USING ARCHIVED ITS DATA FOR SENSITIVITY ANALYSES IN THE ESTIMATION OF MOBILE SOURCE EMISSIONS

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16. Abstract

The study described in this paper demonstrates the use of archived ITS data from San Antonio's TransGuide traffic management center (TMC) for sensitivity analyses in the estimation of on-road mobile source emissions. Because of the stark comparison between previous speed/volume data sets used for emissions analyses and ITS data sets, the primary goal of the research team was to ascertain the effects that the additional level of detail in the ITS data sets had on estimating emissions. In particular, researchers wanted to determine the effects of input data aggregation level on emission estimates.

The authors found that for monthly total emission estimates, aggregation level had little effect on the sum total of emissions. Differences between using 20-second and 60-minute speed and volume data were less than 5%, and aggregated data typically underestimated emissions estimates. When calculating emissions for particular hours-of-day, however, the authors found that aggregation level had a moderate effect on emission estimates, ranging to as much as 20% during the early morning hours of light traffic. Emission differences for NOx were never more than ± 5%, presumably due to the flat shape of the NOx curve. The authors conclude that, for existing applications and models, data aggregation may not have significant effects on the model estimate. The results largely depend on the 1) nature and complexity of the relationship between input data and unknown variable (e.g., shape of the emission curve or form of the equation); or 2) the time frame/duration of the analysis.

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ABSTRACT

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EXECUTIVE SUMMARY

INTRODUCTION

The continuing deployment of intelligent transportation systems (ITS) on urban and rural roadways is increasingly providing significant information about the transportation system and its operation. For example, ITS sensors and detectors currently collect detailed information about vehicle volumes and speeds at frequent points along urban freeways. In real-time, this and other ITS data help traffic managers more efficiently operate the transportation system. When properly collected and archived, ITS data can improve transportation planners and analysts understanding of existing traffic flows and their impacts, such as congestion delay or mobile source emissions. Many transportation analysts are beginning to take advantage of the rich data sets available through ITS for applications such as congestion monitoring, traffic model development and calibration, and traffic flow research.

The research described in this report was focused on the use of archived ITS data in mobile source emissions modeling. The research effort was centered on the following analyses: determining the effects of speed and volume data aggregation level on emission estimates; and evaluate current speed and emissions estimate models based on available ITS data.

Objectives of Research

This study demonstrates the use of archived ITS data from San Antonio's TransGuide traffic management center (TMC) for the estimation of on-road mobile source emissions. The vehicle volume and speed data is collected every 20 seconds by the TransGuide center at more than 800 locations along major freeways. The detailed nature of this vehicle volume and speed data results in large input data sets (200 or more megabytes per day), which dwarf the size of existing volume/speed data sets used to calibrate mobile source emission models

Thus, the primary goal of this research was to ascertain the effects of input data aggregation level on mobile source emission estimates. On-road mobile source emissions were estimated using two basic inputs:

- hourly distributions of vehicle miles of travel (VMT) versus speed at various aggregation levels, including 20-second, 1-, 5-, 15-, and 60-minute levels; and

- hour-of-day emission rates for volatile organic compounds (VOC), carbon monoxide (CO) and nitrous oxide (NO_X), which were generated from MOBILE 5 for specific application in San Antonio.

The research team analyzed the differences in emissions estimates for different aggregation levels, as well as differences in VMT-speed distributions used to calculate emissions. The results should be particularly useful for transportation and air quality analysts who wish to utilize archived ITS data to improve their emissions analyses.

SUMMARY OF FINDINGS

For monthly total emission estimates, aggregation level had little effect on emission estimates (Table S-1). Differences between using 20-second and 60-minute speed and volume data were less than 5%. Aggregated data typically underestimated emission estimates. Based on this finding, it appears that 1-hour aggregate data is sufficient to estimate total daily emissions using MOBILE 5 inputs.

For hour-of-day emission estimates, aggregation level had a moderate effect on emission estimates (Tables S-2, S-3, and S-4 for VOC, CO and NOx, respectively). The differences between aggregation levels were typically less than 5% from 7 a.m. to 11 p.m. During early morning hours of very light traffic, emission differences were much higher, ranging from 5% to 20%. Emission differences for NOx were never more than ± 5%, presumably due to the flat shape of the NOx curve. Based on this finding, it appears that detailed data (either 20-second or 1-minute) should be used to estimate emissions by hour of day.

In examining a congested subset of the San Antonio system, researchers found that emission differences were slightly greater than those for the entire San Antonio system, particularly during peak hours of the congested data set. Based on this finding, it appears that in congested locations, analysts should consider using detailed data (20-second or 1-minute) to minimize error due to aggregation.

TABLE S-1
Total Emissions Estimates for ITS-Instrumented Freeways in San Antonio
(Units = 10^6 grams)

Aggregation Level	VOC		CO		NOx	
	Total	% Error	Total	% Error	Total	% Error
20 seconds ("raw" data)	187.82	-	2,379.91	-	314.59	-
1 minute	184.52	1.76%	2,358.09	0.92%	315.44	-0.27%
5 minutes	183.27	2.42%	2,345.26	1.46%	315.83	-0.39%
15 minutes	182.94	2.60%	2,340.73	1.65%	315.82	-0.39%
60 minutes	182.32	2.93%	2,329.38	2.12%	315.40	-0.26%

Note: Average percent errors are based on difference from emissions estimates calculated using 20-second data.

TABLE S-2
Summary of Percent Error for VOC Estimates, May 1999

		Hours of the Day											
Day	**Agg**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M-Th	1	6.14	9.13	9.77	10.37	10.34	6.15	1.82	1.25	1.27	1.44	1.42	1.24
	5	9.96	16.24	17.71	19.95	17.59	8.60	2.38	1.93	1.75	1.82	1.78	1.59
	15	10.39	17.43	19.01	21.80	18.55	8.76	2.49	2.38	2.01	1.87	1.84	1.64
	60	10.52	17.61	19.33	22.28	18.74	8.79	2.71	3.84	2.77	1.95	1.88	1.66
Fr	1	7.55	10.00	9.51	10.45	9.26	5.00	1.05	0.67	0.72	1.04	1.07	1.00
	5	10.40	16.46	15.80	19.60	16.57	7.28	1.26	1.21	1.05	1.39	1.36	1.29
	15	10.57	16.96	16.51	21.08	17.74	7.42	1.32	1.61	1.23	1.41	1.36	1.33
	60	10.64	17.03	16.63	21.26	17.89	7.48	1.48	2.85	1.75	1.40	1.36	1.42
Sat	1	3.17	6.61	7.30	9.30	10.31	8.73	4.89	2.89	1.84	1.46	1.25	1.04
	5	5.21	9.49	10.04	14.65	17.03	12.55	6.01	3.29	2.10	1.65	1.44	1.21
	15	5.38	9.65	10.21	15.16	17.74	12.75	6.06	3.32	2.11	1.66	1.45	1.21
	60	5.48	9.70	10.22	15.22	17.83	12.84	6.12	3.35	2.14	1.69	1.44	1.20
Sun	1	3.98	6.40	6.78	9.09	10.21	9.53	7.62	6.02	4.75	2.72	1.88	1.65
	5	5.02	8.51	9.04	13.93	17.76	15.71	10.41	7.44	5.66	3.14	2.16	1.86
	15	5.10	8.62	9.19	14.44	18.79	16.49	10.54	7.46	5.69	3.20	2.19	1.88
	60	5.10	8.73	9.18	14.45	19.03	16.59	10.49	7.44	5.81	3.26	2.25	1.87

		Hours of the Day											
Day	**Agg**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
M-Th	1	1.14	1.13	1.01	0.82	0.79	0.92	0.93	1.38	1.92	2.24	3.25	4.73
	5	1.45	1.42	1.32	1.20	1.25	1.63	1.29	1.67	2.38	2.83	4.12	6.67
	15	1.49	1.49	1.38	1.33	1.50	2.10	1.54	1.72	2.41	2.91	4.23	6.83
	60	1.53	1.58	1.46	1.62	2.06	3.08	2.34	1.88	2.42	2.97	4.38	6.90
Fr	1	0.95	0.84	0.80	0.76	0.84	0.92	0.74	0.88	1.40	1.61	1.88	2.73
	5	1.25	1.25	1.26	1.19	1.50	1.73	1.18	1.21	1.76	2.07	2.39	3.55
	15	1.38	1.33	1.39	1.43	1.91	2.37	1.46	1.25	1.80	2.18	2.47	3.64
	60	1.52	1.40	1.53	1.94	2.81	3.54	2.36	1.30	1.80	2.23	2.49	3.65
Sat	1	0.90	0.99	0.96	1.07	1.10	1.06	1.16	1.39	1.64	1.78	1.80	2.63
	5	1.08	1.24	1.18	1.29	1.30	1.30	1.40	1.56	1.97	2.22	2.43	3.39
	15	1.10	1.33	1.26	1.35	1.34	1.30	1.40	1.55	2.01	2.29	2.53	3.46
	60	1.08	1.47	1.46	1.45	1.43	1.29	1.43	1.64	2.03	2.33	2.61	3.52
Sun	1	1.37	1.24	1.19	1.42	1.34	1.28	1.33	1.68	2.25	2.70	3.18	4.47
	5	1.60	1.55	1.46	1.64	1.56	1.48	1.48	1.88	2.62	3.29	3.78	6.81
	15	1.69	1.68	1.53	1.67	1.58	1.64	1.52	1.87	2.67	3.38	3.85	7.07
	60	1.84	1.97	1.79	1.73	1.61	2.05	1.67	1.89	2.65	3.40	3.89	7.14

Note: Shaded cells represent hours of the day where emissions estimates were statistically greater than 5% different than estimates using 20-second data (alpha = .05).

TABLE S-3
Summary of Percent Error for CO Estimates, May 1999

		Hours of the Day											
Day	**Agg**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M-Th	1	3.53	5.66	6.06	6.59	6.22	3.18	0.91	0.97	0.83	0.70	0.61	0.53
	5	5.98	10.42	11.21	12.78	10.54	4.46	1.24	1.76	1.39	1.03	0.88	0.82
	15	6.28	11.29	12.08	13.99	11.06	4.49	1.33	2.39	1.74	1.08	0.91	0.85
	60	6.36	11.48	12.30	14.32	11.14	4.45	1.67	4.69	3.07	1.14	0.92	0.85
Fr	1	4.37	5.97	5.53	6.36	5.27	2.32	0.43	0.76	0.57	0.56	0.55	0.54
	5	6.22	10.04	9.27	11.98	9.47	3.32	0.53	1.56	1.07	0.90	0.83	0.88
	15	6.37	10.37	9.59	12.85	10.08	3.31	0.58	2.21	1.32	0.89	0.76	0.89
	60	6.44	10.41	9.58	12.88	10.05	3.35	0.76	4.31	2.28	0.83	0.74	1.07
Sat	1	1.60	3.60	3.85	5.20	6.07	4.66	2.17	1.15	0.56	0.46	0.40	0.29
	5	2.77	5.20	5.28	8.13	9.95	6.60	2.61	1.21	0.57	0.47	0.47	0.34
	15	2.87	5.26	5.29	8.33	10.26	6.55	2.58	1.23	0.53	0.41	0.42	0.29
	60	2.88	5.32	5.25	8.28	10.21	6.58	2.63	1.25	0.55	0.45	0.32	0.20
Sun	1	2.19	3.51	3.68	5.16	6.03	5.42	3.50	2.48	1.88	0.81	0.41	0.27
	5	2.95	4.80	4.99	7.81	10.37	8.84	4.34	2.69	1.97	0.79	0.38	0.20
	15	3.06	4.87	5.04	8.02	10.86	9.19	4.24	2.54	1.89	0.77	0.36	0.17
	60	3.03	4.90	4.95	7.90	10.96	9.15	3.99	2.43	2.03	0.77	0.41	0.10

		Hours of the Day											
Day	**Agg**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
M-Th	1	0.49	0.49	0.52	0.53	0.64	0.75	0.39	0.33	0.77	1.41	1.88	2.65
	5	0.75	0.75	0.88	1.06	1.33	1.65	0.75	0.40	1.06	2.09	2.65	3.89
	15	0.73	0.82	0.96	1.24	1.74	2.33	1.10	0.41	1.06	2.25	2.84	4.03
	60	0.75	0.85	1.06	1.70	2.75	3.81	2.49	0.65	1.01	2.34	3.11	4.13
Fr	1	0.58	0.57	0.60	0.76	0.97	0.90	0.52	0.32	0.83	1.42	1.41	1.52
	5	0.99	1.08	1.26	1.50	1.97	1.94	1.11	0.50	1.28	2.27	2.20	2.21
	15	1.19	1.23	1.48	1.85	2.61	2.86	1.50	0.56	1.34	2.53	2.34	2.35
	60	1.28	1.38	1.73	2.59	4.19	4.72	2.87	0.60	1.29	2.66	2.36	2.32
Sat	1	0.31	0.37	0.31	0.30	0.27	0.18	0.23	0.37	0.83	1.40	1.26	1.53
	5	0.43	0.58	0.50	0.41	0.36	0.22	0.31	0.39	1.23	2.19	2.05	2.28
	15	0.43	0.66	0.58	0.52	0.37	0.16	0.28	0.31	1.29	2.36	2.24	2.41
	60	0.32	0.83	0.82	0.59	0.45	0.08	0.34	0.41	1.31	2.47	2.35	2.56
Sun	1	0.46	0.65	0.45	0.40	0.16	0.17	0.11	0.27	1.00	1.76	1.87	2.47
	5	0.58	1.03	0.67	0.56	0.19	0.13	0.01	0.22	1.33	2.57	2.55	4.13
	15	0.69	1.22	0.75	0.61	0.18	0.22	0.03	0.14	1.44	2.81	2.67	4.36
	60	0.93	1.77	1.16	0.73	0.15	0.54	0.28	0.17	1.32	2.85	2.78	4.44

Note: Shaded cells represent hours of the day where emissions estimates were statistically greater than 5% different than estimates using 20-second data (alpha = .05).

TABLE S-4
Summary of Percent Error for NOx Estimates, May 1999

		Hours of the Day											
Day	Agg	0	1	2	3	4	5	6	7	8	9	10	11
M-Th	1	-0.50	-0.55	-0.58	-0.54	-0.64	-0.59	-0.31	-0.11	-0.19	-0.29	-0.30	-0.27
	5	-0.87	-1.06	-1.18	-1.23	-1.32	-0.98	-0.49	-0.08	-0.25	-0.44	-0.46	-0.40
	15	-0.97	-1.21	-1.37	-1.44	-1.51	-1.09	-0.52	0.08	-0.17	-0.49	-0.50	-0.44
	60	-1.02	-1.26	-1.45	-1.52	-1.59	-1.15	-0.50	0.92	0.22	-0.49	-0.53	-0.46
Fr	1	-0.58	-0.65	-0.69	-0.64	-0.68	-0.60	-0.29	-0.04	-0.16	-0.24	-0.25	-0.23
	5	-0.92	-1.19	-1.35	-1.39	-1.38	-1.05	-0.46	0.01	-0.21	-0.39	-0.39	-0.32
	15	-1.02	-1.33	-1.54	-1.63	-1.61	-1.16	-0.49	0.17	-0.18	-0.43	-0.45	-0.37
	60	-1.04	-1.41	-1.66	-1.75	-1.74	-1.21	-0.47	0.85	0.04	-0.48	-0.48	-0.36
Sat	1	-0.43	-0.64	-0.74	-0.78	-0.71	-0.78	-0.66	-0.52	-0.48	-0.39	-0.35	-0.32
	5	-0.79	-1.10	-1.24	-1.51	-1.44	-1.37	-1.00	-0.79	-0.70	-0.60	-0.51	-0.49
	15	-0.88	-1.23	-1.39	-1.71	-1.66	-1.54	-1.10	-0.84	-0.77	-0.65	-0.57	-0.55
	60	-0.95	-1.25	-1.42	-1.81	-1.78	-1.57	-1.17	-0.88	-0.77	-0.69	-0.62	-0.58
Sun	1	-0.51	-0.66	-0.68	-0.73	-0.72	-0.75	-0.87	-0.83	-0.72	-0.58	-0.49	-0.46
	5	-0.75	-1.03	-1.10	-1.43	-1.59	-1.52	-1.57	-1.36	-1.13	-0.87	-0.70	-0.69
	15	-0.81	-1.12	-1.23	-1.62	-1.84	-1.74	-1.73	-1.49	-1.21	-0.92	-0.75	-0.74
	60	-0.85	-1.16	-1.30	-1.73	-1.95	-1.85	-1.87	-1.56	-1.20	-0.94	-0.76	-0.79

		Hours of the Day											
Day	Agg	12	13	14	15	16	17	18	19	20	21	22	23
M-Th	1	-0.26	-0.25	-0.21	-0.16	-0.10	-0.05	-0.22	-0.35	-0.36	-0.27	-0.35	-0.45
	5	-0.39	-0.37	-0.31	-0.21	-0.09	0.04	-0.29	-0.53	-0.52	-0.37	-0.47	-0.72
	15	-0.44	-0.39	-0.33	-0.21	-0.01	0.23	-0.22	-0.57	-0.57	-0.39	-0.49	-0.78
	60	-0.45	-0.40	-0.34	-0.10	0.35	0.71	0.13	-0.54	-0.65	-0.40	-0.42	-0.80
Fr	1	-0.19	-0.15	-0.14	-0.08	-0.00	0.01	-0.13	-0.24	-0.24	-0.15	-0.22	-0.36
	5	-0.27	-0.21	-0.18	-0.07	0.09	0.15	-0.14	-0.41	-0.34	-0.14	-0.27	-0.55
	15	-0.26	-0.22	-0.17	-0.01	0.26	0.43	-0.07	-0.44	-0.37	-0.13	-0.27	-0.60
	60	-0.24	-0.20	-0.13	0.23	0.85	1.11	0.33	-0.44	-0.45	-0.10	-0.30	-0.64
Sat	1	-0.28	-0.27	-0.28	-0.29	-0.30	-0.32	-0.34	-0.36	-0.31	-0.21	-0.25	-0.38
	5	-0.43	-0.39	-0.40	-0.44	-0.46	-0.52	-0.52	-0.55	-0.42	-0.24	-0.34	-0.52
	15	-0.46	-0.41	-0.42	-0.44	-0.50	-0.57	-0.58	-0.61	-0.46	-0.25	-0.36	-0.56
	60	-0.51	-0.39	-0.38	-0.44	-0.48	-0.62	-0.59	-0.62	-0.51	-0.24	-0.38	-0.58
Sun	1	-0.32	-0.23	-0.29	-0.34	-0.39	-0.38	-0.42	-0.47	-0.39	-0.31	-0.40	-0.50
	5	-0.48	-0.32	-0.43	-0.51	-0.57	-0.57	-0.63	-0.68	-0.56	-0.39	-0.55	-0.78
	15	-0.50	-0.32	-0.45	-0.55	-0.63	-0.56	-0.63	-0.74	-0.59	-0.39	-0.60	-0.84
	60	-0.50	-0.22	-0.39	-0.56	-0.63	-0.47	-0.60	-0.76	-0.70	-0.44	-0.61	-0.88

CONCLUSIONS

For existing applications and models, data aggregation may not have significant effects on the model estimate. The results largely depend on the 1) nature and complexity of the relationship between input data and unknown variable (e.g., shape of the emission curve or form of the equation); or 2) the time frame/duration of the analysis. These effects of these two variables are discussed further in the following paragraphs.

In this project, researchers calculated total emissions using emission rate profiles generated from MOBILE 5, the current standard for most emission analyses. Given these emission rates and the ITS data, we found that using detailed ITS data did not significantly affect our estimates under most conditions. The research team concludes that this lack of difference using detailed data is due mostly to the process and not the input data. In other words, some existing models (e.g., MOBILE 5) may not be capable of taking advantage of the detailed nature of data now available. However, researchers cannot assume that data aggregation is not important simply because it does not effect results using existing models. Detailed data at the lowest aggregation level will be necessary in developing and/or calibrating the next generation of transportation and emission models (e.g., TRANSIMS and modal emissions models).

In demonstrating the use of archived ITS data for emission estimates, researchers found that 20-second data produced approximately the same total emission estimate as did 60-minute aggregated data for a monthly period. However, they also found significant differences in different aggregation levels when looking at a particular hour within a particular day. Thus, researchers concluded that when using ITS data to calculate averages or sums over longer periods of time (e.g., emissions total for the month of May as in this example), the initial aggregation level may not have a significant impact. If, however, analysts are interested in the particulars (e.g., hour within a single day), then the aggregation level is significant and using the most detailed data available is recommended.

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CHAPTER 1. INTRODUCTION

The continuing deployment of intelligent transportation systems (ITS) on urban and rural roadways is increasingly providing significant information about the transportation system and its operation. For example, ITS sensors and detectors currently collect detailed information about vehicle volumes and speeds at frequent points along urban freeways. In real-time, this and other ITS data help traffic managers more efficiently operate the transportation system. When properly collected and archived, ITS data can improve transportation planners and analysts understanding of existing traffic flows and their impacts, such as congestion delay or mobile source emissions. Many transportation analysts are beginning to take advantage of the rich data sets available through ITS for applications such as congestion monitoring, traffic model development and calibration, and traffic flow research.

The research described in this report was focused on the use of archived ITS data in mobile source emissions modeling. The research effort was centered on the following analyses: determining the effects of speed and volume data aggregation level on emission estimates; and evaluating current speed and emissions estimate models based on available ITS data.

The Texas Natural Resources Conservation Commission (TNRCC) has identified the need to improve estimates of on-road mobile source emissions. The Urban Airshed Model (UAM) is sensitive to on-road emissions by time-of-day, and requires traffic volumes and speeds as model inputs. Collecting hourly traffic volume data can be accomplished at a reasonable cost; however, collecting hourly vehicle speed data can be very expensive. Because of the expense, hourly speed data is currently estimated based on a model that uses the hourly volume-to-capacity ratio by direction for each classification of roadway. However, emission analysts could save substantial money and resources by utilizing traffic volumes and speeds collected by traffic management centers (TMC) in many of Texas' urban areas. It is necessary to demonstrate the usefulness and practicality of using archived ITS data for emissions analyses.

This report presents a study of the effect of aggregated speed data on emissions estimates, thus it is an analysis-specific study of speed aggregation levels. This is in contrast to the general study by Gajewski et al (1), where optimal aggregation levels were found independent of the application. ITS is used to collect speed data from which vehicle emissions estimates are calculated with 20-second aggregated speeds and compared to estimates with higher aggregation levels. This study will assist researchers in selection of appropriate aggregation levels for vehicle emissions estimation. Aggregation levels appropriate for calculation produce estimates close to the truth. ITS data are collected from the San Antonio TransGuide TMC. Estimates are calculated at the macro and micro levels.

Although most TMCs collect ITS traffic monitoring data from local controllers in 20- to 30-second intervals, the time intervals for archiving data vary considerably from 1, 5, 15, or even 60 minutes. Previous research by Turner et al. (1, 2) developed two generalized approaches for determining optimal aggregation levels for archived data when the particular application was unknown. The two statistical techniques were focused on determining minimal sufficient statistics to capture traffic parameter variability throughout the day. Both techniques calculated optimal aggregation levels of 60 minutes or more during periods of low traffic variability. Similarly, both techniques calculated optimal aggregation levels of one minute or less during periods of high traffic variability (e.g., congestion). This data aggregation research was focused on the archiving of traffic speed data for later use in a wide variety of applications.

Research by Park et al. (*3*) also investigated aggregation levels for real-time data. The particular application for this research was link and route travel time estimation and forecasting. The research by Park et al. and Turner et al. (*1*,*2*) both computed optimal data aggregation levels but using different "loss" functions. Turner et al. uses a cross-validated mean squared error, whereas Park et al. compares the speeds to a smooth function. In Turner et al., the authors assume dynamic optimal aggregation levels, whereas Park et al. assumes static aggregation levels throughout the day. In this sense, the research by Turner et al. generalizes Park et al. because it is temporally dynamic. Park et al. extends the optimal aggregation analysis to a specific application, that is, link and route travel time forecasting. By minimizing the overall mean square error for the travel time in a corridor, an optimal aggregation level was chosen for forecasting using artificial neural networks. This shows that the optimal aggregation problem can be modified by changes in the specific application.

This document will help researchers better understand the effect aggregation, time-of-day, day-of-week, volume, and type of emission profiles, have on emission's relative error. This report is organized as follows. Chapter 2 presents a literature review on speed models, application of speed models, speed and volume data collection methods, and methods for summarizing speed and volume data. Chapter 3 presents a discussion of the Bureau of Public Roads (BPR) curves used for testing the accuracy of speed estimate models using ITS data. Chapter 4 describes how emissions are calculated with ITS data using emissions profiles. Chapter 5 presents the results of the emissions calculation using the ITS data from San Antonio and Chapter 6 discusses the results and presents recommendations based on the report.

CHAPTER 2. LITERATURE REVIEW

TNRCC notes that on-road mobile source emissions estimates need to be improved. These estimates are provided by air quality models, which require relatively reliable estimates of vehicle demand, vehicle speed, and vehicle operating mode. Vehicle demand and speed are often obtained from travel demand models that are designed to forecast travel demand but are not as reliable for forecasting vehicle speeds.

Eisele et al. (4) found that fuel consumption models that incorporated detailed speed and acceleration characteristics provided statistically different results than those that incorporated average speeds on freeway or arterial sections. They propose that models that incorporate acceleration characteristics are expected to provide more accurate estimates of mobile source emissions and energy consumption than models that do not incorporate this information. They collected their data using a distance-measuring instrument (DMI), but collecting speed data by hour is very expensive. However, the implementation of ITS technology provides an opportunity to improve the collection of speed data by using data that is routinely collected as part of the freeway management system. The focus of this literature is on urban freeway systems due to the availability of ITS data for San Antonio. The objective of this review is to summarize literature in the following areas:

- speed models used for planning applications, focusing on those used in conjunction with urban travel forecasting models;
- application of speed with existing and emerging mobile source emissions rate models;
- collection of speed and volume data using ITS technology with a concentration on urban freeway systems; and
- statistical methods for summarizing and characterizing speed and volume data.

SPEED MODELS

The first type of literature surveyed includes that related to speed models used for planning applications with a concentration on those used in conjunction with urban travel forecasting models. Urban transportation forecasting models originally were used to guide future highway and transit planning and funding decisions. As congestion became more of a problem, the time-of-day and peak-period travel demand estimation became more important.

Travel demand models generally are based on the BPR speed-flow equation to estimate mean vehicle speeds. In these models, a roadway's free-flow speed and capacity is estimated based on look-up tables that require information on the type of roadway (arterial, freeway, etc.) and the location of the roadway (suburban, urban, rural, etc.). The BPR equations then estimate the mean speed on the roadway based on the volume/capacity (v/c) ratio for the roadway. Travel demand modelers have attempted to improve the estimates of speed from travel demand forecasts using post-processor techniques or improved speed-flow curves.

This section relies heavily on *Travel Model Speed Estimation and Post Processing Methods for Air Quality Analysis* by Dowling Associates (5).

Speed Estimation

As mentioned earlier, most travel demand models rely on the BPR speed-flow curve to predict mean vehicle speed. This curve requires three types of information: the free-flow speed, the capacity, and volume. The standard BPR equation is:

$$S = \frac{S_f}{1 + a(v / c)^b}$$

where:

S = predicted mean speed;
S_f = free flow speed, which is 1.15 times the speed at the practical capacity;
v = volume;
c = practical capacity, which is 80% of capacity;
a = 0.15, and determines the ratio of free-flow speed to the speed at capacity; and
b = 4, and determines how abruptly the curve drops from free-flow speed. A high value of b causes speed to be insensitive to v/c until v/c gets close to 1.0, and then the speed drops abruptly.

Dowling Associates (5) states that many MPO's have been concerned about inaccuracies in the speeds estimated by the BPR curve. They list several weaknesses of the current BPR curve that include:

1. The accuracy of the curve depends on the accuracy of the free-flow speed and capacity estimates that are used as inputs. Dowling et al. (6) found that using actual link capacities and free-flow speeds rather than the default estimates contained in BPR's look-up tables can reduce the error in BPR's speed estimation by 50%;

2. The BPR curve was fit to freeway data that was used to create the 1965 Highway Capacity Manual (HCM). At that time, the speed-density relationship was modeled as a polynomial curve. The current HCM is based on recent data that shows that the speed-flow relationship for freeways is flat (speed is not sensitive to flow) until flow approaches capacity;

3. The standard BPR curve underestimates the delays associated with congestion; and

4. Although this does not affect freeways, which are the focus of this study, the BPR curve does not include significant variables that affect travel time on signalized arterials. In reality, the v/c ratio has little impact on travel time until volume exceeds capacity.

The improvements to the BPR model focus on three aspects: improved free-flow speed estimation techniques, improved capacity estimation techniques, and improved speed-flow relationships.

Improved Free-Flow Speed Estimation Techniques
There are two main techniques for improving free-flow speed estimation on freeways. The HCM method starts with an "ideal" speed and adjusts it downwards based on geometric conditions. The NCHRP 3-55(2) method estimates free-flow speed based on the posted speed limit.

Highway Capacity Manual Method. The HCM (7) provides simple methods for estimating facility freeflow speeds but the methods often require data that is not easily obtainable by planners. Dowling Associates (5) is not aware of any actual applications of HCM freeflow speed equations in travel demand modeling practice.

The 1997 HCM update provides a freeway equation that assumes that the ideal freeflow speed is 70 mph. The ideal freeflow speed is reduced for factors based on the number of lanes, the lane width, the lateral clearance, and the number of interchanges per mile.

$$FFS = 70 - F_n - F_{lw} - F_{lc} - F_{id}$$

where:

FFS	=	freeflow speed for a basic freeway segments (mph);
F_n	=	an adjustment factor for the effect of the number of lanes;
F_{lw}	=	adjustment factor for the effect of lane width;
F_{lc}	=	adjustment factor for the effect of lateral clearance; and
F_{id}	=	adjustment factor for the effect of interchange density.

NCHRP 3-55(2) Method. Dowling et al. (6) propose a set of linear equations to estimate the free-flow speed based on data gathered on mean speed and the posted speed limit. The equation used for freeways is that for high-speed facilities, whose speed is greater than 50 mph. The equation was derived from actual data, but it has not been tested in actual traveling demand modeling practice. Following is the equation:

Customary Units: Mean Speed (mph) = 0.88 × (the Posted Speed Limit in mph) + 14.

Dowling Associates (5) noted that Florida Department of Transportation (FDOT) personnel have suggested that simply adding five to seven mph (eight to 11 kph) to the posted freeway speed limit would probably be as accurate as using the above linear regression curves. They further note that these equations are not applicable if local agencies have used "atypical" criteria for setting the speed limits. The 85th percentile speed should be used instead of the posted speed limit in those cases.

Summary. Both of the above techniques are expected to be an improvement over the BPR tables. The HCM methods are difficult to implement because the required geometric data is not readily available to planners. The NCHRP 3-55(2) methods may not be applicable in all instances. However, neither has been used in actual travel demand modeling practice, and thus their effectiveness has not been tested.

Improved Capacity Estimation Techniques
The most accepted method for link capacity estimation is the HCM method. However, it requires much data that is not readily available to planners. The Florida DOT and NCHRP 3-55(2) methods are alternatives that can be used when the data required by the HCM is not available.

Highway Capacity Manual Method. The HCM method focuses on converting real world traffic volumes into ideal traffic flow rates, which are then compared to ideal capacity estimates to obtain an ideal v/c ratio. Unfortunately, this produces unrealistic flows for capacity analysis. The ideal capacities for freeways are 2,300 vehicles per hour per lane (vphpl) for six-lane freeways, and 2,200 vphpl for four-lane freeways.

FDOT Method. FDOT developed a Level of Service (LOS) Manual (*8*) in 1995 that contains techniques and tables to assist in estimating maximum service flow rates using data that is generally available to planners. The techniques are based on the 1994 HCM, but defaults are substituted for some of the data that are more difficult for planners to obtain.

The Florida LOS manual contains generalized look-up tables of maximum service volumes and software that enables planners to estimate service volumes based on specific facility and area characteristics. The software consists of spreadsheets that enable planners to estimate tables of service volumes for the entire facility and a software version of Chapter 11 of the HCM (ARTPLAN).

The generalized LOS tables are presented by facility type and by the following area types: urbanized area, transition area, developed places (less than 5,000 population), and undeveloped rural areas. The tables were created using the 1994 HCM methodology and sets of agreed upon average assumptions for each area type. The following tables present the FDOT Generalized Level of Service estimates and the assumptions used by FDOT to generate these tables (Table 1 and Table 2). The tables were created by assuming default input data for each type of facility and area, and applying HCM methods to this default data. FDOT notes that planners should use the software to accommodate for specific facility characteristics when estimating level of service instead of relying on the generalized tables, which are to be used only for a preliminary analysis.

TABLE 1

Florida Generalized Peak Hour Directional Volume for Freeways in Various Areas[1]

Facility	Lanes	Level of Service				
		A	B	C	D	E
Freeways in Urbanized Areas (Group 1)[2]	4	1,110	1,760	2,640	3,350	4,040
	6	1,660	2,640	3,970	5,030	6,340
	8	2,210	3,530	5,290	6,700	8,460
	10	2,760	4,410	6,620	8,380	10,570
Freeways in Urbanized Areas (Group 2)[3]	4	1,060	1,700	2,550	3,230	3,900
	6	1,600	2,560	3,840	4,860	6,310
	8	2,130	3,410	5,110	6,480	8,170
	10	2,670	4,260	6,390	8,100	10,210
Transition Area[4]	4	1,110	1,770	2,640	3,330	3,750
	6	1,670	2,670	3,980	5,020	5,910
	8	2,230	3,560	5,310	6,690	7,890
	10	2,790	4,460	6,630	8,370	9,860
Cities With Less Than 5,000 People[5]	4	1,150	1,840	2,700	3,310	3,610
	6	1,730	2,780	4,080	4,990	5,700
	8	2,310	3,700	5,430	6,660	7,600
Rural Undeveloped Areas	4	1,150	1,840	2,700	3,310	3,610
	6	1,730	2,780	4,080	4,990	5,700
	8	2,310	3,700	5,430	6,660	7,600

1 Adapted from Dowling Associates (9) Tables 3, 7, 11, and 13.

2 Group 1 Freeways are located within an urbanized area with over 500,000 population and the freeways lead to or are within five miles of the primary Central Business District.

3 Group 2 freeways are freeways not falling within Group 1.

4 Transitional areas are those transitioning into urbanized areas, or areas with a population over 5,000 but not in an urbanized area.

5 This area includes cities or developed areas not in an urbanized area and with a population less than 5,000.

TABLE 2
Default Input Data for Freeways in Various Areas[1]

Input Data	Freeways in Urbanized Areas (Group 1)[2]	Freeways in Urbanized Areas (Group 2)[3]	Transition Areas[4]	Cities With Less Than 5,000 People[5]	Rural Undeveloped Areas
Traffic Characteristics					
Peak Hour Factor	0.950	0.950	0.950	0.950	0.950
Adjusted Saturation Flow Rate					
2 Lanes	2,125	2,050	1,975	NA	NA
4 Lanes	2,225	2,150	2,075	1,900	1,900
6 Lanes	2,225	2,150	2,075	2,000	2,000
8 Lanes	2,225	2,150	NA	2,000	2,000
10 Lanes	2,225	2,150	NA	NA	NA
Road Characteristics					
Through Lanes	4 – 12	4 – 12	4 – 8	4 - 8	4 – 8
Free-Flow Speed	60	60	65	70	70
Medians	Yes	Yes	Yes	Yes	Yes

1 Adapted from Dowling Associates (9) Tables 6, 10, 12, and 15.
2 Group 1 Freeways are located within an urbanized area with over 500,000 population and the freeways lead to or are within five miles of the primary Central Business District.
3 Group 2 freeways are freeways not falling within Group 1.
4 Transitional areas are those transitioning into urbanized areas, or areas with a population over 5,000 but not in an urbanized area.
5 This area includes cities or developed areas not in an urbanized area and with a population less than 5,000.

NCHRP 3-55(2) Method. The NCHRP 3-55(2) method takes the HCM equations for converting actual traffic volumes into ideal volumes and adapts them to convert actual capacities into ideal capacities. Most HCM adjustments are preserved, but default data (mainly FDOT values) are suggested for data unavailable to the planner. The following equation is used to estimate the ideal capacity of a freeway:

$$\text{Capacity (vph)} = \text{Ideal Cap} \times N \times F_{hv} \times PHF$$

where:

Ideal Cap = 2,400 passenger cars per hour per lane (pcphl) for freeways with 70 mph (110 kph) or greater freeflow speed;

= 2,300 pcphl for all other freeways (free-flow speed less than 70 mph [110 kph]);

N = number of through lanes;

F_{hv} = heavy vehicle adjustment factor; and

PHF = peak hour factor.

This equation requires facility-specific geometric data that are not readily available to planners, so it is recommended that planners develop sets, based on area type and location type, of these types of default tables as were developed by FDOT. The following tables, adapted from Dowling Associates (9), present a procedure for selecting default values and computing a look-up table of capacities by area (rural or urban) and terrain (level, rolling, or mountainous) type for freeways. Depending on the nature of the roadway, other classifications may be appropriate.

Table 3 shows that a rural freeway in level or rolling terrain is assumed to have a freeflow speed greater than 70 mph (112 kph), 2% heavy vehicles, and a peak hour factor of 0.85. An urban freeway is assumed to have a freeflow speed less than 70 mph (112 kph), 2% heavy vehicles, and a peak hour factor of 0.90 because of the lower design speeds, heavier passenger car volumes, and flatter peak volumes in urban areas.

TABLE 3
Example Table for Entering Default Values for Computing Capacity by Functional Class and Area/Terrain Type for Freeways*

Area Type	Terrain Type	Lanes	Freeflow Speed	PHF	% Heavy Vehicles
Rural	Level	All	> 70 mph	0.85	5%
	Rolling	All	> 70 mph	0.85	%%
	Mountain	All	< 70 mph	0.85	5%
Urban	All	All	< 70 mph	0.85	2%

* Adapted from Dowling Associates (9) Table 16.

Table 4 presents the computation of capacities based on the assumptions in Table 3. These figures have been rounded to the nearest 50 to 100 vphpl. The capacities per lane in this table are then be multiplied by the number of lanes (in one direction) at the critical point to determine the facility capacity at the critical point.

TABLE 4
Example Computations of Default Capacities by Functional Class and Area/Terrain Type for Freeways*

Area Type	Terrain Type	Lanes	Ideal Capacity	PHF	Fhv	Capacity/ Lane
Rural	Level	All	2,400	0.85	0.98	2,000
	Rolling	All	2,400	0.85	0.91	1,900
	Mountain	All	2,300	0.85	0.80	1,600
Urban	All	All	2,300	0.85	0.98	2,000

* Adapted from Dowling Associates (9) Table 17.

Summary. The HCM procedures are the most widely accepted methods of estimating highway capacity. However, the data required to implement the procedures are not readily available to planners. Therefore, many planning agencies have substituted default values into the HCM. The Florida LOS Manual provides one substitute data set that can be used as input for the HCM, while NCHRP 3-55(2) allows the selective substitution of unavailable default values. While the Florida LOS Manual has been used to create default capacities for the Florida Statewide Urban Travel Modeling System (FSUTMS), the NCHRP 3-55(2) provides a newer variation of the FDOT method that has not yet been implemented in a model.

Potential Improved Speed Flow Relationship
This section describes various methods that have been proposed to improve vehicle speed estimation in conjunction with travel demand forecasting models. Most models involve a single equation to estimate speed as a function of free-flow speed and the v/c ratio.

Horowitz Adaptation of HCM. Horowitz (10) developed a set of speed-flow equations and capacity and free-flow speed look-up tables based on the 1985 HCM. He fitted three alternative functions (the BPR, Spiess (11), and Overgaard) to the HCM data and found that all three specifications could fit the data well if the equation parameters were chosen appropriately. However, the appropriate parameters varied significantly between freeflow speeds. Table 5 illustrates the results for the BPR equation.

TABLE 5
Parameters of the BPR Equation that Horwitz Found to Best Fit the 1985 HCM[1]

Free Speed	a[2]	b[3]
70 mph	0.88	9.8
60 mph	0.83	5.5
50 mph	0.56	3.6

1 Adapted from Dowling Associates (7) Table 18.
2 "a" is the recommended coefficient.
3 "b" is the recommended power.

If only one equation with one set of parameters is allowed by the software, then Horowitz recommends that the BPR equation with the parameters a = 0.83 and b = 5.5 be used to predict link travel times.

Akcelik/Davidson Formula. Akcelik (12) proposed an equation derived from classical queuing theory for predicting the travel time on any facility. The travel time per unit distance is estimated as a function of the free-flow travel time rate, the length of the analysis period, the capacity of the link, and the travel time rate when the link is at capacity:

$$t = t_0 + \left\{ 0.25T \left[(x-1) + \sqrt{(x-1)^2 + \frac{8J_A}{QT} x} \right] \right\}$$

where:

t = average travel time per unit distance (hours/mile);
t_0 = freeflow travel time per unit distance (hours/mile);
T = the flow period, typically one hour (hours);
x = the degree of saturation = v/c;
Q = capacity (vph); and
J_A = the delay parameter.

This equation states that the travel time (t) is equal to the free-flow travel time (t_0) plus the average overflow queue divided by the capacity. The portion of the equation in braces to the right of the t_0 term is the average overflow queue divided by the capacity. Akcelik estimated the average overflow queue equation to account for variations in queue lengths caused by random variations in arrivals.

The delay function, J_A, is a function of the number of delay-causing factors in the section of the road and the variability of demand. Akcelik suggests lower values of J_A for freeways and coordinated signal systems and higher values for secondary roads and isolated intersections. If the difference in the rate of travel (hours per mile) between capacity and free flow conditions on the facility is known, the value of J_A can be computed. Substituting x=1.00 in the previous equation and solving for J_A yields:

$$J_A = \frac{2Q}{T}\left(t_c - t_0\right)^2$$

where t_c = the rate of travel at capacity (hours per mile). This equation explicitly considers the delays caused by queuing and the equation can be applied to any facility type. The assumptions are that there is no peaking of demand within the analysis period (T) and that there is no queue at the start of the analysis period.

Recent work by Dowling (5) suggests that, because the Akcelik curve becomes essentially linear at high v/c ratios, the Akcelik curve can achieve accuracy superior to that of the standard BPR curve while also reducing the number of iterations required to reach equilibrium in the traffic assignment process.

Conical Delay Functions. Spiess developed a speed-flow equation that enables computers to compute equilibrium traffic flows more quickly than the standard BPR curve. There are three characteristics of the BPR curve that tend to slow down computer calculations:

1. the curve is highly volatile; that is, a slight change in the forecasted volumes results in large changes in the estimated speed.
2. it is too insensitive at low v/c ratios; that is, large changes in volumes result in minor changes in speed, and
3. it uses high power functions (exponents greater than two) which slow down computer travel model computations of equilibrium traffic volumes.

Spiess suggests a conical delay function that is similar to the BPR curve while being more computationally efficient. It drops off constantly over lower ranges of v/c ratios and does not increase as rapidly as the BPR curve at higher v/c ratios ranges. It was developed by applying simulation models to several different facilities using different demand patterns obtained from field accounts. The simulations accounted for delays due to incidents, peak spreading observed in the field, day to day variations in demand, and decreases in capacity when demand exceeds capacity.

The equation is:

$$\tau = \tau_0 \times \left[{}^{\tau_\chi}\!/_{\tau_0} + \sqrt{\alpha^2 \times (1-\xi)^2 + \beta^2} - \alpha \times (1-\xi) - \beta \right]$$

where

t = travel time (seconds);

t_0 = the travel time under freeflow conditions (seconds);

t_c = the travel time at capacity (Spiess uses $t_c/t_0=2.0$);

a = a calibration parameter that must be greater than 1;

b = $(2a-1)/(2a-2)$; and

x = v/c ratio.

Note that at capacity (x=1), the formula yields "$t=t_c$," and at zero volume (x=0), the formula yields "$t=t_0$."

NCHRP 3-55(2) Updated BPR Curves. For facilities other than signalized arterials, Dowling (6) recommended the following parameters for the BPR curve based on work by Skabardonis (9) that fitted the BPR curve to various freeway and arterial data sets: "a," the coefficient of the BPR curve, equals 0.20, and "b," the exponent of the BPR equation, equals10.

STEAM Model. Cambridge Systematics (13) developed a speed model for use in its Surface Transportation Efficiency Analysis Model (STEAM) computer program. The model predicts mean daily, peak, and off-peak speeds given the ratio of average daily traffic to the facility's hourly capacity:

$$S = \frac{1}{\frac{1}{S_f} + D}$$

$$D = c_1 x^{c_2} \exp(c_3 x) \text{ for } x <= c_0$$

$$D = c_4\left(1 - c_5 x^{c_6} \exp(c_7 x)\right) \text{ for } x > c_0$$

where

S = average speed in miles per hour;

S_f = freeflow speed in miles per hour. (Freeflow speed is that which occurs when traffic volumes are very low. On interrupted flow facilities, they include delays due to traffic control devices but exclude any congestion-related delays.);

D = congestion delay in hours per vehicle mile;

x = ratio of the average daily weekday traffic to hourly capacity for the section (AWDT)/Capacity; and

c_0 to c_7 = constants shown in Table 6.

TABLE 6
Constants for the STEAM Computer Program for Mean Daily, Peak, and Off-Peak Freeway Speeds

Constant	Daily	Peak	Off-Peak
c_0	10.5	12.1	11.1
c_1	2.39E-08	2.35E-07	1.13E-07
c_2	3.75	3.29	2.52
c_3	0.287	0.235	0.259
c_4	0.05	0.05	0.05
c_5	1.494E-02	2.865E-04	1.058E-03
c_6	3.42	7.00	4.91
c_7	-0.372	-0.797	-0.449

Summary. The standard BPR curve underestimates mean vehicle speed for flows below capacity and overestimates speeds for demands greater than capacity. It was consistent with the 1965 HCM, but is not consistent with recent versions of the HCM.

Horowitz and Dowling (6) both propose changes to the parameters of the BPR curve that would improve its accuracy, make it more consistent with the current edition of the HCM, and allow the equation to be used with actual capacity instead of practical capacity. The Horowitz equations were fit to the 1965 HCM, while the Dowling equations were fit to the 1994 HCM.

Horowitz also adds the capability to calculate node delay using techniques similar to those in the 1985 HCM. It is not known how speed estimate accuracy is affected by this addition. Multiple equilibria are generated when node delay is introduced. While this is a problem theoretically, it may not be a practical problem if the nodes are close together.

Speiss proposes a speed equation that can be estimated more quickly than the standard BPR curve. Akcelik suggests a speed-flow relationship based on time dependent queuing with random arrivals. Through limited testing, Dowling (*6*) rates this equation superior to the standard BPR curve in its ability to replicate the speed estimates for "over capacity" conditions on freeways.

Summary
There are three methods available to improve estimation of free-flow speeds. The method suggested by Dowling (6) considers the posted speed limit. The HCM and NCHRP 3-45 equations are sensitive to geometric design parameters.

Link capacities may be estimated using Florida LOS Manual look-up tables of general volumes or by using Florida table generating spreadsheets. NCHRP 3-55(2) formulae may be used if greater sensitivity to geometric conditions is desired.

The parameters of speed-flow equations can be updated using forms of the BPR curve recommended by Dowling (6) or Horowitz. In addition, the Akcelik equation, which is based on queuing theory, can also be used. These equations require actual capacities, not the lower planning capacities used in the standard BPR curve. Providing for peak spreading may also increase the accuracy of the estimates.

Assignment Post-Processors

Assignment post-processors are more elaborate speed estimation procedures that cannot be incorporated in current travel demand model traffic assignment procedures either because of their more extensive data requirements or because of their impact on processing times. The following sections discuss two post-processors.

Dowling and Skabardonis Method (6)

A problem with queuing analysis is the difficulty in tracking both the geographical extent and duration of the queue. Dowling and Skabardonis show that reasonably accurate estimates of total system delay could be obtained by ignoring the geographical extent of the queues.

Their method involves extending the peak hour forecast to a multi-hour peak period using locally available data on travel demand by hour of the day. Peak period demand is forecast for each hour of the peak period based on the peak hour forecast.

For each hour of the peak period, average link speeds are then computed using hourly demands. The delay due to queuing is computed and added to the link travel time, if the demand during a particular hour exceeds the link capacity. Queues are carried over to the subsequent hour of the peak period and are stored on the link where demand exceeds capacity. Queues are not backed up upstream or used to reduce the flow downstream. The result of this simplification is a series of overestimates and underestimates of queuing that appeared to cancel out under their limited testing.

NCHRP 255 Procedures

Pedersen and Samdahl (14) suggested a set of procedures for computing speed, delay, and queue length for freeways in over-capacity and under-capacity conditions. The under-capacity procedures differ from the 1985 HCM procedure in one respect: they reduce the design speed reported in the 1965 HCM to average speeds using a formula developed by Makigami, Woodie, and May (15), as follows:

$$AS = OS - [DS/10 \times (1 - v/c)]$$

where:
AS = average speed;
OS = operating speed;
DS = design speed; and
v/c = v/c ratio.

The American Association of State Highway and Transportatlion Officials (AASHTO) defines operating speed as "the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions...." They define design speed as "the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern." Operating speed must be less than or equal to the design speed.

These procedures can be updated by using the procedures contained in Chapters 3 and 11 of the 1994 HCM. The new HCM reports average speed, so there is no need to convert operating speed to average speed.

Pedersen and Samdahl also suggest procedures, originally suggested by Curry and Andersen (*16*), for extending the HCM methods to overcapacity situations. The procedure applicable to freeways is "shock wave" analysis.

Freeway Shock Wave Analysis Procedure. This procedure uses the lower limb of the speed-flow curve for freeways that was reported in the 1985 HCM but is no longer included in the 1994 edition.

The freeway is split into three sections:

1. The bottleneck where the upstream demand exceeds capacity - often the section of freeway just downstream from an on-ramp,

2. the queue immediately upstream from the bottleneck - often the section immediately upstream from an on-ramp, and

3. the remaining portion of the freeway upstream of the queue - this section may not exist if the queue extends the full length of the freeway study section. The freeway study section needs to be extended if the queue extends upstream beyond the section initially selected for the freeway study section.

The average speed over the entire freeway section is determined by averaging the speed in each subsection as shown in the following equation:

$$ARS = \frac{L}{\frac{L - L_b - L_q}{ARS_{nq}} + \frac{L_q}{ARS_q} + \frac{L_b}{ARS_b}}$$

where:

ARS = average running speed of the entire freeway section;
ARS_b = average running speed of the bottleneck subsection of freeway;
= speed at capacity;
ARS_q = average running speed in the queue subsection upstream of the bottleneck;
ARS_{nq} = average running speed in the subsection upstream of the queue;
L = length of the entire freeway section;
L_b = length of the bottleneck section; and
L_q = length of the queue, which is calculated using an equation below.

The bottleneck and non-queuing subsection speeds can be determined using the speed-flow curves in Chapter 3 of the HCM. The average speed of the queue section must be determined using the lower limb (forced flow) section of the speed-flow curve in the 1985 HCM.

The following equation, by Dowling, provides an approximate fit to the lower limb curve:

$$ARS_q = A \times \exp\left[\ln B \times \left(\frac{v}{c}\right)^{1.27}\right]$$

where:

A = 5;
B = 6; and
v/c = the flow rate under queuing conditions.

This curve approaches 30 mph at v/c = 1.00 and 5 mph at v/c = 0.00. Parameters "A" and "B" can be modified according to the following equation if different speeds are desired:

where:

A = the speed at v/c = 0.0; and
B = {the speed at v/c = 1.00} divided by "A"

The length of the queue (L_q) is computed using the following equation:

$$L_q = \{QR \times T\}/\{2DQ\}$$

where:

Lq = the average queue length during the analysis period (miles);
QR = the queuing rate (vehicles/hour);
= upstream demand - bottleneck capacity;
T = the length of time that the level of demand occurs (length of peak hour or peak period)(hours) - note that the queue is building and not dissipating during this period;
DQ = the change in vehicle density between queue and upstream non-queued subsection; and
= {bottleneck capacity}/ARS_q - {upstream demand}/ARS_{nq}.

NCHRP 7-13 (Lomax) Curves
Lomax et al. (17) used linear regression to estimate a set of speed flow curves to various data sets they obtained as part of their research. The curves predict speed based on the v/c ratio, signal spacing, and frequency of access points. The following equation predicts the speed on freeways:

$$\text{Speed} = 91.4 - 0.002[\text{ADT/Lane}] - 2.85[\text{APM}]$$

where:
Speed = mean peak hour speed (mph);
ADT = average daily traffic; and
APM = access points per mile.

Margiotta Formulae
Margiotta et al. (18) used the TRAF family of traffic simulation models to estimate quadratic equations to predict mean facility speeds as a function of the ratio of ADT to the hourly capacity of the freeway. The function predicts delay due to the traffic flow. The delay is added to the free-flow travel time to obtain total travel time.

The following equations were developed for freeways and multi-lane highways:

If $x <= 8$, then: $d = 0.0611x + 0.00777x^2$
If $8 < x <= 12$, then: $d = 28.4 - 7.16x + 0.467x^2$
If $x > 12$, then: $d = -31.7 + 2.98x + 0.0393x^2$

where:
x = the ratio of ADT to hourly capacity; and
d = the ratio of hours of delay to 1,000 VMT.

These delay equations are quick and easy to apply and ideal for estimation of speed for the Highway Performance Monitoring System (HPMS). Since they approximate simulated model results from artificial data sets they can only be applied to the particular facility types and conditions on which the equations were developed.

The Highway Performance Monitoring System (HPMS) Analytical Process
With the FHWA HPMS Analytical Process (19), link speeds are estimated as a function of an initial running speed with various adjustments for pavement conditions, curves, grades, speed change cycles, stop cycles, and idle time. The initial running speed is determined from a look-up table based on the facility type and the congestion level.

The speed adjustments are applied in sequence: first, the initial running speed is reduced according to pavement conditions, and the result is further reduced for the effect of curves, etc. If the safe speed on the curve is lower than the reduced speed based on pavement conditions, a speed adjustment for curves is applied. The speed adjustment for grades is applied only to trucks. The adjustment for speed change, stop cycles, and idle time is a function of facility type and v/c ratio.

Ruiter Adaptation of HCM

Ruiter (20) demonstrated how the analysis procedures contained in the 1985 HCM could be used to develop facility-specific speed-flow relationships by substituting specific default values for various input HCM items. The defaults are selected based on the type of facility, facility subgroup, and area. The substitution of default values results in simplified equations that can be used to predict link speed. Ruiter shows how the simple equation, combined with a look-up table, can be used to predict freeway speeds. The equations cannot be generalized because they depend on specific default values. However, they can be used in any situation where the HCM techniques can be applied. The following equation can be used to extend the HCM speed predictions to freeways and expressways where demand exceeds capacity:

$$S_p = S_{p1} \times (0.555 + 0.444 \times (V/C)^{-3})$$

where:

S_{p1} = speed at V/C = 1.00.

This equation was developed for the Phoenix area. Ruiter recommends using peak spreading to avoid over-prediction of delay for high demand volumes that would result from these equations.

In the Houston-Galveston area, speed models were estimated to facilitate the emissions inventories required because the area did not meet the air quality standards set forth in the 1990 Clean Air Act Amendments (Benson et al. [21]).

Speed models for the Houston-Galveston region were estimated based on equations by Ruiters (Benson, et al.). The models rely on the speed-volume relationships in the HCM. They focus on the decay in speed from a freeflow speed to a level-of-service E (LOS E) speed as the level of congestion on the line increases from a zero-volume condition to a v/c ratio of 1.0. Speed reduction factors, derived from figure 3-4 of a revision of Chapter 3 in the HCM, are used to describe the decay in speed from a freeflow speed to a LOS E speed for v/c ratios from 0.0 to 1.0. The equation for freeway speeds is as follows:

$$S_p = S_{ff} - SRF \times (S_{ff} - S_e)$$

where:

S_p = the predicted speed for the link;

S_{ff} = the freeflow (or zero-volume) speed of the link;

SRF = the speed reduction factor corresponding to the link's v/c ratio; and

S_e = the LOS E speed of the link.

The extensions of the freeway model for v/c ratios above 1.0 are based on the traditional BPR impedance adjustment function:

$$S_p = S_{p1} \times (1.15/(1.0 + (0.15 \times V/C)^4))$$

where:

S_p = the predicted speed for the link;

S_{p1} = the speed estimated on the link for a v/c ratio greater than 1.0 using the Houston-Galveston speed model; and

V/C = the estimated v/c ratio for the link.

Direct Travel Impact Model (DTIM2) Speed Post Processor

SAI created the DTIM2 computer program for Caltrans (Ireson and Fieber [22]). DTIM2 reads the loaded highway network produced by transportation planning software and computes the corresponding pollutant emissions by 2 km grid cells in the region. The DTIM model contains an optional speed post-processor by Dowling (6) that uses the 1985 HCM techniques and queuing analysis to compute more accurate hourly link speeds over a 24-hour period.

The DTIM2 speed processor contains a set of speed-flow curves and equations for signalized and unsignalized facilities that have been verified on California roadways. The DTIM data collection showed that rural highways have similar to freeways when adjusting for the different free-flow speeds. Therefore, only one set of equations is used for both freeways and unsignalized highways.

The HCM procedures contained in DTIM are only valid when volume is less than capacity. Therefore, the speed processor also contains a queuing analysis algorithm for use when volumes exceed capacity. The queuing algorithm divides the 24-hour day into hour-long intervals, and allocates total demand to each time slot based on peaking information provided by the user.

Speeds that have been estimated with DTIM2 are significantly lower than those estimated using traditional BPR curves. Therefore, planners have difficulty switching over to DTIM2 because its estimates are inconsistent with earlier BPR estimates.

NCHRP 3-55(2) Procedure

NCHRP 3-55(2) recommended a post processor technique that estimates the space mean speed and the LOS for one direction of travel over the entire peak period that accounts for queuing delays. This procedure is based on Chapters 3, 7, and 8 of the 1994 HCM. The facility is divided into subsections, within where demand and capacity are relatively constant. If the peak period is more than one hour, the traffic demand in the peak period is divided into a sequence of hourly demand rates. A simplified HCM analysis is then applied to each segment for each hour of the peak period. Excess demand in one hour is carried over to the next hour, but the queue is not propagated upstream to reduce computational complexity. The procedure also does not account for the capacity and delay impacts of ramp merge, diverge points, and weaving sections. Following is the procedure:

1. The hourly capacity of each segment in one direction is determined using the capacity equations by facility type. These capacities are entered in a table of hourly capacities.

2. Next, each segment is reviewed to determine if its demand for any hour exceeds the capacity for any hour in the peak period. In these instances, excess demand must be carried over to the following hour and the queue delay must be computed for the current hour.

3. If a queue exists, then the queuing delay is computed using the following equation:

$$d_q = 3600 \times T \times \left(\frac{V_{t-1} + V_t}{2c} - 1 \right)$$

where:

d_q = mean delay due to excess demand (seconds);
T = duration of time period (hours);
3600 = factor to convert hours to seconds;
t-1 = leftover demand from the previous time period (t-1);
V_t = additional demand occurring in the current time period (t); and
c = capacity of the segment in subject direction (vehicles/hour).

4. The segment running times are computed for each segment (i) and time period (t) using the following equation:

$$R_{i,t} = 3600 \times \frac{\left(1 + a\left(\frac{v}{c}\right)^b_{i,t}\right)}{S_f}$$

where:

$R_{i,t}$ = mean segment running time per unit length for segment "T" and time period "t" (sec/mi, sec/km);
S_f = mean segment freeflow speed (mph or kph)
v/c_{it} = ratio of volume to capacity for the segment;
a = 0.20; and
b = 10.

5. The space mean speed over the entire peak period and the total study section length of a freeway using the following equation. Delays due to demand exceeding capacity on any segment are added to the individual segment travel times, which are then summed for the study section to determine the total travel time for the length of the study section. The total travel time is then divided by the length of the study section to determine the space mean speed for the study section.

$$s = \frac{3600 \times N_t \times \sum L_i}{\sum_{i,t} R_{i,t} \times L_i + \sum_{i,t} dq_{i,t}}$$

where:

s = space mean speed over the length of the facility (mph or kph);
L_i = length of segment "I" (mph or kph);
$R_{i,t}$ = running time for segment "I" during time period "t" (sec/mile or sec/km);
$dq_{i,t}$ = delay due to queuing on segment "I" and time period "t" (seconds); and
N_t = number of time periods being analyzed.

Dowling (6) compared the speeds estimated by the NCHRP 3-55(2) post processor with field data and found that the post processor estimates were superior to non-post processor methods (BPR and Enhanced BPR), but were inferior to HCM methods.

Summary

Most of the post processor techniques estimate speed and capacity in travel demand models based on the analytical methods of the HCM. Default values in the HCM are provided for data that is difficult for planners to obtain, and HCM figures are converted to look-up tables. Iterative HCM procedures are either omitted or replaced with a simplified approach.

The HCM does not apply to situations where demand exceeds capacity so many post processors include a method for calculating the delay due to queuing. The Dowling and Skabardonis (6) method computes queues on individual links without considering the effects on upstream and downstream links. It extends the peak hour analysis to the peak period. The NCHRP 255 method does not address multi-hour analysis, but it can be extended to peak period analysis by calculating excess demand for each hour, and carrying the excess demand over to the next hour. It is not designed to process multiple queues that might interfere with each other. It is designed to analyze specific facilities on a network.

The methods by Margiotta and Lomax avoid the HCM and estimate linear or curvilinear equations to real world or simulated data, and avoid the HCM and its data requirements. These methods must be carefully implemented outside of their calibration range.

The HPMS method is oriented to facility-specific analysis. The initial running speed is determined by look-up tables (by facility type, speed limit, congestion level, development type, number of lanes, etc.). The initial speed is then modified based on grade, curves, and speed change cycles on the selected facility. This method is difficult to update because the look-up tables must be revised each time the HCM was revised.

Ruiter proposes a method of developing link-specific speed-flow relationships based on the HCM. The link-specific information is substituted into the HCM procedures that are solved for specific speed-flow equations for that facility. Look-up tables are used for uninterupted flow facilities for which there are not specific HCM speed-flow equations. Queuing delay equations enable the HCM method to be extended to overcapacity situations.

The DTIM2 method applies HCM techniques to estimating speed along with a multi-hour queuing procedure. Hourly demand within the peak period is estimated using user-specified or default peaking factors. Planners are able to specify default input data by facility and area type with this method, which is automated and can be applied to the entire freeway network. California research indicates that this method produces significantly lower speed estimates than traditional BPR approaches.

The NCHRP 3-55(2) post processor is oriented to the analysis of a single facility or up to a dozen links. The overall average through travel speed for the facility is estimated for the entire peak period. The method divides the time period into hour-long intervals and the facility into segments. Queuing is identified and excess demand is carried over to the following hour without considering the impacts of upstream and downstream links.

Post processing methods may be appropriate for a planning agency that has the data and additional resources for a post processing method and desires more accurate speed estimates (without affecting the travel demand model calibration). Limited testing shows that the overall gain in accuracy may not be proportional to the additional data and effort required. The major advantage of post processors is that they allow the planner to test the impacts of facility design and operation options that cannot be tested in a traditional travel demand model. They also enable planners to analyze traffic operations over the entire peak period instead of confining them to 24-hour or peak hour analysis.

It is possible that queuing analysis will improve accuracy, but congestion may be overestimated if the impact of congestion on peak spreading is ignored. Ruiter recommends that queuing and peak spreading be implemented simultaneously.

APPLICATION OF SPEED MODELS WITH EMISSIONS MODELS

The next type of literature surveyed included that related to the application of speed with existing and emerging mobile source emissions rate models. Air quality analysis combines travel demand and vehicle emissions forecasting. One weakness in this analysis is that travel demand models have traditionally been used to forecast demand but not speed. However, speed is a critical factor in emission rate estimation.

SPEED AND VOLUME DATA COLLECTION USING ITS TECHNOLOGY

The third type of literature surveyed described the collection of speed and volume data, primarily on urban freeway systems, using ITS technology. There are two main methods of collecting speed and volume data. The first is the use of vehicle detectors (e.g., inductance loop, video, infrared, sonic, or radar) to collect information about vehicle volumes, speeds, and lane occupancies. The second is the use of automatic vehicle identification (AVI), which uses transponder polling to collect vehicle information at instrumented locations, enabling collection of travel times and speeds along roadway sections.

This section focuses on research by Turner et al. (2, 23). In 1997, these researchers surveyed 15 TMCs in North America about their ITS data management systems. Attempts were made to contact these TMCs again in 1999, and two TMCs that were planning to store ITS data were contacted. Table 7 presents a list of the surveyed centers and an indication of whether or not they collected speed and/or volume data in 1997. Most TMCs collected volume data, but some estimated speed data instead of collecting it. The center in Montgomery County, MD, is the only TMC that they specifically state does not collect data on freeways.

Phoenix Traffic Operations Center

The Traffic Operations Center (TOC) in Phoenix began operation in September 1995 and monitored 41.5 miles of freeway. Closed-circuit television (CCTV) and inductance loops were used to monitor the system. Due to privacy concerns, CCTV images were not recorded. Loop stations were spaced approximately 0.33 miles apart throughout the coverage area and one loop was located in each lane of traffic. The loops collected volume, vehicle length, speed, and lane occupancy data. This information was sent to the TOC every 20 seconds, and the 20-second data had been saved in a UNIX format since the center opened. The TOC had saved data in a five-minute format for each lane for one year, and the personnel indicated that that data was much easier to access than the 20-second data. Freeway maps on their web site presented 15-minute real-time summaries of the loop data.

TABLE 7
Selected TMCs and Their Collection of Speed and/or Volume Data

Name of Traffic Management Center	Speed Data Collected?	Volume Data Collected?
Phoenix Traffic Operations Center	✔	✔
Los Angeles District 7 Traffic Management Center	1	✔
San Francisco Bay Area Traffic Management Center	✔	✔
Georgia DOT Advanced Transportation Management System	1	✔
Illinois Traffic Systems Center		✔
Montgomery County Transportation Management Center[2]		
Detroit, Michigan ITS Center [3]	4	✔
Minneapolis, Minnesota Traffic Management Center	5	✔
TRANSCOM [3]	✔	
INFORM	5	✔
MetroCommute		
TranStar Traffic Management Center	✔	✔
TransGuide Advanced Traffic Management System	✔	✔
North Seattle Advanced Traffic Management System	✔	✔
Toronto's COMPASS	✔	✔

Source: Derived from Turner et al. (23).
1 Speed is estimated from the collected volume and occupancy data.
2 Only arterials are monitored.
3 There is not enough to determine if freeways are included in the system.
4 Speed is estimated two ways: 1) from the collected volume, lane occupancy, and vehicle length data, and 2) from loop detectors spaced 0.33 miles apart. The latter provide better estimates of speed.
5 Speed is estimated from collected volume, occupancy, and vehicle length data

Los Angeles (Caltrans District 7) TMC

The Los Angeles TMC had been operating for several years and monitored 748 directional miles of roadway. The monitoring system used CCTV and inductance loops. The CCTV images again were not recorded due to privacy (and liability) concerns. The 1,000+ loop stations were single loops spaced approximately 0.5 miles apart in each lane. The loops provided volume and occupancy data that were used to estimate speed data. The TMC polled the loop stations every 30 seconds, and three days of 30-second data were temporarily stored along with four days of five-minute summaries. The TMC had saved the 30-second summaries on circular tapes since it began operation, but the data in temporary storage was much easier to access. Special software developed by DOT personnel was necessary for data retrieval from the mainframe.

The survey in 1999 revealed that a new archiving system has been implemented. This system allows on-line access to 13 months of data. Data older than 13 months is stored on magnetic tape, but storage on CDs is anticipated in the future.

San Francisco Bay Area TMC

At the time of Turner et al.'s study (23), the San Francisco TMC had expected to monitor all freeways in the nine-county bay area in the near future. The TMC did not use CCTV at the time, but was expecting to use it in the future. Loop detectors were used to obtain volume, speed, and lane occupancy data. Vehicle class was estimated using the volume, speed, and lane occupancy data. Loop data were sent to the TMC every 30 seconds in a binary format and were eventually converted to an ASCII-text format. The data was not archived at the time of the study, but they were hoping to produce 5- and 15-minute summaries six months from the time of the survey.

Georgia DOT Advanced Transportation Management System

The advanced transportation management system (ATMS) in Georgia was opened in May 1996. It monitored 63 miles of freeway in the Atlanta metropolitan area using 360 video detection cameras. The cameras were located approximately every 0.33 miles in the monitored system. They collected vehicle volume and occupancy data with which to estimate speeds. Data sent to the ATMS from the loop stations every 20 seconds were not being archived at the time of the survey. However, they had begun efforts to save the data in hourly and 15-minute time periods.

Illinois Traffic Systems Center

The Traffic Systems Center (TSC) was monitoring 136 miles of freeway in 1997, and had expanded to include 210 miles in 1999. The TSC also operated CCTV cameras for monitoring purposes. Originally, the system had included approximately 2,250 single loops spaced approximately 0.5 miles apart to collect volume and occupancy data, while speed was estimated. With the expanded system, detectors are spaced every three miles and at entrance and exit ramps. At half-mile intervals, detectors in the center lane collect data with which to obtain lane occupancy and estimate travel time. The loop data is recorded in real-time-that is, each "pulse" is sent to the TSC when a vehicle passed over a loop detector. The points are aggregated to the 20-second, one minute, and five-minute aggregation levels.

The data for travel time and lane occupancy is stored for the hours 5:00 a.m. to 10:00 a.m. and 2:00 p.m. to 7:00 p.m. in five-minute binary format. Hourly volume data across all lanes are saved for the detector stations that are spaced three miles apart. Both are permanently archived on magnetic tapes.

Montgomery County TMC
The TMC in Montgomery County, MD, only monitored arterial facilities. In 1997, the TMC operated 46 CCTVs and expected to expand the system to 200 CCTVs. They also had approximately 1,000 loop detectors. In 1997, they did not save the data, and the interrupted nature of the data from arterial streets made it less meaningful for non-real time applications. They currently collect one-minute data and aggregate it to five minutes before saving the data.

Detroit, Michigan ITS Center
The Michigan ITS (MITS) Center began operating in 1981. The older system, in place in 1997, monitored 32 miles of roadway. There were approximately 12 CCTVs and 1,300 detector loops. The CCTV video was not saved. The loops were spaced approximately 0.33 miles apart. The system collected average vehicle length, volume, and lane occupancy data and estimated average speed. Double-loop detectors were spaced approximately every three miles, and these provided improved speed estimates. The center personnel aggregated the data to the one-minute level for display on the Internet. They had been saving one-hour summaries of volume data since 1994.

The newer system covers 150 miles of roadway. It includes single loop detectors spaced approximately 0.33 miles apart. The data is scanned every 10 milliseconds and aggregated to hourly lane volumes, that are saved on tape. The new system also includes double loop detectors that are spaced two miles apart. The data are saved every 20 seconds and then are sent to the center, where they are aggregated to one minute. Volume, occupancy, and speed data are saved. The center keeps one week of data on-line at the one-minute aggregation level. Data older than one week are saved on tapes.

MITS personnel were very concerned about loop detector failures and the accuracy of the loop data that they were collecting. As at other ITS centers, loop detector reliability was questioned and maintenance was high. A useful technique to address these problems involves using software that provides a reasonable estimate of "smoothed" speeds along a roadway. Programs included algorithms to create flow maps by comparing determined or reported speeds to those in adjacent sections.

Minneapolis, Minnesota GuideStar TMC
The Minnesota TMC monitored 175 miles or 75% of freeways in the twin cities metropolitan area. There were 180 CCTVs in place one mile apart to monitor incidents and verify algorithms. In 1997 there were approximately 3,000 loop detectors spaced approximately 0.5 miles apart. There are now 3,800 detectors. They collect average volume and occupancy across lanes at a given location. These data were used to estimate average speed with an assumed vehicle length. Loop data were polled by the TMC every 30 seconds as an average across lanes. The data were aggregated and saved every five minutes. The five-minute data has been automatically compressed from 2.3 MB to 1.5 MB every day and saved on a hard disk since the TMC opened in 1993. The 30-second mainlane loop data were also archived and logged, and accessible through the Internet. A seven-day "wrap around" file was kept in readily accessible disk storage for easy access.

TRANSCOM
The Transportation Operations Coordinating Committee (TRANSCOM) began operating in 1986 to coordinate traffic management in New York, New Jersey, and Connecticut. One of their projects was their System for Managing Incidents and Traffic (TRANSMIT). The system was using vehicles equipped with AVI transponders. In addition to their use for toll collection, these "E-Z Pass" tags allowed vehicles to be used as probes of traffic flow. Speed and travel time data were used for incident detection. AVI data was the only data saved by TRANSCOM. CCTV data was only used to verify the AVI system and to manage incidents.

INFORM
INFORM (INformation FOR Motorists) monitored 35 miles of the central corridor of the Long Island Expressway (Route 495). There were 2,400 loop detectors spaced 0.5 miles apart, one per lane, to collect volume, lane occupancy, and vehicle length data. Vehicle speeds were estimated from this data. The loop detectors were polled 60 times per second, and they were aggregated to 1/4 second-, one minute-, and 15 minute-formats. The 15-minute data were saved every day in a compressed ASCII text file on tape. These files were archived for a three-month period and then were overwritten.

MetroCommute
MetroCommute was a private New York company that provided traveler information to the state. They obtained their data through a link to the INFORM system. They added incident and construction information to the INFORM data, and provided detour information to commuters. They have archived their data in one-minute intervals since June 1996.

TranStar TMC
In 1997 the Houston TranStar TMC monitored 160 miles of the Houston freeway system, but was expected to cover 230 miles by 1998. Loop detectors, now covering 30 miles of freeway, were spaced at 0.5-mile intervals to provide real-time volume, occupancy, and speed data, but the data have not been archived. CCTVs were also used for surveillance, but the video was not recorded. There was also an extensive AVI system, including 300,000 vehicles with tags, and reads on the tags were provided to the TMC on a real-time basis. The AVI data were stored in 15-minute summaries.

TransGuide ATMS
Phase I of the TransGuide ATMS covered 26 miles of freeway in San Antonio in 1997, and was expected to be expanded to 53 miles. Double-loop detectors were spaced 0.5 miles apart to collect volume, lane occupancy, and speed data. TransGuide servers polled the loop stations every 20 seconds. This data and 15-minute summaries of the data for one month are available on their Internet site, (ftp://www.transguide.dot.state.tx.us/lanedata). They expect the data to be on CDs in the near future. An AVI system now covers 98 miles on roadways that did not have loop detectors. The AVI system was expected to produce vehicle travel time and average speeds.

North Seattle ATMS
The North Seattle TMS monitored approximately 100 miles of the freeway system in the Seattle area. CCTVs were operated for monitoring purposes only. Loop detectors were spaced approximately 0.5 miles apart to collect volume, lane occupancy, and speed data. The data was automatically sent to the ATMS every 20 seconds. The data was stored at the five-minute aggregate level, and six months of data were stored per CD since 1992. Data was also saved in the early 1980s, but not in CD form.

Toronto's COMPASS
The COMPASS traffic management center monitors portions of Highway 401 in Toronto, Canada. They monitor numerous video surveillance cameras and approximately 2,800 loops spaced 600 meters to 800 meters apart. The loops provided volume, occupancy, average speed, and average vehicle data to the TMC every 20 seconds. Average speed is calculated using an assumed vehicle length. The data is aggregated into five-minute, 15-minute, hourly, daily, and monthly time periods. All 20-second and five-minute data are archived. Only volume data is saved for summaries of more than 15 minutes. Traditionally, data have been archived on 8 mm data cartridges that are read by special equipment. Since 1997, the data has been saved on CDs that has its own software, but the data is slow to access. The COMPASS computer systems can hold two days of 20-second loop data, 30 days of 5-minute and 15-minute data, and about 200 days of hourly data.

Fort Worth, Texas TransVISION
The Fort Worth TransVISION TMC was expected to be open by September 1999. The data that is expected to come into the center include traffic incident information, ramp meter timing, dynamic message sign (DMS) stored messages, lane control signal (LCS) patterns, geographic information system (GIS) data, traffic signal timing, CCTV control functions, electronic work orders, detection system data, road construction, maintenance, and special events data. One server will be able to store about one month's worth of real-time data in short-term storage and another will store about one year's worth of data. After one year, the data will be archived to permanent storage, such as CD.

Summary
The objective of this section was to review literature on the collection of speed and volume data using ITS technology with a concentration on urban freeway systems. The permanently stored data and volume data increments for the TMCs discussed above are presented in Table 8. In general, volume data is collected and speed data is either collected or estimated. Data is stored and available for various time increments, from 1/4 of a second to hourly, but various amounts of data are stored in formats of varying levels of accessibility.

TABLE 8
Level of Permanent Data Aggregation at Selected TMCs in North America[1]

Name of Traffic Management Center	**Type of Data Collected: V = Volume = Speed ES = Estimated Speed**	**< 1 min.**	**1 min.**	**5 min.**	**15 min.**	**Data Not Stored**
Phoenix Traffic Operations Center	V, S	✔		✔	✔	
Los Angeles District 7 TMC	V, ES	✔				
San Francisco Bay Area TMC	V, S					✔
Georgia DOT Advanced Transportation Management System	V, ES					✔
Illinois Traffic Systems Center	V			✔		
Montgomery County TMC						✔
Detroit, Michigan ITS Center	V, ES		✔[2]			
Minneapolis, Minnesota TMC	V, ES	✔		✔		
TRANSCOM	ES				✔	
INFORM	V, ES	✔	✔		✔[3]	
MetroCommute	V, ES		✔			
TranStar TMC	V, S				✔	
TransGuide Advanced Traffic Management System	V, S	✔			✔	
North Seattle Advanced Traffic Management System	V, S			✔		
Toronto's COMPASS	V, S	✔		✔		

Source: Derived from Turner et al. (23).

[1] Stored data for the TMCs indicated in this table are from inductive loop detectors except for TRANSCOM (AVI) and TranStar (AVI).

[2] Only volume data is stored.

[3] Tapes are saved for three months and then are overwritten.

STATISTICAL METHODS FOR SUMMARIZING SPEED AND VOLUME DATA

The last type of literature surveyed described statistical methods for summarizing and characterizing speed and volume data. This discussion relies heavily on research using TransGuide data by Turner et al. (23).

Turner et al. (23) studied Phase I of the TransGuide System, which covered 26 miles of the freeway that encircles downtown San Antonio. Loop detectors were located in every lane and were spaced approximately every 0.5-mile. Loop detectors were also included on every entrance and exit ramp for the 26-mile freeway segment. Each loop detector station on the main freeway lanes is located in a trap, or double-loop, configuration, where two loops are spaced about 30 feet apart. The first loop detector collects lane occupancy (the percent of the time that the loop is occupied by vehicles) and vehicle counts. The arrival time difference between consecutive loops is used with assumptions about vehicle length to calculate a spot speed at the detector station. LCUs in the field store and aggregate the collected information and two computer servers at the TransGuide Center poll, or retrieve, the aggregated data from the LCUs in a sequential fashion. Every 20 seconds, the system gathers the following data from each lane loop detector station:

- average spot speed (mph);
- vehicle volume (number of vehicles); and,
- lane occupancy (percent of the time the loop is occupied).

Figure 1 presents an example of the data obtained from each loop detector station presented by Turner et al. (23). Data are posted to a computer (file transfer protocol, or FTP) server and are available to anyone with Internet access. The TransGuide loop detector files contain a date and time stamp, a location cost, and the corresponding speed, volume, and occupancy measurements. The location code (e.g., L1-OU35N-155.252) consists of three parts separated by a dash:

1. Lane location and designation (e.g., L1):
   L = main freeway lanes, EN = entrance lanes, and EX = exit lanes; and
   Sequential numbering starts from the median and goes to outside lanes.

2. Freeway and direction designation (e.g., OU35N):

0010 = I-10		0L10	=	I-10, lower deck
OU10 = I-10, upper deck	and	N	=	North
0035 = I-35		E	=	East
0L35 = I-35, lower deck		S	=	South
OU35 = I-35, upper deck		W	=	West
0037 = I-37				
0090 = US 90				
0281 = US 281				

3. Milepost: freeway milepost of loop detector stations (e.g., 155,252).

Date	Time	Location	Speed[a]	Volume	Occupancy[b]
07/15/97	**07:00:03**	L1-0L10E-568.241	Speed=75	Vol=009	Occ=007
07/15/97	07:00:03	L1-0U10E-568.248	Speed=64	Vol=007	Occ=005
07/15/97	07:00:03	L2-0L10E-568.241	Speed=63	Vol=006	Occ=006
07/15/97	07:00:03	L2-0U10E-568.248	Speed=72	Vol=006	Occ=004
07/15/97	07:00:03	L3-0U10E-568.248	Speed=57	Vol=006	Occ=006
07/15/97	07:00:04	EN1-0U10E-568.845	Speed=-1	Vol=006	Occ=018
07/15/97	07:00:04	EX1-0U10E-568.764	Speed=-1	Vol=002	Occ=003
07/15/97	07:00:04	L1-0L10E-568.802	Speed=67	Vol=005	Occ=004
07/15/97	07:00:04	L1-0U10E-568.807	Speed=62	Vol=006	Occ=005
07/15/97	07:00:04	L2-0L10E-568.802	Speed=67	Vol=001	Occ=001
07/15/97	07:00:04	L2-0U10E-568.807	Speed=60	Vol=008	Occ=007
07/15/97	07:00:04	L3-0U10E-568.807	Speed=46	Vol=008	Occ=008

Source: Turner et al. (23)

Notes: [a] Speed – 1 indicates that no speed has been measured (single loop detector).
[b] Occupancy is the percentage of time the loop detector is occupied.

FIGURE 1. Example of Loop Detector Data from TransGuide

Point Measures of Average Spot Speed and Volume

The first type of summary statistics presented here includes the point measures of average spot speed and person volume. The five-minute summaries for these measures are presented in Table 9 for this example. By assuming an average corridor or sub-regional average, person volume for all of these examples can be estimated. The average vehicle occupancy is assumed at 1.20 persons per vehicle in all examples.

Average spot speeds and estimated person volumes on a 20-second basis are presented in the far right columns of Table 9, while the lane-by-lane averages for a five-minute period are presented in the bottom row. Note that the spot speed observations were weighted by the number of persons to provide a statistically true average.

Freeway Section Summary

An example of a 15-minute summary that is related to a particular freeway section is presented in Table 10. An assumption has been made that the spot speeds obtained at the loop detector stations are approximately equivalent to the average speeds halfway to the next detector station. This assumption may yield reasonable link-based measures under free-flow traffic conditions, but it may produce inaccurate results for congested traffic operations and stop-and-go traffic.

The five-minute average speeds and total person volumes shown in Table 10 are calculated using the formulas presented in Table 9. The remaining columns are calculated using formulas shown in Table 10. Person movement speed is the product of average speed and person volume. The link travel time is estimated based on the average spot speed and the distance between the two adjacent loop detector stations. Person delay is calculated by selecting a threshold at which delay or congestion occurs-55 mph in this example.

Corridor Performance Measures

Data from individual links can be aggregated to obtain corridor performance measures, as shown in Table 11. The basic inputs for most performance measures are average speed and person volume per lane. The corridor mobility index is defined as the person speed normalized by a value that represents a typical lane operating at capacity. The normalizing value in this example is 161,000, which represents a typical freeway operating at capacity. The speed of person movement is more efficient than regular freeway mainlanes (HOV lanes or rail lines) when the index is greater than 1.0. Estimated travel time and person delay are calculated as shown in Table 10. The person-miles and person-hours of travel in congestion are calculated by using the same congestion threshold that was used in calculating person-delay.

TABLE 9
Example of Five-Minute Point Summaries of 20-Second Loop Detector Data

Time Starting (a.m.)	Lane 1			Lane 2			Lane 3			Avg. Spot Speed (mph)	Est. Person Volume
	Spot Speed (mph)	Vehicle Volume	Est. Person Volume	Spot Speed (mph)	Vehicle Volume	Est. Person Volume	Spot Speed (mph)	Vehicle Volume	Est. Person Volume		
7:40:00	25	12	14	24	10	12	34	11	13	28	39
7:40:19	17	9	11	14	10	12	24	8	10	19	33
7:40:39	19	10	12	17	10	12	28	6	7	20	31
7:41:00	19	12	14	24	10	12	25	8	10	22	36
7:41:20	22	11	13	21	9	11	23	12	14	22	38
7:41:40	30	11	13	19	12	14	20	8	10	23	37
7:41:59	23	10	12	17	9	11	28	8	10	23	33
7:42:20	23	14	17	21	8	10	32	8	10	25	37
7:42:40	20	10	12	19	12	14	28	7	8	22	34
7:43:00	23	7	8	11	7	8	20	7	8	18	24
7:43:20	24	13	16	16	8	10	19	7	8	20	34
7:43:39	26	10	12	22	9	11	23	7	8	24	31
7:44:00	25	14	17	21	10	12	25	8	10	24	39
7:44:20	27	13	16	19	10	12	32	8	10	26	38
7:44:40	23	11	13	21	10	12	25	8	10	23	35
Average 7:40-7:45	$\bar{x}$=23	∑=167	∑=200	$\bar{x}$=19	∑=144	∑=173	$\bar{x}$=26	∑=121	∑=146	$\bar{x}$=23	∑= 519

$$\text{average spot speed}, \overline{S}_i = \frac{\sum \text{spot speed} \times \text{persons}}{\sum \text{persons}} (\text{weighted by persons}) \quad (24)$$

Source: San Antonio TransGuide (Station 0035N-152.590) July 15, 1997. Adapted from Turner et al. (23).

TABLE 10
Example of 15-Minute Link Summaries of Loop Detector Data

Starting Time (a.m.)	Average Speed[a] (mph)	Est. Person Volume	Person Movement Speed (person-mphpl)	Est. Travel Time[b] (sec)	Person Delay[c] (person-hr)
7:45 to 7:50	22	506	n.a.	82	6.75
7:50 to 7:55	40	472	n.a.	46	1.57
7:55 to 8:00	55	383	n.a.	33	0.00
Average 7:45 to 8:00 am	$\bar{x}$ = 37 mph	$\sum$ = 1,361persons or 1,815 pers/phpl	$\bar{x}$ = 67,518 person-mphpl	$\bar{x}$ = 49 sec	$\sum$ = 8.32 person-hr

$$\textit{person movement speed} = \frac{\textit{person volume}}{(\textit{persons per hour per lane})} \times \textit{average speed (mph)} \qquad (\underline{24})$$

$$\textit{estimated travel time (sec.)} = \frac{3{,}600 \times \textit{equivalent link length (mi)}}{\textit{average speed (mph)}} \qquad (\underline{12})$$

$$\frac{\textit{person delay}}{(\textit{person - hr})} = \frac{1 \textit{ hour}}{3{,}600 \textit{ sec}} \times \left(\frac{\textit{estimated}}{\textit{travel time (sec)}} - \frac{\textit{travel time at}}{\textit{congestion threshold (sec)}} \right) \times \frac{\textit{person}}{\textit{volume}} \qquad (\underline{21})$$

Source: San Antonio TransGuide (Station 0035N-152.590), July 15, 1997. Adapted from Turner et al. (23).

Notes: [a] Average spot speed calculated for each 5-minute period using the first equation.
[b] Assumes that spot speed approximates time-mean speed over section link length of 0.5 mi.
[c] Assumes that delay is incurred at speeds less than 55 mph (travel time greater than 34 sec).

TABLE 11
Example of Peak-Hour Corridor Summaries from Loop Detector Data

Freeway and Milepost	Equiv. Link Length (mi)	Lane mi	Average Speed (mph)	Est. Person Volume per Lane	Person Speed (per-mphpl)	Corridor Mobility Index	Est. Travel Time (sec)	Person Delay (person-hr)	PMT in Congestion	PHT in Congestion
0035N-152.005	0.283	0.849	41	2,040	83,232	0.52	25	10.07	578	42.69
0035N-152.590	0.504	1.513	38	1,960	74,088	0.46	48	22.82	988	78.57
0035N-153.048	0.494	1.484	44	1,930	85,692	0.53	40	10.50	954	64.33
0035N-153.614	0.551	1.652	55	1,760	97,152	0.60	36	0.00	0	0.00
0035N-154.187	0.548	2.195	53	1,350	72,090	0.45	37	0.00	0	0.00
0U35N-154.738	0.515	1.030	43	1,860	80,352	0.50	43	7.99	958	44.06
0L35N-154.750	0.515	1.030	43	1,560	66,456	0.41	44	7.54	803	37.79
0U35N-155.252	0.544	1.631	47	1,190	56,406	0.35	41	4.45	647	41.02
0L35N-155.252	0.538	1.076	46	1,500	69,300	0.43	42	4.41	807	34.81
0035N-155.863	0.508	2.540	54	1,190	64,260	0.40	34	0.00	0	0.00
0U35N-156.304	0.397	0.794	49	1,620	78,732	0.49	30	2.41	643	26.63
0L35N-156.304	0.358	0.715	51	1,500	76,500	0.48	25	0.75	536	20.87
0L35N-156.603	0.436	0.871	53	1,460	77,964	0.48	30	0.00	0	0.00
0U35N-156.684	0.401	1.202	55	910	50,232	0.31	26	0.00	0	0.00
0U35N-157.134	0.432	1.295	53	900	48,060	0.30	29	0.00	0	0.00
0L35N-157.206	0.472	0.943	49	1,410	68,526	0.43	35	2.48	665	27.43
0035N-157.578	0.401	2.005	41	1,190	49,266	0.31	35	12.52	477	57.52
0035N-158.036	0.442	1.324	46	1,790	81,624	0.51	35	7.57	790	52.21
0035N-158.492	0.440	1.762	50	1,310	66,024	0.41	32	2.47	577	45.69
0035N-158.947	0.220	0.881	56	1,240	69,192	0.43	14	0.00	0	0.00
Corridor	$\sum = 9.00$	$\sum = 26.79$	$\bar{x} = 47.7$	$\bar{x} = 1,483$	$\bar{x} = 70,757$	$\bar{x} = 0.44$	$\sum = 680$	$\sum = 95.99$	$\sum = 9,424$	$\sum = 573.64$

TABLE 11
Example of Peak Hour Corridor Summaries from Loop Detector Data (Continued)

$$\textit{lane-mi} = \begin{matrix}\textit{equivalent link}\\ \textit{length (mi)}\end{matrix} \times \begin{matrix}\textit{number}\\ \textit{of lanes}\end{matrix} \qquad (\underline{24})$$

$$\begin{matrix}\textit{corridor}\\ \textit{mobility index}\end{matrix} = \frac{\textit{person speed (person-mphpl)}}{\textit{161,000 (normalizing value)}} \qquad (\underline{21})$$

$$\begin{matrix}\textit{person-miles of travel}\\ \textit{(PMT) in congestion}\end{matrix} = \begin{matrix}\textit{person volume}\\ \textit{(persons)}\end{matrix} \times \begin{matrix}\textit{equivalent}\\ \textit{link length}\end{matrix} \begin{bmatrix}\textit{when average speeds drop}\\ \textit{below congestion threshold}\\ \textit{(e.g., 55 mph)}\end{bmatrix} \qquad (\underline{12})$$

$$\begin{matrix}\textit{person-hours of travel}\\ \textit{(PHT) in congestion}\end{matrix} = \begin{matrix}\textit{person volume}\\ \textit{(persons)}\end{matrix} \times \begin{matrix}\textit{estimated travel}\\ \textit{time (sec)}\end{matrix} \times \frac{\textit{1 hour}}{\textit{3,600 sec}} \begin{bmatrix}\textit{when average speeds drop}\\ \textit{below congestion threshold}\\ \textit{(e.g., 55 mph)}\end{bmatrix} \qquad (\underline{13})$$

Source: Adapted from Turner et al. (23).

CHAPTER 3. BPR ANALYSIS

INTRODUCTION

This section discusses the accuracy of testing speed estimation models using ITS data. For estimating speeds, the planning community typically uses BPR curves.

BPR CURVES

The research team studied three variations of the BPR curves. These curves are suggested in Dowling (6). The curves studied are "Update of the BPR curve," the "Phoenix curve," and the "Dallas/Fort Worth curve."

The models are shown below with the "recommended" parameters, where s is the speed, and s_f is the freeflow speed, both in mph. The value vc is the v/c ratio.

1. Update of the BPR curve

$$s = \frac{s_f}{1 + a(vc)^b}$$

where:
a = *0.20* and
b = *10* (Dowling[8])

2. Pheonix BPR

$$s = \begin{cases} \dfrac{s_f}{1 + a(vc)^b}, & vc \leq 1.33 \\ s_f\left[d + e(vc)^f\right] & vc > 1.33 \end{cases}$$

where:
a = *.1225;*
b = *.4374;*
d = *.25;*
e = *.4374;* and
f = *-3.*

3. DFW BPR

$$s = \frac{s_f}{1 + a\exp(b(vc))}$$

where:
a = *0.015,* and
b = *4 to 6.*

Estimating Freeflow Speed
The freeflow speed is calculated from the data. This is accomplished by two methods. The first method requires the calculation of a new freeflow speed every day. The second method for calculating the freeflow speed is to use one freeflow speed based on speeds corresponding to low v/c ratios using all of the data.

Estimating Capacity
Capacity is calculated from the HCM recommendations.

$$c = IdealCapxNxF_{hv}xPHF$$

where:
IdealCap is 2,400 vphpl (70 mph or less) or 2,300 vphpl (70 mph or more), and
N is the number of lanes.

$$F_{hv} = \frac{1}{1 + 1/2HV}$$

where:
HV is the heavy vehicle proportion (default is .05), and
PHV is the ratio of the peak 15-minute flow rate to average hourly flow rate (default .9).

Space Mean Speed
The BPR models are built with the assumption that space mean speeds are observed. ITS data directly measures time mean speed (at a spot). The space speed is estimated with the assistance of the variance in the time speeds. This relationship is shown using a Taylor expansion.

The time mean speed is s_i. The space mean speed is related to travel time. To calculate this, use the inverse of the time mean speed and calculate the expectation. The derivation of the average travel time is:

$$1/s_i \approx 1/E[s_i] - 1/E[s_i]^2 (s_i - E[s_i]) + 1/E[s_i]^3 (s_i - E[s_i])^2$$

Then use the expectation of both sides to obtain the following:

$$E[1/s_i] = 1/E[s_i] + 1/E[s_i]^3 E\left[(s_i - E[s_i])^2\right]$$

Relating this to the space mean speed and time mean speed produces:

$$\frac{1}{\mu_{sms}} = \frac{1}{\mu_{TMS}} + \frac{1}{(\mu_{TMS})^3} \sigma_{TMS}^2$$

Then use the inverse of this equation to obtain space speeds.

$$\mu_{sms} = \frac{1}{\frac{1}{\mu_{TMS}} + \frac{\sigma^2_{TMS}}{\mu^3_{TMS}}}$$

This equation is different from the referenced equation because it is a function of the variance of the time speed (which is estimated with ITS data) and not of the space mean speed. Notice that:

$$\mu_{sms} = \frac{1}{\frac{1}{\mu_{TMS}} + \frac{\sigma^2_{TMS}}{\mu^3_{TMS}}} < \frac{1}{\frac{1}{\mu_{TMS}} + \frac{0}{\mu^3_{TMS}}} = \mu_{TMS}$$

(since $\sigma^2_{TMS} > 0$). Therefore, the equation is consistent with a statement in the HCM, which states that space mean speed is generally smaller then time speed.

The data are time mean speed averaged every 30 seconds. Assume that every vehicle comes from the same distribution, therefore:

$$\bar{s}_i \sim N\left(\mu, \sigma^2 / n_i\right)$$

It can be easily shown that the unbiased estimates of the mean and the variance within a 15-minute period are:

$$\hat{\mu}_{SMS} = \sum_{i=1}^{N} n_i \bar{s}_i / \sum_{i=1}^{N} n_i \text{ and}$$

$$\hat{\sigma}^2_{TMS} = \sum_{i=1}^{N} n_i \left(\bar{s}_i - \hat{\mu}_{SMS}\right) / (N-1).$$

Goodness of Fit

The goodness-of-fit (GOF) measure is used as the median percent error for all 15-minute periods at a particular loop within a certain time of day.

$$R_i = \left|s_i - \hat{s}_i\right| / s_i$$
$$GOF = median(R).$$

The research team chose this measure because it is easily interpreted.

Data

There were nine double-loop detectors selected from the TransGuide ITS traffic monitoring system in San Antonio. The locations are:

- I-10 E, milepost 555.360;
- I-10 W, milepost 566.641;
- I-10 W, milepost 567.744;
- I-35 S, milepost 152.590;
- HWY 286 N, milepost 145.396;
- HWY 410 E, milepost 15.107;
- HWY 410 E, milepost 16.056;
- HWY 410 S, milepost 13.117; and
- HWY 1604 E, milepost 32.619.

All of the locations have three lanes, except for the loop at milepost 566.744, which has five lanes. The speed and volume are recorded every 30 seconds. All speeds are aggregated at the 15-minute level. That is, the mean and the variance of the spot speeds are recorded every 15 minutes. The data are collected for all time periods of the day from February 14 to February 29.

FINDINGS

Goodness of Fit

More than 99% of the data have v/c values less than 1.3. The GOF measures for the BPR curves are calculated for the following ranges of v/c: 0 to .5, .5 to 1, 1 to 1.3, and 1.3 on. Table 12 shows the GOF results for this comparison.

TABLE 12
Median Percent Differences *

Mile Marker	V/C	Number of V/C	BPR1	BPR2	BPR3
555.360	0-.5	1483	2.50	2.50	4.90
566.641	0-.5	864	2.30	2.30	3.20
	.5-1	609	7.80	7.80	13.40
	1-1.3	7	2.80	2.80	35.50
567.744	0-.5	1416	6.40	6.40	4.10
	.5-1	19	22.70	22.70	8.60
152.590	0-.5	1114	2.00	2.00	4.00
	.5-1	320	4.10	4.10	10.80
	1-1.3	5	5.10	4.10	34.70
145.396	0-.5	1408	2.10	2.10	3.20
	.5-1	76	271.40	271.40	223.20
15.107	0-.5	1064	3.20	3.20	4.70
	.5-1	362	4.30	4.30	14.00
	1-1.3	3	558.70	558.70	334.20
	1.3-	6	98.70	850.90	94.30
16.056	0-.5	783	6.30	6.30	6.70
	.5-1	522	7.50	7.50	19.70
	1-1.3	13	11.90	11.90	41.10
13.117	0-.5	1470	2.70	2.70	2.60
	1-1.3	6	364.50	364.50	316.00
32.619	0-.5	1391	3.00	3.00	3.30
	.5-1	46	10.30	10.30	9.10
		Weighted Average	**5.71**	**6.06**	**7.11**

* The freeflow speed was calculated with the median of the values with a v/c <.1, freeflow speed changes by time of day.

For mile markers 13.117 and 567.744, the BPR3 has a lower median error than BPR1 when v/c is 0-.5. When v/c is .5-1 for the mile markers 567.744, 145.396, and 32.619, BPR3 performed better than BPR1, but only 1.3%, 5.12%, and 9.1% of the data values had a v/c ratio between .5-1. In the cases where BPR1 beat BPR3, the percentages of v/c are 41%, 22%, 25%, and 39%. This suggests that heavy congested mile markers support BPR1. There was very little data above v/c of 1, thus little support exists for the models in this v/c range.

Table 13 describes the average speed and average v/c for speeds found to be outliers. In this discussion, outliers are defined to be values that are two or more standard deviations from the mean. Generally, the speeds were low (below 35 mph for seven of the nine mile markers).

TABLE 13
Average Speed and Average V/C *

Mile Marker	Average Speed	Average V/C	Number
555.360	59.28	0.02	9
566.641	13.78	0.78	110
567.744	35.47	0.13	44
152.590	NaN	NaN	0
145.396	14.02	0.48	112
15.107	11.38	0.50	131
16.056	27.03	0.44	68
13.117	14.62	0.41	84
32.619	52.76	0.48	33

* This is the average speed and volume for the different mile markers for BPR 1, when the residual is +-2std away from the mean of BPR1, freeflow speed changes by time of day.

Expected Variation for the Mean Predicted Speed

Table 14 presents the expected variation when the speeds are greater than the 35 mph average speed limit. The research team selected this number since the BPR curve adequately estimates speeds in the "freeflow state."

TABLE 14
Expected Variation for Speeds Greater Than 35 mph

Mile Marker	Expected Variation	Expected Variation (Robust)	Number Above 35	Total
555.360	1.89	2.51	1483	1483
566.641	3.55	3.50	1367	1480
567.744	4.86	4.18	1381	1435
152.590	2.29	1.89	1427	1439
145.396	2.78	1.81	1372	1484
15.107	3.75	2.65	1292	1435
16.056	5.17	4.78	1204	1318
13.117	2.55	2.32	1398	1476
32.619	3.20	2.83	1437	1437

Table 15 presents the results for fitting the three curves to all of the data with one freeflow speed. This calculation reflects the median percent error in practice. The freeflow speed is calibrated before the actual model is used. Table 15 supports the conclusion that BPR1 is better than BPR3.

TABLE 15
Median Percent Differences *

Mile Marker	V/C	Number of V/C	BPR1	BPR2	BPR3
555.36	0-.5	1483	2.6	2.6	5.1
566.641	0-.5	864	2.9	2.9	3.3
	.5-1	609	7.8	7.8	12.4
	1-1.3	7	3.4	3.4	35.9
567.744	0-.5	1416	6.5	6.5	3
	.5-1	19	19.8	19.8	6.2
152.59	0-.5	1114	1.9	1.9	4.4
	.5-1	320	3.9	3.9	11.5
	1-1.3	5	6.9	6.9	36
145.40	0-.5	1408	2.2	2.2	3.6
	.5-1	76	274.1	274.1	225.3
15.11	0-.5	1064	3	3	5.1
	.5-1	362	4.5	4.5	12.1
	1-1.3	3	526.4	526.4	312.9
	1.3-	6	98.6	860.9	94.2
16.06	0-.5	783	10.1	10.1	11.3
	.5-1	522	5.9	5.9	19.4
	1-1.3	13	9.1	9.1	39.8
13.12	0-.5	1470	2.6	2.6	2.5
	1-1.3	6	362.5	362.5	314.2
32.62	0-.5	1391	2.9	2.9	3.1
	.5-1	46	9.3	9.3	9
		Weighted Mean	**5.90**	**6.25**	**7.29**

* The freeflow speed was calculated with the median of the values with a v/c <.1, fixed freeflow.

Table 16 illustrates the skewness in the percent error for each mile marker. For example the median (50th percentile) percent error for mile marker 16.056 is 3.23%, but the 90th percentile is 56.91%. Thus illustrates that the BPR curves have high percentage errors over 90% of the time (this range is 5.18% to 56.91%).

TABLE 16
Percent of Error Summary Statistics

Mile Marker	Percentile				
	10%	25%	50%	75%	90%
555.360	0.54	1.32	2.62	3.96	5.18
566.641	0.81	2.17	4.82	8.88	21.53
567.744	1.34	3.48	6.61	11.26	17.59
152.590	0.36	0.98	2.21	4.18	7.06
145.396	0.52	1.16	2.29	4.96	14.93
15.107	0.52	1.48	3.23	6.89	56.91
16.056	1.49	3.93	8.36	15.11	39.10
13.117	0.52	1.28	2.59	4.57	7.84
32.619	0.62	1.51	2.96	4.89	7.75

CONCLUSIONS AND RECOMMENDATIONS

The BPR1 fits the true data better than BPR3 in median percent error. However, the median percent error has a skewed distribution, thus illustrating that the BPR curves perform poorly during peak conditions as illustrated in Table 16.

CHAPTER 4. CALCULATING EMISSIONS

Vehicle emissions are estimated using speed-emissions profiles calibrated by the Federal Test Procedure (FTP). Therefore, three major items contribute to emissions: speed-volume distributions, emissions profiles, and measurement error. This section describes how the three major items produce emissions estimates. This relationship is summarized in Figure 2. The VMT from the TransGuide ITS data are fused with the emissions rates, which create emission estimates. The details of this figure are presented below.

Thus, the primary goal of this research was to ascertain the effects of input data aggregation level on mobile source emissions estimates (Figure 2). On-road mobile source emissions were estimated using two basic inputs:

- hourly distributions of VMT versus speed at various aggregation levels, including 20-second, 1-, 5-, 15-, and 60-minute levels; and
- hour-of-day emission rates for volatile organic compounds (VOC), carbon monoxide (CO) and nitrous oxide (NOx), which were generated from MOBILE 5 for specific application in San Antonio.

The research team analyzed the differences in emissions estimates for different aggregation levels, as well as differences in VMT-speed distributions used to calculate emissions. The results should be particularly useful for transportation and air quality analysts who desire to use archived ITS data to improve their emissions analyses.

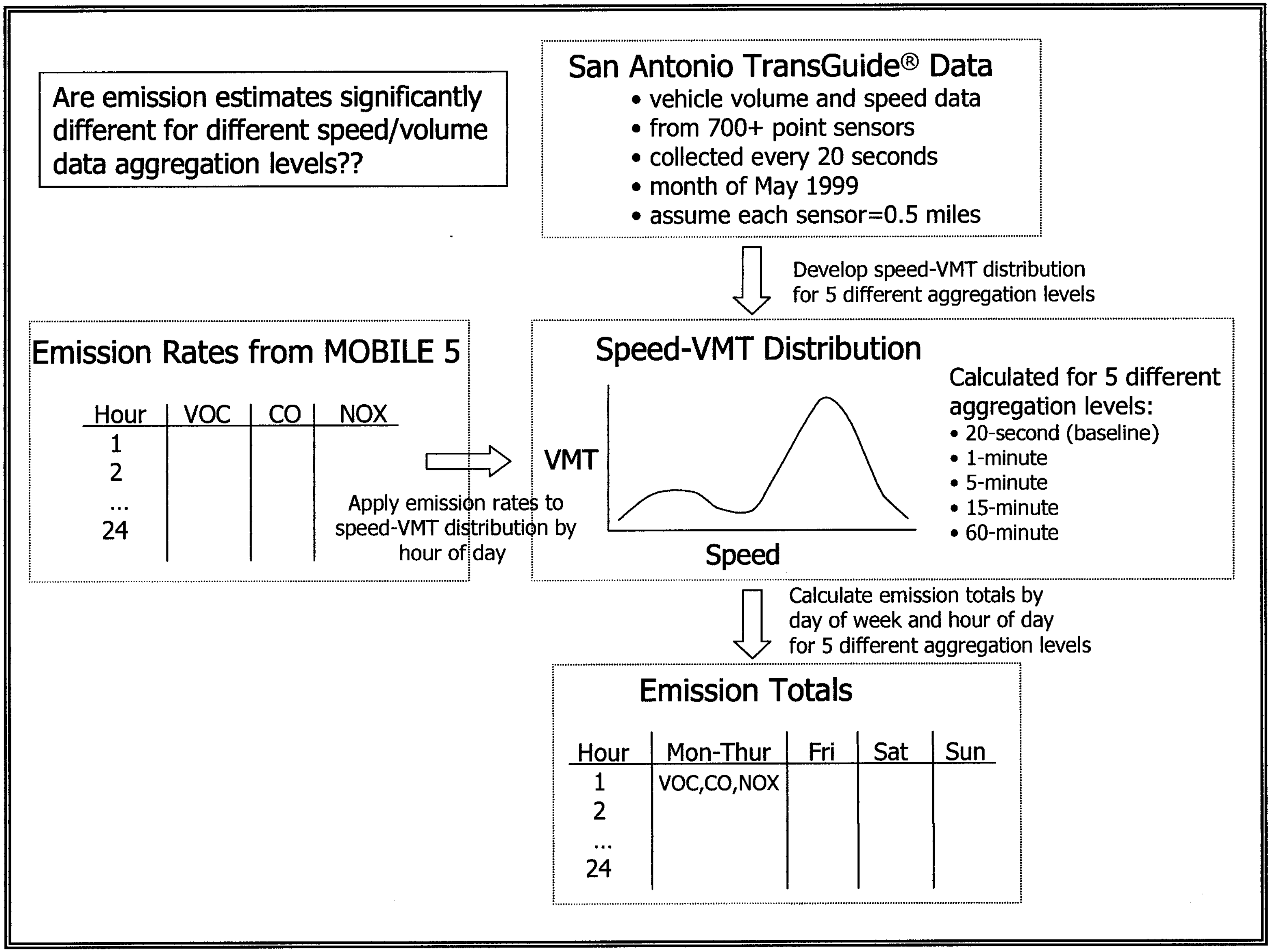

FIGURE 2. Study Design for Using Archived ITS Data in Emissions Analysis

DESCRIPTION OF ITS DATA

TransGuide in San Antonio collects traffic data using point detectors (e.g., inductive loops) and probe vehicles (e.g., AVI transponders). For this study, the research team focused on calculating emissions from loop detector data. Figure 3 shows a map of the San Antonio area freeways. The TransGuide loop detectors are typically located in every lane and nominally spaced every 0.5 miles (0.8 km) (loop detectors are also located on all entrance and exit ramps). Each loop detector station on the main freeway lanes is located in a trap, or double-loop configuration, where two loops are spaced about 30 feet (10 m) apart. The first loop detector collects vehicle counts and lane occupancy (e.g., percent of time that vehicles occupy the loop). The arrival time difference between consecutive loops is used to calculate a spot speed for each lane loop detector. LCUs in the field accumulate the collected information, and three computer servers at the TransGuide center poll, or retrieve, the aggregated data from the LCUs in a sequential pattern. The system gathers the following from each lane loop detector station every 20 seconds:

- average spot speed (mph);
- vehicle volume (number of vehicles); and,
- lane occupancy (percent of time loop is occupied).

A full month of archived ITS data (May 1999) was used to compare emissions estimates at various aggregation levels.

VMT is calculated from the measured speed and volume at each double loop detector. Since they are spot speeds, we assign a nominal length of 0.5 miles to each loop. Thus the VMT is calculated every 20-seconds and each VMT number is placed in a speed bin (0-200 mph). A VMT distribution for May 3, 1999 is shown in Figure 4. When the speed is aggregated (i.e., 5 minutes) then a new VMT distribution is calculated from these data. Aggregation widths of 20-seconds, 1-minute, 5-minutes, 15-minutes, and 60-minutes are shown also in Figure 4. As the aggregation width increases, the distribution is less variable. This eliminates the higher and lower speeds from being accounted for. Figure 5 shows the VMT for three congested locations. Emissions estimates will be calculated all locations, including the three congested locations, and the three congested locations by themselves. Figures 6 to 15 quantify the error using aggregated speeds relative to 20-second VMT.

Figures 6 and 7 show the raw differences by speed. The biggest differences occur in the 10-20 mph, and 50-mph to 70 mph ranges. Figures 8 to 15 show the chi-squared value. The chi-squared measure is similar to a relative error. Figures 8 and 9 reflect the effect of aggregation and time of day has on the error. The error is largest for the peak periods as well as increases as the aggregation width increases. Figure 10 and 11 show that on Sunday and Saturday there is little error changes relative to Monday-Thursday. Figures 12 to 15 show the effect of aggregation width for the time-of-day. These figures clearly indicate that the day-of-week is a factor in the errors between 20-second data and other aggregated data. The figures shown here indicate time-of-day and day-of-week will be clear factors in emissions estimates. The next section discusses the inclusion of the factors because of their effect on emissions profiles.

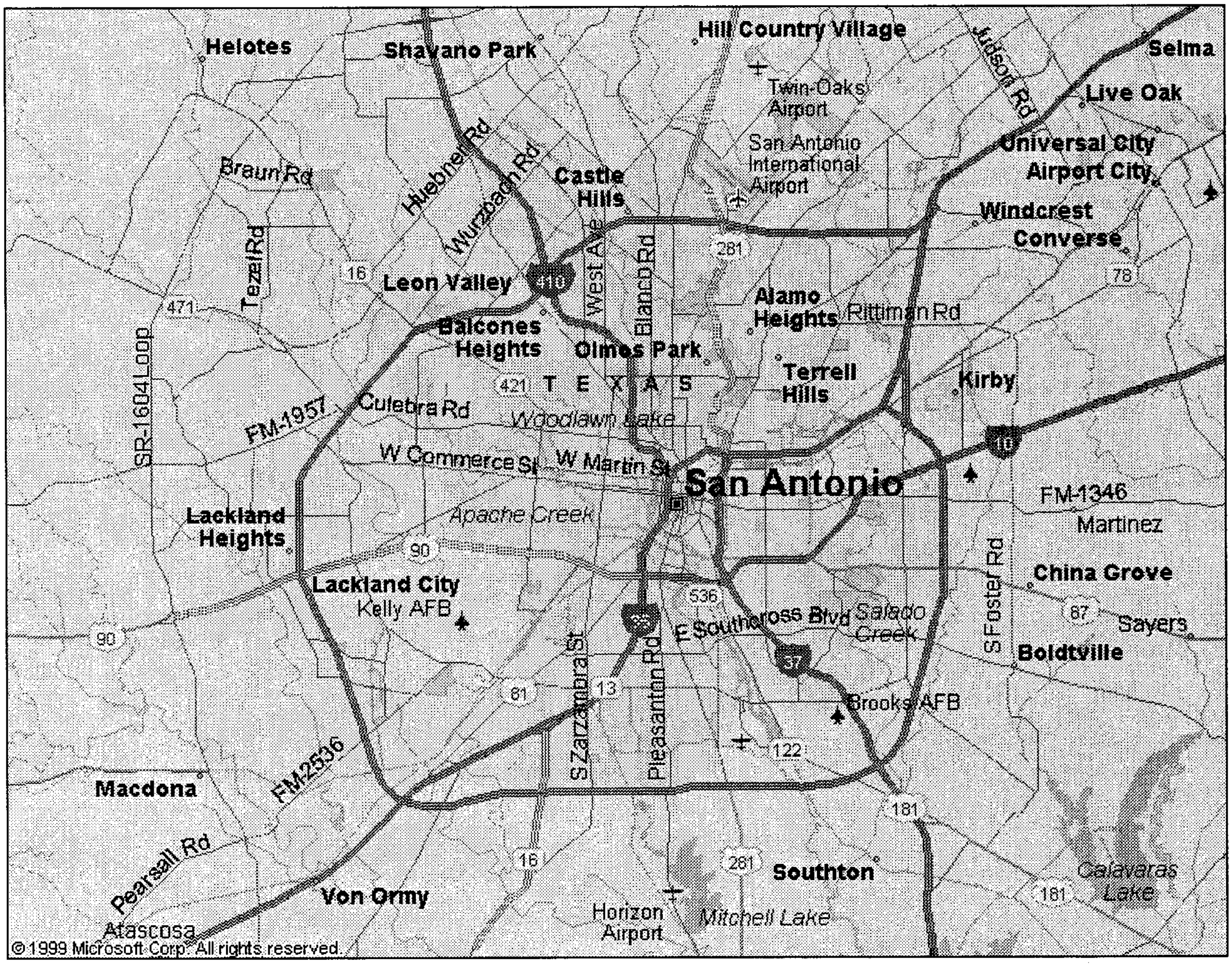

FIGURE 3. Map of San Antonio Area Freeways

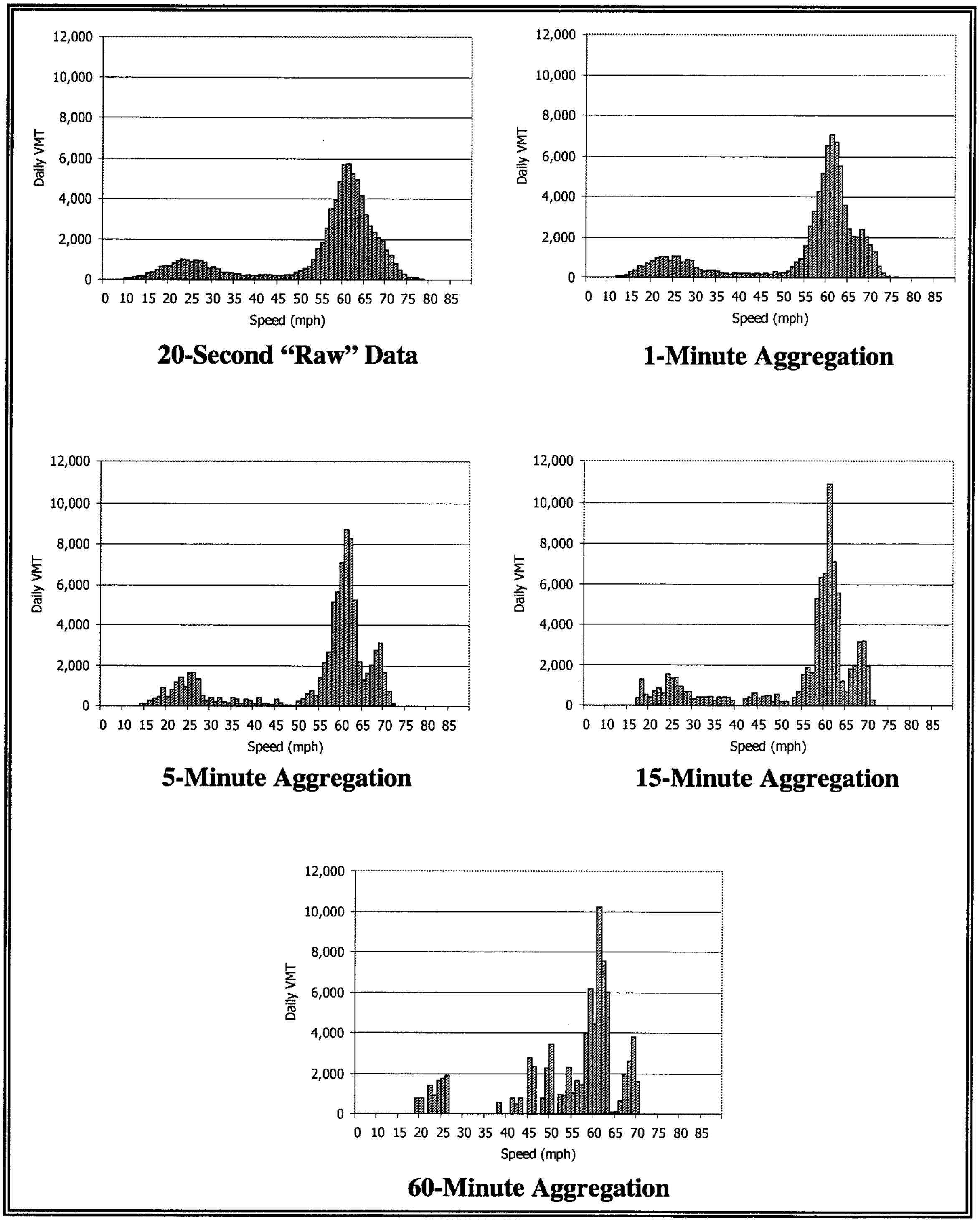

FIGURE 4. Daily VMT-Speed Distributions for Various Aggregation Levels (All Locations, May 3, 1999)

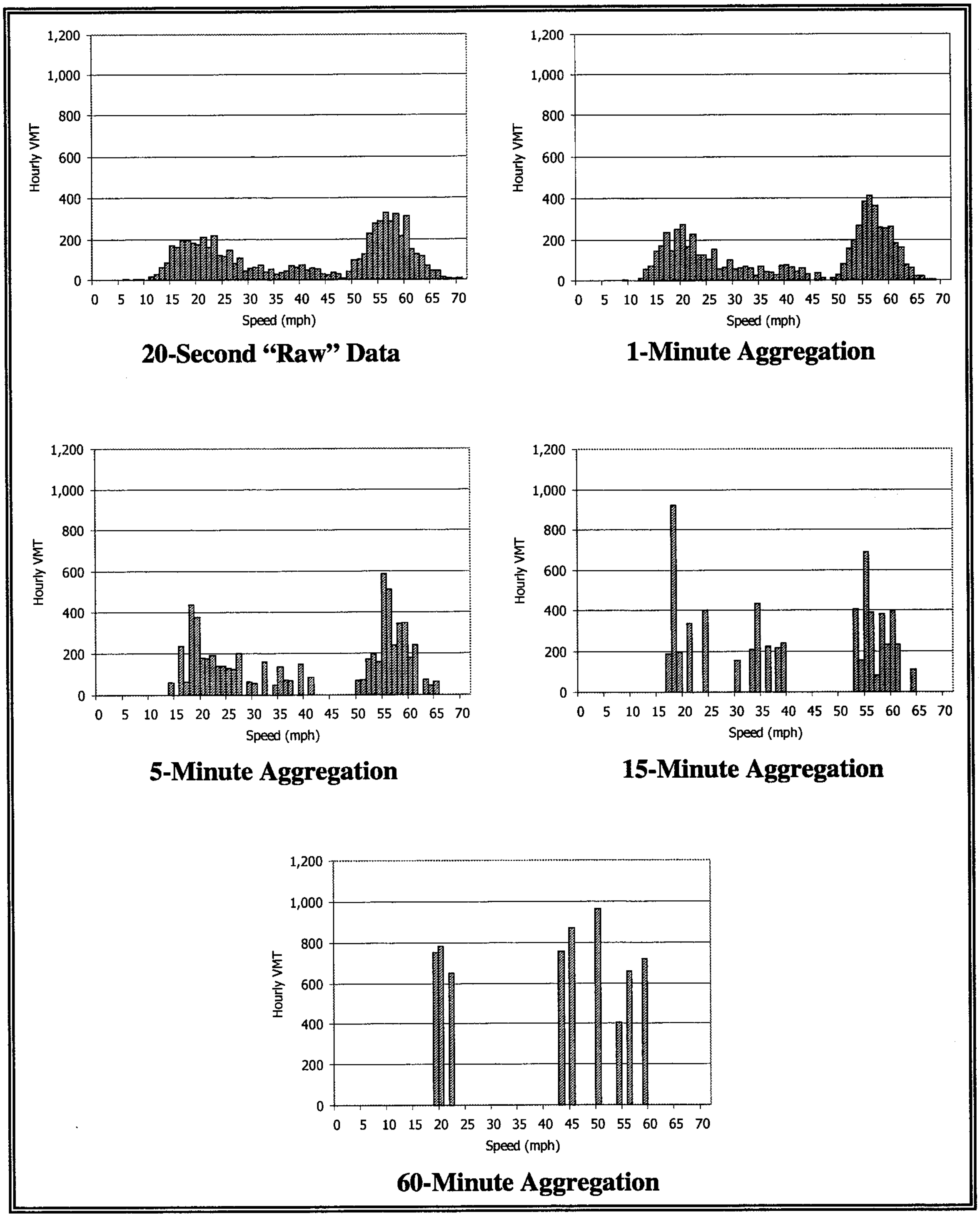

FIGURE 5. Hourly VMT-Speed Distributions for Various Aggregation Levels (Three Congested Locations, May 3, 1999, 5 p.m. to 6 p.m.)

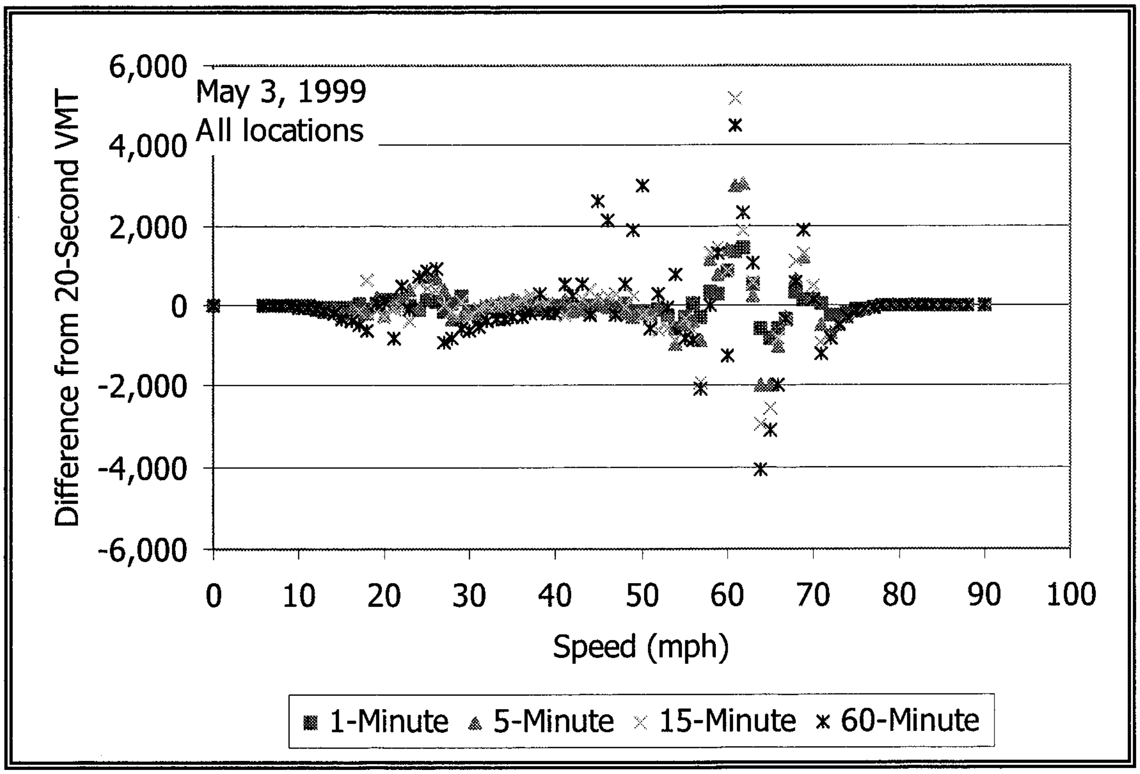

FIGURE 6. Differences in Aggregated Daily VMT Estimates

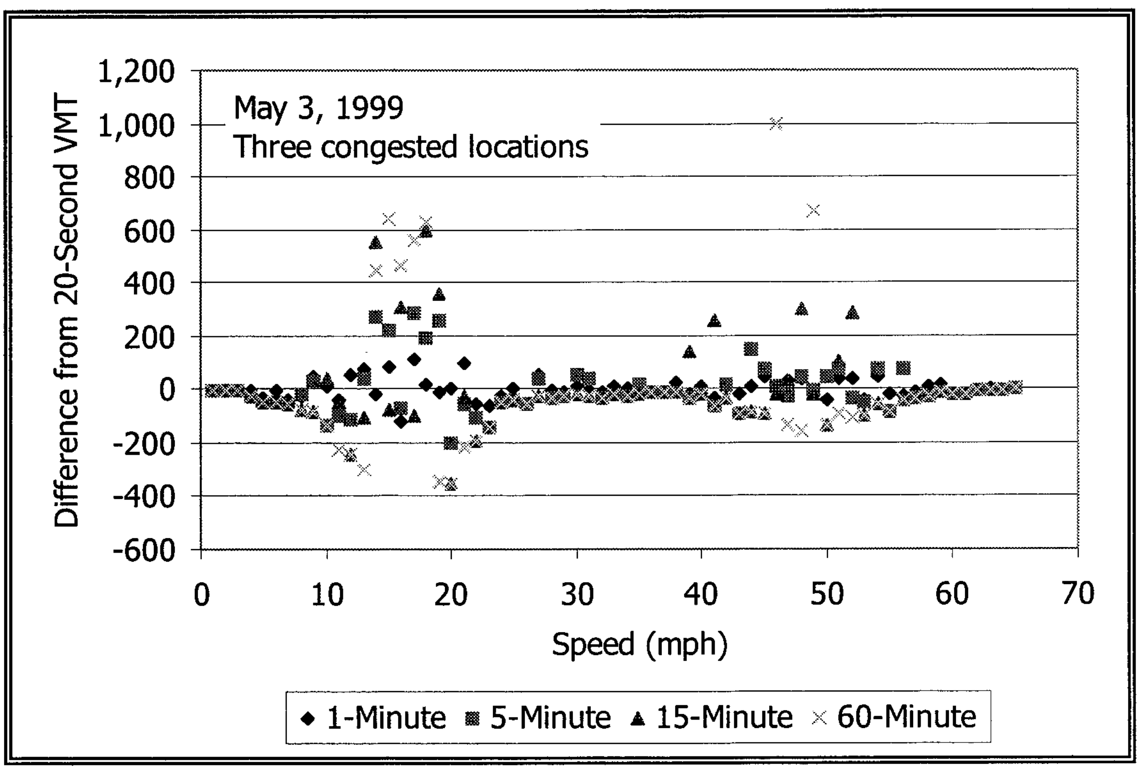

FIGURE 7. Differences in Aggregated Hourly VMT Estimates

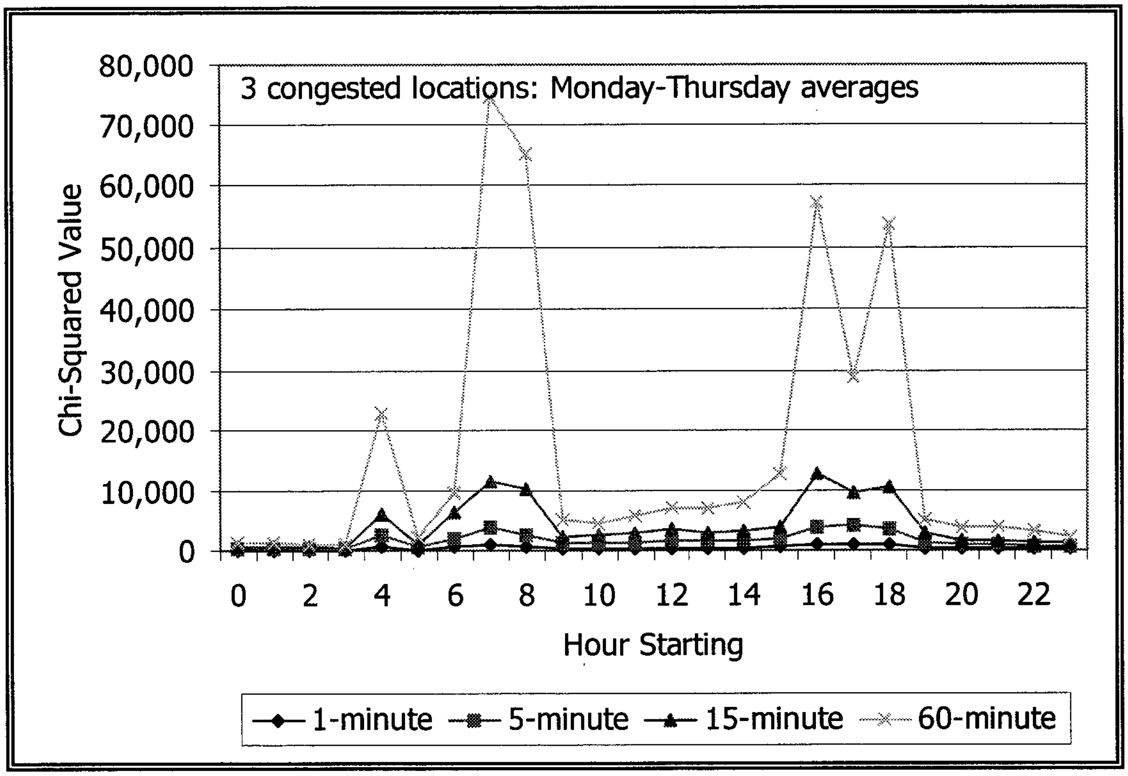

FIGURE 8. Chi-Squared Values for Monday-Thursday VMT Averages, May 1999

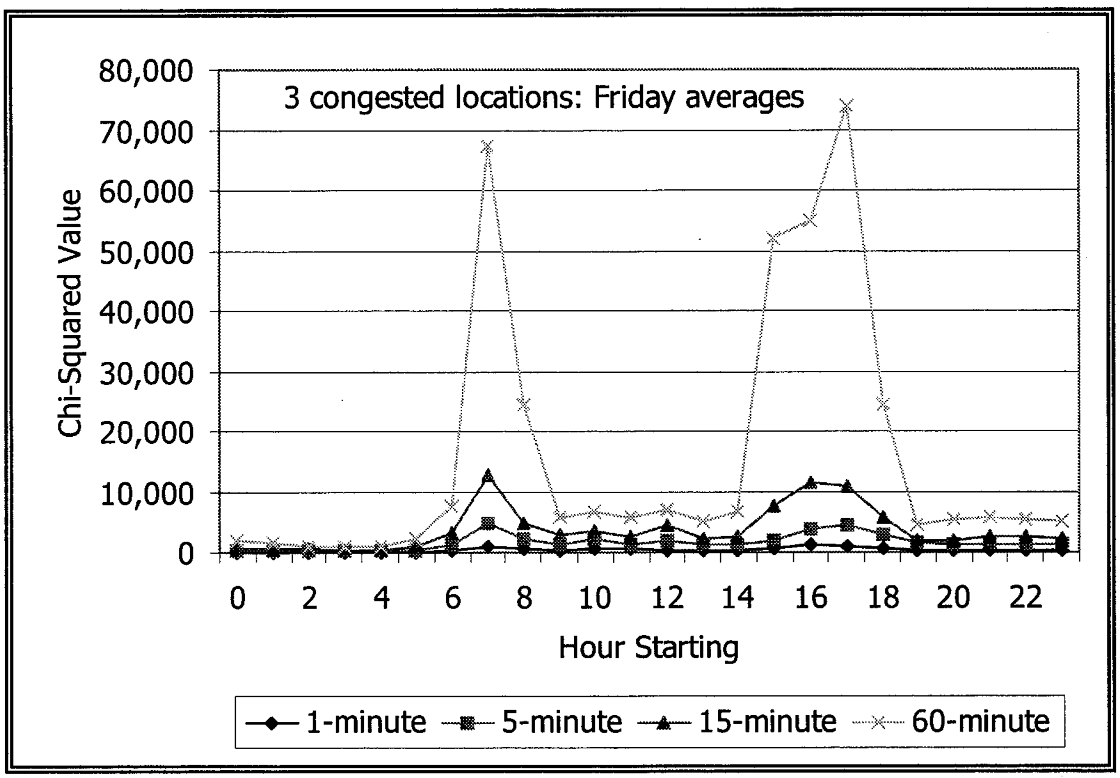

FIGURE 9. Chi-Squared Values for Friday VMT Averages, May 1999

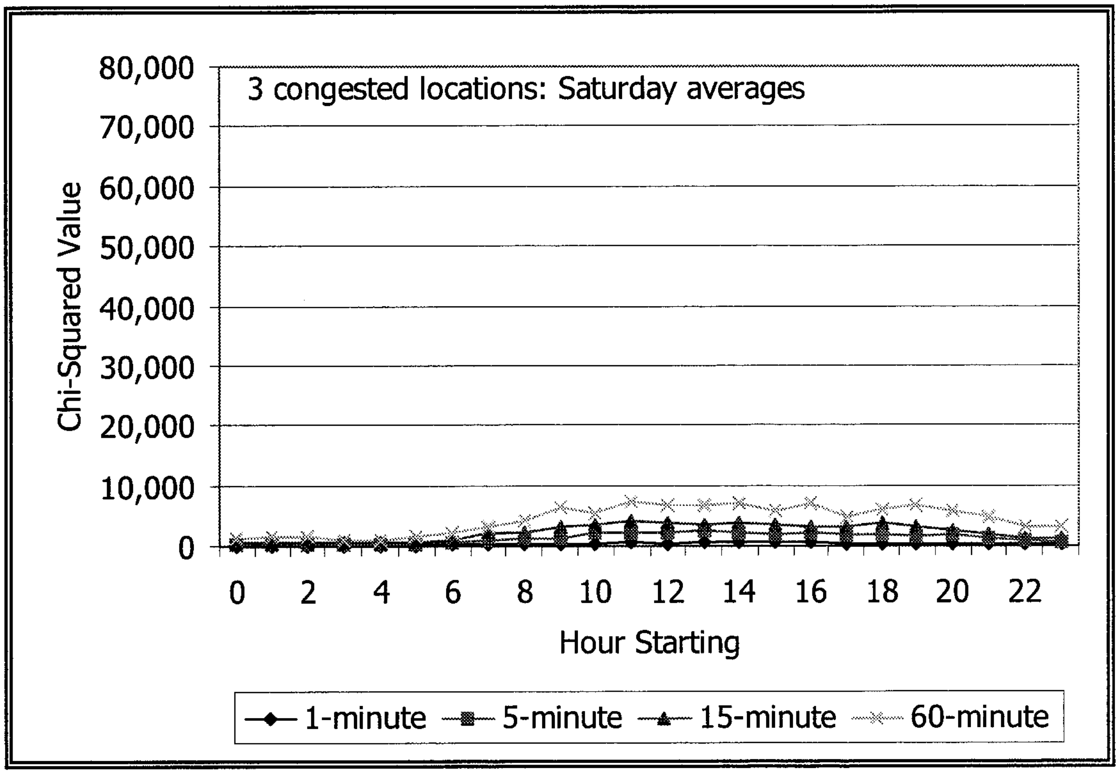

FIGURE 10. Chi-Squared Values for Saturday VMT Averages, May 1999

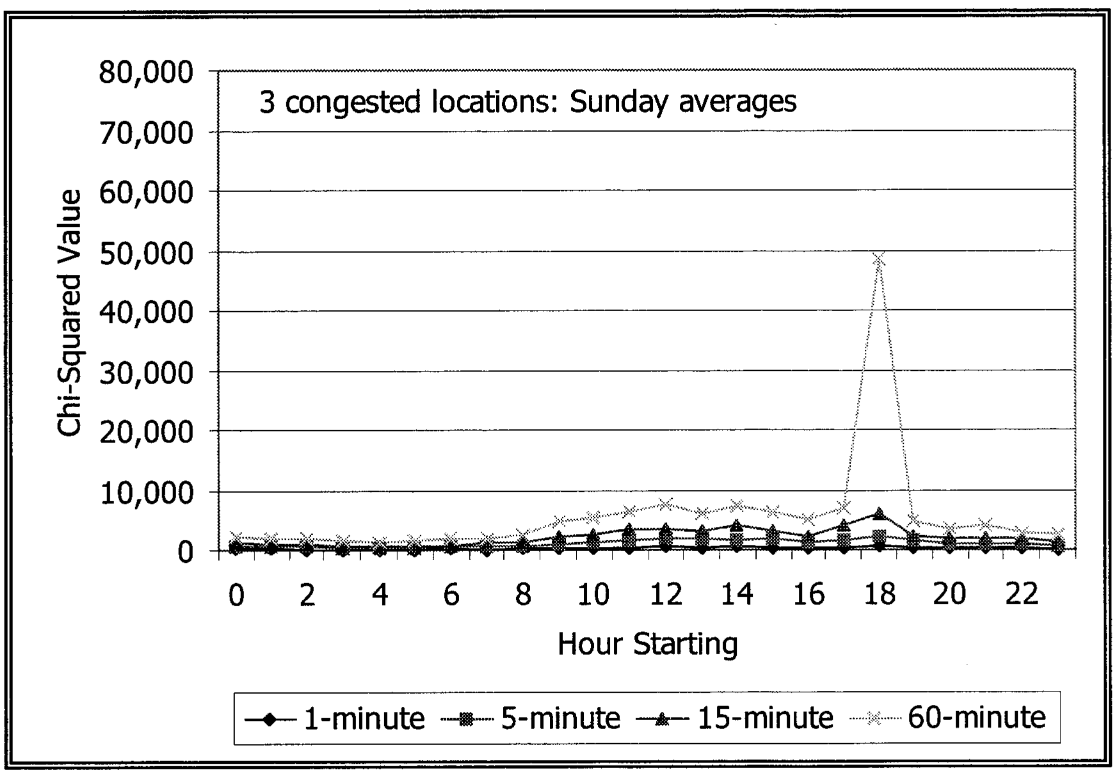

FIGURE 11. Chi-Squared Values for Sunday VMT Averages, May 1999

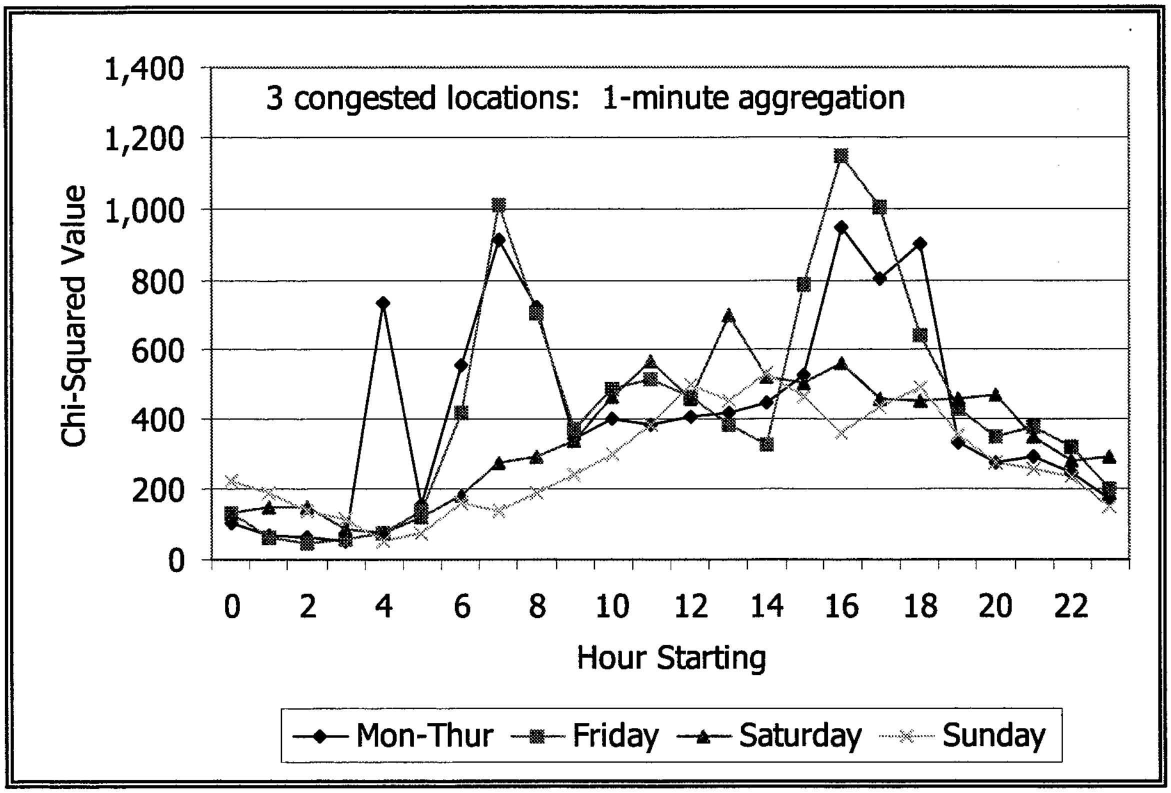

FIGURE 12. Chi-Squared Values for 1-Minute VMT Aggregation, May 1999

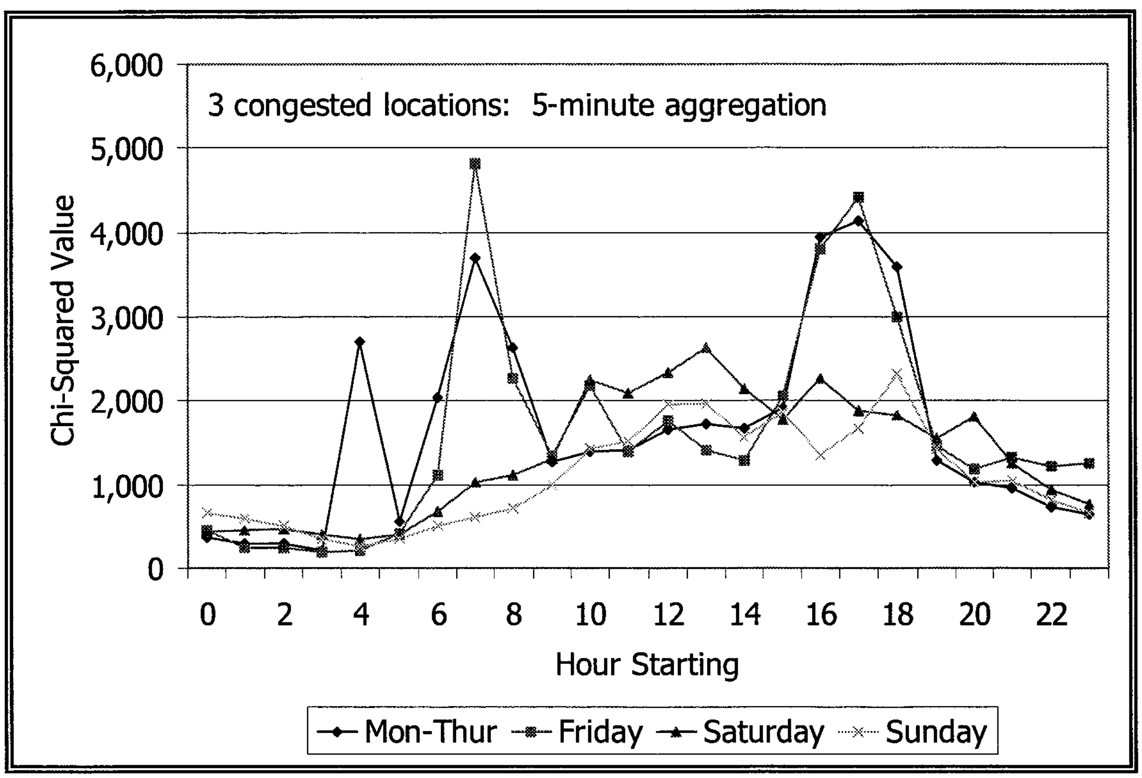

FIGURE 13. Chi-Squared Values for 5-Minute VMT Aggregation, May 1999

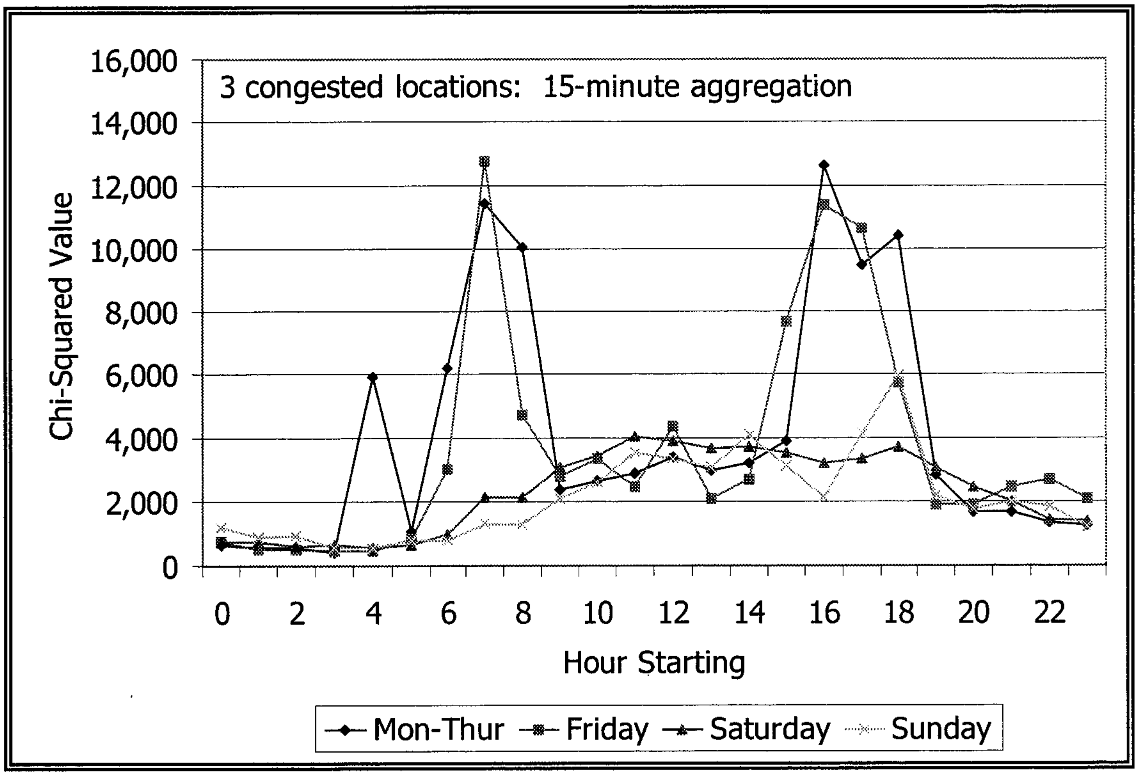

FIGURE 14. Chi-Squared Values for 15-Minute VMT Aggregation, May 1999

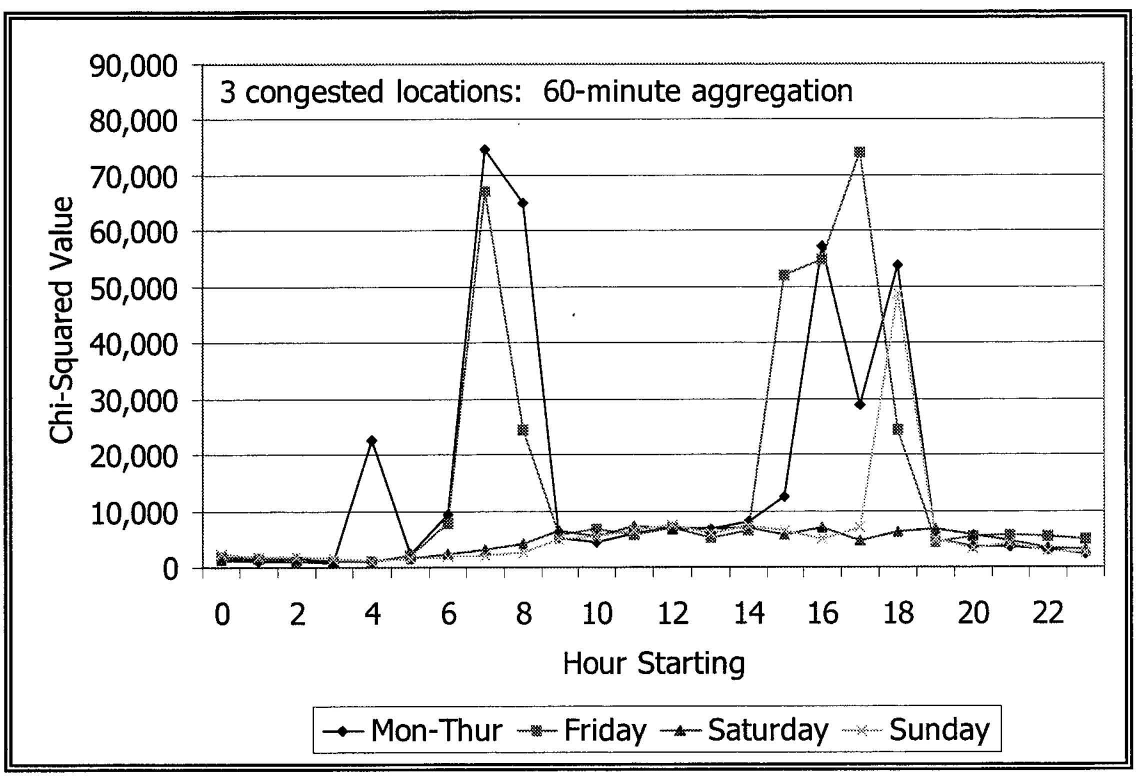

FIGURE 15. Chi-Squared Values for 60-Minute VMT Aggregation, May 1999

EMISSIONS PROFILES

VOC, CO, and NOx are three types of emissions profiles, measured in grams. Emissions profiles are built from vehicle speed, time-of-day and day-of-week. Typical emissions profiles are high for low speeds, low for medium speeds, high for high speeds, and are typically shaped like a bowl (concave up). Examples of such profiles are shown in Figure 16. The profiles are normalized in order to view the relative shape. CO and VOC are steep "bowls" relative to NOx. The magnitude of relative error, for emissions is driven by the steepest part of the bowl. Slight bowls cause the variation in speeds to be a non-factor, and steep bowls cause the variation in speeds to be significant. These bowl shapes change by time-of-day and day-of week.

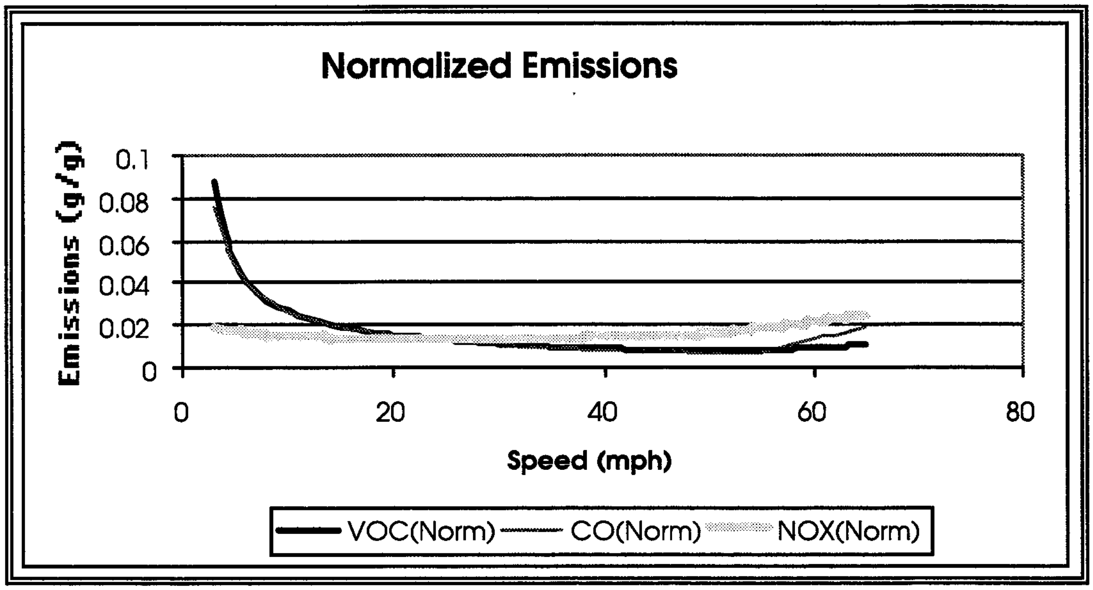

FIGURE 16. Normalized Emissions

Time alters emissions profiles because different temperatures cause different chemical reactions. Molecules vibrate slowly in the low temperatures. This retards the reaction process. Temperature effect changes by hour of the day, therefore there are distinct emissions profiles by the time of the day.

The day of the week effects emissions because the types of vehicles are different from day to day. Trucks are more likely to inhabit the roads on the weekdays then on the weekends. The day factor has four levels. The levels are Monday-Thursday, Friday, Saturday, and Sunday.

EMISSIONS CALCULATIONS

Emissions are calculated using the emissions profiles and the observed VMT. They are summed over the following: time-of-day, day of week, and over all detectors. Let $e_{td}(t)$ be the emissions profile as a function of time-of-day ($t = 1,2,3,\ldots,24$) and the day-of-week ($d = 1,2,3,4$). For example $e_{24}(30)$ are the emissions at hour two on the fourth level of day for an average vehicle speed of 30 mph. Total emissions (TE_k) are calculated from the vehicle volume (v_{tdki}), emissions profile ($e_{td}(t)$) and distance of the detector (D_k). Let $i = 1,2,3,\ldots,180$ reflect the number of 20-second values within an hour. The 20-second speed is s_{tdki}. Notice that $k = 1,2,3,\ldots,K$ is the index for the number of detectors (for example there are $k = 3$ detectors in the congested analysis).

The effect different speed distributions have on emissions is the main concern of this study. Aggregated speed data is used to calculate emissions, which will underestimate emissions with steep profiles, and large speed variability. The total emission estimates at detector k, is:

$$TE_k = \left(\sum_{d=1}^{4} \sum_{t=1}^{24} \sum_{i=1}^{180} e_{td}(s_{tdki}) v_{tdki} \right) D_k$$

The impact of speed and emissions profiles on emissions estimates are easily explained with an example. Suppose there are two 20-second periods, the first 20-second period has 20 cars within an average speed of 5 mph, and the second has 15 cars within an average speed of 60 mph. The CO level at a one-mile detector using the previous equation is:

$$\begin{aligned} TE_k &= e(5)20 + e(60)15 \\ &= 60(20) + 25(15) \\ &= 1{,}575 \text{ g.} \end{aligned}$$

where $e(5)$ and $e(60)$ are calculated with the CO profile. Specifically $e(5)$ is calculated by locating 5 mph on the x-axis of the CO emissions profile and matching the 60 g/VMT on the y-axis. The research team then compared the 20 seconds emissions with an average of the two speeds. $T\hat{E}_k$ is the estimated emissions using aggregated speeds. This is an estimate of TE_k The speed data (s_{tdki}) is replaced with the averaged speed ($\bar{s}_{tdk\bullet}$). The following is the aggregated estimate:

$$T\hat{E}_k = \left(\sum_{d=1}^{4} \sum_{t=1}^{24} e_{td}(\bar{s}_{tdk\bullet}) v_{tdk\bullet} \right) D_k$$

The above example is then estimated as (the estimated value of TE_k is represented as $T\hat{E}_k$):

$$\begin{aligned} T\hat{E}_k &= e(29)35 \\ &= 19(35) \\ &= 665 \text{ g} \end{aligned}$$

Therefore the relative error is:

$$\left| \frac{T\hat{E}_k - TE_k}{TE_k} \right| \times 100\% = \left| \frac{\text{Estimate} - \text{Truth}}{\text{Truth}} \right| \times 100\% = 57\%$$

This relative error is caused by the two extreme speeds, 5 and 60 in conjunction with the steep CO bowl shaped emissions. These speeds are plugged into the steepest portions of the emissions profiles. The mean speed is in the middle of the bowl, resulting in lower emissions when estimated with the weighted mean speed. By using NOx profiles, the relative error would be miniscule.

THEORETICAL MAXIMUM ERROR

The error differences between the two previous equations (6, 22) can be explained with a Taylor series approximation (25). The basis for this series is that all mathematical functions are approximately polynomials where f is a function of x and c is a fixed constant. The first order Taylor series expansion is then:

$$\begin{aligned} f(x) &= f(c)+(x-c)f'(c)+R_2(x) \\ &\approx f(c)+(x-c)f'(c)+(x-c)^2 f''(c)/2 \end{aligned}$$

where:

$R_2(x)= f''(u)(x-c)^2/2$. $R_2(x)$ is the error.

the equation[9] is estimated using this expansion.

$$TE_k \approx \hat{TE}_k + \sum_{d=1}^{4}\sum_{t=1}^{24}\left(\sum_{i=1}^{n}(s_{tdki}-\bar{s}_{tdk\bullet})v_{tdki}\right)e'_{td}(\bar{s}_{tdk\bullet}) + \sum_{d=1}^{4}\sum_{t=1}^{24}\left(\sum_{i=1}^{n}(s_{tdki}-\bar{s}_{tdk\bullet})^2 v_{tdki}\right)e''_{td}(\bar{s}_{tdk\bullet})/2$$

Therefore the relative error using a second order expansion is:

$$Error = \left|\frac{\sum_{d=1}^{4}\sum_{t=1}^{24}\sum_{i=1}^{n}\left\{(s_{tdki}-\bar{s}_{tdk\bullet})v_{tdki}e'_{td}(\bar{s}_{tdk\bullet})+(s_{tdki}-\bar{s}_{tdk\bullet})^2 v_{tdki}e''_{td}(\bar{s}_{tdk\bullet})/2\right\}}{TE_k}\right| \times 100$$

Large second derivatives are found in steeply shaped emissions profiles. This results in large errors. NOx and CO contain large second derivatives at low and high speeds (large second derivatives are like steep bowls). Second derivatives are large in the steep regions. When steep regions occur the numerator in the last equation is inflated, which will be large for non-zero second derivatives when the speed variation is high $[(s_{tdki}-s_{tdk.})^2]$. Large speed variation with bowl shaped profiles result in large emissions errors.

CHAPTER 5. DATA ANALYSIS

Emissions were estimated using the San Antonio data for May 1999, by summing the equation in the previous section for all detectors for VOC, CO, and NOx. The "ground truth" estimate (from 20-second data) is compared to emissions estimates using aggregated data (aggregation widths of 1, 5, 15, and 60 minutes).

The overall emissions estimates, for May 1999 in San Antonio's Phase 1 TransGuide system, are summarized in Table 17. The ground truth for VOC is 187.82 million grams. The overall relative error for aggregation levels 1, 5, 15, and 60 minutes were 1.76%, 2.42%, 2.60%, and 2.93% respectively. The ground truth for CO is 2,380 million grams. The overall relative error for aggregation levels 1, 5, 15, and 60 minutes were .92%, 1.46%, 1.65%, and 2.12% respectively. The ground truth for NOx is 3.1459 million grams. The overall relative error for aggregation levels 1, 5, 15, and 60 minutes were –0.27%, -0.39%, -0.39%, and -0.26% respectively. None of the differences was particularly large, but the VOC, CO percent errors were larger than the NOx errors, as expected, by their relative emissions profiles.

TABLE 17
Total Emissions Estimates in San Antonio for May 1999
(Units = 10^6 grams)

Aggregation Level	VOC		CO		NOx	
	Total	% Error	Total	% Error	Total	% Error
20-second	187.82	-	2,379.91	-	314.59	-
1 minute	184.52	1.76%	2,358.09	0.92%	315.44	-0.27%
5 minutes	183.27	2.42%	2,345.26	1.46%	315.83	-0.39%
15 minutes	182.94	2.60%	2,340.73	1.65%	315.82	-0.39%
60 minutes	182.32	2.93%	2,329.38	2.12%	315.40	-0.26%

Note: Average percent errors are based on difference from emissions estimates calculated using 20-second data.

Aggregated VMT underestimates the ground truth for VOC and CO as the aggregation width grows. The steep bowl shapes to these profiles cause the underestimates. Aggregated VMT overestimates the ground truth for NOx. The shallow bowl shape to this profile causes this overestimation.

The relative error is now studied at a microscopic level. Recall that the time-of-day and the day-of-week are two factors that change emissions estimates. Monday-Thursday, Friday, Saturday, and Sunday are the four levels for day-of-week. The 24 hours in a day are the levels in time-of-day. The relative error is studied at every factor combination. A Monday-Thursday and time-of-day plot for all aggregation levels illustrates this. This is shown in Figures 17-19, which presents the upper limit of a 95% confidence interval, calculated for every hour. For example, for the first hour they are calculated with 17 0:00-hour realizations for Monday-Thursday at each time period. These 17 realizations are treated as independent observations. Therefore, standard confidence intervals are calculated. The relative error is highest in the morning for all three compounds, because the true emissions are smallest in the morning, as shown in Figures 20 and 21. Therefore, the denominator inflates the relative error. The results for the percent error for all days, compounds, and all detectors are shown in Tables 18-20. The shaded regions are the significant differences from 5% error at the .05 error level. VOC and CO have morning-shaded values, and NOx has no shaded regions. This shows that percent errors are not significant during the peak periods of the day. The peak periods are what drive the overall percent error, because the volume of vehicles is highest. This reflects the small overall percent error in Table 18.

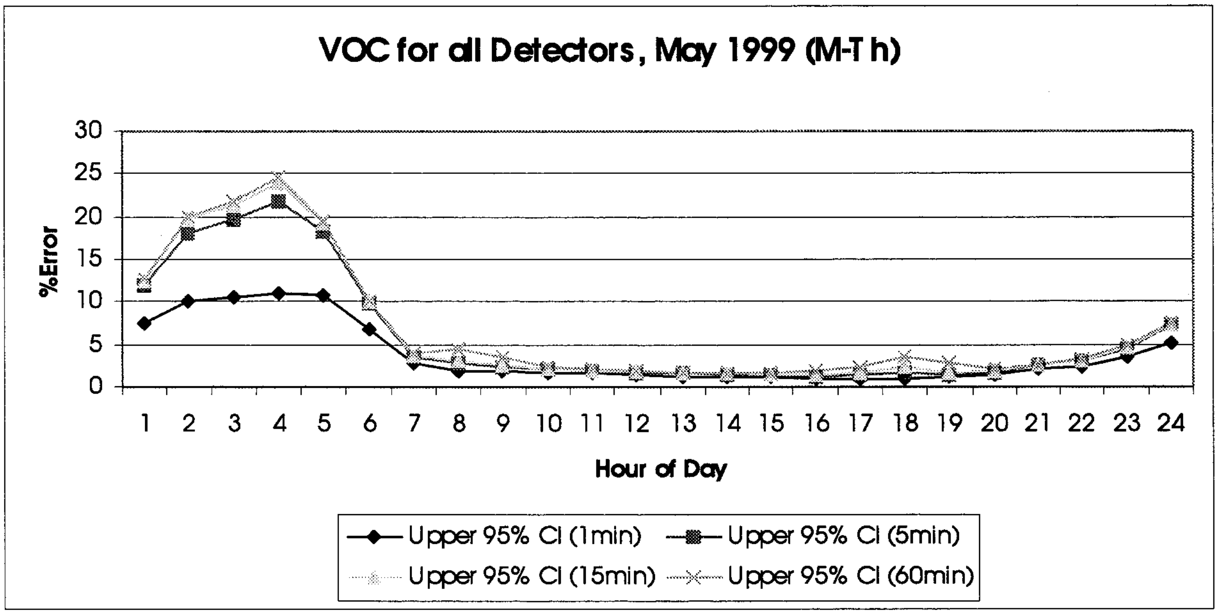

FIGURE 17. VOC for all Detectors

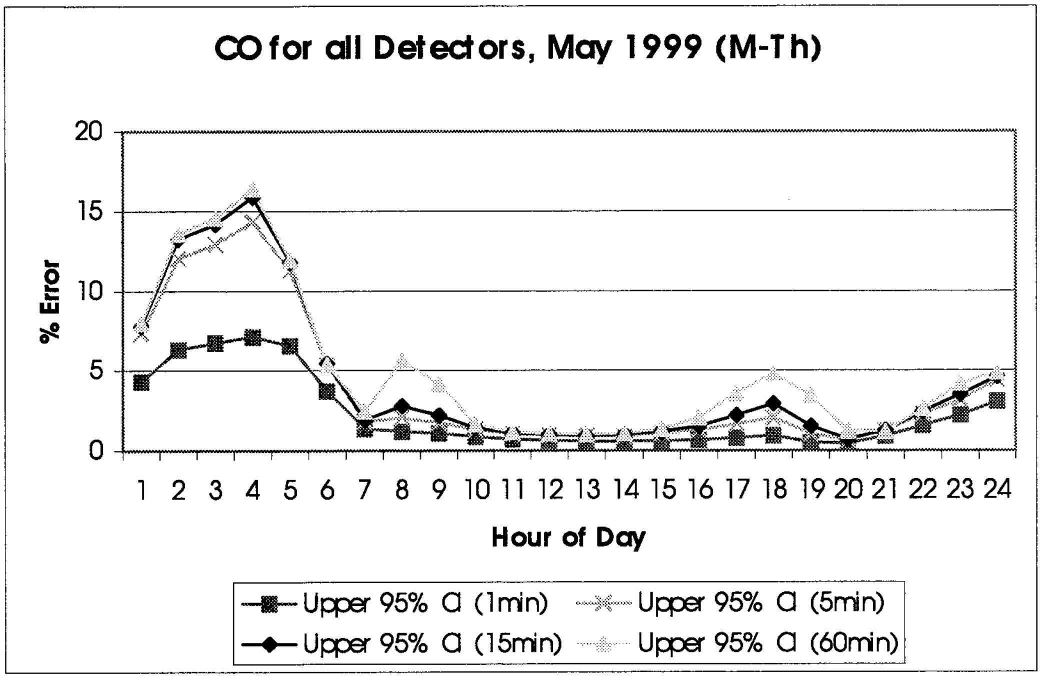

FIGURE 18. CO for all Detectors

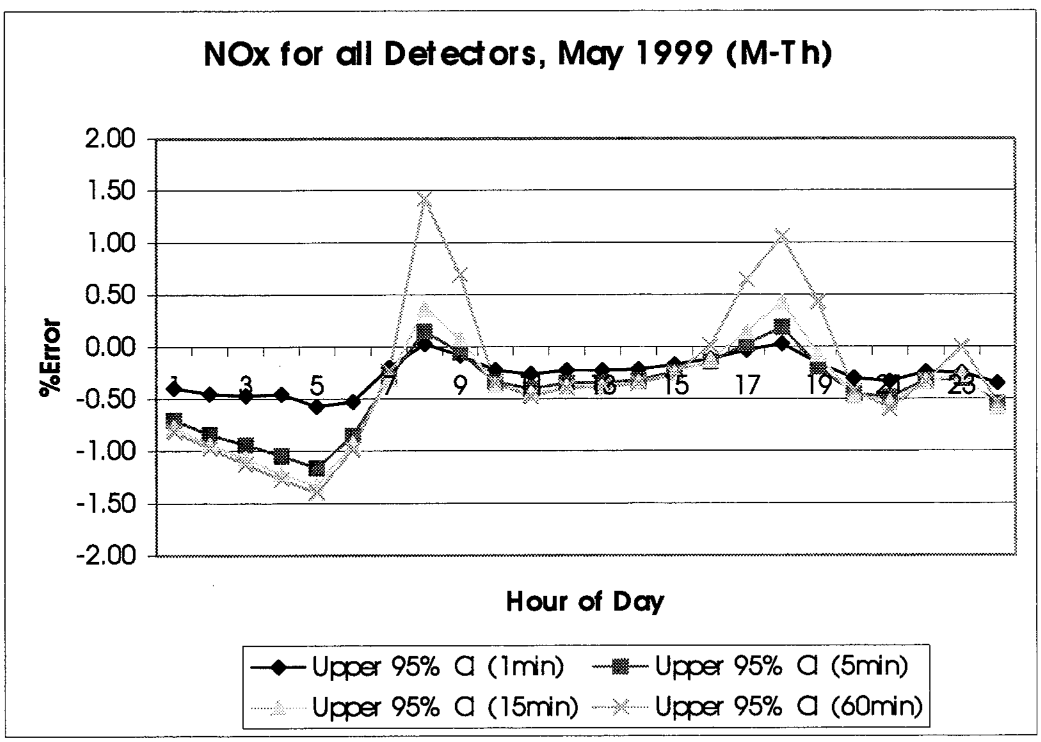

FIGURE 19. NOx for all Detectors

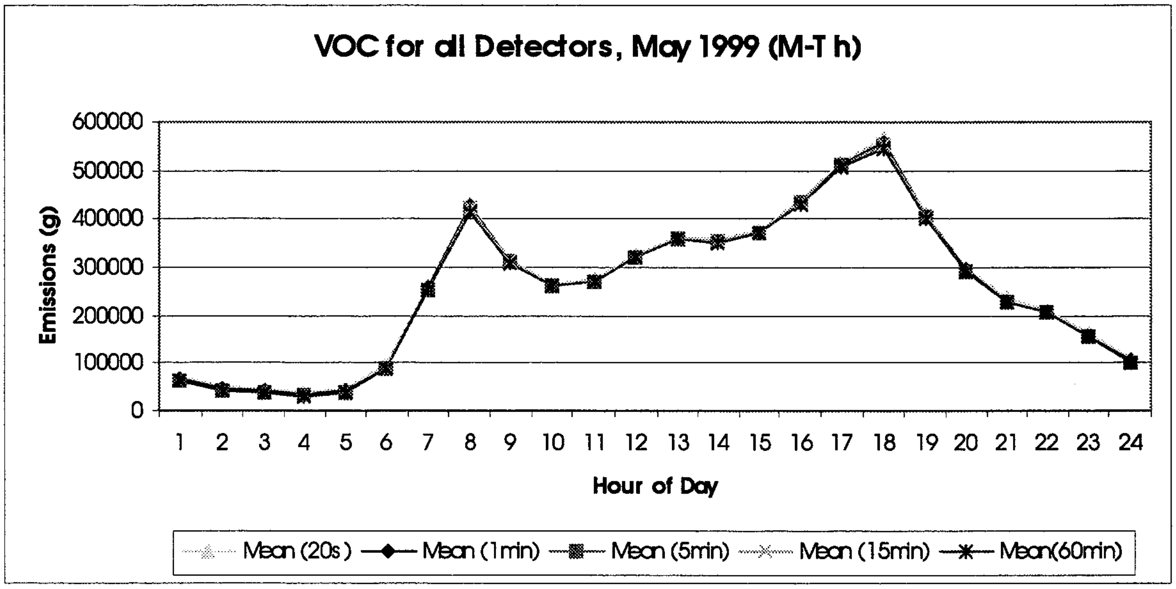

FIGURE 20. VOC for all Detectors

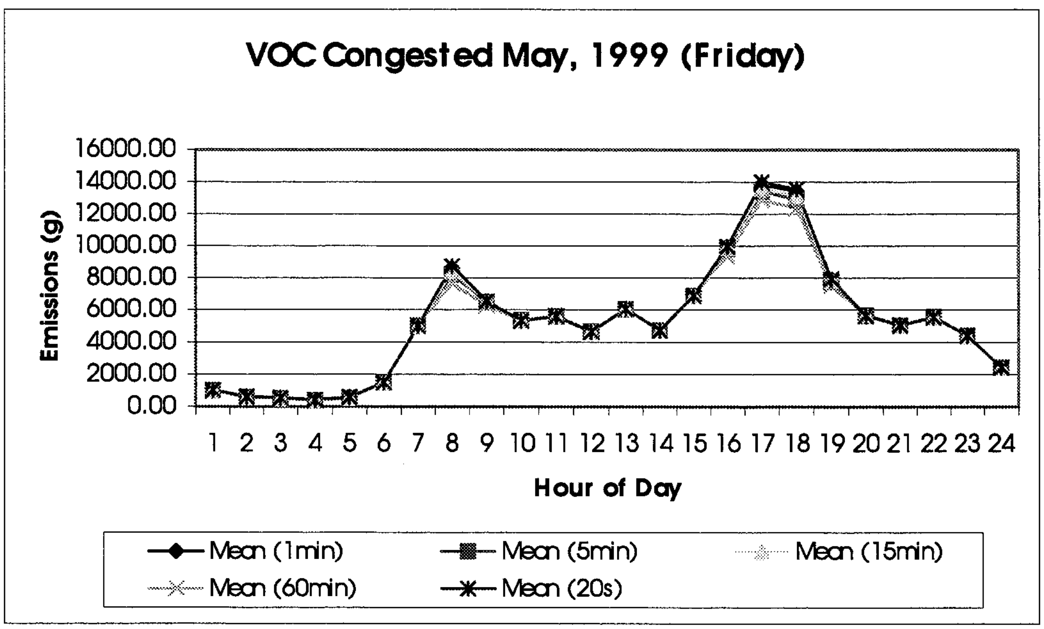

FIGURE 21. VOC Congested

TABLE 18
Results of Percent Error for VOC Estimates During May 1999 for all Detectors from the San Antonio Loops*

Day	Agg	0	1	2	3	4	5	6	7	8	9	10	11
		Hours of the Day											
M-Th	1	6.14	9.13	9.77	10.37	10.34	6.15	1.82	1.25	1.27	1.44	1.42	1.24
	5	9.96	16.24	17.71	19.95	17.59	8.60	2.38	1.93	1.75	1.82	1.78	1.59
	15	10.39	17.43	19.01	21.80	18.55	8.76	2.49	2.38	2.01	1.87	1.84	1.64
	60	10.52	17.61	19.33	22.28	18.74	8.79	2.71	3.84	2.77	1.95	1.88	1.66
Fr	1	7.55	10.00	9.51	10.45	9.26	5.00	1.05	0.67	0.72	1.04	1.07	1.00
	5	10.40	16.46	15.80	19.60	16.57	7.28	1.26	1.21	1.05	1.39	1.36	1.29
	15	10.57	16.96	16.51	21.08	17.74	7.42	1.32	1.61	1.23	1.41	1.36	1.33
	60	10.64	17.03	16.63	21.26	17.89	7.48	1.48	2.85	1.75	1.40	1.36	1.42
Sat	1	3.17	6.61	7.30	9.30	10.31	8.73	4.89	2.89	1.84	1.46	1.25	1.04
	5	5.21	9.49	10.04	14.65	17.03	12.55	6.01	3.29	2.10	1.65	1.44	1.21
	15	5.38	9.65	10.21	15.16	17.74	12.75	6.06	3.32	2.11	1.66	1.45	1.21
	60	5.48	9.70	10.22	15.22	17.83	12.84	6.12	3.35	2.14	1.69	1.44	1.20
Sun	1	3.98	6.40	6.78	9.09	10.21	9.53	7.62	6.02	4.75	2.72	1.88	1.65
	5	5.02	8.51	9.04	13.93	17.76	15.71	10.41	7.44	5.66	3.14	2.16	1.86
	15	5.10	8.62	9.19	14.44	18.79	16.49	10.54	7.46	5.69	3.20	2.19	1.88
	60	5.10	8.73	9.18	14.45	19.03	16.59	10.49	7.44	5.81	3.26	2.25	1.87

Day	Agg	12	13	14	15	16	17	18	19	20	21	22	23
		Hours of the Day											
M-Th	1	1.14	1.13	1.01	0.82	0.79	0.92	0.93	1.38	1.92	2.24	3.25	4.73
	5	1.45	1.42	1.32	1.20	1.25	1.63	1.29	1.67	2.38	2.83	4.12	6.67
	15	1.49	1.49	1.38	1.33	1.50	2.10	1.54	1.72	2.41	2.91	4.23	6.83
	60	1.53	1.58	1.46	1.62	2.06	3.08	2.34	1.88	2.42	2.97	4.38	6.90
Fr	1	0.95	0.84	0.80	0.76	0.84	0.92	0.74	0.88	1.40	1.61	1.88	2.73
	5	1.25	1.25	1.26	1.19	1.50	1.73	1.18	1.21	1.76	2.07	2.39	3.55
	15	1.38	1.33	1.39	1.43	1.91	2.37	1.46	1.25	1.80	2.18	2.47	3.64
	60	1.52	1.40	1.53	1.94	2.81	3.54	2.36	1.30	1.80	2.23	2.49	3.65
Sat	1	0.90	0.99	0.96	1.07	1.10	1.06	1.16	1.39	1.64	1.78	1.80	2.63
	5	1.08	1.24	1.18	1.29	1.30	1.30	1.40	1.56	1.97	2.22	2.43	3.39
	15	1.10	1.33	1.26	1.35	1.34	1.30	1.40	1.55	2.01	2.29	2.53	3.46
	60	1.08	1.47	1.46	1.45	1.43	1.29	1.43	1.64	2.03	2.33	2.61	3.52
Sun	1	1.37	1.24	1.19	1.42	1.34	1.28	1.33	1.68	2.25	2.70	3.18	4.47
	5	1.60	1.55	1.46	1.64	1.56	1.48	1.48	1.88	2.62	3.29	3.78	6.81
	15	1.69	1.68	1.53	1.67	1.58	1.64	1.52	1.87	2.67	3.38	3.85	7.07
	60	1.84	1.97	1.79	1.73	1.61	2.05	1.67	1.89	2.65	3.40	3.89	7.14

- Shaded regions are statistically different from 5% at the .05 level

TABLE 19
Results of Percent Error for CO Estimates During May 1999 for all Detectors from the San Antonio Loops*

		Hours of the Day											
Day	**Agg**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M-Th	1	3.53	5.66	6.06	6.59	6.22	3.18	0.91	0.97	0.83	0.70	0.61	0.53
	5	5.98	10.42	11.21	12.78	10.54	4.46	1.24	1.76	1.39	1.03	0.88	0.82
	15	6.28	11.29	12.08	13.99	11.06	4.49	1.33	2.39	1.74	1.08	0.91	0.85
	60	6.36	11.48	12.30	14.32	11.14	4.45	1.67	4.69	3.07	1.14	0.92	0.85
Fr	1	4.37	5.97	5.53	6.36	5.27	2.32	0.43	0.76	0.57	0.56	0.55	0.54
	5	6.22	10.04	9.27	11.98	9.47	3.32	0.53	1.56	1.07	0.90	0.83	0.88
	15	6.37	10.37	9.59	12.85	10.08	3.31	0.58	2.21	1.32	0.89	0.76	0.89
	60	6.44	10.41	9.58	12.88	10.05	3.35	0.76	4.31	2.28	0.83	0.74	1.07
Sat	1	1.60	3.60	3.85	5.20	6.07	4.66	2.17	1.15	0.56	0.46	0.40	0.29
	5	2.77	5.20	5.28	8.13	9.95	6.60	2.61	1.21	0.57	0.47	0.47	0.34
	15	2.87	5.26	5.29	8.33	10.26	6.55	2.58	1.23	0.53	0.41	0.42	0.29
	60	2.88	5.32	5.25	8.28	10.21	6.58	2.63	1.25	0.55	0.45	0.32	0.20
Sun	1	2.19	3.51	3.68	5.16	6.03	5.42	3.50	2.48	1.88	0.81	0.41	0.27
	5	2.95	4.80	4.99	7.81	10.37	8.84	4.34	2.69	1.97	0.79	0.38	0.20
	15	3.06	4.87	5.04	8.02	10.86	9.19	4.24	2.54	1.89	0.77	0.36	0.17
	60	3.03	4.90	4.95	7.90	10.96	9.15	3.99	2.43	2.03	0.77	0.41	0.10

		Hours of the Day											
Day	**Agg**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
M-Th	1	0.49	0.49	0.52	0.53	0.64	0.75	0.39	0.33	0.77	1.41	1.88	2.65
	5	0.75	0.75	0.88	1.06	1.33	1.65	0.75	0.40	1.06	2.09	2.65	3.89
	15	0.73	0.82	0.96	1.24	1.74	2.33	1.10	0.41	1.06	2.25	2.84	4.03
	60	0.75	0.85	1.06	1.70	2.75	3.81	2.49	0.65	1.01	2.34	3.11	4.13
Fr	1	0.58	0.57	0.60	0.76	0.97	0.90	0.52	0.32	0.83	1.42	1.41	1.52
	5	0.99	1.08	1.26	1.50	1.97	1.94	1.11	0.50	1.28	2.27	2.20	2.21
	15	1.19	1.23	1.48	1.85	2.61	2.86	1.50	0.56	1.34	2.53	2.34	2.35
	60	1.28	1.38	1.73	2.59	4.19	4.72	2.87	0.60	1.29	2.66	2.36	2.32
Sat	1	0.31	0.37	0.31	0.30	0.27	0.18	0.23	0.37	0.83	1.40	1.26	1.53
	5	0.43	0.58	0.50	0.41	0.36	0.22	0.31	0.39	1.23	2.19	2.05	2.28
	15	0.43	0.66	0.58	0.52	0.37	0.16	0.28	0.31	1.29	2.36	2.24	2.41
	60	0.32	0.83	0.82	0.59	0.45	0.08	0.34	0.41	1.31	2.47	2.35	2.56
Sun	1	0.46	0.65	0.45	0.40	0.16	0.17	0.11	0.27	1.00	1.76	1.87	2.47
	5	0.58	1.03	0.67	0.56	0.19	0.13	0.01	0.22	1.33	2.57	2.55	4.13
	15	0.69	1.22	0.75	0.61	0.18	0.22	0.03	0.14	1.44	2.81	2.67	4.36
	60	0.93	1.77	1.16	0.73	0.15	0.54	0.28	0.17	1.32	2.85	2.78	4.44

- Shaded regions are statistically different from 5% at the .05 level

TABLE 20
Results of Percent Error for NOx Estimates During May 1999 for all Detectors from the San Antonio Loops

		Hours of the Day											
Day	**Agg**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M-Th	1	-0.50	-0.55	-0.58	-0.54	-0.64	-0.59	-0.31	-0.11	-0.19	-0.29	-0.30	-0.27
	5	-0.87	-1.06	-1.18	-1.23	-1.32	-0.98	-0.49	-0.08	-0.25	-0.44	-0.46	-0.40
	15	-0.97	-1.21	-1.37	-1.44	-1.51	-1.09	-0.52	0.08	-0.17	-0.49	-0.50	-0.44
	60	-1.02	-1.26	-1.45	-1.52	-1.59	-1.15	-0.50	0.92	0.22	-0.49	-0.53	-0.46
Fr	1	-0.58	-0.65	-0.69	-0.64	-0.68	-0.60	-0.29	-0.04	-0.16	-0.24	-0.25	-0.23
	5	-0.92	-1.19	-1.35	-1.39	-1.38	-1.05	-0.46	0.01	-0.21	-0.39	-0.39	-0.32
	15	-1.02	-1.33	-1.54	-1.63	-1.61	-1.16	-0.49	0.17	-0.18	-0.43	-0.45	-0.37
	60	-1.04	-1.41	-1.66	-1.75	-1.74	-1.21	-0.47	0.85	0.04	-0.48	-0.48	-0.36
Sat	1	-0.43	-0.64	-0.74	-0.78	-0.71	-0.78	-0.66	-0.52	-0.48	-0.39	-0.35	-0.32
	5	-0.79	-1.10	-1.24	-1.51	-1.44	-1.37	-1.00	-0.79	-0.70	-0.60	-0.51	-0.49
	15	-0.88	-1.23	-1.39	-1.71	-1.66	-1.54	-1.10	-0.84	-0.77	-0.65	-0.57	-0.55
	60	-0.95	-1.25	-1.42	-1.81	-1.78	-1.57	-1.17	-0.88	-0.77	-0.69	-0.62	-0.58
Sun	1	-0.51	-0.66	-0.68	-0.73	-0.72	-0.75	-0.87	-0.83	-0.72	-0.58	-0.49	-0.46
	5	-0.75	-1.03	-1.10	-1.43	-1.59	-1.52	-1.57	-1.36	-1.13	-0.87	-0.70	-0.69
	15	-0.81	-1.12	-1.23	-1.62	-1.84	-1.74	-1.73	-1.49	-1.21	-0.92	-0.75	-0.74
	60	-0.85	-1.16	-1.30	-1.73	-1.95	-1.85	-1.87	-1.56	-1.20	-0.94	-0.76	-0.79
		Hours of the Day											
Day	**Agg**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
M-Th	1	-0.26	-0.25	-0.21	-0.16	-0.10	-0.05	-0.22	-0.35	-0.36	-0.27	-0.35	-0.45
	5	-0.39	-0.37	-0.31	-0.21	-0.09	0.04	-0.29	-0.53	-0.52	-0.37	-0.47	-0.72
	15	-0.44	-0.39	-0.33	-0.21	-0.01	0.23	-0.22	-0.57	-0.57	-0.39	-0.49	-0.78
	60	-0.45	-0.40	-0.34	-0.10	0.35	0.71	0.13	-0.54	-0.65	-0.40	-0.42	-0.80
Fr	1	-0.19	-0.15	-0.14	-0.08	-0.00	0.01	-0.13	-0.24	-0.24	-0.15	-0.22	-0.36
	5	-0.27	-0.21	-0.18	-0.07	0.09	0.15	-0.14	-0.41	-0.34	-0.14	-0.27	-0.55
	15	-0.26	-0.22	-0.17	-0.01	0.26	0.43	-0.07	-0.44	-0.37	-0.13	-0.27	-0.60
	60	-0.24	-0.20	-0.13	0.23	0.85	1.11	0.33	-0.44	-0.45	-0.10	-0.30	-0.64
Sat	1	-0.28	-0.27	-0.28	-0.29	-0.30	-0.32	-0.34	-0.36	-0.31	-0.21	-0.25	-0.38
	5	-0.43	-0.39	-0.40	-0.44	-0.46	-0.52	-0.52	-0.55	-0.42	-0.24	-0.34	-0.52
	15	-0.46	-0.41	-0.42	-0.44	-0.50	-0.57	-0.58	-0.61	-0.46	-0.25	-0.36	-0.56
	60	-0.51	-0.39	-0.38	-0.44	-0.48	-0.62	-0.59	-0.62	-0.51	-0.24	-0.38	-0.58
Sun	1	-0.32	-0.23	-0.29	-0.34	-0.39	-0.38	-0.42	-0.47	-0.39	-0.31	-0.40	-0.50
	5	-0.48	-0.32	-0.43	-0.51	-0.57	-0.57	-0.63	-0.68	-0.56	-0.39	-0.55	-0.78
	15	-0.50	-0.32	-0.45	-0.55	-0.63	-0.56	-0.63	-0.74	-0.59	-0.39	-0.60	-0.84
	60	-0.50	-0.22	-0.39	-0.56	-0.63	-0.47	-0.60	-0.76	-0.70	-0.44	-0.61	-0.88

Note: No regions are statistically different from 5% at the .05 level

COMPARISON IN CONGESTED AREAS

A comparison was performed on data in congested areas. It was believed that congested detectors would have higher percent error marks during the peak periods. The research team selected three detectors for this analysis. The results are summarized in Tables 21-23. They summarize VOC, CO, and NOx respectively. Significant errors occur rarely for VOC and CO. Significant errors do not occur at all for NOx. The significant values do occur in non-morning times. For example 1600 hours on the Monday-Thursday, 60-minute aggregation has an 11.8% error. This is in contrast to the overall results.

TABLE 21
Results of Percent Error for VOC Estimates During May 1999 for Congested Detectors from the San Antonio Loops*

Day	Agg	0	1	2	3	4	5	6	7	8	9	10	11
		Hours of the Day											
M-Th	1	2.50	4.25	4.19	5.03	4.03	1.54	0.22	0.76	0.23	-0.09	-0.04	-0.07
	5	3.66	5.84	5.81	6.65	5.67	1.28	0.11	1.81	0.64	-0.16	0.06	-0.18
	15	3.51	5.88	5.70	6.51	5.25	1.05	0.39	3.25	1.98	-0.11	0.20	-0.15
	60	3.39	5.96	5.59	6.49	5.05	0.90	2.09	8.19	5.95	0.19	0.18	-0.33
Fr	1	1.38	2.88	3.33	7.70	3.55	1.10	-0.21	1.39	0.05	-0.31	-0.05	0.01
	5	1.60	4.76	6.35	8.21	5.20	0.72	-0.47	3.69	0.02	-0.52	-0.31	-0.20
	15	1.46	4.36	5.90	7.73	4.67	0.14	-0.78	6.43	0.07	-0.61	-0.31	-0.18
	60	1.69	4.24	5.33	7.56	4.68	0.06	-0.83	12.89	2.42	-0.69	-0.42	-0.47
Sat	1	0.95	2.38	3.46	4.64	3.99	2.18	0.66	-0.30	-0.35	-0.11	-0.24	-0.13
	5	0.85	2.68	4.04	6.20	5.43	2.52	0.24	-0.75	-0.72	-0.18	-0.32	-0.23
	15	0.84	2.39	3.75	6.05	5.27	2.23	0.03	-0.88	-0.84	-0.13	-0.27	-0.15
	60	0.71	2.25	3.96	6.11	5.17	2.16	0.01	-0.81	-0.85	-0.10	-0.33	-0.18
Sun	1	0.86	2.09	3.66	3.57	5.35	4.09	2.22	0.85	0.45	0.36	-0.26	-0.28
	5	0.62	2.02	4.04	3.64	6.16	4.58	1.93	0.70	-0.24	-0.07	-0.56	-0.37
	15	0.43	1.82	3.86	3.46	5.72	4.32	1.74	0.44	-0.21	-0.19	-0.56	-0.41
	60	0.53	1.57	3.71	3.60	5.68	4.47	1.20	0.47	-0.02	-0.05	-0.59	-0.62

Day	Agg	12	13	14	15	16	17	18	19	20	21	22	23
		Hours of the Day											
M-Th	1	-0.12	-0.12	0.08	0.09	0.33	0.62	0.38	-0.12	-0.06	0.27	0.62	1.44
	5	-0.14	-0.22	0.15	0.26	1.25	1.91	1.24	-0.24	-0.17	0.18	0.52	1.24
	15	-0.19	-0.22	0.24	0.60	2.78	2.64	2.51	-0.26	-0.16	0.20	0.52	1.17
	60	-0.24	-0.14	0.63	1.48	6.75	3.54	10.45	-0.32	-0.20	0.15	0.76	1.35
Fr	1	0.03	0.04	-0.07	0.14	0.90	0.96	0.18	-0.10	-0.05	0.03	0.10	0.37
	5	0.01	-0.17	-0.17	0.44	2.44	3.09	0.70	-0.19	-0.05	-0.02	0.12	0.07
	15	0.17	-0.25	-0.12	0.88	3.98	5.02	1.45	0.19	-0.21	-0.04	0.08	-0.00
	60	0.16	0.02	-0.27	4.20	8.74	9.55	3.11	0.92	-0.20	-0.23	0.11	0.75
Sat	1	-0.17	-0.08	-0.05	-0.15	-0.12	-0.17	-0.03	-0.23	0.02	0.10	0.16	0.36
	5	-0.14	0.08	-0.09	-0.18	-0.16	-0.24	0.02	-0.18	0.10	0.12	0.02	0.13
	15	-0.04	0.55	-0.15	-0.26	-0.18	-0.36	-0.12	-0.25	0.18	-0.06	-0.08	0.14
	60	-0.10	1.11	-0.34	-0.18	-0.27	-0.03	-0.16	-0.26	0.35	-0.02	-0.00	0.21
Sun	1	-0.01	0.08	-0.05	-0.03	-0.03	-0.09	0.13	0.07	0.43	0.56	1.06	1.60
	5	0.09	0.27	-0.08	-0.06	-0.18	-0.12	0.15	-0.25	0.24	0.45	0.76	1.96
	15	0.40	0.30	-0.18	0.02	-0.25	0.07	0.33	-0.26	0.12	0.43	0.71	1.90
	60	0.41	0.22	0.01	0.08	-0.46	0.26	2.19	-0.25	-0.03	0.29	0.70	2.20

* Shaded regions are statistically different from 5% at the .05 level

TABLE 22
Results of Percent Error for CO Estimates During May 1999 for Congested Detectors from the San Antonio Loops*

		Hours of the Day											
Day	Agg	0	1	2	3	4	5	6	7	8	9	10	11
M-Th	1	-0.25	0.76	0.54	1.09	0.19	-0.83	-0.65	0.60	-0.30	-0.74	-0.66	-0.61
	5	-1.02	0.32	-0.81	-0.68	-1.39	-2.11	-1.13	1.60	-0.04	-1.02	-0.81	-1.02
	15	-1.51	-0.31	-1.46	-1.63	-2.47	-2.69	-0.87	3.52	1.87	-1.02	-0.86	-0.97
	60	-1.85	-0.09	-1.98	-2.11	-3.00	-3.07	2.56	11.40	9.04	-0.36	-0.92	-1.47
Fr	1	-1.47	-0.59	-0.29	2.42	-0.20	-1.01	-1.08	1.57	-0.29	-0.91	-0.55	-0.38
	5	-3.14	-2.41	-1.61	-0.71	-2.26	-2.62	-1.74	4.70	-0.77	-1.53	-1.30	-1.05
	15	-3.50	-3.48	-2.82	-2.01	-3.63	-4.03	-2.50	9.25	-0.90	-1.74	-1.28	-1.00
	60	-2.92	-3.79	-4.35	-2.46	-3.59	-4.23	-2.63	20.23	2.84	-1.98	-1.62	-1.85
Sat	1	-0.79	-0.45	-0.30	0.50	-0.04	-0.97	-1.46	-1.63	-1.36	-1.07	-0.91	-0.64
	5	-1.95	-1.67	-1.41	-0.64	-1.62	-2.67	-2.59	-2.74	-2.31	-1.27	-1.15	-0.95
	15	-2.00	-2.45	-2.17	-1.32	-2.06	-3.38	-3.12	-3.04	-2.59	-1.16	-1.05	-0.74
	60	-2.34	-2.80	-1.64	-1.20	-2.31	-3.57	-3.17	-2.84	-2.63	-1.08	-1.19	-0.83
Sun	1	-1.10	-0.95	0.01	-0.31	1.10	0.32	-1.05	-1.79	-1.85	-1.48	-1.53	-1.34
	5	-1.94	-2.24	-1.35	-2.83	-1.68	-1.38	-2.86	-3.53	-3.74	-2.60	-2.33	-1.64
	15	-2.44	-2.77	-1.82	-3.56	-2.82	-2.08	-3.35	-4.15	-3.76	-2.90	-2.33	-1.75
	60	-2.18	-3.41	-2.23	-3.22	-2.95	-1.72	-4.70	-4.10	-3.29	-2.55	-2.43	-2.35

		Hours of the Day											
Day	Agg	12	13	14	15	16	17	18	19	20	21	22	23
M-Th	1	-0.68	-0.66	-0.36	-0.23	0.06	0.15	-0.28	-0.92	-0.88	-0.58	-0.76	-0.92
	5	-0.82	-1.06	-0.66	-0.24	1.07	1.18	0.68	-1.29	-1.27	-0.89	-1.20	-2.10
	15	-0.99	-1.11	-0.54	0.34	3.58	2.27	2.25	-1.36	-1.23	-0.86	-1.20	-2.31
	60	-1.12	-0.96	-0.19	1.84	11.88	3.98	17.64	-1.53	-1.36	-1.01	-0.62	-1.90
Fr	1	-0.33	-0.16	-0.49	-0.11	1.09	0.86	-0.25	-0.52	-0.59	-0.46	-0.62	-1.12
	5	-0.67	-0.87	-0.95	0.16	3.01	3.85	0.40	-0.96	-0.78	-0.71	-0.81	-2.01
	15	-0.32	-1.11	-0.81	0.46	6.22	7.13	1.47	-0.45	-1.41	-0.93	-0.95	-2.24
	60	-0.37	-0.26	-1.28	5.53	16.88	15.37	4.62	1.16	-1.29	-1.38	-0.80	-0.66
Sat	1	-0.65	-0.47	-0.58	-0.79	-0.72	-0.81	-0.56	-0.88	-0.57	-0.42	-0.41	-0.87
	5	-0.69	-0.41	-0.79	-0.96	-0.87	-1.08	-0.66	-0.81	-0.47	-0.45	-0.83	-1.64
	15	-0.42	-0.07	-1.00	-1.24	-0.93	-1.46	-1.09	-1.03	-0.35	-0.95	-1.11	-1.63
	60	-0.60	1.21	-1.57	-0.98	-1.23	-0.50	-1.24	-1.07	0.13	-0.84	-0.90	-1.43
Sun	1	-0.39	-0.19	-0.51	-0.67	-0.68	-0.72	-0.88	-1.28	-0.90	-0.83	-0.86	-0.85
	5	-0.20	0.39	-0.66	-0.82	-1.19	-0.99	-1.06	-2.18	-1.48	-1.17	-1.70	-1.28
	15	0.47	0.49	-0.95	-0.58	-1.43	-0.86	-1.02	-2.22	-1.81	-1.24	-1.83	-1.45
	60	0.44	0.34	-0.38	-0.40	-2.11	-0.45	2.92	-2.20	-2.23	-1.60	-1.85	-0.65

* Shaded regions are statistically different from 5% at the .05 level

TABLE 23
Results of Percent Error for NOx Estimates During May 1999 for Congested Detectors from the San Antonio Loops*

		Hours of the Day											
Day	Agg	0	1	2	3	4	5	6	7	8	9	10	11
M-Th	1	-0.25	0.76	0.54	1.09	0.19	-0.83	-0.65	0.60	-0.30	-0.74	-0.66	-0.61
	5	-1.02	0.32	-0.81	-0.68	-1.39	-2.11	-1.13	1.60	-0.04	-1.02	-0.81	-1.02
	15	-1.51	-0.31	-1.46	-1.63	-2.47	-2.69	-0.87	3.52	1.87	-1.02	-0.86	-0.97
	60	-1.85	-0.09	-1.98	-2.11	-3.00	-3.07	2.56	11.40	9.04	-0.36	-0.92	-1.47
Fr	1	-1.47	-0.59	-0.29	2.42	-0.20	-1.01	-1.08	1.57	-0.29	-0.91	-0.55	-0.38
	5	-3.14	-2.41	-1.61	-0.71	-2.26	-2.62	-1.74	4.70	-0.77	-1.53	-1.30	-1.05
	15	-3.50	-3.48	-2.82	-2.01	-3.63	-4.03	-2.50	9.25	-0.90	-1.74	-1.28	-1.00
	60	-2.92	-3.79	-4.35	-2.46	-3.59	-4.23	-2.63	20.23	2.84	-1.98	-1.62	-1.85
Sat	1	-0.79	-0.45	-0.30	0.50	-0.04	-0.97	-1.46	-1.63	-1.36	-1.07	-0.91	-0.64
	5	-1.95	-1.67	-1.41	-0.64	-1.62	-2.67	-2.59	-2.74	-2.31	-1.27	-1.15	-0.95
	15	-2.00	-2.45	-2.17	-1.32	-2.06	-3.38	-3.12	-3.04	-2.59	-1.16	-1.05	-0.74
	60	-2.34	-2.80	-1.64	-1.20	-2.31	-3.57	-3.17	-2.84	-2.63	-1.08	-1.19	-0.83
Sun	1	-1.10	-0.95	0.01	-0.31	1.10	0.32	-1.05	-1.79	-1.85	-1.48	-1.53	-1.34
	5	-1.94	-2.24	-1.35	-2.83	-1.68	-1.38	-2.86	-3.53	-3.74	-2.60	-2.33	-1.64
	15	-2.44	-2.77	-1.82	-3.56	-2.82	-2.08	-3.35	-4.15	-3.76	-2.90	-2.33	-1.75
	60	-2.18	-3.41	-2.23	-3.22	-2.95	-1.72	-4.70	-4.10	-3.29	-2.55	-2.43	-2.35

		Hours of the Day											
Day	Agg	12	13	14	15	16	17	18	19	20	21	22	23
M-Th	1	-0.68	-0.66	-0.36	-0.23	0.06	0.15	-0.28	-0.92	-0.88	-0.58	-0.76	-0.92
	5	-0.82	-1.06	-0.66	-0.24	1.07	1.18	0.68	-1.29	-1.27	-0.89	-1.20	-2.10
	15	-0.99	-1.11	-0.54	0.34	3.58	2.27	2.25	-1.36	-1.23	-0.86	-1.20	-2.31
	60	-1.12	-0.96	-0.19	1.84	11.88	3.98	17.64	-1.53	-1.36	-1.01	-0.62	-1.90
Fr	1	-0.33	-0.16	-0.49	-0.11	1.09	0.86	-0.25	-0.52	-0.59	-0.46	-0.62	-1.12
	5	-0.67	-0.87	-0.95	0.16	3.01	3.85	0.40	-0.96	-0.78	-0.71	-0.81	-2.01
	15	-0.32	-1.11	-0.81	0.46	6.22	7.13	1.47	-0.45	-1.41	-0.93	-0.95	-2.24
	60	-0.37	-0.26	-1.28	5.53	16.88	15.37	4.62	1.16	-1.29	-1.38	-0.80	-0.66
Sat	1	-0.65	-0.47	-0.58	-0.79	-0.72	-0.81	-0.56	-0.88	-0.57	-0.42	-0.41	-0.87
	5	-0.69	-0.41	-0.79	-0.96	-0.87	-1.08	-0.66	-0.81	-0.47	-0.45	-0.83	-1.64
	15	-0.42	-0.07	-1.00	-1.24	-0.93	-1.46	-1.09	-1.03	-0.35	-0.95	-1.11	-1.63
	60	-0.60	1.21	-1.57	-0.98	-1.23	-0.50	-1.24	-1.07	0.13	-0.84	-0.90	-1.43
Sun	1	-0.39	-0.19	-0.51	-0.67	-0.68	-0.72	-0.88	-1.28	-0.90	-0.83	-0.86	-0.85
	5	-0.20	0.39	-0.66	-0.82	-1.19	-0.99	-1.06	-2.18	-1.48	-1.17	-1.70	-1.28
	15	0.47	0.49	-0.95	-0.58	-1.43	-0.86	-1.02	-2.22	-1.81	-1.24	-1.83	-1.45
	60	0.44	0.34	-0.38	-0.40	-2.11	-0.45	2.92	-2.20	-2.23	-1.60	-1.85	-0.65

* Shaded regions are statistically different from 5% at the .05 level

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

For monthly total estimates, aggregation level had little effect on emissions estimates. Differences between using 20-second and 60-minute speed and volume data were less than 5%. Aggregated data typically underestimated emissions estimates. Based on this finding, the research team suggests that 1-hour aggregate data is sufficient to estimate total daily emissions.

For hour-of-day emission estimates, aggregation levels were typically less than 5% from 7 a.m. to 11 p.m. During early morning hours of very light traffic, emissions differences were much higher, ranging from 5% to 20%. Emissions differences for NOx were never more than 5%, presumably due to the flat shape of the NOx curve. Based on this finding, the research team suggests that detailed data (20-second or 1-minute) be used to estimate emissions by hour of day.

For a congested subset of the San Antonio system, emissions differences were slightly greater than for the entire San Antonio system, particularly during peak hours of the congested data set. Therefore, aggregation sizes should be reduced for analyses that require low percent error values during peak periods of congested loop sites.

For existing applications and models, data aggregation may not have significant effects on the model estimate. The results largely depend on the 1) nature of the relationship between input data and unknown variable (e.g., shape of the emission curve or the form of the equation); and 2) the complexity of the model process. In other words, some existing models may not be capable of taking advantage of the detailed nature of ITS data now available.

However, one cannot assume that data aggregation is not important simply because it does not effect results using existing models. Detailed data at the lowest aggregation level is necessary in developing and/or calibrating the next generation of transportation models (e.g., TRANSIMS).

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