PB2002-104354

FINAL
CONTRACT REPORT

EXAMINATION OF CORE CONCEPTS IN THE *HIGHWAY CAPACITY MANUAL* PART II: FREEWAY TRAFFIC LANE DISTRIBUTION

BRIAN L. SMITH, Ph.D.
Assistant Professor
Department of Civil Engineering
School of Engineering & Applied Science
University of Virginia

V · I · R · G · I · N · I · A
VTRC
TRANSPORTATION RESEARCH COUNCIL

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

Reproduced from
best available copy.

PROTECTED UNDER INTERNATIONAL COPYRIGHT
ALL RIGHTS RESERVED
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE

REPRODUCED BY:
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

Standard Title Page - Report on Federally Funded Project

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VTRC 02-CR4		

4. Title and Subtitle Examination of Core Concepts in the Highway Capacity Manual: Part II: Freeway Traffic Lane Distribution	5. Report Date January 2002
	6. Performing Organization Code
7. Author(s) Brian L. Smith, Ph.D.	8. Performing Organization Report No. VTRC 02-CR4
9. Performing Organization and Address Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agencies' Name and Address Virginia Department of Transportation — FHWA 1401 E. Broad Street — P.O. Box 10249 Richmond, VA 23219 — Richmond, VA 23240	13. Type of Report and Period Covered Contract: February 1, 2000 – September 30, 2001
	14. Sponsoring Agency Code
15. Supplementary Notes	

16. Abstract

An important consideration of transportation management is the distribution of lane use by vehicles. This distribution plays a significant role in how traffic management devices, such as variable message signs, lane control signals, and ramp meters, are used. Unfortunately, according to the *Highway Capacity Manual (HCM),* "when two or more lanes are available for traffic in a single direction, the distribution in lane use varies widely … there are not 'typical' lane distributions."

An investigation of this concept using a large set of data from freeways in the urbanized Hampton Roads region of Virginia led to the following conclusions:

- The distribution of vehicles along a specific link of a freeway system does tend to follow predictable trends by time-of-day.
- A missing data estimation procedure can be developed that exploits the consistency of lane distribution by time-of-day and location. This estimation methodology proved to accurately estimate missing detector data, generally producing results within the 6%-8% error range.

Finally, the report presents the following recommendations to VDOT:

- VDOT should collect and archive traffic data at the lane level to support future applications, such as the missing data estimation methodology.
- VDOT should use the lane distribution-based missing data estimation methodology described in this report in Smart Traffic Centers and permanent count stations located on freeways.

17 Key Words	18. Distribution Statement
highway, capacity, lane distribution	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	14	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL CONTRACT REPORT

EXAMINATION OF CORE CONCEPTS IN THE *HIGHWAY CAPACITY MANUAL*
PART II: FREEWAY TRAFFIC LANE DISTRIBUTION

Brian L. Smith, Ph.D.
Assistant Professor
Department of Civil Engineering
School of Engineering & Applied Science
University of Virginia

Contract Research Sponsored by
Virginia Transportation Research Council

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

Charlottesville, Virginia

January 2002
VTRC 02-CR4

NOTICE

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

Copyright 2002 by the Commonwealth of Virginia.

NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

ABSTRACT

The *Highway Capacity Manual (HCM)* is one of the most widely used traffic engineering guidance documents in the world. It was originally published in 1950, and has been under constant revision since. Unfortunately, due to past cost and time constraints associated with traffic data collection, much of information in the manual is based on research conducted using relatively small data sets. This calls into question the statistical significance of some of the manual's material.

The Virginia Smart Travel Laboratory is a nationally unique research facility. The distinguishing feature of the laboratory is its direct connection to operational VDOT transportation management systems. This gives the laboratory access to unprecedented quantities of traffic data. The purpose of this research project is to use this data to investigate a key concept of the *HCM:* freeway traffic lane distribution.

An important consideration of transportation management is the distribution of lane use by vehicles. This distribution plays a significant role in how traffic management devices, such as variable message signs, lane control signals, and ramp meters are utilized. Unfortunately, according to the *HCM*, "when two or more lanes are available for traffic in a single direction, the distribution in lane use varies widely ... there are not "typical" lane distributions."

An investigation of this concept using a large set of data from freeways in the urbanized Hampton Roads region of Virginia led to the following conclusions:

- The distribution of vehicles along a specific link of a freeway system does tend to follow predictable trends by time-of-day.

- A missing data estimation procedure can be developed that exploits the consistency of lane distribution by time-of-day and location. This estimation methodology proved to accurately estimate missing detector data, generally producing results within the 6%-8% error range.

Finally, the report presents the following recommendations to VDOT.

- VDOT should collect and archive traffic data at the lane level to support future applications, such as the missing data estimation methodology.

- VDOT should use the lane distribution-based missing data estimation methodology described in this report in Smart Traffic Centers and permanent count stations located on freeways.

- VDOT should formally transmit this report to TRB for committee consideration as the next version of the *HCM* is developed.

FINAL CONTRACT REPORT

EXAMINATION OF CORE CONCEPTS IN THE *HIGHWAY CAPACITY MANUAL* PART II: FREEWAY TRAFFIC LANE DISTRIBUTION

Brian L. Smith, Ph.D.
Assistant Professor
Department of Civil Engineering
School of Engineering & Applied Science
University of Virginia

INTRODUCTION

The *Highway Capacity Manual (HCM)* is widely used by transportation planners, designers, and operators as a resource of technical information (TRB, 2000). The manual has been revised many times since it was originally published in 1950. These revisions have been based on research conducted throughout North America. Therefore, the quality of future *HCMs* is directly dependent on continued research to uncover more knowledge of traffic characteristics. Much of the material in the current manual is based on research conducted many years ago when large traffic data sets were simply not available. This is a serious limitation, as described by Hurdle, Merlo, and Robertson, "relationships (in the *HCM*) are the result of committee consensus arrived at on the basis of limited data" (1997). Therefore, there is a need to revisit many of the concepts and procedures described in the *HCM* using larger, more comprehensive sets of data that will allow for statistically significant conclusions.

The Virginia Smart Travel Laboratory provides an ideal research facility to support the development of enhancements to the *HCM*. The laboratory is directly integrated with Virginia Department of Transportation (VDOT) transportation management systems. Specifically, the Smart Travel Laboratory receives speed, volume, and occupancy measurements from freeway locations throughout the Commonwealth collected using short polling intervals (2-minutes or less). These data have been archived in the Smart Travel Laboratory since May 1998, providing an enormous set of data to use in addressing highway capacity issues.

As a starting point in examining core *HCM* concepts, this project focuses on a fundamental traffic flow concept: freeway traffic lane distribution. This area, addressed in Chapter 2 of the *HCM*, "Traffic Characteristics," must be well understood in order to address more complex concepts and procedures, such as speed-flow relationships.

An important transportation management consideration is the distribution of freeway lane use by vehicles. This distribution plays a significant role in how traffic management devices, such as variable message signs, lane control signals, and ramp meters are utilized. Knowledge of lane distribution is important both in the design of systems and operations. For example, vehicle detectors frequently fail in transportation management systems. When this occurs, transportation mangers are essentially "blind" at that location. If one has knowledge of "normal" lane

distribution at that location, it would be possible to estimate the characteristics of traffic in the lane of a failed detector with knowledge of the characteristics of adjacent lanes.

Unfortunately, according to the *HCM*, "when two or more lanes are available for traffic in a single direction, the distribution in lane use varies widely ... there are no "typical" lane distributions" (2000). While this may be true from a national perspective, it may very well be that consistent patterns in lane distribution may be observed at particular types of sections of freeway, or even regionally. Because of the usefulness of this information, this concept demands further exploration.

PURPOSE AND SCOPE

The purpose of this research was to investigate the lane distribution of freeway traffic from a location specific and a regional perspective. In addition, this study sought to determine if it is possible to use historical average lane distributions, coupled with available current detector data, to estimate missing detector data.

The scope of this study was restricted based on the availability of quality data to support analysis. For this reason, this study did not address possible seasonal variations in lane distribution trends.

METHODOLOGY

The following methodology guided the research effort.

1. *Literature review.* Literature was reviewed to uncover past research that addressed highway capacity issues, focusing on freeway traffic lane distribution.

2. *Data Collection and Reduction.* Hampton Roads' area freeway traffic flow data are currently being collected on a continuing basis in the Smart Travel Laboratory. Loop detector stations are installed at 203 locations in the Norfolk and Virginia Beach areas of Hampton Roads. The stations collect, on a lane-specific basis, traffic flow, occupancy, and speed at 2-minute intervals. These data are transferred to the Smart Travel Laboratory and stored in an Oracle database. Data have been collected, and is available, for all days starting in May 1998 through the present. The purpose of this task is to make use of this resource to provide the data needed to conduct the subsequent analyses.

   The following activities were required in this task:

   - Sites were selected for analysis. The sites were chosen to reflect different traffic conditions, roadway geometry, and traffic control devices. The goal of this step was to select sites that comprise a representative sample of common freeway sections.

- Once sites were identified, dates and times were selected for analyses. Again, this selection was driven by the goal to develop a representative sample of freeway traffic conditions.

- Given that the sensors used to measure traffic conditions operate in a very hostile environment, their failure or malfunction is not uncommon. Therefore, the extracted data were examined manually, and with software tests developed in the Smart Travel Laboratory, to ensure that it is reliable. Any suspect data were identified based on established data screening rules (Turochy and Smith, 2000) and not used in further analysis.

3. *Examination of Lane Distribution Trends.* For the sites selected in Task 2, lane distribution trends will be examined by calculating/creating the following:

   - Average daily lane distribution tables, by site.

   - Plots of average lane distribution by time-of-day

The following equations are presented to detail how average lane distributions (ALD) were calculated.

$$\mathrm{ALD}_{x_i,t} = \frac{\sum_{j=1}^{J} LD_{x_i,t,d}}{J} \qquad (1)$$

$$\mathrm{LD}_{x_i,t,d} = \frac{Vol_{x_i,t,d}}{TLV_{t,d}} \qquad (2)$$

$$\mathrm{TLV}_{T,D} = \sum_{i=1}^{I} Vol_{X_i,T,D} \qquad (3)$$

where

$ALD_{x_i,t}$ = Average Percentage of Traffic in Lane x_i at Time of Day t

$\mathrm{LD}_{x_i,t,d}$ = Percent of Traffic in Lane x_i at Time of Day t on Date d

$\mathrm{TLV}_{t,d}$ = Total Link Volume at Time of Day t on Date d for the selected link

$Vol_{x_i,t,d}$ = Volume in Lane x at Time of Day t on Date d

x_i = the ith Lane of the Road

I = Total Number of Lanes on the Selected Link

d = the date in the historical data set

J = total number of records in the historical data set

4. *Develop Missing Data Estimation Methodology.* Based on the experience and insight gained in Task 3, a missing data estimation methodology was developed. This methodology sought to use both patterns in lane distributions, and current traffic condition data.

5. *Evaluate Missing Data Estimation Methodology.* To test this approach, one lane of data was eliminated for a particular link. Using the volumes in the remaining two lanes and the historical data from the second data set, the volume for the eliminated lane was estimated. The estimated values were then compared to the real value for that lane to determine the error of the estimation.

RESULTS

Literature Review

Lane distribution for a given link is defined as the proportion of total link volume served by each lane. For example, a three-lane link with a measured flow rate of 4000 vehicles/hour (veh/hr) over a 15-minute interval from 2:00 – 2:15 p.m. carries 1000 veh/hr in lane 1, 2000 veh/hr in lane 2, and 1000 veh/hr in lane 3. In this case, the lane distribution for the 2:00 – 2:15 interval is 25%/50%/25%.

Pages 8-12 in the *HCM* include several general statements concerning the concept of lane distribution:

> *When two or more lanes are available for traffic in a single direction, the distribution in lane use varies widely. The volume distribution by lane depends on traffic regulations, traffic composition, speed and volume, the number and location of access points, the origin-destination patterns of drivers, the development environment, and local driver habits.*
>
> *Because of these factors, there are no typical lane distributions. Data indicate that the peak lane on a six-lane freeway, for example, may be the shoulder, middle, or median lane, depending on local conditions.*
>
> *Table 5 gives daily lane distribution data for various vehicle types on selected freeways. The data are illustrative and are not intended to represent typical values.*
>
> *The trend indicated in Table 5 is reasonably consistent throughout North America.*

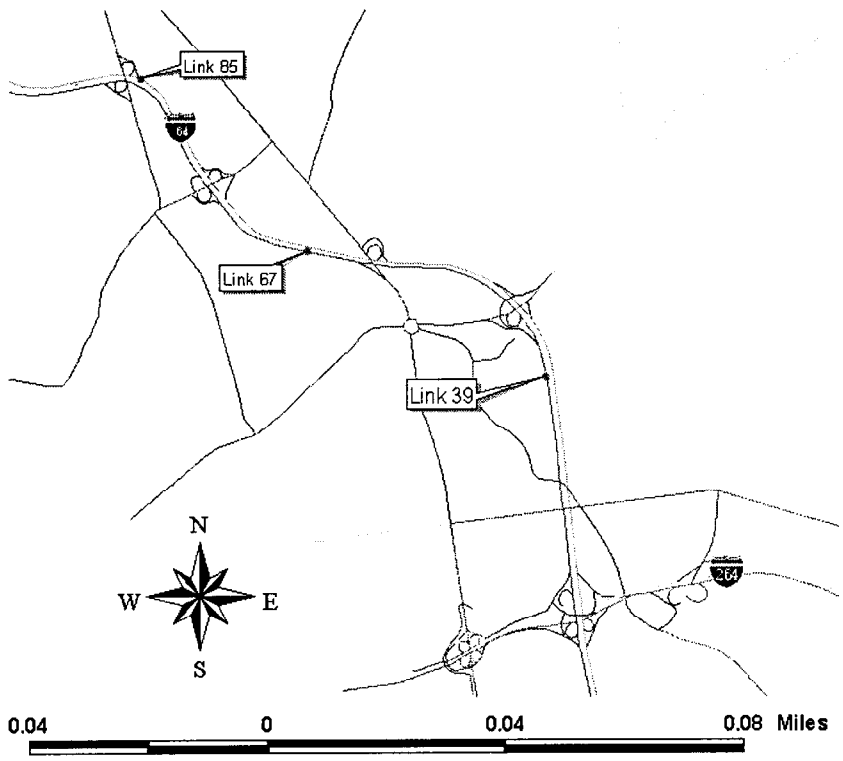
In these statements, the *HCM* lists a series of factors that affect lane distributions on roadways. It then goes on to say as a result of the variance in all of these factors "there are no typical lane distributions." This implies that lane distribution patterns *may* exist at a local level where traffic regulations, traffic composition, speed and volume, the number of and location of access points, the origin-destination patterns of drivers, development environment, and local driver habits are constant.

Data Collection and Reduction

Data sets were collected from three mainline freeway links in Hampton Roads - links 39,67, and 85, as shown in Figure 1. Two independent sets of data were collected to support the research. In both sets, the data were aggregated to 10-minute interval volume data.

Furthermore, only weekday data were used in this study to account for consistent weekday travel trends.

Figure 1. Map of Analyzed Links



The first set, collected from May 1, 2000, to August 1, 2000, was used to calculate historical lane distribution percentages for use in Task 3. This resulted in a data set containing 21,904 records. Finally, in order to evaluate the estimation technique developed in Task 5, a second set of independent data were collected from August 1, 2000, to August 3, 2000, for the same three links – 39,67, and 85. This independent data set will allow for an unbiased evaluation.

Examination of Lane Distribution Trends

Table 1 presents the average daily lane distributions determined in this research effort. In general, one will note that lane 1 tended to be used more heavily in Hampton Roads than the values reported in the *HCM* (an average of 33% as opposed to values of roughly 30% reported in the *HCM*) and lane 3 tended to be used less frequently (an average of 26% as opposed to values of over 30% reported in the *HCM*). However, given that the *HCM* states the values are illustrative, and the fact that the differences from Hampton Roads are not striking, the results of this research tend to support the manual's statement that daily lane distributions are not consistent by location. However, Figures 2, 3, and 4, which present average lane distribution by

time-of-day for the three Hampton Roads' links do clearly show that lane distribution also varies significantly by time-of-day – even at a single location.

Figure 2. Average Lane Distribution by Time of Day for Link 67

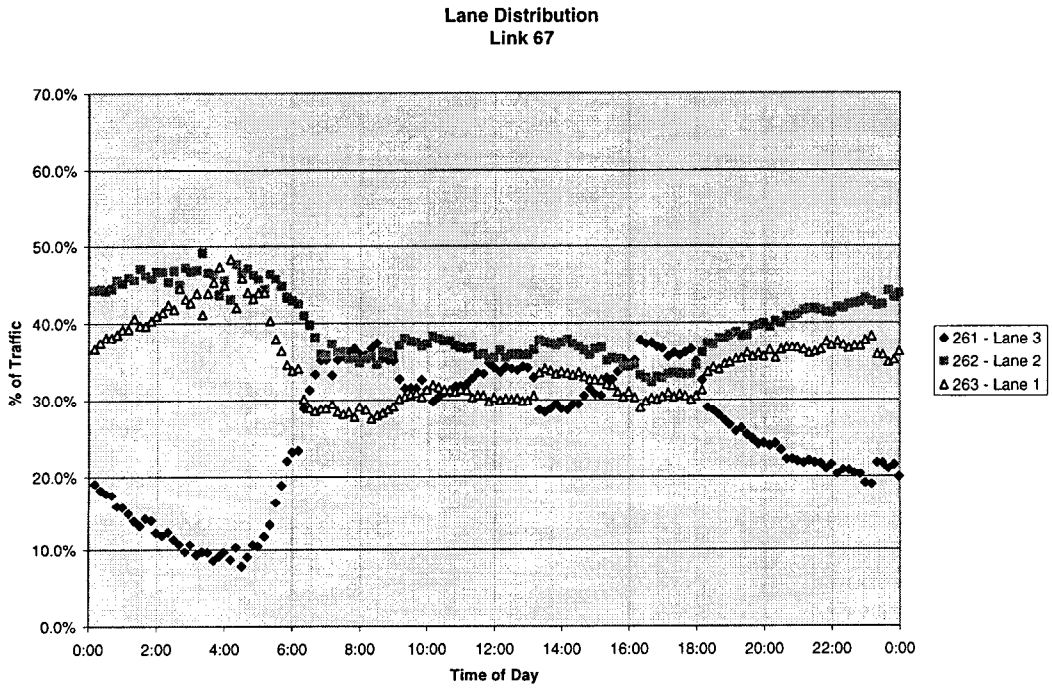


Figure 3. Average Lane Distribution by Time of Day for Link 39

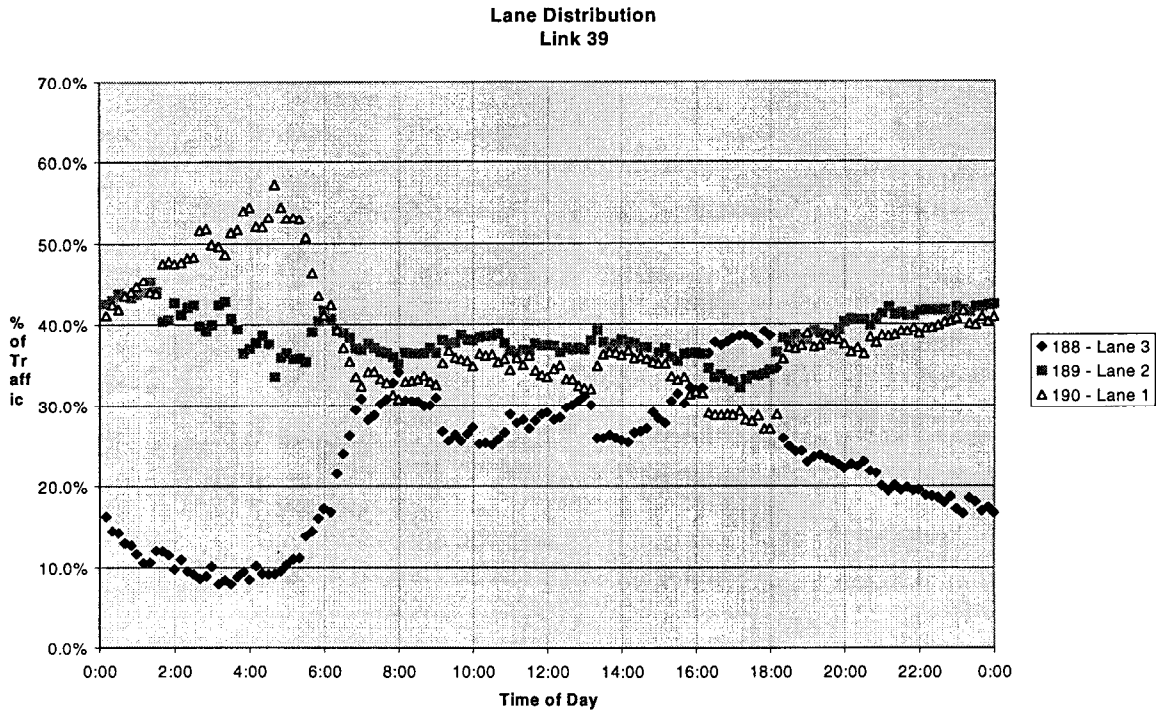


Figure 4. Average Lane Distribution by Time of Day for Link

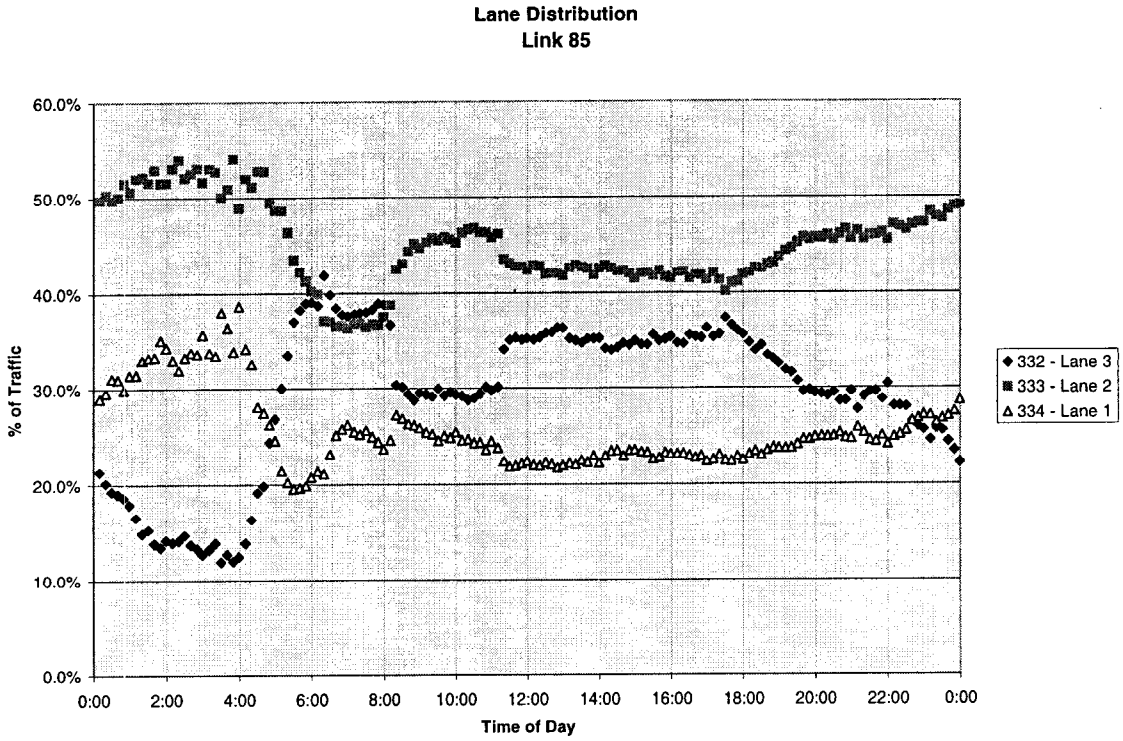


Table 1. Average Daily Lane Distributions

Average Daily Lane Distributions			
	Lane 1	Lane 2	Lane 3
Link 39	38.6%	38.5%	22.9%
Link 67	34.6%	39.6%	25.7%
Link 85	25.7%	45.0%	29.3%
Average	33.0%	41.1%	26.0%

These figures show that the average lane distribution varies significantly by time of day. However, consideration of the standard deviation of lane distribution for a particular lane and a particular time of day reveal that lane distribution does remain consistent by location and time of day. For example, Table 2 shows the average lane distributions for Link 85 by time of day and the corresponding standard deviations over the three-month period. The fact that the standard deviation values are so low indicates that the lane distribution at a given time of day does not vary significantly by location.

Table 2. Sample Average Lane Distribution and Standard Deviation for Link 85

T	Shoulder		Middle		Median	
	$ALD_{1,T}$ (%)	Standard Deviation (%)	$ALD_{2,T}$ (%)	Standard Deviation (%)	$ALD_{3,T}$ (%)	Standard Deviation (%)
...	...	...	...	...	...	...
8:20	27.2	2.1	42.5	3.5	30.3	3.0
8:30	26.8	2.7	43.0	3.2	30.1	3.1
8:40	26.3	2.1	44.4	2.5	29.4	2.9
8:50	26.1	1.9	45.1	3.1	28.8	2.8
9:00	25.8	2.0	44.7	2.9	29.5	2.6
9:10	25.4	2.3	45.3	3.0	29.3	2.8
9:20	25.2	2.4	45.7	2.6	29.1	2.9
9:30	24.5	2.3	45.5	3.0	30.0	3.3
9:40	25.0	2.2	45.8	3.0	29.2	3.1
9:50	24.9	2.0	45.6	3.1	29.6	2.9
10:00	25.4	2.3	45.3	2.7	29.3	3.0
10:10	24.6	2.3	46.2	2.6	29.2	3.3
...	...	...	...	...	...	...

Develop Missing Data Estimation Methodology

The finding that lane distribution is consistent by location and time-of-day provides the needed foundation to go forward in developing a procedure to estimate missing detector data based on lane distribution patterns. The methodology that was developed is described in detail below.

Calculate the average lane distributions for each time of day based on equations (1), (2), and (3).

$$\frac{ALD_{x_1,t_j}}{ALD_{x_2,t_j}} \quad \frac{ALD_{x_1,t_j}}{ALD_{x_3,t_j}} \quad \frac{ALD_{x_3,t_j}}{ALD_{x_2,t_j}} \text{ for } j=1,2,\ldots,144$$

Calculate volume estimate for missing data.

$$EstVol_{x,t,d}(X) = \left[\frac{\sum_{\substack{i=1 \\ i \neq m}}^{I} PtEstVol_{x,t,d}(x_i)}{I} \right] \tag{4}$$

where

$$PtEstVol_{x,t,d}(Y) = Vol_{x,t,d} \cdot \frac{ALD_{x,t}}{ALD_{y,t}} \tag{5}$$

$$PtEstVol_{x,t,d}(Y) = \left\langle \begin{array}{c} \text{Estimated Volume for Lane x based on Volume in Lane Y} \\ \text{at Time of Day t on Date d} \end{array} \right\rangle$$

$$\text{EstVol}_{x,t,d}(X) = \left\langle \begin{array}{c} \text{Estimated volume of traffic in lane x} \\ \text{at Time of Day t on Date d based on all other lanes} \in \text{X} \end{array} \right\rangle$$

I = total number of lanes

X = The set of lanes along the specified link

Evaluate Missing Data Estimation Methodology

The evaluation of the methodology focused on the hours between 6:00 and 18:30 when traffic is the heaviest (resulting in a total of 111 estimates per day). The results of the evaluation show that 92% of the estimated values were within 10% of the actual volume of the lane, and all of the estimated values were within 15% of the actual volume (Figure 5). The average error for each link is reported in Table 3.

It is important to note that a 6% average error is not significant when one considers the application of this methodology in a transportation management system. For example, the average 10-minute vehicle counts by lane at 9:30 AM on link 67 are 202, 239, and 195 respectively in lanes 1, 2, and 3. In this situation, a 6% error would represent approximately a 12-, 14-, and 12-vehicle error during this 10-minute interval. For the purposes of transportation management applications, such as ramp metering and the provision of traveler information, this error is negligible. Furthermore, the benefit of having "complete" data outweighs the detriment of a small amount of error.

Figure 5. Histogram for the Average Estimation Error for the Values between 06:00 and 18:30 on Links 39, 67, 85

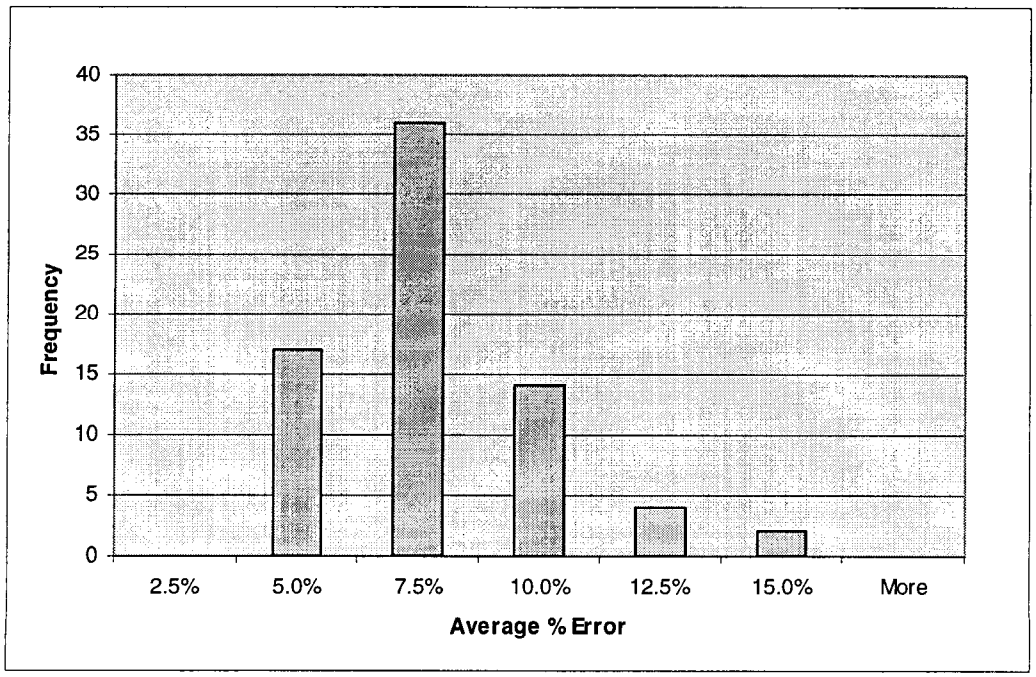


Table 3. Evaluation Results

Link	Detector ID	Average Error between 6:00 - 18:30 8/1/2000	8/2/2000	8/3/2000
39	188	11.8%	6.0%	10.4%
	189	5.9%	5.2%	7.4%
	190	6.6%	5.1%	7.3%
	Average	8.1%	5.4%	8.4%
67	261	7.0%	7.6%	7.0%
	262	5.5%	4.4%	5.5%
	263	6.4%	6.5%	6.4%
	Average	6.3%	6.2%	6.3%
85	332	7.2%	7.4%	9.9%
	333	5.5%	5.4%	5.7%
	334	6.2%	7.2%	8.2%
	Average	6.3%	6.7%	7.9%

CONCLUSIONS

This research effort demonstrated that the distribution of vehicles along a specific link of a freeway system does tend to follow predictable trends by time-of-day. This finding will serve as an important supplement to the information currently reported in the *HCM*. Finally, the missing data estimation procedure developed that exploits the consistency of lane distribution by time-of-day and location proved to accurately estimate missing detector data. The results of an

evaluation of this procedure found that the error associated with such an estimation technique is within the 6%-8% range.

RECOMMENDATIONS

The results of this research support a number of recommendations for VDOT practice, and for further research and analysis in the area of highway capacity. The following specific recommendations are presented to VDOT.

- VDOT should collect and archive traffic data at the lane level to support future applications, such as the missing data estimation methodology.

- VDOT should use the lane distribution-based missing data estimation methodology described in this report in Smart Traffic Centers and permanent count stations located on freeways.

- VDOT should formally transmit this report to TRB for committee consideration as the next version of the *HCM* is developed.

REFERENCES

Hurdle, V. F., Merlo, M. I., and Robertson, D. (1997). Study of Speed-Flow Relationships on Individual Freeway Lanes. *Transportation Research Record 1591*, pp. 7-13.

Transportation Research Board. (2000). *Highway Capacity Manual.* Transportation Research Circular – Special Report 209. National Research Council, Washington, D.C.

Turochy, R. E., and Smith, B. L. (2000). New Procedure for Detector Data Screening in Traffic Management Systems. *Transportation Research Record 1727.*