Variability of Vehicle Emissions and Congestion Forecasting

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Abstract

There is an increasing reliance on mobile source emissions analyses as part of the transportation planning process, including regional and hot-spot analyses to fulfill the requirements of the transportation conformity rule and project-level highway air quality assessments in response to the requirements of the National Environmental Policy Act. The general procedure of an emissions analysis is to employ the U.S. Environmental Protection Agency's MOBILE6.2 model to obtain on-road mobile source emission factors, and multiply by the vehicle miles of travel to construct emission inventories. Critical to the outcome of such studies are future predictions of vehicle activity. This is especially true in evaluating transportation alternatives to assess how well a proposed project may or may not mitigate vehicle congestion and reduce emissions. This paper investigates one aspect of vehicle congestion and emissions forecasting by applying different vehicle speed estimating methodologies used for sketch planning purposes and shows the variability of MOBILE6.2 emission factors as a function of travel demand and the associated capacity (i.e., volume-to-capacity ratio).

Introduction

In the current regulatory framework, potential changes in mobile source emissions among transportation alternatives are evaluated using the U.S. Environmental Protection Agency's (EPA) MOBILE6.2 model (U.S. EPA, 2003), along with forecasts of vehicle miles of travel (VMT). Emission factor predictions obtained from the MOBILE6.2 model are also a function of numerous vehicle activity parameters such as VMT fraction by vehicle class, by hour of the day, by highway functional system, by vehicle speed, as well as others. While additional inputs such as external conditions (e.g., ambient temperature); vehicle fleet characteristics; vehicle fuel specifications; and state programs (e.g., implementation of an inspection maintenance program and/or use of reformulated gasoline) can affect the magnitude of emissions specific to a locale; these would be common to all alternatives under review. The most important factors affecting emission differences among the available transportation options are distinctions in vehicle activity. An essential facet of a mobile source emissions analysis is to determine the extent to which a project alternative is expected to mitigate congestion on links of a transportation network operating at or over capacity. Anticipated changes in MOBILE6.2 emission factors as a function of congestion mitigation is investigated herein along with the variability of results produced among several vehicle speed forecasting methodologies.

Vehicle Congestion Forecasting

The sensitivity of MOBILE6.2 emission factors to changes in vehicle speeds has been documented by the U.S. EPA (2002a) and the Federal Highway Administration (FHWA) (Tang, 2003; Tang, 2005). Surveys of vehicle speed forecasting techniques are also available from a variety of sources (NCHRP, 1997;

Dowling Associates, 1997; NHI, 2003). The de facto standard for computing travel speeds is the Highway Capacity Manual (HCM) (TRB, 2000). However, as acknowledged by the U.S. EPA (2001), the HCM techniques require detailed, facility-specific information that is unlikely to be available at the planning level. Because of this practical consideration, the U.S. EPA (2001) recommends that the Bureau of Public Roads (BPR) formula be applied instead to forecast vehicle speeds on a regional basis for typical urban areas.

In its most recent update in 2000, the Highway Capacity Manual provides recommended procedures for forecasting highway performance measures for area-wide planning applications, including speed estimation. Because of the recognized practical considerations, these procedures are simplifications of the more elaborate techniques provided elsewhere in the HCM. An alternative technique is also provided in the HCM based on the traditional BPR formula. A third technique, based on methodology developed by the Texas Transportation Institute (TTI) for the National Highway Institute (2003) is examined as well.

The data required to compute vehicle speeds on a link vary by facility type or functional class and generally consist of demand data (daily traffic, peak hour volume); data for estimating free-flow speed (facility type, speed limit); and data for estimating capacity (number of lanes, percent trucks, terrain). Facility types are used in the HCM; the TTI method uses FHWA's Highway Performance Monitoring System (HPMS) area types and functional classes; and MOBILE6.2 uses its own facility driving cycle definitions. Table 1 provides a suggested association of HPMS area type/functional class to HCM facility type to MOBILE6.2 facility type.

The HCM approach for computing vehicle speed on a link is to divide the link length (in mi) by the link travel time (in h). The link travel time in turn is a function of the link travel time at the free-flow link speed; the zero-flow control delay at signalized intersection; the expected duration of demand; the link volume to capacity ratio (V/C); a calibration factor; and the link length as provided in Equation 30-5 of the Highway Capacity Manual (TRB, 2000). An alternative computation of the link travel time is provided in Equation C30-1 of the Highway Capacity Manual, based on the BPR curve. In this equation, the link travel time is a function of the link travel time at the free-flow link speed; the link V/C; and BPR parameters. The TTI method is to characterize vehicle link speed as the harmonic mean of two components: the free-flow speed and delay speed (NHI, 2003; Claggett, 2006a). The delay speed is a function of the link V/C above a minimum amount of delay.

Congested vehicle speeds were computed using the three methods for conditions representative of the HPMS small urbanized area type for interstate and other principal arterial functional classifications. Speeds were computed for volume-to-capacity ratios ranging from 0.05 to 1.25 in increments of 0.05. Emission factors provided by the MOBILE6.2 model are for an average trip, the basis of which is the Federal Test Procedure adopted to simulate a typical urban trip of 7.5 mi in length. Consequently, a link length of 7.5 mi was used in the speed computations. The other assumptions adopted are provided in Table 2.

Table 1. HPMS functional class – HCM facility type – MOBILE6.2 facility type mapping.

HPMS Area Type	HPMS Functional Class	HCM Facility Type	MOBILE6.2 Facility Type
Rural	Interstate	Basic Freeway	Freeway/Freeway Ramp
	Other Principal Arterial	Rural Multilane Highway	Freeway
	Minor Arterial	Rural Two-Lane Highway	Arterial/Collector
	Major Collector	Rural Two-Lane Highway	Arterial/Collector
	Minor Collector	Rural Two-Lane Highway	Arterial/Collector
	Local	Rural Two-Lane Highway	Arterial/Collector or Local
Small Urban (Population 5,000 to 49,999)	Interstate	Basic Freeway	Freeway/Freeway Ramp
	Other Freeways	Basic Freeway	Freeway/Freeway Ramp
	Other Principal Arterial	Class I	Arterial/Collector
	Minor Arterial	Class II	Arterial/Collector
	Collector	Class III	Arterial/Collector
	Local	Class IV	Local
Small Urbanized (Population 50,000 to 199,999)	Interstate	Basic Freeway	Freeway/Freeway Ramp
	Other Freeways	Basic Freeway	Freeway/Freeway Ramp
	Other Principal Arterial	Class II	Arterial/Collector
	Minor Arterial	Class II	Arterial/Collector
	Collector	Class III	Arterial/Collector
	Local	Class IV	Local
Large Urbanized (Population 200,000 or more)	Interstate	Basic Freeway	Freeway/Freeway Ramp
	Other Freeways	Basic Freeway	Freeway/Freeway Ramp
	Other Principal Arterial	Class III	Arterial/Collector
	Minor Arterial	Class III	Arterial/Collector
	Collector	Class III	Arterial/Collector
	Local	Class IV	Local

Table 2. Speed calculation parameters.

Technique	Parameter	Interstate	Other Principal Arterial
HCM Approach	Free-flow speed, mph [a]	65	40
	Link length, mi	7.5	7.5
	Calibration parameter, h^2/mi^2 [a]	1.48E-05	5.02E-04
	Signals per mile [a]	0	0.6
	Average effective green time per cycle for all signals on link [b]	0	0.45
	Average cycle length for all signals on link, s [c]	0	100
	Speed at capacity, mph [a]	52	18
BPR Formula	Free-flow speed, mph [a]	65	40
	Link length, mi	7.5	7.5
	a [d]	0.25	0.38
	b [d]	9.0	5.0
TTI Method	Free-flow speed, mph [a]	65	40
	A [e]	0.015	0.050
	B [e]	4.2	3.9
	M [e]	5.0	6.0

[a] Highway Capacity Manual (TRB, 2000), Exhibit 30-4
[b] Highway Capacity Manual (TRB, 2000), page 10-23
[c] Highway Capacity Manual (TRB, 2000), Exhibit 10-16
[d] Highway Capacity Manual (TRB, 2000), Exhibit C30-2
[e] National Highway Institute (2003)

Emission Factor Forecasting

The EPA's MOBILE6.2 model (dated 24-Sep-2003) was used to forecast episodic emission factors of carbon monoxide (CO) and the precursors to ozone formation (volatile organic compounds, VOC and nitrogen oxides, NOx); as well as, annual average emission factors of selected mobile source air toxic (MSAT) compounds (benzene and diesel particulate matter, DPM). MOBILE6.2 was run using EPA's corrected external file for computing particulate matter emission factors (dated March 2006). FHWA's Easy Mobile Inventory Tool (EMIT) (Claggett, 2006b) was employed as an interface to MOBILE6.2 to facilitate the creation of speed look-up tables.

The evaluation months and temperatures utilized in the analysis depend on the pollutant evaluated. Typically, highest CO levels are observed in the wintertime and highest ozone levels are observed in the summertime. The appropriate context for evaluating MSAT compounds is the long term – an annual basis at a minimum. For CO, the MOBILE6.2 model was run for January assuming the median of the normal

daily minimum and maximum temperatures measured in the U.S. during the coldest month of the year (which happens to be January) – 23.5 ºF and 41.0 ºF, respectively. For the precursors to ozone formation (VOC and NOx), an evaluation month of July and the median of the normal daily minimum and maximum temperatures measured in the U.S. during the warmest month of the year (which happens to be July) were used – 64.0 ºF and 86.1 ºF, respectively. For the selected MSAT compounds (benzene and DPM), seasonal emission factors were developed as the basis for computing annual averages. For the January through March winter season, the evaluation month is January; the calendar year is 2010; and the median of the average daily minimum and maximum temperatures measured in the U.S. are 27.8 ºF and 47.0 ºF, respectively. For the April through September summer season, the evaluation month is July; the calendar year is 2010; and the median of the average daily minimum and maximum temperatures measured in the U.S. are 55.5 ºF and 77.7 ºF, respectively. For the October through December winter season, the evaluation month is January; the calendar year is 2011; and the median of the average daily minimum and maximum temperatures measured in the U.S. are 35.2 ºF and 54.3 ºF, respectively.

Emission factors of DPM include the organic carbon, elemental carbon, and sulfate portions of diesel exhausts for the maximum particle size cutoff of 10 µm that can be considered in the MOBILE6.2 model. The diesel fuel sulfur level used is consistent with the 49-state average value reflecting more stringent federal controls (i.e., 11 ppm for 2010). The analysis was based on the 2007/2020 30 ppm fuel specifications for the northeastern states with no reformulated gasoline program (U.S. EPA, 2002b). Emission reductions that may be realized from a local inspection/ maintenance program or anti-tampering program were not taken into account.

The emissions analysis was conducted by accounting for the vehicle emission types specific to the operation on a link, e.g., the exhaust running and evaporative running loss emissions components. The evaluation relied on the VMT fractions by vehicle type calculated internally by the MOBILE6.2 model based on the specified calendar year of evaluation and from national average default data for: 1) vehicle population for the 16 composite vehicle classes; 2) vehicle registration by age distribution; 3) diesel fractions; and 4) mileage accumulation rates. A single distribution is computed to represent the fraction of total highway VMT accumulated by each of 16 combined vehicle types for a day. Speed look-up tables of emission factors were constructed by employing the AVERAGE SPEED command and specifying vehicle speeds from 5 mph to 65 mph in 1 mph increments for freeway and arterial roadway scenarios. The key assumptions employed in the MOBILE6.2 modeling are summarized in Table 3.

Results

Congested vehicle speeds characteristic of HPMS small urbanized area interstates and other principal arterials are presented in Figures 1 and 2, respectively, as a function of changes in the volume-to-capacity ratio. A graph of the freeway mobile source emission factors contained in the speed look-up tables are provided in Figure 3. Emission factors for arterials exhibit nearly identical speed profiles.

Table 3. Emission factor calculation parameters.

Parameter	Season		
	Winter	Summer	Winter
Pollutant: CO			
Calendar Year	2010	–	–
Evaluation Month	January	–	–
Min/Max Temp (°F)	23.5 / 41.0	–	–
Reid Vapor Pressure (psi)	13.2	–	–
Pollutant: VOC / NOx			
Calendar Year	–	2010	–
Evaluation Month	–	July	–
Min/Max Temp (°F)	–	64.0 / 86.1	–
Reid Vapor Pressure (psi)	–	8.6	–
Pollutant: BENZ / DPM			
Calendar Year	2010	2010	2011
Evaluation Month	January	July	January
Min/Max Temp (°F)	27.8 / 47.0	55.5 / 77.7	35.2 / 54.3
Reid Vapor Pressure (psi)	13.2	8.6	13.2
Aromatic Content (%)	23.1	27.1	23.1
Olefin Content (%)	14.1	9.9	14.1
Benzene Content (%)	0.73	1.03	0.73
E200 (%) [a]	51.8	44.4	51.8
E300 (%) [b]	83.3	81.1	83.3
MTBE Content (%)	0.6	3.4	0.6
Diesel Sulfur (ppm)	11.0	11.0	11.0

[a] Vapor percent of gasoline at 200 °F
[b] Vapor percent of gasoline at 300 °F

Figures 4 through 9 relate the information on traffic congestion and emission factors to offer insights into how vehicle emissions are expected to vary from an over-capacity to under-capacity operating condition and vice-versa. Emission factors for CO, VOC/NOx, and benzene/DPM are given for a wide range of volume-to-capacity ratios for small urbanized area interstates and other principal arterials. To facilitate a ready comparison of the pollutant emission factors, the appropriate figures are also grouped on a single page for small urbanized area interstates (refer to Attachment 1) and other principal arterials (refer to Attachment 2).

What's notable in the comparison of the different vehicle speed estimating methodologies is how well the HCM approach and BPR formula track each other for small urbanized area interstates – at least for the calculation parameter set adopted. Different results are likely if different assumptions are made. For small urbanized area other principal arterials, the HCM approach and TTI method give similar results for V/C ≤ 0.75. Substantially lower speeds are predicted with the TTI method for overcapacity conditions on small urbanized area interstates and other principal arterials compared to the HCM approach and BPR formula. So comes the question of

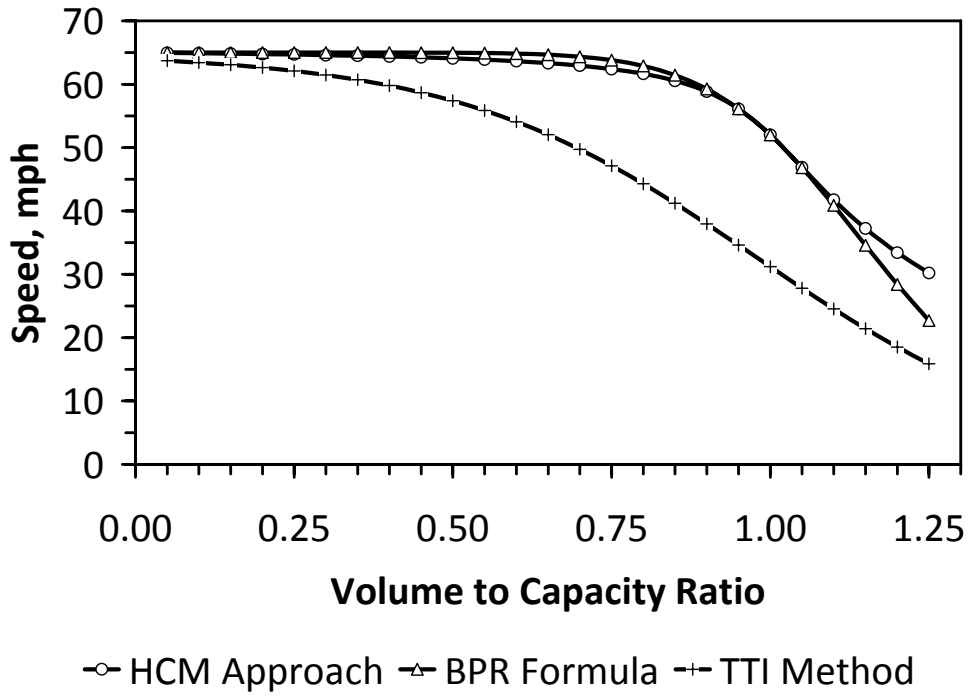


Figure 1. Forecast travel speeds for a small urbanized area interstate.

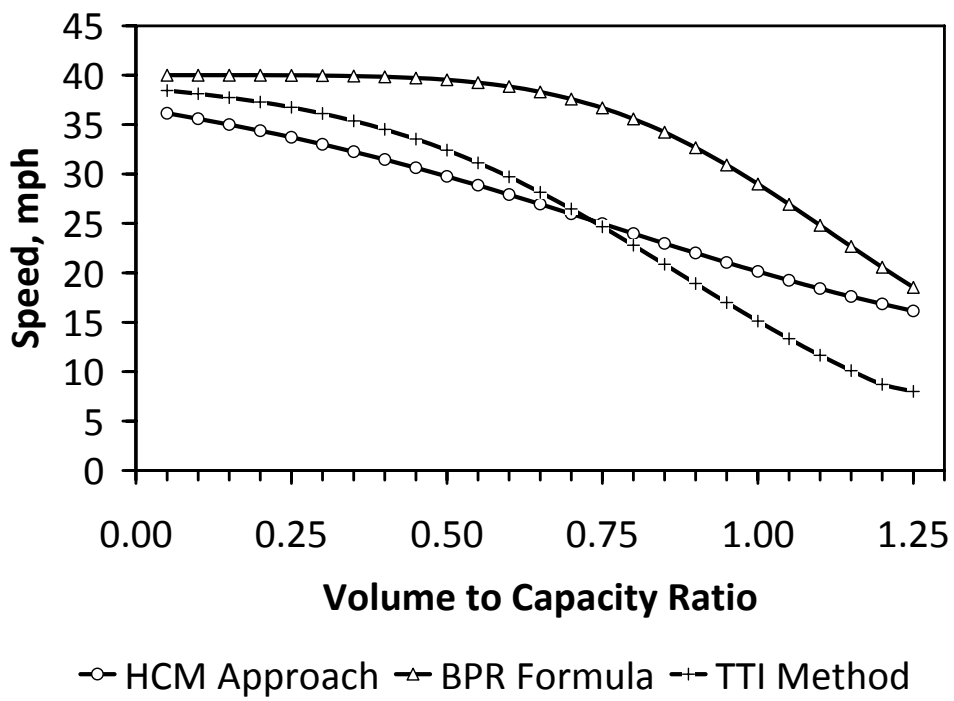


Figure 2. Forecast travel speeds for a small urbanized area other principal arterial.

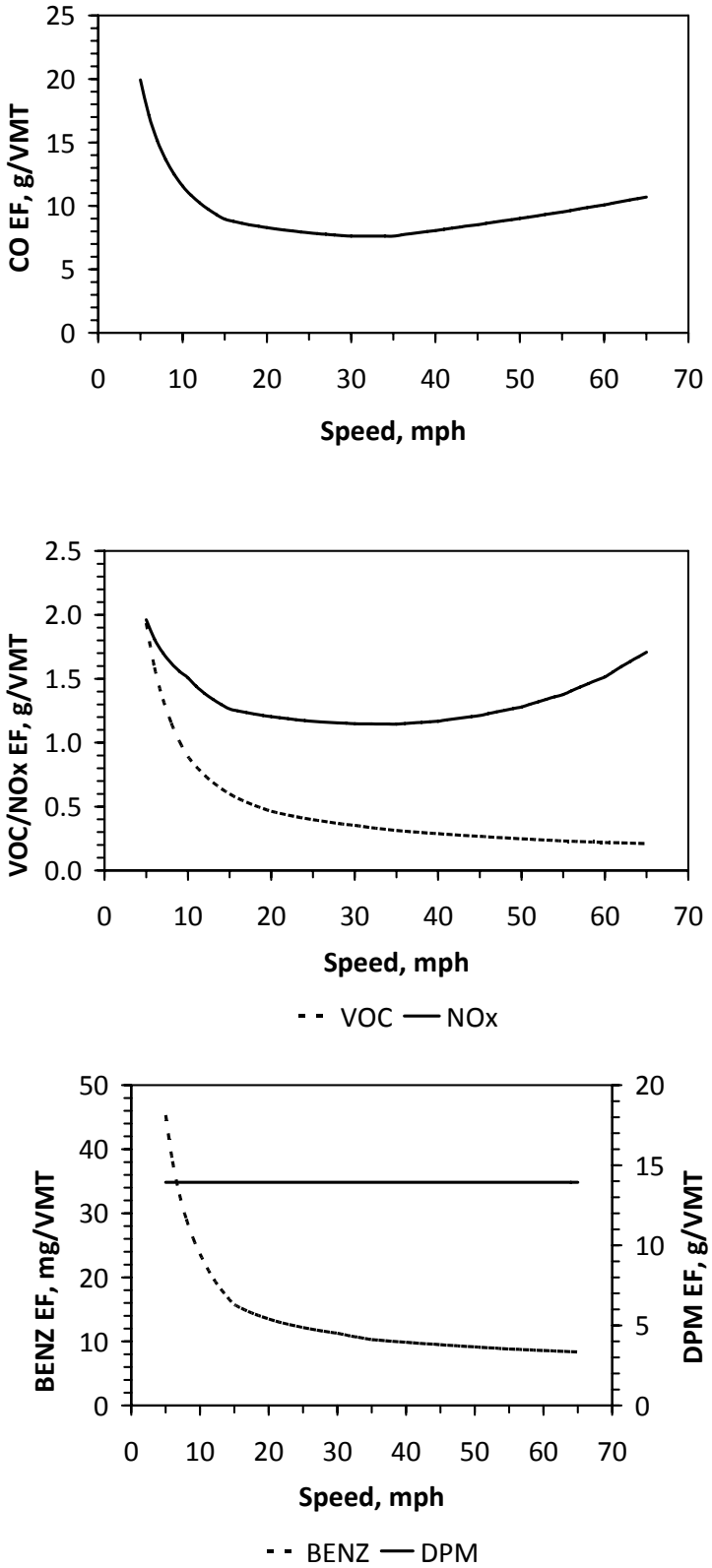


Figure 3. Forecast MOBILE6.2 emission factors for a small urbanized area interstate.

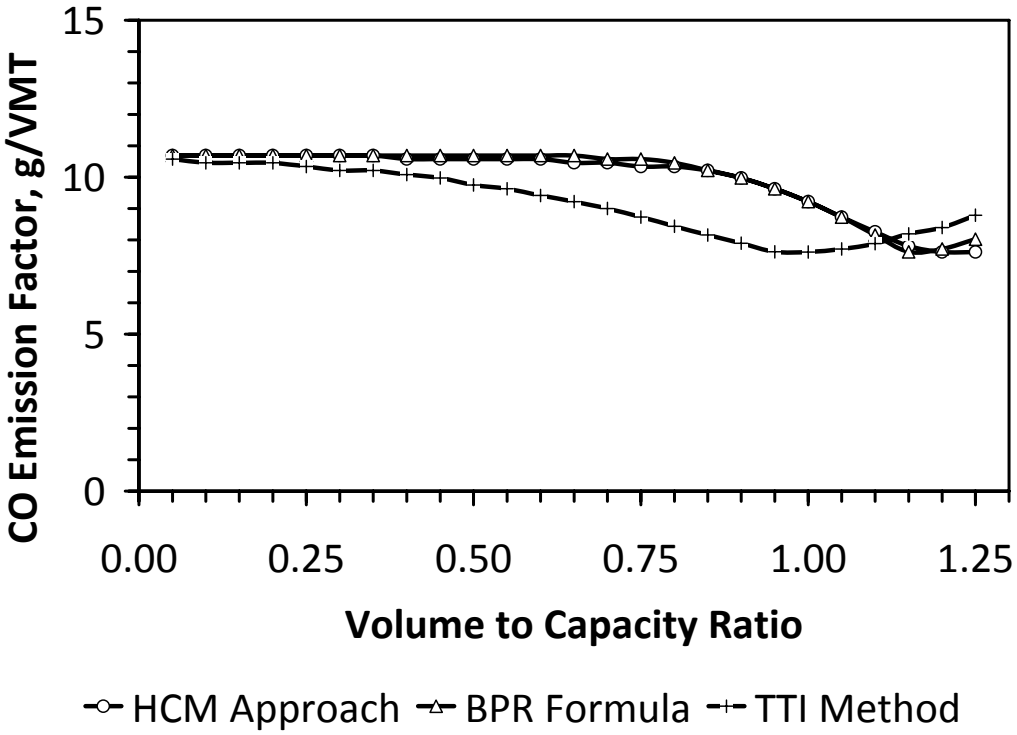
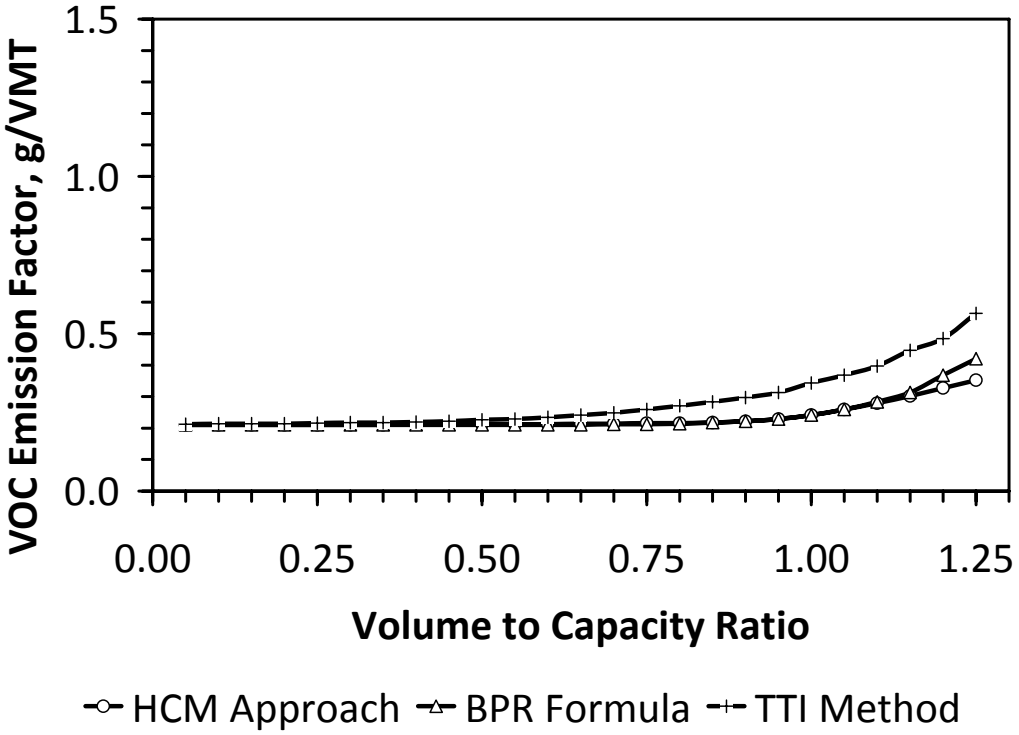


Figure 4. CO emission factors versus level of congestion for a small urbanized area interstate.



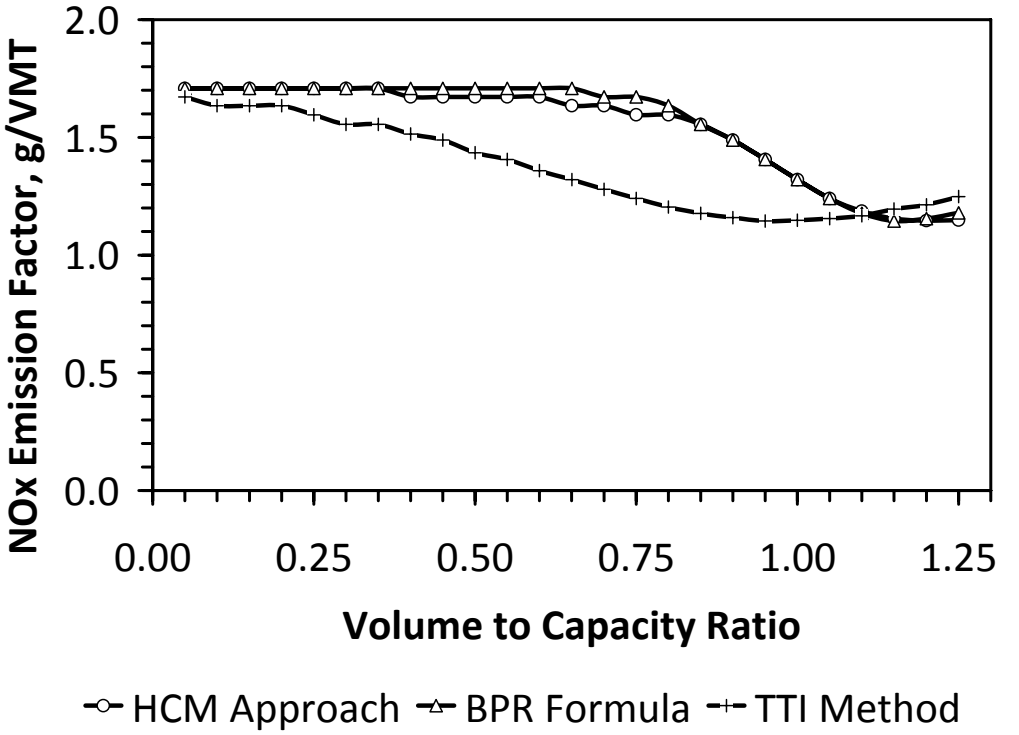


Figure 5. VOC and NOx emission factors versus level of congestion for a small urbanized area interstate.

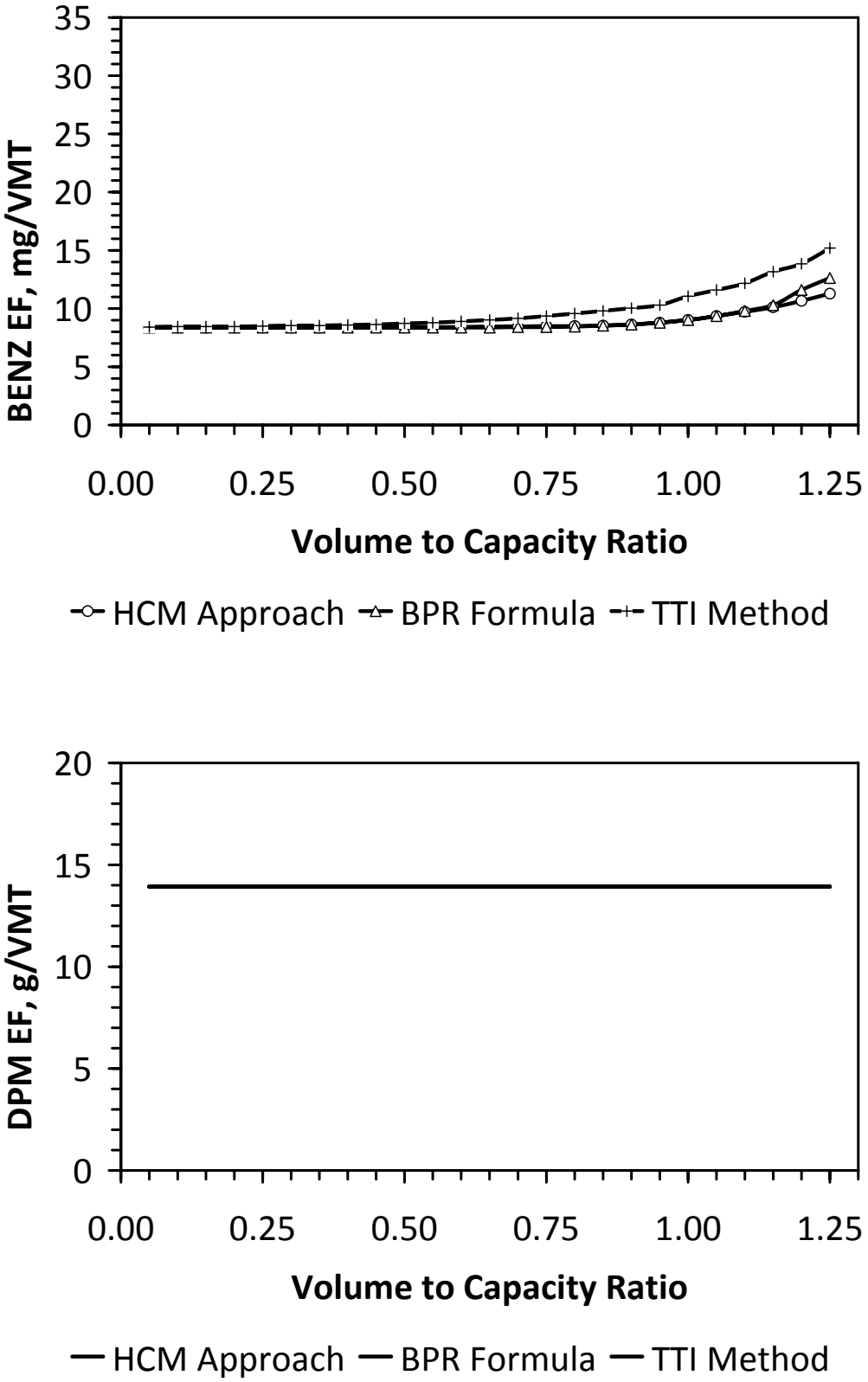


Figure 6. Benzene and DPM emission factors versus level of congestion for a small urbanized area interstate.

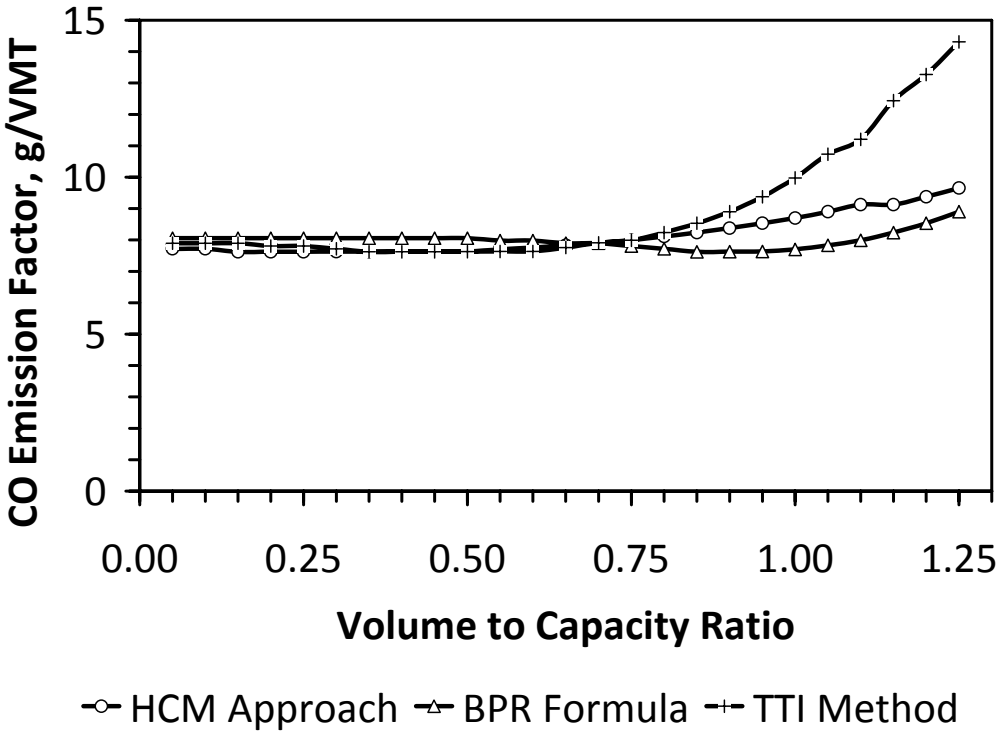
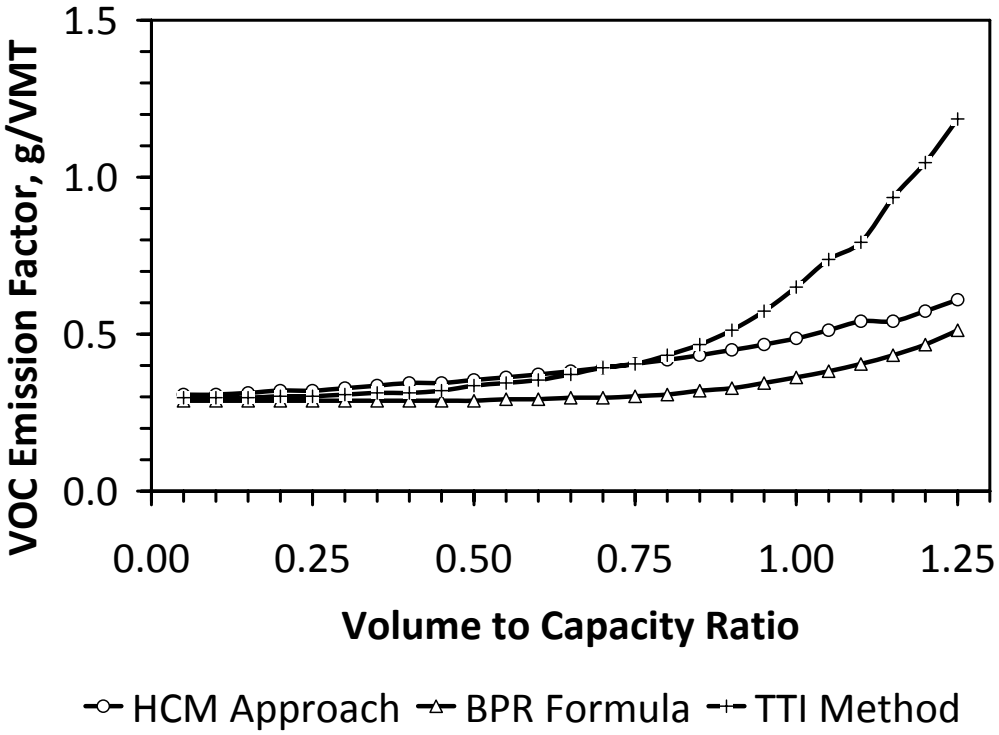


Figure 7. CO emission factors versus level of congestion for a small urbanized area other principal arterial.



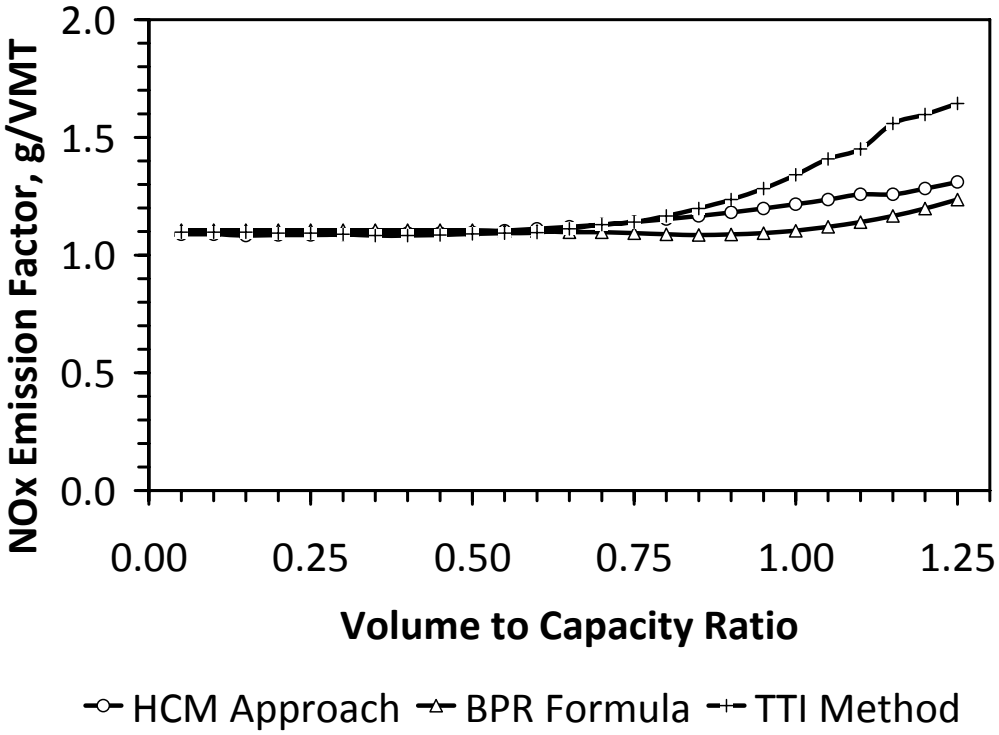


Figure 8. VOC and NOx emission factors versus level of congestion for a small urbanized area other principal arterial.

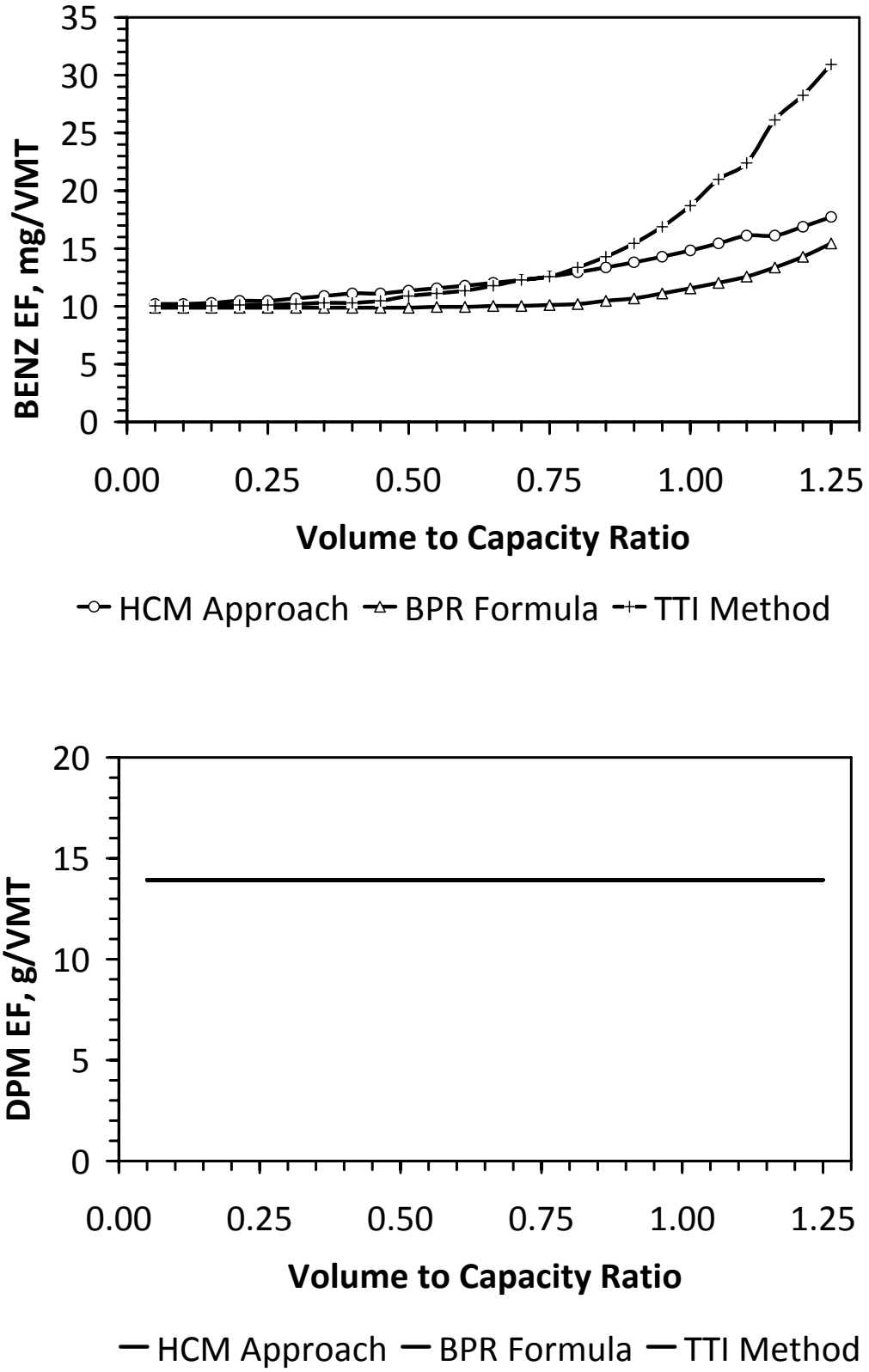


Figure 9. Benzene and DPM emission factors versus level of congestion for a small urbanized area other principal arterial.

which speed forecasting technique provides reasonable estimates for highly congested traffic conditions. One indicator is to contrast speed estimates to EPA's test cycles used for developing speed correction factors in MOBILE6.2. Table 4 provides an evaluation of vehicle speeds obtained from each of the forecasting techniques for overcapacity conditions to the average speeds of EPA's highly congested test cycles for freeways and arterials. The EPA's level of service (LOS) G for freeways is interpreted as an extreme breakdown or forced-flow condition. Forecasts from the TTI method compare favorably to EPA's congested speed test cycles.

The profile of MOBILE6.2 emission factors with speed is typified by high emissions at slow vehicle speeds for all pollutants with the exception of particulate matter (refer to Figure 3). Consequently, there is no sensitivity to changes in speed for DPM. For CO and NOx, emission factors increase again for speeds above 30 mph, while for VOC and benzene, emissions decrease throughout the entire range from slow to fast speeds.

The implication of this for congestion mitigation projects is the prospect of diminishing emissions by improving persistently slow vehicle speeds. But since some emission factors also increase with increasing speeds above roughly 30 mph, a mixed result can occur for freeway congestion mitigation projects. According to the HCM approach and BPR formula, speeds for exceedingly overcapacity conditions on small urbanized area interstates are a minimum of 28 to 31 mph – right around the infection point on the emission factor versus speed curves for CO and NOx. Much slower speeds are forecast with the TTI method (i.e., a minimum of 16 mph). Thus, as indicated by the HCM approach or BPR formula, relieving this congested condition will increase CO and NOx emissions. This is somewhat contradicted by

Table 4. Reasonableness check of congested vehicle speeds.

Interstate				
Speed Methodology	Small Urbanized		Large Urbanized	
	V/C = 1.0	V/C = 1.25	V/C = 1.0	V/C = 1.25
HCM 2000	52	30	51	29
BPR Formula	52	23	51	27
TTI Method	31	16	30	16
EPA – LOS F	19			
EPA – LOS G	13			

Other Principal Arterial				
Speed Methodology	Small Urbanized		Large Urbanized	
	V/C = 1.0	V/C = 1.25	V/C = 1.0	V/C = 1.25
HCM 2000	20	16	13	11
BPR Formula	29	19	18	9
TTI Method	15	8	14	8
EPA – LOS E-F	12			

the TTI method, whereby CO and NOx emissions are predicted to decrease if congestion is improved to a volume-to-capacity ratios approaching 1.0. Traffic flow improvements beyond this point will increase CO and NOx emissions.

Any congestion relief will reduce CO, VOC/NOx, and benzene emissions for small urbanized area other principal arterials. The degree of the reduction depends on the speed estimating approach with the TTI method projecting the largest. Because of limitations inherent in the MOBILE6.2 model, no emission changes for DPM (or particulate matter) are affected by mitigating congestion on roadways.

Conclusions

Mitigating persistent congestion on highways reduces emissions from motor vehicles on a unit vehicle-mile of travel basis. In forecasting potential emission benefits, the degree to which emissions are expected to decrease depends largely on the speed estimating methodology implemented and the manner in which it is employed. For the assumptions used in this investigation, the TTI method predicted the greatest congestion intensity and consequently, the largest emission benefits associated with congestion relief. For small urbanized area interstates, the HCM approach and the BPR formula produced similar results. For small urbanized area other principal arterials, the BPR formula predicted the least amount of congestion and the smallest benefits associated with congestion relief. Admittedly, different result may be obtained with different assumptions.

However, any real world analysis should apply the speed estimating technique that most aptly reflects local conditions. A selection should be made objectively, adopting a transparent process of investigation, testing via reasonableness checks, documentation, and review. Subjective criteria, such as which methodology affords the largest or smallest benefit associated with congestion relief, should not be considered. It is critical to determine the speed estimating methodology most representative of vehicle congestion in a locale, especially for situations when travel demand exceeds capacity.

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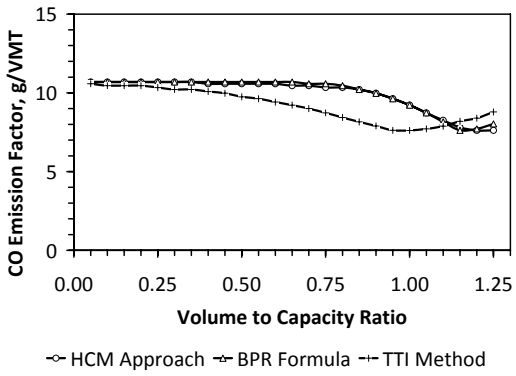
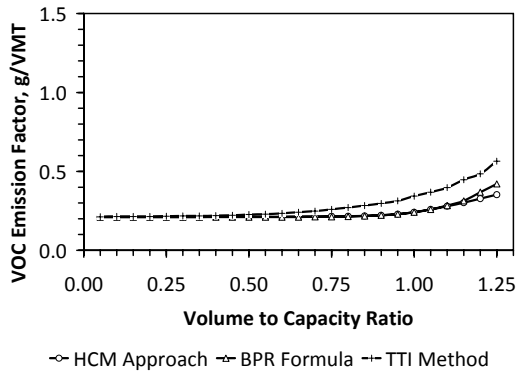
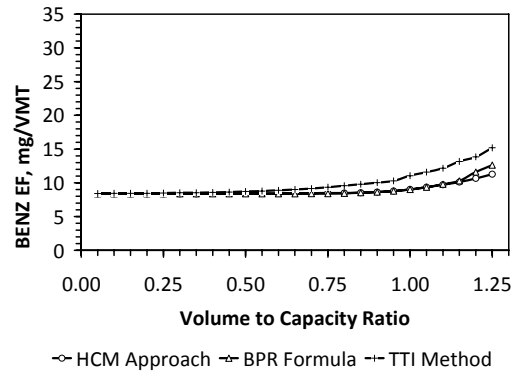
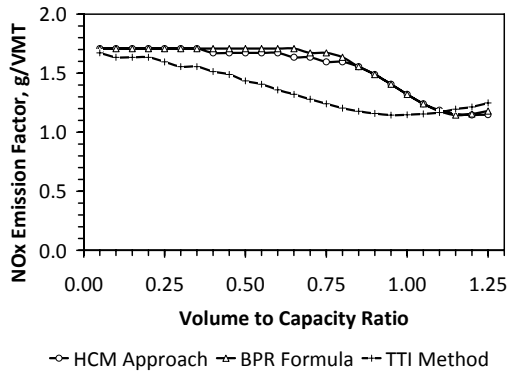
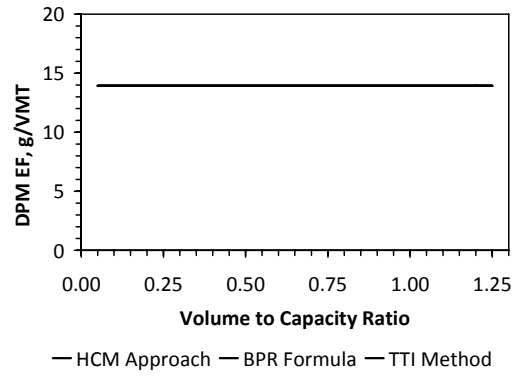


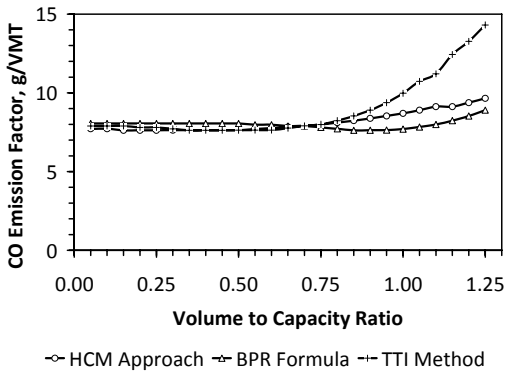


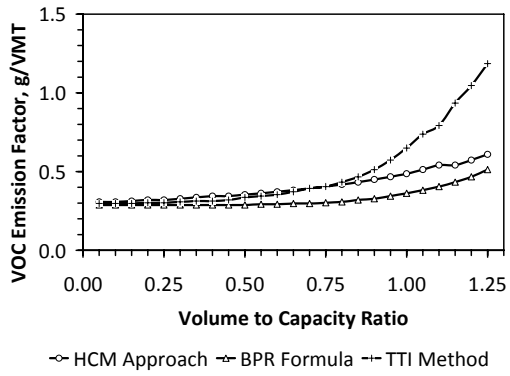


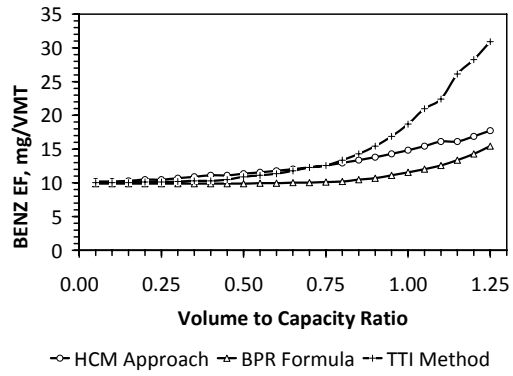


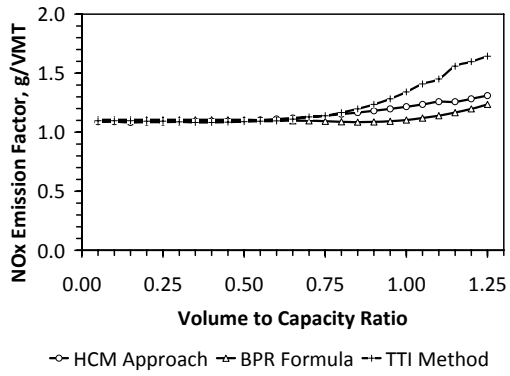


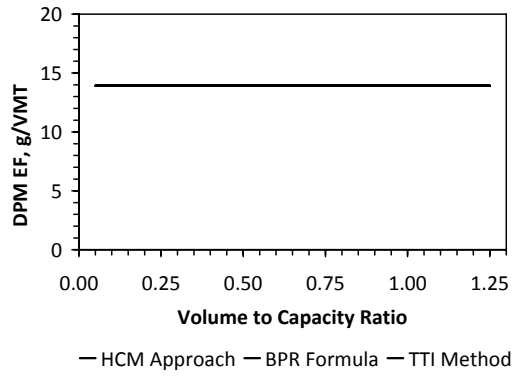
Attachment A-1.
Emission factors versus level of congestion for a small urbanized area interstate.











Attachment A-2.
Emission factors versus level of congestion for a small urbanized area other principal arterial.