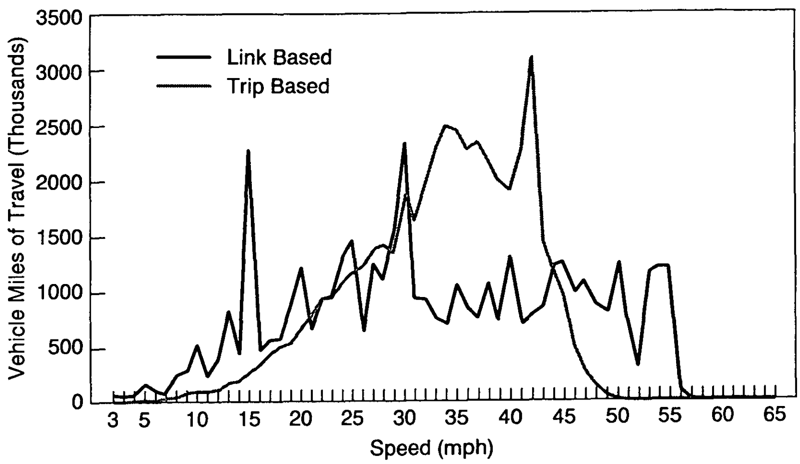


FIGURE 11 Comparison of VMT by speed.

CONCLUSIONS

This paper has presented a trip-based approach for estimating emissions with the MOBILE model by using travel model output and travel survey data. The approach can overcome some problems with the link-based approach used in current practice. Application of the procedure was demonstrated with a hypothetical example and a real-world example of an urban area, and it was demonstrated that the link-based approach can be used with the trip-based approach to improve estimates of changes in travel characteristics as a result of TCMs. Comparison of emissions estimates by using the trip-based approach with results from the link-based approach for the real-world example indicates differences in emissions estimates. Further investigation is necessary to determine whether the differences are merely a chance occurrence or there are biases in estimates on the basis of the approach used. Also further research is needed to determine if accuracies of estimates are in fact improved by use of the trip-based approach and whether further disaggregation of trips (e.g., into trip categories based on vehicle type or trip length, in addition to average speed) will result in differences in estimates or in improved accuracy.

Notwithstanding accuracy considerations there are many advantages of the trip-based approach.

1. Estimation of local VMT is automated and does not require off-model procedures as in the link-based approach.
2. Impacts of TCMs such as park-and-ride lots on VMT and travel characteristics are more easily estimated.
3. The approach is more consistent with FTP cycle "trips" used as the basis for the MOBILE model, and therefore future enhancements to MOBILE can more easily be reconciled with the trip-based approach.

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