FINAL REPORT

FIELD VALIDATION OF SPEED ESTIMATION TECHNIQUES FOR AIR QUALITY CONFORMITY ANALYSIS

John S. Miller, Ph.D., P.E.
Senior Research Scientist

G. Michael Fitch
Senior Research Scientist

Lance E. Dougald
Engineer

Scott R. Kreissler
Undergraduate Research Assistant

David H. Hill
Undergraduate Research Assistant

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

May 2004
VTRC 04-R19

ABSTRACT

The air quality conformity analysis process requires the estimation of speeds for a horizon year on a link-by-link basis where only a few future roadway characteristics, such as forecast volume and capacity, are known. Accordingly, the Virginia Department of Transportation (VDOT) has at its disposal a variety of techniques, known as "speed post processors" that estimate average travel speeds on each roadway link based on projected volumes from urban travel demand models.

Using field data collected at 15 sites in Richmond and Charlottesville, the accuracy of three post-processing techniques was determined by comparing predicted average travel speed and measured average travel speed. On average, the mean absolute errors for the post processors were relatively similar, ranging between 8 and 12 mph. The post processors overpredicted speeds on some links and underpredicted speeds on others; the average of these positive and negative errors for the post processors was between 2 and 6 mph. Based on MOBILE6 simulation runs with Richmond area data, the differences in speed predictions from the speed post processors would have led to at most a 2.5 percent difference in estimated emissions of volatile organic compounds. All three post processors would have underestimated Richmond area emissions of nitrogen oxides by less than 2 percent. Although differences in national fleet data and Richmond fleet data hamper a direct comparison, additional MOBILE6 simulation results with national data suggest these Richmond results are indicative of the sensitivity of MOBILE6 emissions to changes in estimated vehicle speed.

For a class of nine suburban arterial roadways, this study showed that the error associated with any of the post processors could be reduced through judicious altering of the default capacity. This reduction was effected relatively easily by modifying the group capacity rather than computing a capacity for each link. Therefore, although any of the three post processors can be used, this study recommends, in the short term, sampling a few links for each roadway category to determine the appropriate capacity for the category, following an approach similar to that presented in this study.

For arterial facilities in particular, this study showed what has been anecdotally known in practice: average travel speeds are affected not just by volume but also by other factors such as signal timing. For this study, this proved to be both a curse and a blessing. On the one hand, the twin facts that the speed post processors are volume dependent and that volume explained only a small amount of the variation in travel speed meant that field results did not show the sensitivity to volume expressed in the literature. On the other hand, because average travel speeds tended to stay within a moderate range, this study showed how better calibration with simple post processors can lead to predictions that are within 5 mph of observed data.

FINAL REPORT

FIELD VALIDATION OF SPEED ESTIMATION TECHNIQUES FOR AIR QUALITY CONFORMITY ANALYSIS

John S. Miller, Ph.D., P.E.
Senior Research Scientist

G. Michael Fitch
Senior Research Scientist

Lance E. Dougald
Engineer

Scott R. Kreissler
Undergraduate Research Assistant

David H. Hill
Undergraduate Research Assistant

INTRODUCTION

For metropolitan regions that are classified as maintenance or nonattainment areas, regulations driven by the 1990 Clean Air Act Amendment require Virginia to show that mobile source emissions from anticipated transportation projects are not expected to exceed a specified mobile source emissions budget. The computational method of determining projected emissions from future transportation projects is known as *conformity analysis*. In Virginia, a conformity analysis has been required for Richmond, Hampton Roads, and Northern Virginia since the initiation of the conformity process. Changes in the standards of the U.S. Environmental Protection Agency (EPA), however, are resulting in three new areas—Roanoke, Winchester, and Fredericksburg—being added to the list of locations requiring a conformity analysis.

To perform a conformity analysis for a metropolitan region, the Virginia Department of Transportation (VDOT) typically has hired consultants to carry out five major tasks:

1. *Estimate predicted traffic volumes on each link in a roadway network from a long-range travel demand model such as MINUTP, TP+, or TranPlan.* A typical roadway network may range in size from approximately 1,000 links for the Roanoke area to tens of thousands of links for the Hampton Roads area. For the purposes of this report, a *link* is a homogeneous section of road between ½ mile and 3 miles in length.

2. *Determine the percentage of the EPA*'s *16 vehicle types (e.g., light duty vehicle, heavy duty vehicle) by functional road classification.* This percentage is known as the VMT fraction and is used as an input in the EPA's MOBILE6 emissions model. The

MOBILE6 emission factor model is used to predict gram per mile emissions of hydrocarbons; carbon monoxide; nitrogen oxides; carbon dioxide; particulate matter; and toxics from cars, trucks, and motorcycles under various conditions.

3. *Use the long-range travel demand model inputs and outputs to estimate accurate speeds on the roadway facility.* This estimation process is known as *speed post processing* and can range in complexity from simple equations relating volume to capacity to proprietary software that includes computations of queues. The resultant speeds from the post processor are average travel speeds, rather than spot speeds, and thus incorporate the effects of delay at signals for arterial facilities.[1]

4. *Apply the EPA's MOBILE6 model to determine emissions rates*, in the units of grams per vehicle per mile, for different speed classes (e.g., 0 to 5 mph, 5 to 10 mph) and different vehicle types (e.g., light-duty trucks, passenger cars). Thus the VMT mix from Task 2 and the post processed speeds from Task 3 are inputs for the MOBILE6 model. The outputs of this model are emissions rates in units of grams per mile.

5. *Obtain total emissions for a region* by multiplying the emissions rates from Task 4 by VMT mix from Tasks 1 and 2. This multiplication is done for each vehicle type and speed class. Two types of emissions, volatile organic compounds (VOCs) and nitrogen oxides (NO_x), are determined, with VOCs and NO_x being the key ingredients for the formation of ground level ozone.

VDOT would like to perform this analysis using their own staff rather than consultants. Task 3, which is the process of estimating travel speeds on the roadway links in the long-range urban travel demand model, has raised questions within VDOT. In early 2003, staff from VDOT's Transportation & Mobility Planning Division (TMPD) noted that two of the six Virginia regions, Northern Virginia and Hampton Roads, have a sophisticated travel demand model that yields accurate speeds as a function of volume. For the other four areas, however, three (Richmond, Fredericksburg, and Roanoke) rely on VDOT's Statewide Planning System, a computer application, for data and Winchester does not yet have a model. Thus, for those four locations, a methodology for estimating travel speeds as a function of volume is needed.

During the summer of 2002, staff of the Virginia Transportation Research Council (VTRC) and VDOT worked to identify speed estimation techniques in the literature and VDOT staff identified one post processor that it owns outright and another project-based post processor whose development is underway in the Northern Virginia District.[2] Additional methods for post processing speeds are described in the literature. Thus at this juncture, VDOT's Environmental Division has at its disposal several methods for accomplishing the speed estimation. Although these techniques appear to be based on logical approaches, either they have not yet been validated with field data or the results of such validation efforts are not documented.

The problem identified thus far is that the accuracy of the various speed estimation techniques is not known; that is, VDOT does not know how predicted speeds compare to actual speeds. Further, although it is generally recognized that better speed data will yield better emissions estimations, the extent to which improvements in speed data will improve emissions estimations is not known.

PURPOSE AND SCOPE

The purpose of this project was to compare the accuracy and utility of speed post processors available to VDOT. The scope was limited in five ways:

1. The post processors are limited to data found in VDOT's long-range travel demand models: capacity, free flow speed, and expected volume. Models that would have relied on detailed operational data typically not available in such a model, such as signal timing parameters, were not studied.

2. The geographic domain of this project was limited to data from the greater Richmond and Charlottesville metropolitan areas. Management from the Environmental Division and TMPD had requested that the investigators focus the validation effort on the Richmond area rather than performing a statewide validation, and the investigators chose to add a few Charlottesville links given their proximity and some heavy traffic congestion that was occurring during this time period in the Charlottesville area.

3. The project emphasized arterial facilities instead of interstate facilities, given that the former have not received as much attention as the latter in terms of automated data collection methods or speed-volume relationships.

4. The post processors studied are already owned by VDOT or are in the public domain.

5. This project focused solely on how speed estimation affected air quality conformity analysis rather than other factors that also influence air quality analysis, such as vehicle type.

The project had three objectives:

1. Assess the accuracy with which post processors could replicate speeds at sites in the Charlottesville and Richmond areas.

2. Identify the extent to which roadway classification–specific data can be used to improve the accuracy of speed post processors.

3. Determine the sensitivity of emissions calculations to errors in the prediction of vehicle speeds from the post processor.

METHODOLOGY

Six tasks were performed to evaluate the accuracy of three post processors available to VDOT and the impacts of such accuracy on estimating mobile source emissions.

1. Determine the data available for a typical speed post processor application.

2. Collect speed and flow rate data for sites in the Charlottesville and Richmond areas.

3. Determine a trendline relating volumes to average travel speeds for 15-minute intervals.

4. Apply the speed post-processors for the data collected at each site.

5. Compare the speeds predicted by each post processor to the speeds obtained from the trendline.

6. Estimate the impact of speed post processor accuracy on mobile source emissions.

The highlights of the six tasks are presented here. Additional details for those wishing to replicate this approach, including exceptions to these methods and the application of lessons from traffic engineering texts, are given in the Appendix.[3]

Determining Data Available for Typical Speed Post Processor Application

Although sophisticated traffic simulation or highway capacity analysis models can yield accurate estimates of speed as a function of volume when detailed calibration data are available, such data typically are not available for a metropolitan region and several years into the future. Interviews with TMPD staff and examination of the travel demand models showed that estimates of the peak hour volume, capacity, functional classification, and free flow speed can be obtained.

An example of these data elements for one link, Route 250 in Charlottesville, is shown in Table 1. As indicated, the first five elements are specific to each link in a planning model. The

Table 1. Link Data Typically Available for Conformity Analysis

Specificity of Data	Data Element	Data Available from Appropriate Long-Range Planning Model
Link-specific data elements	Number of lanes in each direction	2
	Link length	1.8 mi
	Functional classification	Freeway or Expressway
	Area type	Non–Central Business District
	Predicted peak hour volume	1,100
Average values for area type and functional class	Corridor free flow speed	48 mph
	Practical Capacity	2,800 vph

next two elements are average values for the group of roadway links within a particular area type and class. The distinction matters, because in a realistic planning application with thousands of links, modelers often do not have the luxury of computing specific free flow speeds and capacities but rather must use such average values.

Collecting Speed and Flow Rate Data

In spring 2003, the study team and TMPD staff identified and visited 15 study sites in Richmond and Charlottesville as listed in Table 2. Figure 1 illustrates a typical data collection site.

The study team collected spot speed, average travel speed, and volume data during site visits that aimed to capture periods of high and low congestion. Generally, four data collectors were required for each site visit.

1. *One person collected volume data and spot speed data with VDOT's Smart Travel Van.* Efforts were made to place this van toward the middle of the link, but the presence of a median or shoulder dictated the safe location of the van. Traffic control was set up for a typical median closure.

2. *Two persons, one at each end of the link, used two-way radios to collect travel times in one direction only.* About twice per minute a caller at one end of the link would narrate an easy-to-understand vehicle description for which the receiver at the other end would be searching. The caller and the receiver entered the times they saw a vehicle by pressing a key on their respective laptop computers; the differences between these times combined with the link distance yielded travel speeds based on these radios.

Table 2. Sites of Speed and Volume Data Collection

Location	Site	Facility Type (VDOT)	Lanes
Richmond	US 60: Huguenot to Robius	Urban Principal Arterial	3
Richmond	Patterson: Forest to Three Chopt	Urban Principal Arterial	2
Richmond	Patterson: Parham to Gaskins	Urban Principal Arterial	2
Richmond	Courthouse: Smoketree to Hull	Urban Principal Arterial	2
Richmond	Parham: Fordsom to Fargo	Urban Principal Arterial	2
Richmond	US 250: Henrico County Line to I-64	Urban Principal Arterial	3
Richmond	US 250: Libbie to Staples Mill	Urban Principal Arterial	3
Richmond	US 33: Glenside to Hermitage	Urban Minor Arterial	3
Richmond	I-64: Exit 183 to Richmond City Line	Urban Interstate	3
Richmond	I-95: Exit 80 to Exit 76B	Urban Interstate	3
Richmond	US 33: Hungary Springs to Parham	Urban Minor Arterial	2
Charlottesville	Park St to Cutler St	Urban Collector/Urban Local	1
Charlottesville	US 29: Hydraulic to 250 Bypass	Urban Other Principal Arterial	3
Charlottesville	US 250: Emmet St to Park St	Urban Freeways and Expressways	2
Charlottesville	Barracks: Preston to US 29	Urban Minor Arterial	1

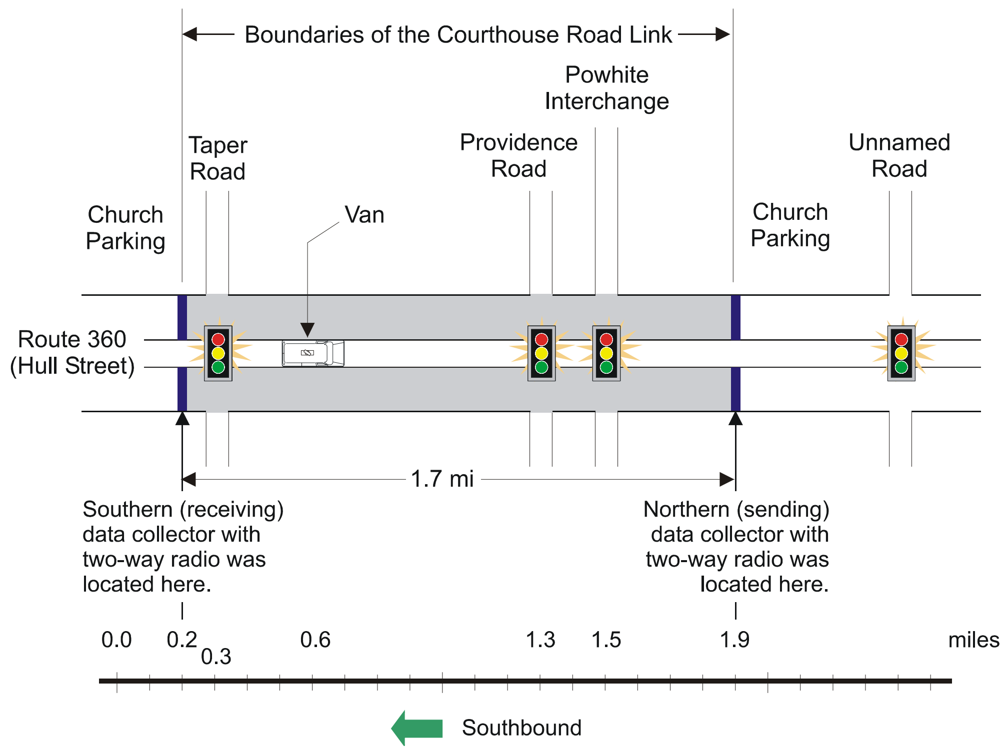


Figure 1. Example Data Collection Effort: Courthouse Road, Richmond, June 11

3. *One person performed travel time runs by continually driving the link, noting the time at which the van was passed and recording the elapsed time with a stopwatch, to yield travel speeds based on travel time runs.* Depending on the link, a travel time run might take 2 to 10 minutes. Initially, the travel time runs performed with a floating vehicle served as a check on the radio times to ensure that at least some data were obtained should failures with the radio equipment arise. By the end of the study, it was apparent that data could be collected much more efficiently with the radios than with a vehicle, provided stopped time was not required. For the post processors under consideration, it was not.

Determining Trendline Relating Volumes to Average Travel Speeds

At each site, two pieces of data were matched for one direction: the volumes collected by the Smart Travel Van and the average travel speeds as collected from radios and travel time runs. From these data, a trendline was developed, comparable to that shown in Figure 2. The purpose of the trendline is to establish a mean speed/volume relationship that an ideal post processor will replicate. Because this relationship is probabilistic, there will be variation even for a specific volume at a specific site. For example, the circled data point in Figure 2 indicates a 15-minute interval where the average travel speed was 29 mph and the 15-minute flow rate was 2,044 vph. If for a subsequent 15-minute interval the flow rate had again been 2,044 vph, it is quite possible that a speed other than 29 mph would have been observed, owing to fluctuations in the sampling of travel speeds, possible changes in minor street traffic that could affect the green time available

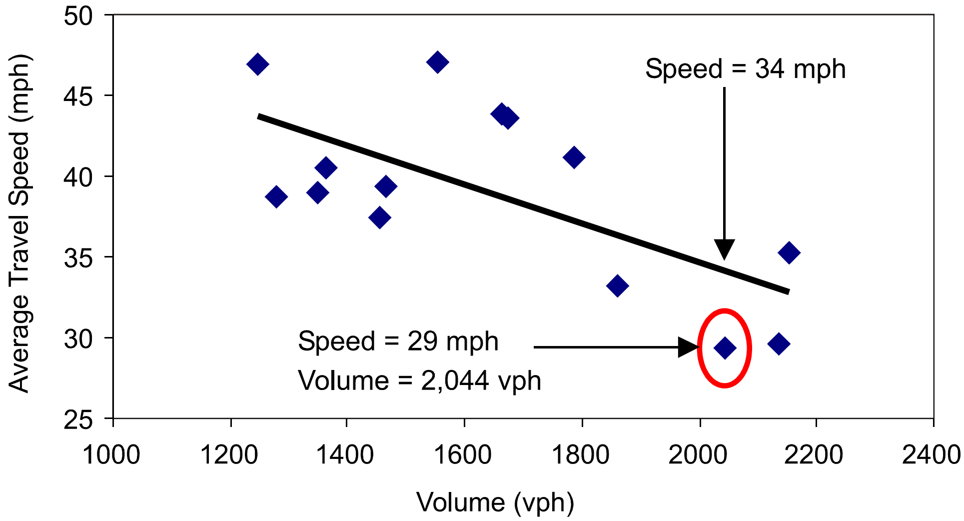


Figure 2. Trendline Speed Data for US 33 Between Glenside and Hermitage, Richmond, June 23

to drivers on Route 33, and other incidents such as the presence of a school bus or ambulance. Had 2,044 vph been observed yet a third time, the speed again might be different from the previous two intervals. The corresponding trendline speed of 34 mph is the best estimate of what would be expected under an infinite number of intervals where the volume was 2,044 vph.

The investigators experimented with analyzing data for 5-minute intervals, which would have been feasible for the analysis of spot speed and volume data. However, even with three persons whose sole responsibility was to collect travel time data, sample sizes based on 5-minute analysis periods were too small to be of value. With three data collectors, a 15-minute period might result in as few as 4 or as many as 14 data points, whereas a 5-minute period might have no data points or as many as 6, depending on the method of data collection.

Applying Speed Post-Processors for Data Collected at Each Site

Three post processors were analyzed in this study:

1. *post processor A,* a post processor based on the literature
2. *post processor B,* a modified version of a post processor delivered by a consultant
3. *post processor C,* an older post processor based on the literature.

The corridor free flow speeds and capacities shown in Eqs. 1 through 5 were obtained from the long-range planning models for the Charlottesville and Richmond areas.[4,5,6] The hourly volumes shown in the denominator of Eqs. 1-5 were obtained from the flow rates tabulated every 15 minutes at each site.

Post Processor A

This post processor is based on *NCHRP Report 387* and is given as the updated Bureau of Public Roads (BPR) equation as follows for signalized facilities where a signalized facility is one where the traffic signals are spaced 2 miles apart or less.[7]

$$speed\ \ for\ signalized\ \ facilities = \frac{corridor\ \ free\ flow\ speed}{1 + 0.05(volume / capacity)^{10}} \qquad \text{[Eq. 1]}$$

For unsignalized facilities, the coefficient in the denominator is changed from 0.05 to 0.20.

Post Processor B

This post processor was developed by Michael Baker Associates and uses two equations for non-interstate facilities: one for undersaturated conditions, when flows are below capacity, and one for oversaturated conditions, when flows are above capacity. For the undersaturated case, the speed post processor is given as

$$speed\ \ for\ \ understatured\ non - interstates = \frac{practical\ \ speed}{1 + 0.8\left(volume /\ practical\ \ capacity\right)^2} \qquad \text{[Eq. 2]}$$

Although similar in form to the modified BPR equation, there are at least two differences. *Practical capacity* is the capacity observed at Level of Service (LOS) C rather than LOS E. *NCHRP Report 387* suggests that this value is 80 percent of the LOS E capacity.[7] The second distinction is that the practical speed is used, which is the corridor free flow speed divided by 1.15.

For the oversaturated case, the formulation for non-interstates is shown as Eq. 3 and is equivalent to Eq. 2 when traffic volume is exactly equal to capacity.

$$speed\ \ for\ \ oversatured\ \ non\text{-}interstates = \frac{Length\ \ of\ \ link}{Uncongested\ \ travel\ \ time\ \left[1.8\right] + \dfrac{0.2\left(volume - practical\ \ capacity\right)}{capacity}} \qquad \text{[Eq. 3]}$$

As will be discussed, Eq. 2 performed better than Eq. 3 even for sites where volumes exceeded practical capacity; thus, for comparison purposes, post processor B was applied with Eq. 2 only.

For interstates, the denominator of Eq. 2 is supposed to be changed such that the 0.8 coefficient becomes 0.15 and the exponent 2 becomes 13.29. Although the former change improved performance, the latter change caused the post processor to have substantially greater errors for predicting interstate speeds. Thus, for interstates, the formulation shown as Eq. 4 was used such that the exponent of 2, rather than 13.29, was retained. Because the application of Eqs. 2 and 4 deviates from the original post processor developed for VDOT, the term *modified* is used to describe post processor B. These modifications made post processor B easier to apply, placing it on a level of difficulty comparable to that of post processors A and C.

$$\textit{speed for interstates} = \frac{\textit{practical speed}}{1 + 0.15\left(\textit{volume} / \textit{practical capacity}\right)^2} \qquad \text{[Eq. 4]}$$

Post Processor C

This post processor is the original Bureau of Public Roads formulation, and it was used because it was found by VDOT's Northern Virginia District to be quite useful. The original formulation was given as

$$\textit{speed} = \frac{\textit{corridor free flow speed}}{1 + 0.15\left(\textit{volume} / \textit{practical capacity}\right)^4} \qquad \text{[Eq. 5]}$$

When the volume to practical capacity ratio exceeds 2.0, however, VDOT modifies the formulation shown in Eq. 5 such that the coefficient changes from 0.15 to 0.60 and the exponent changes from 4 to 2, which yields higher speeds than would otherwise be obtained without the modification. District staff noted that at volume/practical capacity ratios above 2.0, these predicted higher speeds were more realistic in their planning applications than would have been obtained with Eq. 5 only.

Comparing Speeds Predicted by Each Post Processor to Speeds Obtained From Trendline

The ability of each post processor to predict the trendline speed at each volume point was determined, and the mean absolute error (MAE) for each site was computed as the difference between predicted and trendline speeds. Returning to Figure 2, therefore, the ability of each post processor to predict a speed of 34 mph given a volume of 2,044 vehicles was thus computed. As shown in Figure 3, at that particular site, the MAE for post processor A was lower than the MAEs for post processors B and C.

Estimating Impact of Post Processor Accuracy on Mobile Source Emissions

Using the MOBILE6 emissions model, the investigators determined the sensitivity of the quantities of NO_x and VOC to estimated vehicle speeds through two sets of scenarios. In the first set, a default national MOBILE6 dataset served as the baseline and was then altered such that mean vehicle speeds for interstates and arterial roads were modified by increments of –10, –5, +5, and +10 mph. As described in the Appendix, the variability of the dataset was retained but the proportion of vehicles in each speed bin was modified to change the average speeds for each MOBILE6 facility type, i.e., interstates and arterials. The results of the first set of scenarios provided a generalized understanding of how changes in predicted speeds will affect changes in

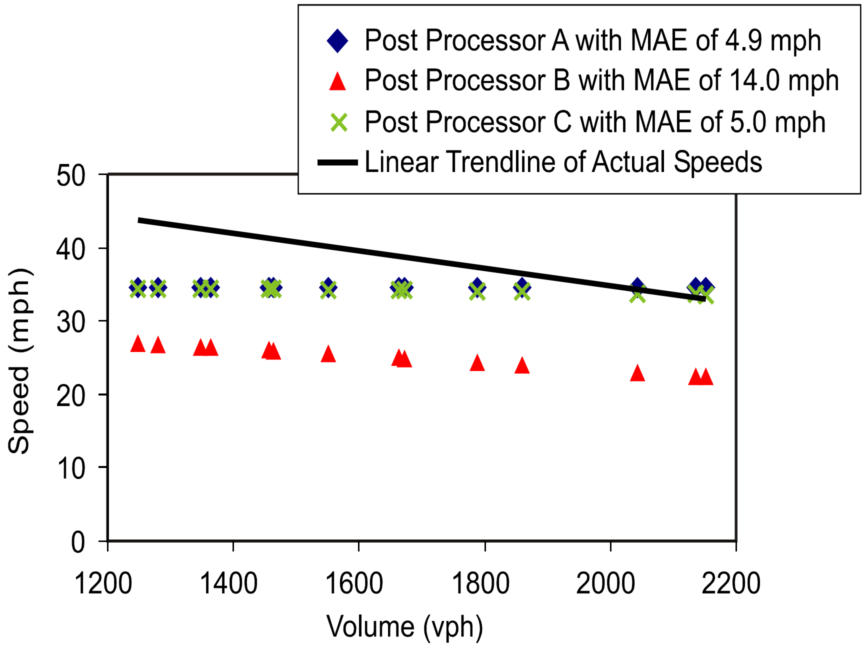


Figure 3. Post Processor Performance for US 33 Between Glenside and Hermitage, Richmond, June 23

predicted emissions. In the second set of scenarios, where a Richmond-specific dataset served as the baseline, the investigators identified the emissions that would have been estimated from using post processor A, post processor B, post processor C, and a hypothetical perfect post processor.

RESULTS

Some of the 15 sites were visited several times. Volume and average travel speed data were collected on 22 days as shown in Table 3, with an emphasis on arterial sites. All sites shown were signalized except for the two interstate sites studied on July 9 and July 16. Data were collected over a 3- to 4-hour period and were analyzed in 15-minute intervals.

The R^2 value in Table 3 indicates the strength of association determined from linear regression between average travel speeds and observed volumes. The maximum possible value for R^2 is 1, which would mean that volumes could be used to predict speeds perfectly. The lowest possible value for R^2 is 0, which would mean that the relationship between speed and volume was random and that volumes were utterly useless for predicting speeds.

For example, for Site 1 on May 14, the volumes observed every 15 minutes explained about 33 percent of the variation in the corresponding average travel speeds observed during those periods. A low R^2 value indicates only the sensitivity of average travel speed to volume; it does not obviate the utility of the speed post processor for predicting speeds observed in the field, as discussed in the Appendix.

Table 3. Sites and Dates Speed and Volume Data Were Collected

Date	Location	Site	Site No.	Facility Type (VDOT)	R^2
May 14	Charlottesville	US 250: Emmet to Park	1	Urban Freeways and Expressways	0.33
May 27	Charlottesville	US 250: Emmet to Park	1	Urban Freeways and Expressways	0.02
May 28	Richmond	US 60: Huguenot to Robius	5	Urban Principal Arterial	0.12
June 3	Richmond	Patterson: Forest to Three Chopt	6	Urban Principal Arterial	0.11
June 10	Richmond	Patterson: Parham to Gaskins	7	Urban Principal Arterial	0.07
June 11	Richmond	Courthouse: Smoketree to Hull	8	Urban Principal Arterial	0.37
June 16	Richmond	Parham: Fordsom to Fargo	9	Urban Principal Arterial	0.00
June 18	Richmond	US 250: Henrico County Line to I-64	10	Urban Principal Arterial	0.56
June 20	Richmond	US 250: Libbie to Staples Mill	11	Urban Principal Arterial	0.04
June 23	Richmond	US 33: Glenside to Hermitage	12	Urban Minor Arterial	0.44
June 25	Richmond	US 33: Glenside to Hermitage	12	Urban Minor Arterial	0.57
June 30	Richmond	US 250: Henrico County Line to I-64	10	Urban Principal Arterial	0.71
July 7	Charlottesville	US 29: Hydraulic to US 250 Bypass	2	Urban Other Principal Arterial	0.10
July 9	Richmond	I-95: Exit 80 to Exit 76B	13	Urban Interstate	0.65
July 11	Richmond	US 33: Hungary Springs to Parham	15	Urban Minor Arterial	0.37
July 14	Charlottesville	Park to Cutler	3	Urban Collector/Urban Local	0.31
July 16	Richmond	I-64: Exit 183 to Richmond City Line	14	Urban Interstate	0.33
July 17	Charlottesville	US 29: Hydraulic to US 250 Bypass	2	Urban Other Principal Arterial	0.01
July 21	Charlottesville	Barracks: Preston to US 29	4	Urban Minor Arterial	0.37
July 28	Charlottesville	US 29: Hydraulic to US 250 Bypass	2	Urban Other Principal Arterial	0.16
July 29	Charlottesville	US 29: Hydraulic to US 250 Bypass	2	Urban Other Principal Arterial	0.31
July 30	Charlottesville	US 29: Hydraulic to US 250 Bypass	2	Urban Other Principal Arterial	0.38

The results of applying the speed post processors using Eqs. 1, 2, and 4 are shown in Table 4. The leftmost columns show the capacity and free flow speed data derived from the travel demand models, and the rightmost columns show the error for each processor. The number in the three rightmost columns is the MAE of the difference between the speed predicted by the processor and the real speed determined from the trendline. A negative sign in front of the MAE indicates that the post processor tended to underpredict speeds; the lack of a sign indicates that the post processor overpredicted actual speeds. In a few cases, the post processor underpredicted some speeds but overpredicted others; in such mixed cases the sign was chosen based on whether mostly underprediction or mostly overprediction occurred.

The average of the daily errors are summed in the last six rows of Table 4. These averages were computed three ways:

1. *By weighting each date equally*. Since there were 22 data collection days, the sum of the values in each column was simply divided by 22 to obtain this average daily error. The average of the daily errors for post processor A is 8.3 mph.

2. *By weighting the 15 sites equally* to avoid bias that might result from visiting a particular site several times. For example, when all sites carry the same weight, post processor A predicted higher-than-actual speeds by an average of 2.6 mph whereas post processor C predicted higher-than-actual speeds by an average of 2.1 mph. Post processor B, on the other hand, predicted lower-than-actual speeds by an average of 6.0 mph.

3. *By stratifying by MOBILE6 roadway classification type* (arterial/collector or freeway/interstate). For example, for arterial sites alone, when those sites were weighted equally, post processor A predicted speeds that were higher than actual speeds by an average of 4.4 mph.

Table 4 also has two rows that indicate "average of absolute error" where the absolute values shown for each site or each day were averaged. For example, when all dates are weighted equally, an average of the absolute value of the errors for post processor A yields 15.2 mph. This absolute value is relatively large because the positive and negative values do not cancel each other.

Table 4. Results of Applying Speed Post Processors for Speed and Volume Data

Date	Site No.	Capacity at LOS C	Speed at LOS C	Capacity at LOS E	Free Flow Speed	Error for Processor A (mph)	Error for Processor B (mph)	Error for Processor C (mph)
May 14	1	1400	42	1750	48.3	20.3	3.1	18.8
May 27	1	1400	42	1750	48.3	10.9	-15.7	2.4[b]
May 28	5[a]	1100	30	1375	34.5	9.2	-4.5	7.6
June 3	6[a]	1100	30	1375	34.5	6.8	-1.5	6.6
June 10	7[a]	1100	30	1375	34.5	5.1[b]	-2.9	4.9
June 11	8[a]	1100	30	1375	34.5	3.7[b]	-11.8	2.3[b]
June 16	9[a]	1100	30	1375	34.5	6.3	-7.2	4.7
June 18	10[a]	1100	30	1375	34.5	13.4	1.6	12.3
June 20	11[a]	1100	30	1375	34.5	7.8	-1.3[b]	7.6
June 23	12[a]	1100	30	1375	34.5	-4.9[b]	-14.0	-5.0[b]
June 25	12[a]	1100	30	1375	34.5	-6.9	-16.7	-7.3
June 30	10[a]	1100	30	1375	34.5	11.8	0.7[b]	10.7
July 7	2	600	40	750	46.0	30.6	5.2	22.1
July 9	13	1300	55	1625	63.3	-15.4[b]	-9.1[b]	-11.6[b]
July 11	15[a]	1100	30	1375	34.5	-3.1[b]	-9.6	-2.8[b]
July 14	3	400	25	500	28.8	-31.0	-28.2	-27.2
July 16	14	1300	60	1625	69.0	-14.5	5.9[b]	-4.3
July 17	2	600	40	750	46.0	32.3	6.7	23.4
July 21	4	600	25	750	28.8	10.5	-4.6	6.1
July 28	2	600	40	750	46.0	29.0	3.8	21.0
July 29	2	600	40	750	46.0	30.9	5.3	22.1
July 30	2	600	40	750	46.0	30.3	4.9	21.7
Average of error (all dates weighted equally)						**8.3**	**-4.1**	**6.2**
Average of absolute error (all dates weighted equally)						**15.2**	**7.5**	**11.5**
Average of error (all physical sites weighted equally)						**2.6**	**-6.0**	**2.1**
Average of absolute error (all physical sites weighted equally)						**11.9**	**7.8**	**9.1**
Average of error (all freeway and interstate sites weighted equally)						**-4.8**	**-3.2**	**-1.8**
Average of error (all arterial sites weighted equally)						**4.4**	**-6.7**	**3.1**

[a]Site classified by the Richmond travel demand model as a "multilane signaled" facility within a "suburban high density" location.
[b]Post processor where both overprediction and underprediction occurred.

Tables 5 and 6 show the results of the two sets of scenarios that investigate the sensitivity of the MOBILE6 model to the calculations from the post processors. In Table 5, default MOBILE6 data were used to compute the baseline case shown as the middle row. To complete Table 5, the proportion of vehicles in each speed bin was modified to change the average speed on interstate facilities and the average speed on arterial facilities by –10, –5, +5, and +10 mph. A similar approach was used to complete Table 6, except that data specific to the Richmond District were used. For example, when simulating the effect of using post processor A instead of a perfect baseline post processor, average speeds for arterials were raised by 4.4 mph. Computational details are described in the Appendix.

From Table 5, it is suggested that consistently overpredicting or underpredicting speeds according to the default MOBILE6 dataset will affect emissions by less than 6 percent. Because the errors of post processors A, B, and C were generally less than 10 mph, it is not surprising in part that Table 6 shows relatively small changes in emissions on a percentage basis. Tables 5 and 6 are also dependent on the particular vehicle mix used in MOBILE6, especially the proportion of diesel vehicles, and thus conceivably different results are possible in other scenarios where the fleet departs from both the national average used to create Table 5 and the Richmond data used to create Table 6.

Table 5. Sensitivity of MOBILE6 Emissions Estimates to Changes in National Default Dataset

Scenario	% Change in VOC Emissions	% Change in NO_x Emissions
Underpredict speeds by 10 mph	4.60	-0.11
Underpredict speeds by 5 mph	3.23	0.29
Baseline case (no change to default dataset)	0.00	0.00
Overpredict speeds by 5 mph	-4.36	0.40
Overpredict speeds by 10 mph	-5.49	2.06

Table 6. Sensitivity of MOBILE6 Emissions Estimates to Changes in Richmond Dataset

Scenario	% Change in VOC Emissions	% Change in NO_x Emissions
Use Post Processor A	-0.71	-1.91
Use Post Processor B	1.75	-0.15
Use Post Processor C	-0.71	-0.56
Use a perfect post processor	0.00	0.00

DISCUSSION

Sources of Variation in Speed Post Processor Data

The fact that a speed post processor does not predict speed perfectly as a function of volume is not surprising given the large number of assumptions that go into such a processor. Regardless of the functional form of the speed post processor, there are three main assumptions that affect the ability of a post processor to accurately predict speeds as applied within a long range-planning context:

1. The average values employed in a post processor represent the specific link in question.

2. The capacity does not vary over time.

3. Travel volumes are the primary determinant of link speeds.

As noted in Table 1, a speed post processor relies on *average* values for determining the capacity and free flow speed for a given link. Using the Richmond model as an example, the several thousand links contained in that model each require a capacity and free flow speed in order for the speed post processors in Eqs. 1, 2, and 4 to be used. These capacities are obtained from a lookup table, an example of which is Table 7.

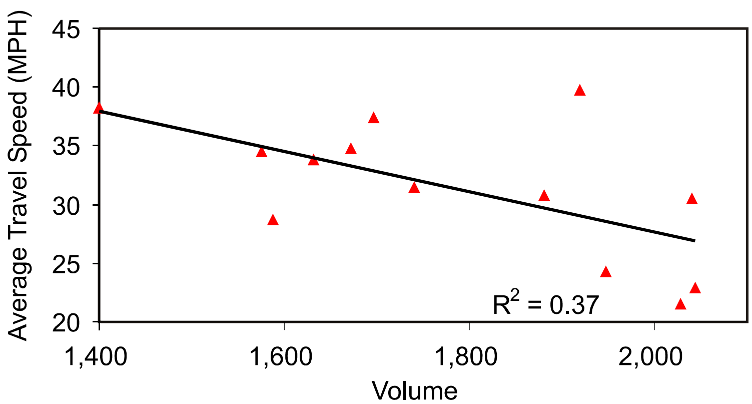
Table 7. Level of Service C Capacity Lookup Table for Richmond Travel Demand Model (Vehicles/Hour/Lane)

Functional Classification	Central Business District (CBD)	Outlying Business District (OBD)	Suburban High Density (SHD)	Suburban Low Density (SLD)	Rural (RUR)
Interstate	1300	1300	1300	1300	1300
Freeway or Expressway	1200	1200	1200	1200	1200
Multilane Signal	800	800	1100	1200	1200
Two-Lane Signal	700	700	1000	1000	1100
Multilane Uninterrupted	800	820	860	990	1150
Two-Lane Uninterrupted	300	300	320	340	360
Local Road	600	600	800	800	1000

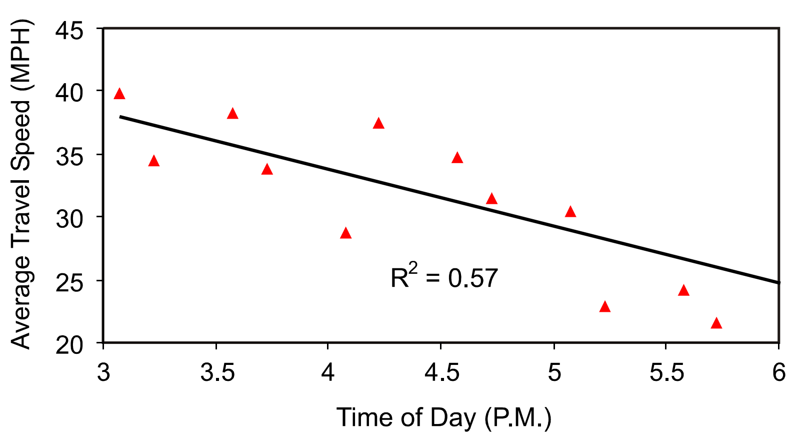
Figure 4. Richmond Sites Classified as Suburban High Density Multilane Signal, US 60, May 28 (left) and Courthouse Road, June 11 (right)

In short, the capacity for each link is based on its area type and facility classification. Thus, a given group in Table 7, such as an urban principal arterial in a suburban high-density district, can represent a wide range of roadway types with different access treatments, such as those shown in Figure 4. Both roads have multiple lanes and a median, but as shown in the figure they have different amounts of uncontrolled access.

In a typical application, there is a single capacity for a given roadway type and functional class for all time periods, despite the fact that capacity on signalized facilities may change as a function of cross-street volume. For example, for the Courthouse Road site shown to the right of Figure 4 and again in Figure 5, as was the case with other sites, as the day progressed, cross-street traffic visibly grew heavier, which led to less green time accorded to the mainline being traveled. This reduction in green time corresponds to a decrease in capacity, even though such capacity decreases are not reflected in the application of the post processor. That is, in theory, when Eqs. 1 through 5 are applied, ideally, the capacity should be modified to reflect the fact that the proportion of the cycle length experienced by mainline drivers decreases as cross-street volumes increase. In practice, however, the speed post processors generally use a single capacity that does not change over time.



(a) Average Travel Speed Versus Volume



(b) Average Travel Speed Versus Time of Day

Figure 5. Courthouse Road Site, Richmond, June 11: Average Travel Speeds as Function of Volume and Time of Day

For this site, the increase in volumes would have explained about 37 percent of the change in average travel speeds, but the change in time increased 57 percent of this variation. In other words, although it can be said that both time of day and traffic volume influence speed, Figure 5 suggests that time of day has a greater influence, as evidenced by the higher R^2 value. Had the time of day been able to explain 100 percent of the variation, all the points would be plotted directly on the trendline with $R^2 = 1.0$. In addition, the time is not physically causing the change in speed; other factors, such as an increase in red time that occurs later in the afternoon, do.

Other factors in addition to traffic volume may influence travel times on a given site visit. At one site studied, a relatively high correlation existed between increasing traffic volumes and increasing travel speeds! The reason was that a rainstorm had acted to slow traffic, and as traffic volumes increased, the rain lessened, resulting in increased travel speeds. Other factors, such as the presence of a school zone or emergency vehicles will also affect speeds. In sum, even though both sites in Figure 6 have the same classification of principal arterial, the disparity between the pictures illustrates how sites within this same classification may be physically different. These differences include changes in weather, different signal timings, or changes in the number of unsignalized commercial driveways along the corridor—all of which affect the corridor's capacity in practice.

Figure 6. Principal Arterial Sites: US 250, Richmond, June 18 (left), and Route 29, Charlottesville, July 7 (right). Despite differences in weather, access management, and signal timing, both sites are principal arterials.

Impact of Complexity with Post Processor B

The added complexity of expressions was not a guarantee of greater accuracy. The additional oversaturated term from post processor B did not generally improve the accuracy of the expressions. As noted in Eq. 3, an additional formulation can be used when a link is over practical capacity.

For example, on July 7 between 3:00 and 3:15 P.M., the practical capacity was estimated from the travel demand model as 1,800 vph for three lanes of traffic whereas the observed flow rate was 1,936 vph for the three lanes of traffic. Instead of Eq. 2, which reflects the undersaturated case, Eq. 3, which denotes the oversaturated case, can be applied. For this particular data point, Eq. 3 predicted a speed of 12 mph whereas Eq. 2 would have predicted a speed of 21 mph. For this particular data point, where the real speed had a value of 16 mph, Eqs. 2 and 3 were roughly equal in terms of accuracy. For most sites, however, Eq. 3 would have made the prediction less accurate. Figure 7 compares the application of speed post processor B without the oversaturation component in Eq. 2 with the application with the oversaturation component in Eq. 3. Because the oversaturation component tends to lower the predicted speeds from post processor B and because post processor B already predicted lower speeds for sites where volumes exceeded practical capacity, only Eq. 2 without oversaturation was used for this study.

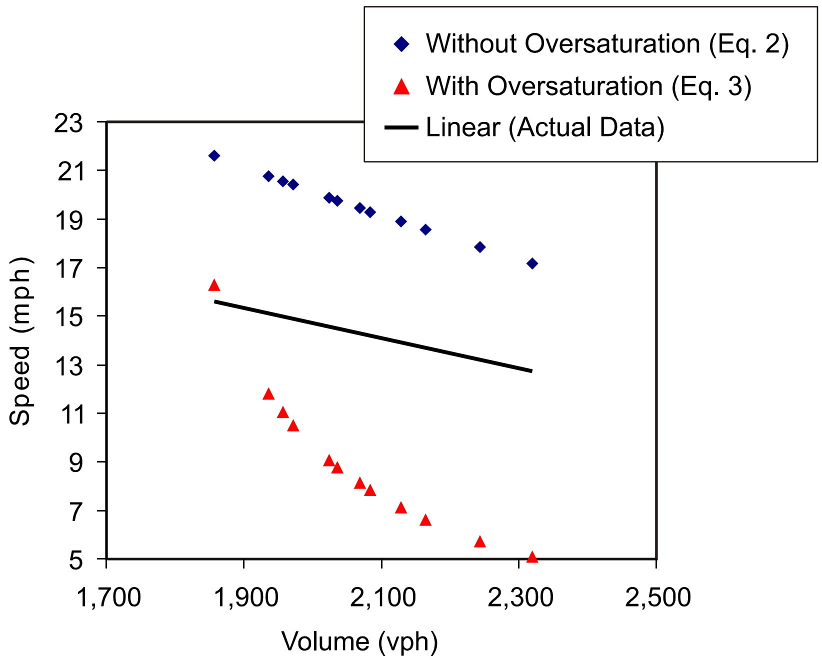


Figure 7. Application of Speed Post Processor B to US 29 Site, Charlottesville, July 7

Improving Performance of Post Processors

The literature has noted that one way to improve the performance of the speed post processor is to focus attention on estimating correct values for the free flow speed and capacity [7]. Although a planner with unlimited resources could determine exact capacities and free flow speeds for each link, such an undertaking would be time-consuming for a large regional area. For example, the current Richmond travel demand model has more than 6,700 links that are post-processed. It is unlikely that a modeler could realistically identify 6,700 free flow speeds and capacities. A reasonable approach, however, might be to verify that link speeds and capacities are accurate within each grouping by functional classification and area type. As shown in Table 6, this would require that the modeler pick only 35 different free flow speeds and capacities.

To investigate the utility of this approach, a common link type from Table 4 was used. For example, the Richmond travel demand model suggests that a "multilane signaled" facility within a "suburban high density area" should have an LOS E capacity of 1,375 and a free flow speed of 34.5 mph. As shown in Table 4, nine such sites fall into this classification system. Those sites are repeated in Table 8 such that the MAE for just those sites is 6.7, 6.1, and 6.0 mph for post processors A, B, and C, respectively.

Table 8. Mean Absolute Errors for Only Richmond Sites Classified as Multilane Signaled and Suburban High Density

Date	Site No.	A	B	C
May 28	5	9.2	4.5	7.6
June 03	6	6.8	1.5	6.6
June 10	7	5.1	2.9	4.9
June 11	8	3.7	11.8	2.3
June 16	9	6.3	7.2	4.7
June 18	10	13.4	1.6	12.3
June 20	11	7.8	1.3	7.6
June 23	12	4.9	14.0	5.0
June 25	12	6.9	16.7	7.3
June 30	10	11.8	0.7	10.7
July 11	15	3.1	9.6	2.8
MAE by site		6.7	6.1	6.0

To change the free flow speed or capacity used in post processors A, B, and C for this group of multilane signaled facilities in suburban high-density locations, subject to the constraint that link-specific values could not be used, a modeler would pick a single capacity or a single free flow speed that would help the post processor predict the actual trendline speeds. Figure 8 shows the MAE for each post processor as a function of the free flow speed, assuming the capacity is held constant at 1,375 vehicles/hour/lane. As indicated in Figure 8, the error for post processors A and C would be reduced to just about 4.0 mph if the free flow speed was changed from the default of 34.5 mph to between 28 and 30 mph. For post processor B, the error would be reduced almost as much (to 4.6 mph) if the free flow speed was changed from the default value of 34.5 mph to 42 mph. Further, by modifying the capacity, post processor B would have an error of 4.0 mph.

Figure 8 indicates a couple of useful lessons for improving the performance of the post processors. First, to the extent that the nine multilane signaled suburban high-density sites chosen in this study represent the many multilane signaled suburban high-density sites for the Richmond area, the free flow speeds can be modified to reduce the prediction error. Second, the free flow speed that should be picked depends on the post processor to be used. In fact, as summarized in Table 9, it is more important to pick the correct free flow speed (or capacity) for a given post processor than it is to pick a particular post processor. An analyst who spent time deliberating among post processors A, B, and C but who did not vary the free flow speed or capacity could reduce the MAE to a value of only about 6.1 mph. If the same analyst could vary the free flow speed or capacity (but not the post processor), he or she could reduce the MAE to almost 4.0 mph.

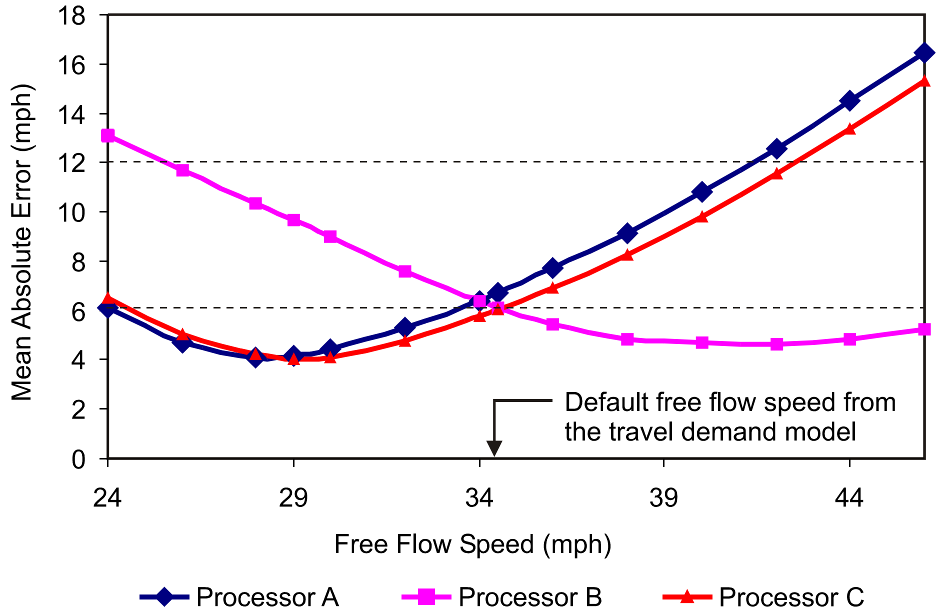


Figure 8. Mean Absolute Errors for Richmond Sites Classified as Multilane Signaled and Suburban High Density as Function of Modifying Free Flow Speed

Table 9. Mean Absolute Error for Richmond Sites Classified as Multilane Signaled and Suburban High Density (mph)

Source of Free Flow Speed and Capacity	Post Processor A	Post Processor B	Post Processor C
Defaults from Richmond travel demand model	6.7	6.1	6.0
Facility data such as that shown in Figure 8	4.1	4.0	4.0

More extreme demonstrations of how better calibration improves post processor performance are evident with links that have larger errors. For example, US 29 in Charlottesville was studied on July 7, 17, 28, 29, and 30 and, as shown in Table 4, errors for post processors A and C were quite large. In fact, the average of the absolute errors was 31 and 22 mph for post processors A and C, respectively. If, however, the free flow speed is changed from the default value in the Charlottesville travel demand model to a link-specific value, the averages of the absolute errors are brought down to 1.6 and 1.7 mph for processors A and C, respectively. This dramatic improvement comes from changing only the corridor free flow speed in Eq. 1 and Eq. 5. Substantially better performance results from simply having an accurate free flow speed, even if the post processor is not acutely sensitive to variations in volume.

Relevance of Post Processors to Emissions Computations

Tables 5 and 6 place the accuracy of the post processors in the context of emissions computations within the conformity process. Table 5, for example, showed that with a 10 mph underprediction for a national dataset, VOC emissions would have been overestimated by about 4.6 percent; overprediction by 10 mph would have led to VOC emissions being underestimated by about 5.5 percent. In short, this 20-mph speed prediction range, as indicated by the top and bottom rows of Table 5, would have led to a net difference in VOC emissions of about 10 percentage points. Given that the errors from post processors A, B, and C as shown in the last two rows of Table 4 were usually less than 10 mph, the expected difference when using post processors A, B, and C would be less.

This expectation was confirmed in Table 6, where post processor A or C could have underpredicted emissions (by 0.71 percent) and post processor B could have overpredicted emissions (by 1.75 percent), for a net differential of 2.46 percent. For NO_x, the differentials are smaller: with a national fleet, errors of plus and minus 10 mph lead to a difference in emissions of about 2.2 percent, as indicated in Table 5. Again, with post processors A, B, and C showing errors smaller than 10 mph, the difference in NO_x emissions based on the Richmond dataset is less than 2 percent, as shown in Table 6. All three post processors would have underpredicted NO_x emissions, with the largest disparity being caused post processor A (1.91 percent under the true value) and the smallest disparity being caused by post processor B (0.15 percent under the true value).

CONCLUSIONS

- *The performance of the three post processors investigated can be measured by comparing travel speeds predicted by the post processors to a trendline of average travel speeds.*

- *On a site-by-site basis, the average of the absolute errors for post processors A, B, and C when using the default free flow speeds and capacities from the appropriate travel demand models were approximately 12, 8, and 9 mph, respectively*.

- *All three post processors overpredict speeds at some sites and underpredict speeds at other sites.* The average of these positive errors and negative errors for post processors A, B, and C was 3, -6, and 2 mph, respectively, when using the default free flow speeds and capacities from the appropriate travel demand models.

- *The performance of the post processors can be improved by modifying the capacity or free flow speed used in the travel demand model.* Using one particular category of roadway links—multilane signaled facilities in suburban high-density locations—it was possible to reduce the MAE to approximately 4.0 mph from values of 6.0 to 7.0 mph. *Thus, all three post processors can provide absolute errors that average less than 5 mph provided that the post processor is calibrated with reasonably realistic free flow speeds and capacities*.

- *The sensitivity of the emissions calculations to the three post processors is less than 5 percent.* The largest net difference between any two post processors for VOC emissions was about 2.5 percentage points. For NOx emissions, the largest net difference for any two post processors was about 1.5 percentage points, with all three-post processors underpredicting NOx emissions. Experiments with a national dataset revealed larger percentage differences in emissions computations only with larger post processor errors of 10 mph.

- *Generally, volumes explain only a portion of the variation in average travel speeds at the sites where data were collected.* Findings suggest that it may be more important to have a reasonably calibrated default speed such that a post processor gives an "approximate" answer than a processor that is acutely sensitive to variations in volume.

- *Given the data available for long-range planning, the larger challenge is simply placing the post processor in the vicinity of observed speeds,* e.g., in the examples provided in Figures 9 through 11, having a predicted speed that is within even 5 mph of the observed speed.

RECOMMENDATIONS

1. *To calibrate the post processors accurately, three characteristics should be ensured:*

    - *For each link category, average travel speeds and volumes on a subset of links should be obtained in the field.* These can be used to ensure reasonable estimates for free flow speed and capacity for the link category, which in turn can help improve the predictions of the post processor.

    - *In order to obtain accurate speed estimates, recognize that different post processors may use different free flow speeds*. The key step is to have a small dataset of average travel speeds and volumes that enable one to match predicted to average speeds.

    - *The computations of the post processor should be understandable on a link-by-link bas*is. The software should not be a "black box" but instead should be transparent such that one can reproduce the predictions of a given speed on a given link. For example, a spreadsheet that illustrates how the computations are done on a step-by-step basis is preferable to proprietary software where such steps cannot be replicated. All three-post processors can be applied in such a transparent fashion.

2. *Time permitting, VDOT district staff should consider whether link categories other than area type and facility type should be used to assign capacities and free flow speeds*. For example, one implication of testing the post processors on arterial facilities is that other factors such as the amount of green time accorded to vehicles are critical elements. In theory, such variations in green time should affect the capacity, but in practice existing travel demand models in smaller Virginia areas use the same capacity value for a given link at all times of day.

3. *As an alternative to Recommendation 2, VDOT may modify the form of the post processor for each facility type rather than modifying the free flow speed and capacity for each facility type.* Such an approach merits study for facilities where, unlike those studied in this effort, speeds are highly dependent on volumes. The decision as to whether the free flow speed, the capacity, or the post processor itself should be changed depends on the type of error observed.

- *Modifying the free flow speed changes is most useful when the post processor is not predicting even close to the correct values, as was often the case in this study.* (See Figure 9.)

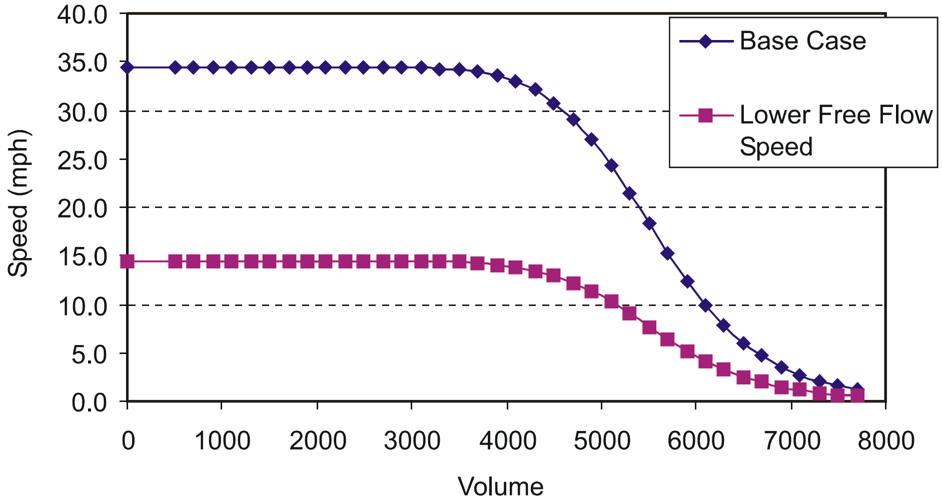


Figure 9. Effect on Predicted Speeds of Modifying Free Flow Speed (But Not Changing Post Processor)

- *Modifying the post processor is the most effective when the post processor is already relatively accurate for the free flow case and instead one is seeking to capture the effects of congestion better.* To create Figure 10, the change was made to the *exponent* of the post processor.

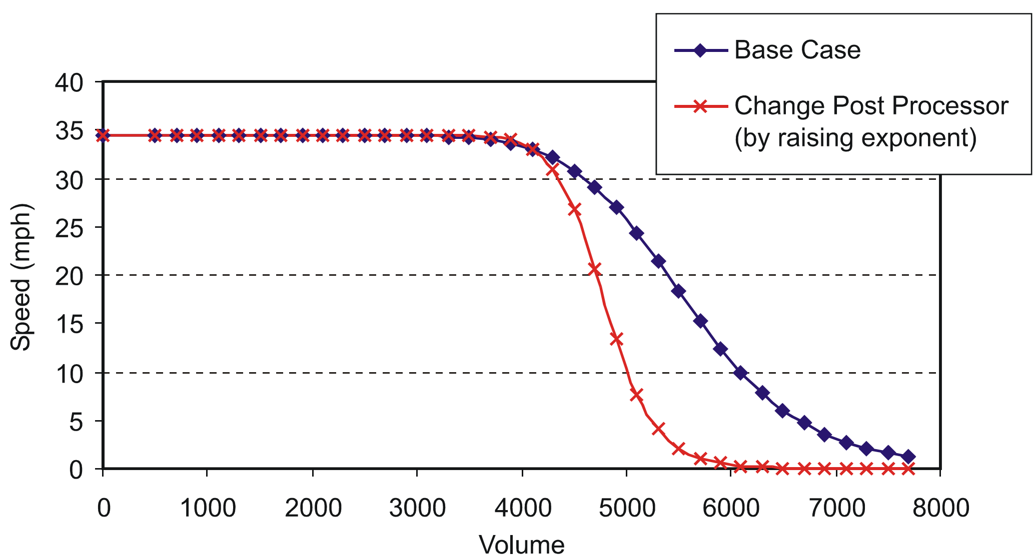


Figure 10. Effect on Predicted Speeds of Modifying Post Processor (But Not Changing Free Flow Speed or Capacity)

- *Modifying the capacity can be useful if one already has the appropriate free flow speed but one finds that the volume at which congestion starts to reduce speed is different than what was expected.* Figure 11 can also be obtained by changing the *coefficient* of the post processor.

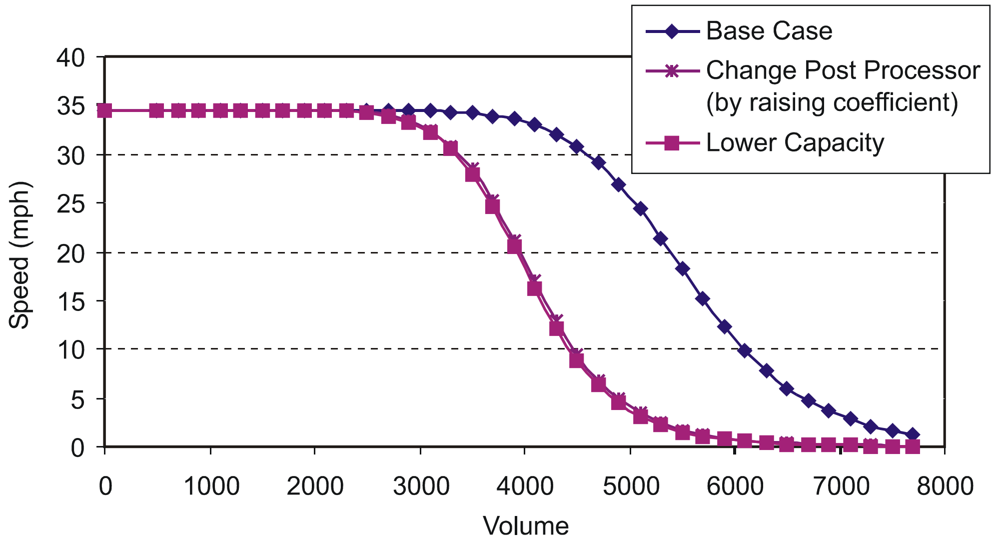


Figure 11. Effect on Predicted Speeds of Modifying Capacity

ACKNOWLEDGMENTS

This project was initially requested by staff from VDOT's Environmental Division and Transportation & Mobility Planning Division, and the authors gratefully acknowledge the assistance of several persons who contributed to this effort. Insights, review comments, and data suggestions were provided by A. Anday, E. Azimi, A. Costello, B. Donaldson, D. Landwehr, M. Hester, W. Johnson, W. Mann, B. Park, H. Pegram, and R. Tambellini. Additional help with data collection was provided by D. Ellington, A. Goswami, and L. Woodson. In yet another feat of transcendental patience, sorely needed editing was provided by L. Evans. Finally, R. Wigton helped the team explore the possibility of automated license plate readers as a data collection option.

REFERENCES

1. Chatterjee, A., Miller, T.L., Philpot, J.W., Wholley, T.F., Guensler, R., Hartgen, D., Margiotta, R.A., and Stopher, P.R. *NCHRP Report 394: Improving Transportation Data for Mobile Source Emission Estimates.* Transportation Research Board, Washington, D.C., 1997.

2. Miller, J.S., Park, B., Fitch, G.M., and Dougald, L.E. *Ways to Estimate Speeds for the Purposes of Air Quality Conformity Analyses*, VTRC 03-TAR8. Virginia Transportation Research Council, Charlottesville, 2002.

3. Garber, N.J. and Hoel, L.A. *Traffic and Highway Engineering*, 3rd ed. Brooks/Cole, Pacific Grove, California, 2001.

4. Johnson, W. Personal communication, July 2003.

5. Michael Baker Jr., Inc. for the Virginia Department of Transportation. *Route 250 Corridor Study: Charlottesville, Virginia 1997 Traffic Model Methodology Report.* Richmond, 1999.

6. Virginia Department of Transportation. *Route 29 Corridor Study: Traffic and Transportation Analysis.* Richmond, 1990.

7. Dowling, R., Kittelson, W., and Zeeger, J. *NCHRP Report 387: Planning Techniques to Estimate Speeds and Service Volumes for Planning Applications*. Transportation Research Board, Washington, D.C., 1997

APPENDIX
DATA COLLECTION AND ANALYSIS DETAILS

To encourage the reproduction of these types of validation studies in locations other than Charlottesville and Richmond this Appendix describes site-specific details that arose during this effort that will likely affect future validation efforts. Four categories of issues are discussed.

1. considerations for collecting and organizing travel speeds and volumes

2. impact of the low R^2 values

3. method for generating MOBILE6 input files based on consistent variances in speed

4. rationale for analyzing oversaturated arterial sites.

Details of the Data Collection Procedures

The placement of the Smart Travel Van or the loop detectors necessarily affected the volume recorded for each link because nearby cross streets can add to siphon traffic. The investigators picked sections that were most representative of the volumes observed on the link, but nonetheless the placement of the loop detector or van will affect somewhat the volumes that are recorded.

Average travel speeds did not always fit neatly into a 15-minute bin; for example, a travel time run might start at 3:58 P.M. but end at 4:04 P.M., which opens the possibility as to whether the travel run should be placed in the 3:45 to 4:00 bin or the 4:00 to 4:15 bin. For most sites, the run would have been placed in the latter bin, but judgment was exercised depending on the characteristics of the site.

Site-specific changes to the data collection approach were necessary in a few cases. For example, in a couple of instances, the radios proved infeasible and travel time runs with the vehicles were performed. In the few sites where VDOT already had volume data from loop detectors for traffic signal systems, the loop detectors were used to collect the data. Finally, although most data collection efforts took place between 2 P.M. and 6 P.M., data at one site were collected between 6 A.M. and 10 A.M. as the peak period at that site was in the morning rather than the evening.

It is conceivable that the method of using two-way radios could introduce a bias, since data collectors were looking for easily recognizable vehicles rather than explicitly sampling vehicles at random. The characteristics that data collectors tended to use to identify vehicles, such as color (bright yellow was easier to describe than mauve), make (a Chrysler PT Cruiser was easier to describe than a Nissan Maxima), unique lettering (a vehicle with a logo was easier to recognize than one without), and any other features that would set a vehicle apart did not seem to lend themselves intuitively to a biased dataset. However, as with any experiment, intrinsic biases of which the investigators are unaware could have affected the vehicles chosen for investigation.

A decision must be made for the time period. At a given site, is it better to have many short time periods or a few long time periods? For this study, with three data collectors, a 15-minute period might result in as few as 4 or as many as 14 data points, whereas a 5-minute period might have no data points or as many as 6, depending on the method of data collection. The investigators found that for this study, generally the use of 15-minute time periods gave higher R^2 values than the use of 5-minute time periods.

Finally, although this study reports the results of three post processors, a wide variety of post processors have formulations similar to those shown in Eqs. 1 through 5. In fact, an additional processor comparable to Eq. 5 but with different a coefficient and exponent for signalized facilities was tested at the request of reviewers (see Eq. A1). Because the accuracy was similar to that of processors A, B, and C, the processor was not discussed in this report.

$$speed = \frac{corridor\ free\ flow\, speed}{1 + 5(volume\,/\,practical\ capacity)^{3.5}} \qquad \text{[Eq. A1]}$$

Impact of the Low R^2 Values

For several sites, the relationship between average travel speed and volume was associated with a very low R^2 value. For those sites, there was less confidence in the trendline. Thus a legitimate question is whether the scatter of the real speeds about the trendline obviates differences among the post processors.

One way to consider the impact of these low R^2 values is to determine whether there is a significant difference among the performance of the post processors. Further, to address the scatter about the trendline, one can hypothesize that the actual observed speeds are ground truth. One can then ascertain whether the trendline itself is a better predictor of these actual speeds than the post processors.

For example, consider the data of May 14, which had shown an R^2 of 0.33, close to the median value observed in this study. Table A-1 presents a subset of the May 14 data and shows speeds for post processors A, B, and C as well as the trendline speed. As stated earlier in the report, the normal convention had been to compare values predicted by post processors A, B, and C to the trendline. However, using the data in Table A-1, it was possible to imagine that the observed speeds were perfect—and to compute, as shown in the last four columns, the error of the trendline, post processor A, post processor B, and post processor C.

These data in Table A-1 are strikingly similar to the data in the first row of Table 2, where again post processor A had the largest error, post processor C had a large error, and post processor B had a smaller error. To detect where there were significant differences in the three post processors and the trendline, a nonparametric test, the Wilcoxon signed rank test, was used on the entire set of observations from May 14. (That is, one tested to determine whether the low

Table A-1. Sample of Speed Post Processors from May 14 (US 250, Charlottesville)

Time Period	Observed Volume	Observed speed	Trendline Speed	Speed A	Speed B	Speed C	Error Trendline	Error A	Error B	Error C
2:25 to 2:29	1,236	29.1	32.1	48.3	36.3	48.0	3.0	19.2	7.3	19.0
2:30 to 2:44	1,409	36.7	30.9	48.3	34.9	47.8	5.7	11.6	1.7	11.2
2:45 to 2:59	1,672	33.5	29.2	48.3	32.7	47.4	4.4	14.8	0.9	13.9
3:00 to 3:14	1,592	27.8	29.7	48.3	33.4	47.6	1.9	20.5	5.6	19.7
3:15 to 3:29	1,860	24.3	27.9	48.3	31.0	46.9	3.6	24.0	6.7	22.6
3:30 to 3:44	1,742	31.3	28.7	48.3	32.1	47.2	2.6	17.0	0.7	15.9
3:45 to 3:49	1,668	27.0	29.2	48.3	32.7	47.4	2.2	21.3	5.8	20.4
4:00 to 4:14	1,896	30.9	27.7	48.3	30.7	46.8	3.2	17.4	0.2	15.9
4:15 to 4:29	2,080	29.0	26.5	48.3	29.1	46.2	2.5	19.3	0.2	17.2
4:30 to 4:44	2,210	24.1	25.6	48.3	28.0	45.6	1.6	24.2	4.0	21.6
4:45 to 4:59	1,888	25.2	27.8	48.3	30.8	46.8	2.5	23.0	5.6	21.6
5:00 to 5:14	2,444	26.2	24.1	48.2	26.1	44.4	2.1	22.0	0.1	18.2
5:15 to 5:29	2,304	25.2	25.0	48.3	27.2	45.2	0.1	23.1	2.1	20.0
5:30 to 5:44	2,100	23.4	26.4	48.3	29.0	46.1	2.9	24.9	5.5	22.7
5:44 to 5:59	1,754	26.0	28.6	48.3	32.0	47.2	2.7	22.3	6.0	21.2
Average							2.7	20.3	3.5	18.7

error associated with the trendline was significantly different from the high error associated with post processor A. One then compared the trendline error with the error from post processor B, and so, testing all possible pairs).

The results showed significant differences in all combinations (p = 0.001) with one exception: the error from post processor B was not significantly different from the trendline error (p = 0.244). Thus, based on the May 14 data, even a site with a low R^2 value can support detection of significant differences among the post processors. The practical interpretation of the fact that the post processor B error was not significantly different from the trendline error suggests that there is not much to be gained by reducing post processor errors below 5 mph in the sense that the error of the post processor shrinks to the experimental error.

A similar test was conducted with two other sites—the June 3 site (very low R^2 = 0.11) and the July 29 site (median R^2 = 0.31). At the latter site, results were comparable to those provided above, except all combinations were significantly different. At the June 3 site, however, results showed overlap between the post processors and the trendline, such that the trendline was not significantly better than the post processors at predicting the raw speeds. This suggests that at sites with very low R^2 values, it may be the case that the regression line is not more accurate than the post processor with the lowest absolute error. However, this does not mean that post processors are not significantly different—instead, a low R^2 simply means that volume explains only a small portion of the variation in average travel speed.

This phenomenon is best illustrated in Figure A-1, which shows the observed volumes, observed speeds, and the trendline for the speed and volume data collected on June 20. The trendline shows a terrible fit to the data, with an R^2 of 0.04. For that particular date, volume does not explain a significant portion of the variability. Figure A-2 shows the performance of the speed post processors with that dataset. Clearly, post processors A and C are the worst performers in the particular case—their predicted speeds are not near the actual observed speeds. On the other hand, post processor B is in the neighborhood of the trendline, and in fact one can debate whether post processor B or the trendline is a better predictor of speeds. In the aggregate, the visual information from Figure A-2 matches the results in Table 4 for June 20: despite the insensitivity of speed to volume, post processor B is closer to observed speeds whereas post processors A and C are not.

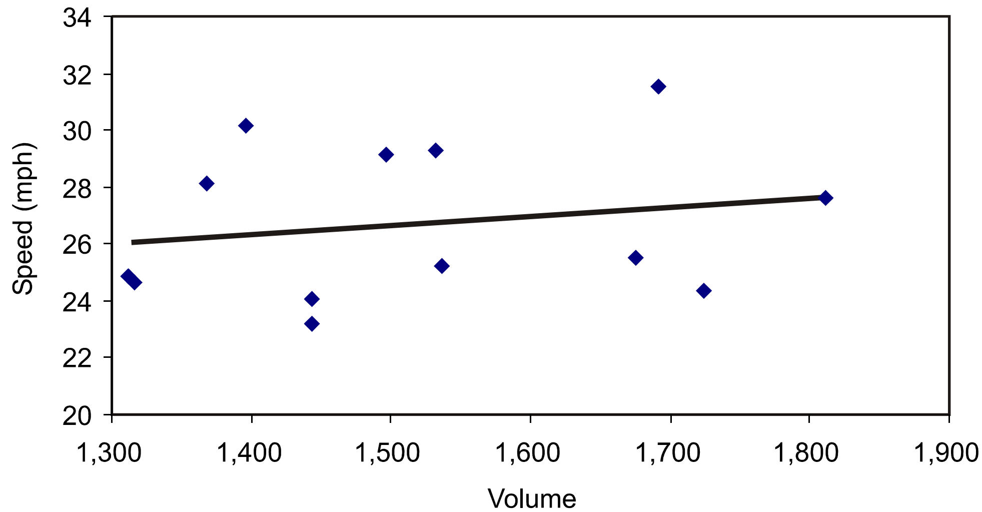


Figure A-1. Speed Versus Volume (US 250: Libbie to Staples Mill, Richmond, June 20)

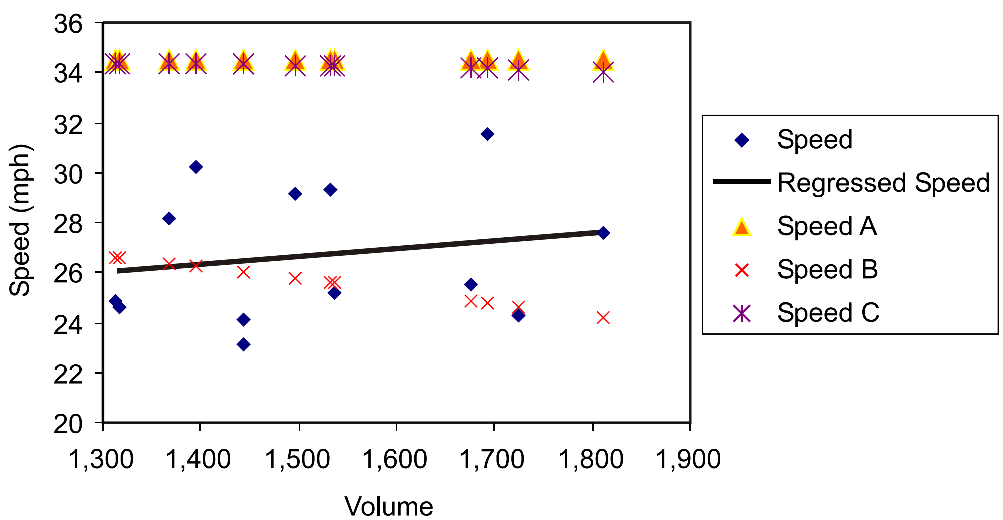


Figure A-2. Speeds from Post Processors A, B, and C Superimposed on Figure A1 (US 250: Libbie to Staples Mill, Richmond, June 20)

Details for Generating the MOBILE6 Input Files

In the preparation of Table 5, the MOBILE6 input files required extensive manipulation. MOBILE6 does not use a single mean speed. Instead, because MOBILE6 requires a speed distribution by bin (14 possible categories), by hour (24 possible categories), and by arterial and interstate (2 possible categories), there are 672 cells that require speed-based input data. Accordingly, three simplifications were made to enable a realistic simulation that could be completed in a timely fashion.

1. *A three-step approach was used to generate a realistic distribution of speeds for the various scenarios*. First, the coefficient of variation was determined from the baseline data. Second, a set of random numbers was generated that yielded the same coefficient of variation but with a new mean and appropriate variance for each scenario. Because speeds are generally normally distributed, a normal distribution was used for these random numbers. Third, a 14-bin histogram, as required by MOBILE6, was created based on these generated vehicle speeds; the histogram places speeds in 5-mph bins (2.5 to 7.5, 7.5 to 12.5, . . . 57.5 to 62.5, as well as below 2.5 or above 62.5 mph). By changing the proportion of vehicle speeds within these speed bins, it was possible to detect how a change in predicted speeds affected the prediction of NO_x and VOC emissions via MOBILE6.

2. *Assumptions had to be made regarding off-peak speeds*. The scenarios in Table 5, which denote the change from the baseline case of the default MOBILE6 dataset, reflect only changes in morning peak period (7 to 10) and evening peak period (4 to 7) speeds. In practice, therefore, Table 5 indicates the sensitivity of changes in peak period speeds on predicting mobile source emissions. The scenarios in Table 6, which use the Richmond dataset as the baseline, used off-peak volumes equal to 50 percent of LOS E capacity to represent the off-peak speed for each post processor.

3. *Errors similar to those shown in the last two rows of Table 5 were used to adjust the average speeds for two MOBILE6 roadway categories in Table 6*. For example, when simulating the effect of using post processor A instead of a perfect baseline post processor, average speeds for arterials were raised by 4.4 mph. In practice, therefore, Table 6 describes how using the different post processors would have affected mobile source emissions estimates for the Richmond area, assuming that the post processor accuracy for freeways/interstates and arterials/collectors was similar to that found in this study. However, post processors B and C were presumed to have errors of –3.3 mph and –1.9 mph for arterial sites. These values are within 0.1 mph of the errors shown in Table 4 but are not identical. The discrepancy of 0.1 mph for that freeway type for post processors B and C is not believed to affect the MOBILE 6 output substantially.

Details for Analyzing Sites Where Demand Volumes Exceed Capacity

Conventional thinking has been that, based on traffic flow theory for uninterrupted facilities, it is impossible to observe in the field a volume (or flow rate) greater than capacity. Thus, one weakness of validating speed post processor performance in the manner described in this study is that at situations where demand volume exceeds capacity, the measured volume from field data will not be the true volume for the post processor. Since capacity is the maximum number of vehicles per hour per lane that can travel past an observer, one is at risk of a situation encapsulated by Figure A-3 when demand volume exceeds capacity. In that illustration, no more than 1,500 vph can use the facility; when more vehicles attempt to use the road than that capacity, the result is that there is a *reduction* in the flow. Thus, if as illustrated in Figure A-3, 2,000 vehicles attempt to use a facility in an hour with a capacity of 1,500 vph, the result will be that *fewer* than 1,500 vehicles pass by the observer; Figure A-3 suggests this value might be 1,000 vph.

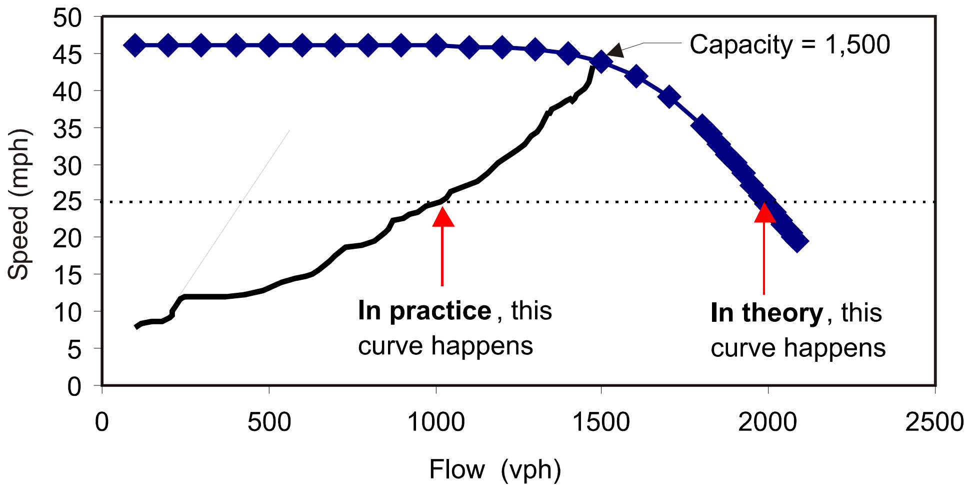


Figure A-3. Speed-Volume Curves According to Practice and Post Processor

Because sites were chosen such that periods of low and high congestion could be observed, the investigators had expected to see speed/volume curves comparable to that shown in the practical curve of Figure A-3 where there is a clear parabola such that low volumes occur with either high speeds (no congestion) or low speeds (over capacity). Indeed, such a curve was observed for the *spot mean speeds* (not the average travel speeds) on the Charlottesville US 29 site as shown in Figure A-4. It is plausible, but not guaranteed, that the spot mean speeds in Figure A-4 are indicative of the average travel speeds between two adjacent signals (e.g., after a vehicle has cleared the upstream signal and before the vehicle gets to the queue for the downstream signal). It is definitely not the case, however, that the spot mean speeds in Figure A-4 are the same as the average travel speeds for the entire US 29 segment, which includes waiting time at two signals.

In fact, when one examines a plot of those average travel speeds from travel time runs versus volume for Route 29, the parabola denoted in Figures A-3 and A-4 was not observed. Instead, as shown in Figure A-5(a), combined data from Route 29 still showed a linearly decreasing speed as a function of volume. Comparable patterns were observed when studying the Route 29 site on a day-by-day basis. Furthermore, as shown in Figure A-5(b), the times of heaviest congestion from the observers' visual inspection—roughly 5 P.M.—did not show lower volumes that one would have expected to arise from a road whose demand volume does exceed capacity.

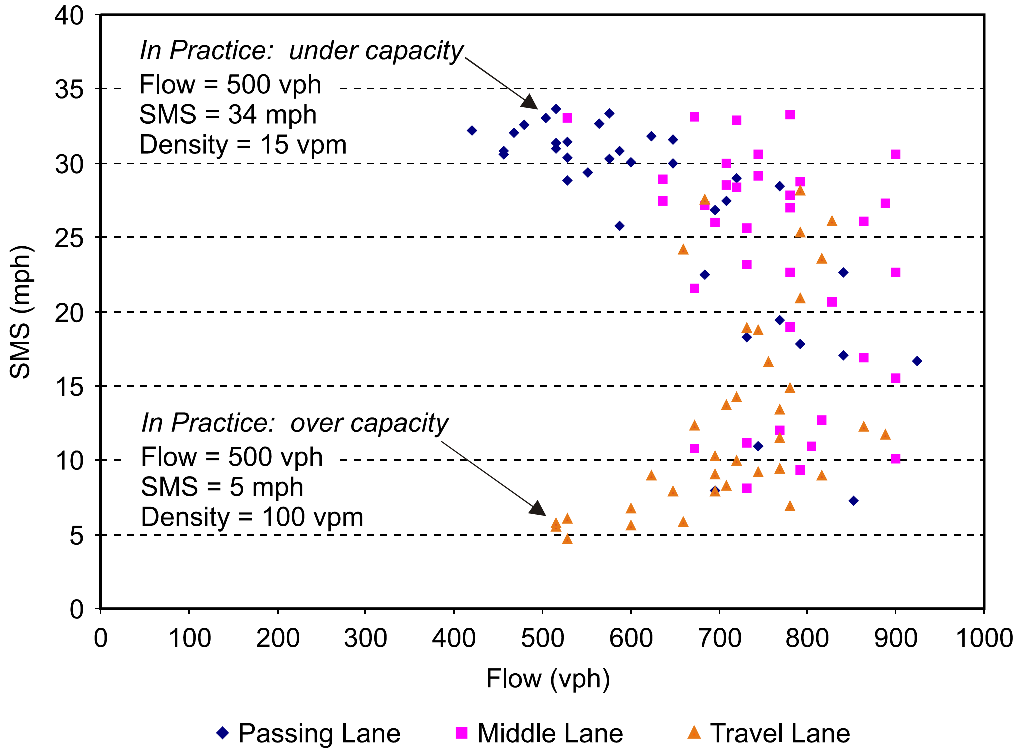
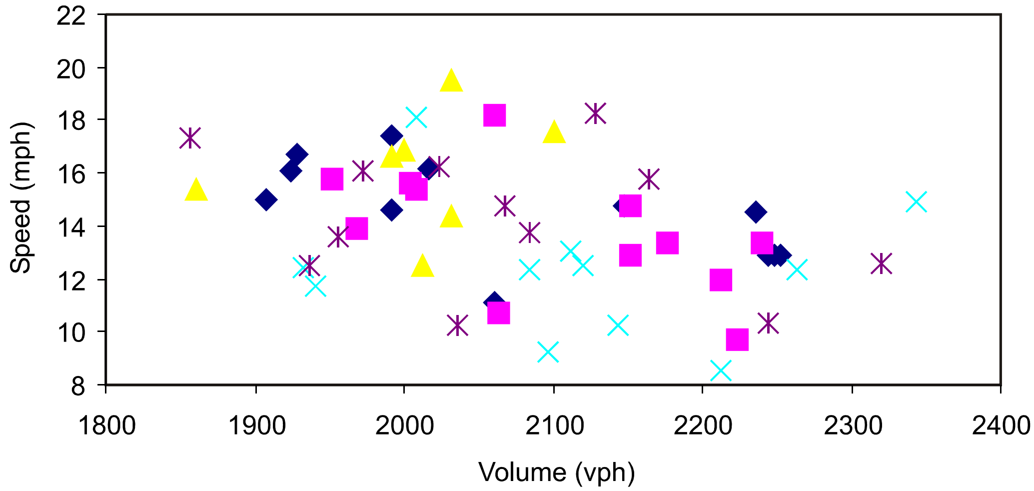


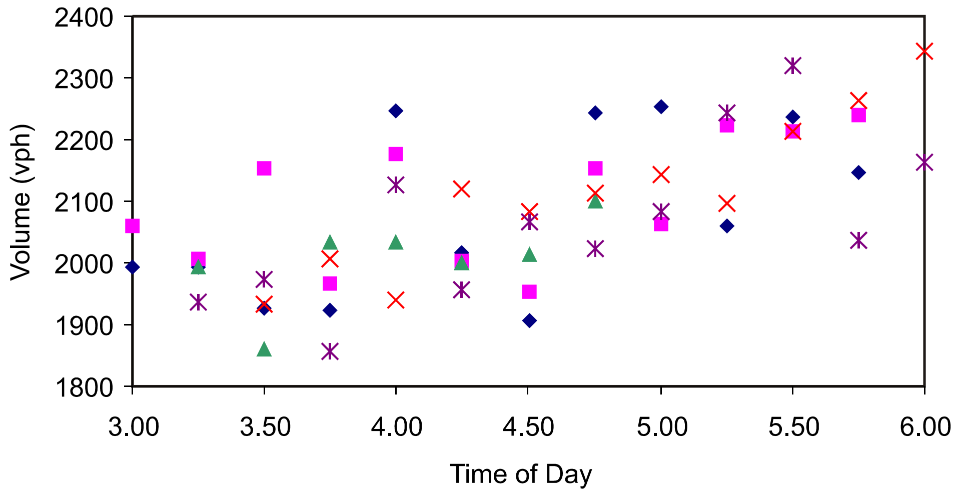
Figure A-4. Spot Mean Speeds Versus Volume, Route 29, Charlottesville, July 29

There are three ways to reconcile the investigators' observations and Figure A-4 (both of which suggested oversaturated conditions) against Figure A-5 (which suggests undersaturated conditions). *The first is that Route 29, like most of the other sites in this study, is an interrupted-flow facility*. In these cases, the predominant determinant of the volume and speed for the length of the facility is the behavior at the signal. Thus, for this interrupted flow facility, the speed-volume curve postulated in Figure A-3 is not applicable because most of the loss of capacity occurs at the signals. During the green phase at the signal, the actual flow rate under oversaturated conditions does not necessarily drop to zero as was reflected in Figure A-3. Instead, after the startup time associated with the first few seconds of green time has elapsed, the vehicles pass through the intersection at a rate equal to the saturation flow rate, which in this case is capacity.[3] Thus, conditions of overcapacity at a signal do not necessarily cause a speed-volume curve comparable to that shown in the lower left hand corner of Figure A-3.

In short, when demand volume significantly exceeds capacity for an uninterrupted-flow facility, then an actual volume substantially lower than capacity will be observed, as reflected in the decreasing curve shown in the lower portion of Figure A-5 and the bottom left tail of the speed-volume curve in Figure A-3. For a signalized facility, however, when demand volume significantly exceeds capacity, a volume that is substantially close to capacity will be observed as shown in the upper portion of Figure A-6. This answer appears to be the most likely explanation. (The exact shape of the curves shown in Figure A-6 will vary by facility; the salient feature is that at a signal, conditions of overcapacity should, in theory, result in the maximum flow rate being observed.)



(a) Average Travel Speed Versus Volume



(b) Volume Versus Time of Day (P.M.)

Figure A-5. Combined Data for Route 29, Charlottesville, July 7, 17, 28, 29, and 30: (a) Average Travel Speed Versus Volume, (b) Volume Versus Time of Day

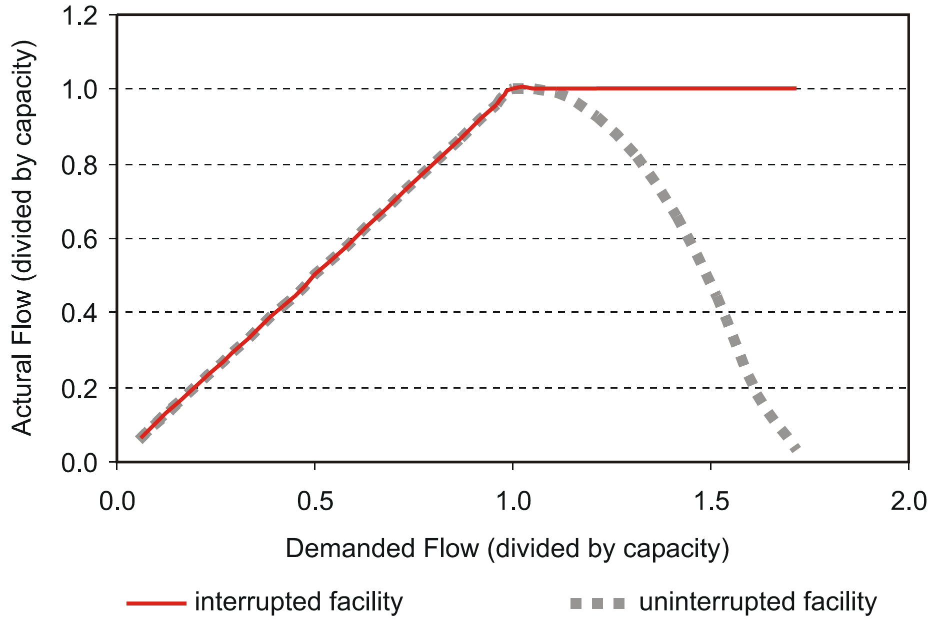


Figure A-6. Possible Relationship Between Demanded Flow and Actual Flow for Interrupted and Uninterrupted Facilities

A complementary possibility is that *the true capacity may be in excess of all values shown in Figure A-5*. Although the travel demand models suggest a LOS E capacity of 2,250 veh/hour for the site, clearly several observations exceeded that value, and it is possible the capacity is substantially higher. *A third possible answer is that the variation in the data may mask some observable breakpoints*. For example, at the site there were coincidentally two time periods where the volumes were 1,968 vph yet the speeds were 19.5 mph (one of the highest observed) and then 13.9 mph (one of the mid-range speeds) in Figure A-5. It is possible, but unlikely, that one of these points represented oversaturated conditions whereas the other did not.