MID-AMERICA
TRANSPORTATION CENTER

Report # MATC-MST: 118

Final Report
25-1121-0001-118

Missouri Work Zone Capacity: Results of Field Data Analysis

Ghulam Bham, Ph.D.
Assistant Professor
Department of Civil, Architectural, and Environmental Engineering
Missouri University of Science and Technology

S. Hadi Khazraee
Graduate Research Assistant

2011

A Cooperative Research Project sponsored by the U.S. Department of Transportation Research and Innovative Technology Administration

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Missouri Work Zone Capacity:
Results of Field Data Analysis

Ghulam H. Bham, Ph.D.
Assistant Professor
Department of Civil, Architectural, and Environmental Engineering
Missouri University of Science and Technology

S. Hadi Khazraee
Department of Civil, Architectural, and Environmental Engineering
Missouri University of Science and Technology

A Report on Research Sponsored by

Mid-America Transportation Center

Iowa State University

University of Nebraska-Lincoln

June 2011

Technical Report Documentation Page

1. Report No. 25-1121-0001-118	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Missouri Work Zone Capacity: Results of Field Data Analysis		5. Report Date June 2011
		6. Performing Organization Code
7. Author(s) Ghulam H. Bham, S. Hadi Khazraee		8. Performing Organization Report No. 25-1121-0001-118
9. Performing Organization Name and Address Mid-America Transportation Center 2200 Vine St. PO Box 830851 Lincoln, NE 68583-0851		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Research and Innovative Technology Administration 1200 New Jersey Ave., SE Washington, D.C. 20590		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code MATC TRB RiP No. 17143
15. Supplementary Notes		

16. Abstract

This report presents the results of work zone field data analyzed on interstate highways in Missouri to determine the mean breakdown and queue-discharge flow rates as measures of capacity. Several days of traffic data collected at a work zone near Pacific, Missouri with a speed limit of 50 mph were analyzed in both the eastbound and westbound directions. As a result, a total of eleven breakdown events were identified using average speed profiles. The traffic flows prior to and after the onset of congestion were studied. Breakdown flow rates ranged between 1194 to 1404 vphpl, with an average of 1295 vphpl, and a mean queue discharge rate of 1072 vphpl was determined. Mean queue discharge, as used by the Highway Capacity Manual 2000 (HCM), in terms of pcphpl was found to be 1199, well below the HCM's average capacity of 1600 pcphpl. This reduced capacity found at the site is attributable mainly to narrower lane width and higher percentage of heavy vehicles, around 25%, in the traffic stream. The difference found between mean breakdown flow (1295 vphpl) and queue-discharge flow (1072 vphpl) has been observed widely, and is due to reduced traffic flow once traffic breaks down and queues start to form. The Missouri DOT currently uses a spreadsheet for work zone planning applications that assumes the same values of breakdown and mean queue discharge flow rates. This study proposes that breakdown flow rates should be used to forecast the onset of congestion, whereas mean queue discharge flow rates should be used to estimate delays under congested conditions. Hence, it is recommended that the spreadsheet be refined accordingly.

17. Key Words work zone, capacity, breakdown, queue discharge		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 61	22. Price

Table of Contents

Executive Summary vi
Chapter 1 Introduction 1
Chapter 2 Literature Review 2
2.1 Conceptual Aspect of Work Zone Capacity 2
2.2 Operational Aspect of Work Zone Capacity 5
Chapter 3 Field Data Collection and Processing 8
3.1 Study Site Description 8
3.2 Data Extraction 11
3.3 Data Validation 12
Chapter 4 Methodology 14
4.1 Capacity as Maximum Sustained Flow 14
4.2 Capacity as Breakdown Flow 14
4.2.1 Description of Traffic Flow Breakdown 16
4.2.2 Definitions of Traffic Flow Breakdown and Recovery 17
4.2.3 Definition of Breakdown Flow Rates 18
4.2.4 Maximum Pre and Post Breakdown Flow Rates 19
Chapter 5 Analysis of Field Data 21
5.1 Westbound Data 21
5.2 Eastbound Data 26
5.3 Summary and Discussion of Results 30
5.3.1 Comparison of Results with Missouri DOT Capacity Values 33
5.3.2 Comparison of Results with HCM 2000 Capacity Values 34
Chapter 6 Conclusions and Recommendations 36
References 39
Appendix A: Data Collection Sites and Analysis 43

List of Figures

Figure 2.1 Segments of a Speed-Flow Curve (Hall, Hurdle, and Banks, 1992).....4
Figure 3.1 Work Zone View from a Data Collection Camera, Interchange at Mile Marker 253, I-44 WB..... 8
Figure 3.2 Data Collection Site Diagram.....10
Figure 3.3 Autoscope Software Used to Extract Traffic Volume and Speed 12
Figure 4.1 Speed and Flow Rate Profile for Westbound Site, June 24th, 2010.....17
Figure 5.1 Speed Profile, 6/9/2010, Westbound.....22
Figure 5.2 Speed Profile, 6/16/2010, Westbound.....23
Figure 5.3 Speed Profile, 6/24/2010, Westbound.....23
Figure 5.4 Speed Profile, 8/12/2010, Westbound.....24
Figure 5.5 Speed Profile, 6/9/2010, Eastbound 27
Figure 5.6 Speed Profile, 6/24/2010, Eastbound 28
Figure 5.7 Histogram of Queue Discharge Flow Rate (EB and WB directions combined) 33

List of Tables

Table 5.1 Maximum Sustained Flow Rate (Pacific Site, I-44 Westbound)..... 21
Table 5.2 Capacity-Related Measures for Each Breakdown (I-44 Westbound)..... 24
Table 5.3 Vehicle and Truck Composition (Westbound) 26
Table 5.4 Maximum Sustained Flow Rate (Eastbound) 26
Table 5.5 Capacity-Related Measures for Each Breakdown Event (Eastbound) 29
Table 5.6 Vehicle and Truck Composition (Eastbound) 29
Table 5.7 ANOVA Results of Breakdown Flow Rates (vphpl)..... 32

Executive Summary

The estimation of work zone capacity is crucial in work zone management. An accurate estimate of work zone capacity helps engineers schedule construction activities to avoid traffic congestion. It can also be used to forecast the delay and user costs associated with congestion. Work zone capacity has been defined differently by different researchers. The capacity analysis method used in this study identifies traffic breakdown events and compares traffic flow before, during, and after the onset of congestion.

This study uses the two most common definitions of work zone capacity: 1) breakdown flow and 2) mean queue discharge flow. Each definition is useful for certain applications. For instance, if the purpose of capacity estimation is to schedule lane closures to avoid traffic congestion, breakdown flow is the appropriate definition to use because it is the flow rate at which traffic is likely to break down. On the other hand, mean queue discharge is more suitable for delay and user cost estimation because it is the average flow rate at which a work zone is likely to operate once queues form.

Field data were collected from a work zone on I-44 around Pacific, Missouri, with a speed limit of 50 mph. Multiple days of traffic data for westbound and eastbound directions of traffic were collected within the work zone. The maximum sustained flow rate was calculated; the average maximum fifteen-minute sustained flow rate was 1340 vehicles per hour per lane (vphpl). Breakdown events were frequent: a total of eleven breakdown events were observed. The breakdown flow rates ranged between 1194 to 1404 vphpl, with an average of 1295 vphpl. The mean queue discharge rate of traffic was 1072 vphpl. The value of mean queue discharge lower than the mean breakdown flow indicates the well-known phenomenon of reduced flow rate following traffic breakdown and the formation of queues.

Capacity based on mean queue discharge converted to passenger cars per hour per lane (pcphpl) yielded 1199 pcphpl. This value is well below the average of 1600 pcphpl prescribed by the HCM (2000) based on the same definition. This reduction in capacity is attributable mainly to reduced lane width and a high percentage of heavy vehicles (around 25%) in the traffic stream.

The results of this study also indicate that traffic breakdown is stochastic and traffic may break down at different flow rates even under the same geometric, environmental, and control conditions. These flow rates also show that traffic does not necessarily break down once it reaches a certain flow rate conventionally assumed to represent capacity. The Missouri DOT currently uses a spreadsheet for estimation of queue length and delay that assumes the queue discharge rate to be equal to the breakdown flow. The current study, however, observed the mean queue discharge rate to be considerably lower than the average breakdown flow rate. This study, therefore, suggests that the Missouri DOT refine the spreadsheet by differentiating between the breakdown and the mean queue discharge flow rates.

Chapter 1 Introduction

Highway construction zones are a major source of traffic congestion. They reduce freeway capacity, and they increase traffic accidents, fuel consumption, vehicle emissions, user costs, and driver frustration. Highway agencies must plan and manage work zones effectively to mitigate these problems. Forecasting of disruptions is necessary to devise traffic control plans at affected facilities. Work zone delays and their effects cannot be quantified without an accurate estimate of work zone lane capacity; therefore, such estimates are critical to the success of traffic management and control plans for work zones.

The objective of this research project was to study traffic operations at construction zones to develop guidelines to estimate work zone capacity on interstate highways in Missouri. Research focused on a construction zone on I-44 around Pacific, Missouri during the summer of 2010. Traffic data were collected for four days for both eastbound and westbound directions, and the traffic breakdown flow was analyzed. Multiple breakdowns were observed in each direction, permitting researchers to study the variability of different measures of capacity. Traffic data were also collected in 2009 for three other work zones. In these cases, however, no traffic breakdowns occurred, so measures of capacity could not be studied. These data sets are presented in Appendix A of this report.

Chapter 2 Literature Review

The Highway Capacity Manual (HCM) 2000 (1) does not explicitly define work zone capacity. HCM 2000 defines highway capacity as: "the maximum hourly rate at which persons or vehicles can be reasonably expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions."

A number of studies have presented varying definitions of freeway work zone capacity. Two aspects of the definition merit particular consideration: the conceptual and the operational. The conceptual considers work zone capacity to refer to either mean queue discharge or breakdown flow. The operational, on the other hand, considers issues such as volume analysis and measurement location. Volume analysis estimates work zone capacity by taking vehicle counts every five, fifteen, or sixty minutes. Measurement location refers to the point at which vehicles should be counted: at the start of the transition area, at the end of the transition area, or within the activity area. These factors directly or indirectly affect work zone capacity.

2.1 Conceptual Aspect of Work Zone Capacity

According to Persaud and Hurdle (2), capacity can be best defined as the mean queue discharge rate. They argue that expected maximum flow is not pertinent to the prediction of congestion because when congestion occurs, the flow is no longer at its maximum but is governed instead by the queue discharge rate, which is usually lower than the (expected) maximum flow. As an example, Dehman et al. (3) observed a significant loss of capacity following weekday peaks at the onset of oversaturated (i.e., queuing) conditions, and they claimed that the capacity drop was mainly due to queue formation.

In one of the earliest studies of work zone capacity, Kermode and Myra (4) measured volumes for three-minute intervals during a lane closure with congested conditions. They

averaged two consecutive three-minute counts separated by one minute. Then they multiplied the average value by 20 to determine the one-hour capacity values. Similarly, Dudek and Richards (5) identified capacity as full-hour volumes counted at lane closures with traffic queued upstream, and they considered consecutive hours at the same location as independent studies. A study by Krammes and Lopez (6) updated the capacity values obtained by Dudek and Richards. It focused on 33 short-term freeway lane closures in Texas and consistently used the same definition, i.e., the mean queue discharge rate at a freeway bottleneck. Again, consecutive hourly volumes at a site were averaged and considered as one observation. These updated values were used in the Highway Capacity Manuals of 1994 and 2000 (7, 1) as a guide for the analysis of work zone lane closures.

Dixon et al. (8) studied 24 work zones in North Carolina. Their study relied on the generalized speed-flow curve presented by Hall et al. (9) to define work zone capacity. This three-segment curve, shown in Figure 2.1, presents speed versus flow relationships for (i) uncongested conditions, (ii) queue discharge (collapse), and (iii) queued behavior. According to this model, the first capacity value occurs during uncongested conditions (shown at the high-flow end of the uncongested curve, i.e., segment 1). The second value appears as a vertical line and represents collapse to queued conditions (segment 2). This flow value is less than the uncongested curve capacity, and it is consistent with behavior generally observed in a work zone. Collapse typically occurs within a range of flow values (not at a static flow value) and generally conforms to the high-flow volume of the queued conditions. Consequently, Dixon's group defined capacity as the flow rate immediately before queuing begins (collapse flow), and they evaluated the speed-flow relationship to determine it. They selected the 95th percentile value of all five-minute within-a-queue observations as capacity because that value most often aligns with

segment 2 of the speed-flow curve, and the 95th percentile value eliminates unusually high, short-term, unsustainable flow rates.

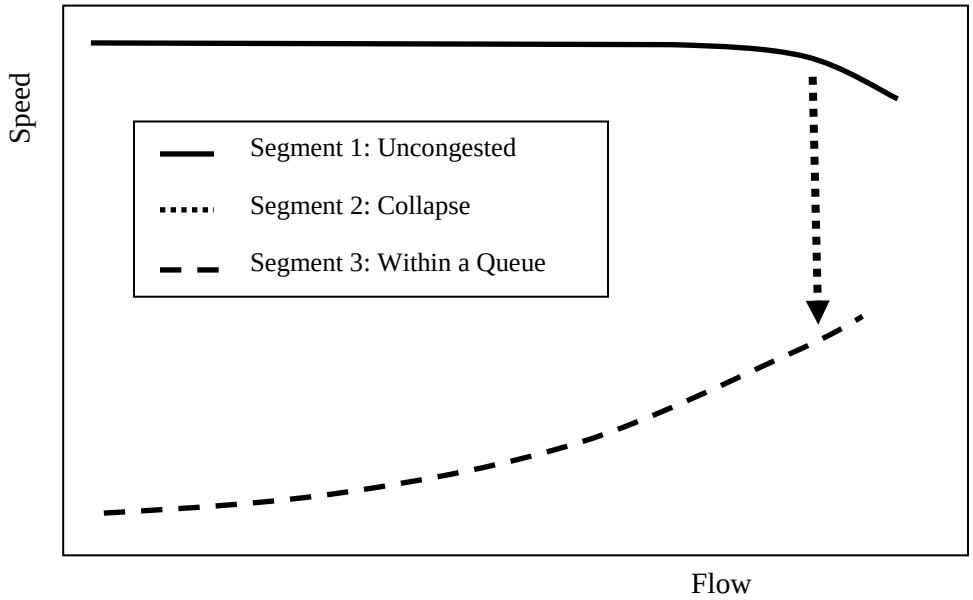

Figure 2.1 Segments of a Speed-Flow Curve (Hall, Hurdle, and Banks, 1992)

Jiang (10) studied capacity at four work zones in Indiana. He considered the North Carolina definition (8) to be the closest to the general definition of capacity provided by the HCM, and he defined the work zone capacity as the traffic flow rate just before a sharp drop in speed, followed by a sustained period of low vehicle speeds and fluctuating traffic flow rates. Similar to the North Carolina definition, this implies that work zone capacity is the level at which traffic behavior quickly changes from uncongested conditions to queued conditions. However, instead of evaluating the speed-flow curve, Jiang plotted the speed profile over time to identify the point at which capacity occurs. This transitional capacity value, however, is not sustainable and can only be measured over a very short time period.

Although the North Carolina and Indiana studies showed a significant capacity drop at the beginning of queue formation, Maze et al. (11) observed no such drop in the data they collected at a work zone in Iowa. To determine capacity during lane closure, they took the average of the ten highest fifteen-minute volumes immediately before and after queuing conditions.

In a recent study (12), 15 days of traffic data were collected from a long-term work zone in Florida. Breakdown events were identified using speed profiles, and four measures of capacity were determined for each breakdown event: maximum pre-breakdown flow, breakdown flow, maximum discharge flow, and average discharge flow. Researchers in this study believe that the method used by Heaslip et al. (12) is a detailed method for capacity analysis so far, because different measures of capacity have specific applications. For instance, breakdown flow is an appropriate measure for prevention of traffic congestion, and queue discharge is appropriate for analysis of queue length and delay.

2.2 Operational Aspect of Work Zone Capacity

Methods to measure capacity also vary considerably. The important operational aspects of work zone capacity analysis include type of equipment to be employed, procedure for traffic count, and location(s) of count stations.

Dixon et al. (8) used magnetic traffic counters and classifiers in a study of North Carolina work zones. They positioned these devices in the center of the lane and collected data at five-minute intervals, analyzing speeds as well. They also deployed classifiers at the end of the transition area because the research previously conducted by Krammes and Lopez (6), on which the HCM guidelines are based, identified this point as the critical capacity location for the evaluation of the speed-flow relationship. An additional classifier was positioned adjacent to the activity area (approximately in the middle of the construction zone) to permit comparison of

vehicle speeds adjacent to the activity area to those vehicles entering the work area. This device was not moved during data collection, but construction activity typically moved forward in the direction of travel over time. As a result, this device monitored speed adjacent to the active work area only during a portion of the collection period. Dixon et al. used similar device configurations for two-to-one, three-to-two, and three-to-one lane closures (where three-to-two means that out of three, two lanes were open for travel).

A South Carolina study of interstate highway lane closures measured queue length, traffic count and vehicle speeds (13). Queue length was measured manually from the beginning of the taper using visible markers. Traffic flow data were collected using video cameras mounted at a height of 30 ft (9 m) and covering the taper and lane closure transition immediately upstream of the work zone. Average speed was measured using a radar gun, and speed was aggregated at five-minute intervals unless it dropped below 35 mph (56 km/h), in which case it was aggregated at one-minute intervals.

The two studies, in North and South Carolina, offer an interesting comparison. The first aggregated volume at five-minute intervals and converted them to hourly flow rates, whereas the second used continuous hourly volumes. The latter case showed a capacity value 11% to 12% lower than that observed in the former. This difference occurred primarily because discrete surges in five-minute passenger vehicle volume in the former case were reduced when combined with several other five-minute periods because an unusually high five-minute volume cannot be sustained over an hour.

In an Ontario study (14), traffic data were recorded using five-minute traffic counts, and each count was converted into an equivalent hourly flow rate. The researchers indicated that this time interval met two important requirements. First, it ensured a sufficient number of

observations for statistical analysis, thus limiting random variation in capacity to an acceptable level. Second, it was deemed long enough to smooth out random fluctuations that would typically occur with shorter time intervals.

To summarize, varying definitions of freeway work zone capacity can be found. This project uses four measures of capacity for each breakdown event i.e., maximum pre-breakdown flow, breakdown flow, maximum discharge flow, and average discharge flow. The maximum pre-breakdown and the breakdown flow both provide appropriate measures for prevention of traffic congestion. The maximum and average discharge flows represent measures of queue discharge that are appropriate for analysis of queue length and delay. Traffic data should be collected from a major bottleneck within the work zone. The bottleneck location can be the end of taper or downstream of merge (on-ramp) within the work zone. Five-minute or shorter aggregate intervals are appropriate for breakdown and queue discharge analysis as they are neither too short to show significant transience nor too long to obscure major changes in speed and flow.

Chapter 3 Field Data Collection and Processing

3.1 Study Site Description

The project to widen I-44 from mile marker 251 to 255 (close to Pacific, Missouri) began in May 2010 with an estimated duration of four months. In the first phase of this project, two median lanes (one in each direction) were added to the existing freeway. The middle lane in each direction was usually closed to traffic during construction to increase safety and to provide sufficient space for construction equipment to move through the work zone. Figure 3.1 shows a snapshot of the camera view used to collect data.

Figure 3.1 Work Zone View from a Data Collection Camera, Interchange at Mile Marker 253, I-44 WB

As shown in Figure 3.1, in addition to the new median lane under construction, the middle lane was also closed; only the rightmost lane remained open to traffic in both directions. This configuration was considered a two-to-one lane closure because the median lanes in both directions were not part of the existing highway. Due to the limited lateral space, the width of the

driving lanes was reduced from 12 ft to 10 ft during construction of the median lanes, and a number of traffic signs warned drivers about the narrower lanes. In the next phases of the project, the existing driving lanes (two in each direction) were overlaid with concrete and leveled with the newly added lanes. The driving lanes were later widened to their standard width of 12 ft after resurfacing. The highway and work zone speed limits were 70 and 50 mph, respectively.

Major work activities in this construction zone (especially concrete pouring) were usually carried out at night with only the rightmost lane open. During the day, Missouri DOT policy required that work be stopped and the middle lane opened as soon as traffic queues reached four miles. Once the middle lane opened, traffic queues dissipated quickly. When two lanes were open, traffic volume never broke down. It was, however, subjected to heavy congestion with one lane open during peak hours. Since I-44 is used by daily commuters to the St. Louis area, the eastbound traffic usually reached its peak during early morning, whereas the westbound traffic peak usually occurred in the afternoon.

Due to the nature of work activity in the construction zone, the length of the work zone was not modified during the entire four months duration of the project. Figure 3.2 shows the length of the work zone, with the work zone ends indicated by bold lines perpendicular to the highway.

Figure 3.2 Data Collection Site Diagram

The work zone was four miles long with two interchanges, one at mile marker 251 and another at 253. Identification of the highway section where traffic breaks down and queues begin to form—the bottleneck—is always critical in a capacity study. This work zone had three potential bottleneck locations in each direction; namely, the end of the taper and the end of the on-ramp acceleration lanes at mile markers 251 and 253. Due to the considerable volume of traffic joining I-44 from Route 100 at Exit 253, the end of the acceleration lanes were deemed to be the most likely locations of bottleneck within the work zone in both the eastbound and westbound directions. The volume of traffic entering I-44 at Exit 251 was lighter than that at Exit 253.

The software used for data extraction, Autoscope (15), mandated that videos be collected from a high location. Due to the terrain of I-44 at Exit 253, the only appropriate location for placement of video cameras was on the overpass across the highway at mile marker 253. Placement of cameras on the bridge hindered the collection of speed and volume data at the end of the acceleration lanes, therefore, the traffic data were collected at a section of highway that was 300–400 ft upstream of the acceleration lane. The speed of vehicles at the bottleneck

location (downstream) was assumed to be similar to that at the data collection location, and the one-minute counts of vehicles entering the freeway from the on-ramp were added to the freeway one-minute counts to find the one-minute total volume.

To study the variation in work zone capacity on a specific highway section and the effects of various work zone characteristics, four days of traffic data were collected at the same location in this work zone. The work zone configuration, the width of the lanes and shoulder remained exactly the same, as shown in Figure 3.1, for all days of data collection. Traffic data were extracted only for periods when only one lane was open to traffic, and videotaping continued until the left lane was opened.

Traffic data were collected on June 9, 16, 24, and August 12. Data collection began early in the morning to capture the breakdown volume. For all four days of data, work activity was very light. In addition, because of the closed middle lane, the distance from the work activity area to the open lane (around 10 ft) was such that the effect of construction activity on drivers was apparently minimal. The weather was sunny during all four days of data collection.

For two days, June 9 and August 12, both lanes in the eastbound direction remained opened for the entire duration of data collection; therefore, eastbound data reflect no capacity issue and were not used in this study. The westbound data for the same days, however, were extracted and included in the data analysis.

3.2 Data Extraction

Separate video cameras were set up at the Exit 253 overpass for collecting data in the east and westbound directions. Speed and traffic volume data were extracted from the videos using Autoscope (15), a video-based traffic flow characteristics processing software. It uses an image processing system and detects vehicle speeds once a video snapshot of the location is correctly

calibrated. Traffic volumes were measured by placing a count detector across the highway. Individual vehicle speeds were measured by placing a speed detector at an appropriate point on the calibrated snapshot. Figure 3.3 shows a typical screen view of the Autoscope software configuration. Speed and vehicle count data were recorded at one-minute intervals throughout the data-sampling period. Vehicles were classified manually to ensure accuracy.

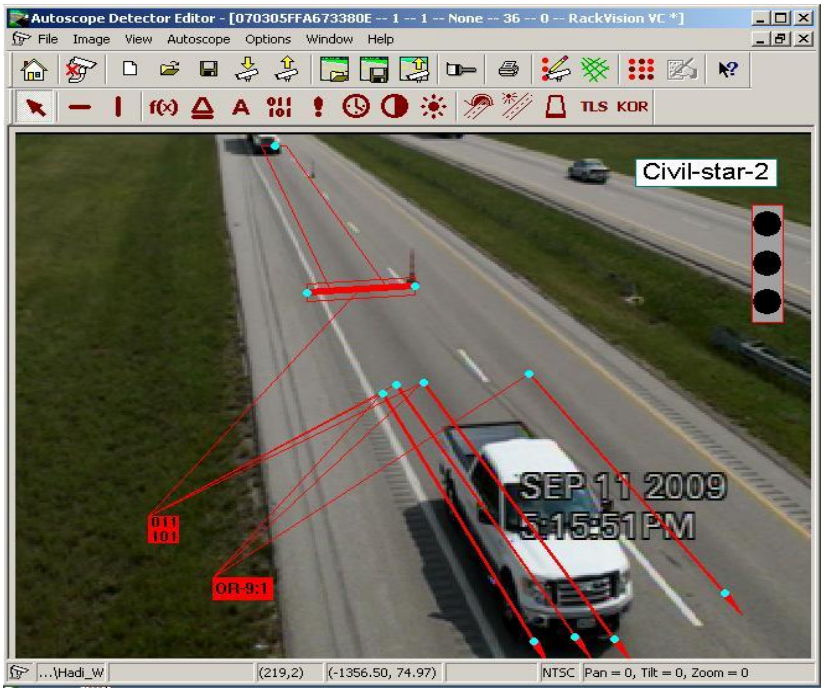

Figure 3.3 Autoscope Software Used to Extract Traffic Volume and Speed

3.3 Data Validation

The volume counts were validated by visual inspection. The extracted speeds during video recordings were validated by speeds captured for a sample of vehicles using a laser speed gun. The individual speeds extracted using Autoscope were compared to corresponding speeds from the speed gun. For each video, the comparison was carried out for at least 25 vehicles.

Based on the results of the one-to-one speed comparisons, adjustment factors in the range of 0.95 to 1.00 were applied as needed to the videos to increase accuracy.

Chapter 4 Methodology

4.1 Capacity as Maximum Sustained Flow

HCM 2000 (1) does not explicitly define work zone capacity; however, freeway capacity is generally defined as the maximum sustained fifteen-minute flow rate that can be accommodated by a uniform freeway segment under prevailing traffic, roadway, and control conditions. One traditional way to measure capacity based on field data is to find the maximum observed flow rate. For instance, a study carried out in Pennsylvania defined the work zone capacity as the hourly traffic flow converted from the maximum recorded five-minute volume (11). The present research computed maximum sustained flow rates based on three different time intervals: fifteen-minute, ten-minute and five-minute. Moving time windows were used by grouping one-minute traffic counts within each time interval. The maximum observed flow rates were then obtained by aggregating counts within an interval. To be consistent with Missouri DOT's units for work zone capacity (16), the maximum observed flow rates were determined based on vehicles per hour (vph). They were also converted to passenger cars per hour (pcph) using HCM-prescribed passenger car equivalents (PCEs) for level terrain (i.e., 1.5 for trucks and buses and 1.2 for recreational vehicles). Conversion of flow rates into units of passenger cars per hour takes into account the adverse effect of heavy vehicles on traffic flow and makes it possible for comparison of capacities between sites with different vehicle compositions.

4.2 Capacity as Breakdown Flow

Although a conventional measure of capacity, the maximum observed flow rate has certain shortcomings. Capacity estimation typically has two main purposes: prevention of traffic congestion and estimation of user delays. If traffic congestion is to be avoided, the traffic flow at which traffic breaks down (referred to here as the breakdown flow) is an important measure of

capacity. As noted above, this definition of capacity has been incorporated in a number of previous work zone studies (8, 10, and 12).

If user delays are to be estimated, the most appropriate measure of capacity is queue discharge rate because once congestion occurs, flow is governed by this rate (17). Most importantly, the capacity estimation model provided by the HCM 2000 (1) is based on studies performed in Texas (6) that measured capacity as the mean queue discharge flow rate at freeway bottlenecks.

In summary, a single value of maximum sustained flow rate does not indicate whether the maximum traffic flow is achieved before or after congestion, and it does not contain sufficient information on the likelihood of breakdown at a specific value of traffic flow. Data analysis should examine traffic flow data collected before, during, and after the transition from uncongested to congested flow (i.e., breakdown) because maximum flow may occur during any one of these three periods (18).

In addition to maximum sustained flow rates, this project used a more elaborate method of analysis proposed by Elefteriadou and Lertworawanich (18) that involves the following steps:

1. Identify and quantify each transition from uncongested to congested flow (i.e., breakdown event), and document the corresponding *breakdown flow*.
2. Identify and document the *maximum pre-breakdown flow*.
3. Identify and document the *maximum queue discharge flow*. This flow is the maximum observed at the site after the occurrence of a breakdown and prior to recovery to uncongested conditions.
4. Identify and document the *average queue discharge flow*. This flow is the average observed at the site between the beginning and end of congestion.

Each of the four traffic flows defined above was determined using five-minute intervals and expressed as equivalent hourly flow rates.

4.2.1 Description of Traffic Flow Breakdown

The method used here to identify breakdown is similar to that proposed by Lorenz and Elefteradiou (19). The current study uses one-minute interval data for speed and vehicle count. The one-minute time-mean-speed data were plotted over time to identify the moment of breakdown. Figure 4.1 illustrates a representative speed profile plot for a data sample collected on June 24 for I-44 westbound. Figure 4.1 also shows the one-minute profile plot of traffic flow. Flow rates are based on five-minute intervals throughout this study because such intervals are neither too short to be affected by transient disturbances, nor too long to mask significant changes in traffic flow characteristics.

From Figure 4.1, the moment of traffic breakdown can be identified. Prior to 9:05 a.m., the average speed was relatively high, and it fluctuated between approximately 40 and 60 mph. At approximately 9:05 a.m., the average speed dropped sharply to below 40 mph and generally remained well below 40 mph for the rest of the data collection period.

The speed profile in Figure 4.1 demonstrates that a speed boundary of approximately 40 mph existed between the congested and uncongested regions. This boundary was confirmed by visual inspection of the videos which revealed that when the work zone operated in an uncongested state (before queue formation), average speeds generally remained above the 40 mph threshold at all times. Conversely, during congested conditions (with vehicles queued upstream of the bottleneck), average speeds rarely exceeded 40 mph, and even at that they were not usually maintained for any substantial length of time. This 40 mph threshold was observed at both westbound and eastbound sites, and in all of the daily data samples showing breakdown.

This is also supported by research in Illinois (20). Chitturi and Benekohal studied the effect of lane width on vehicle speeds in work zones and found that the free-flow speed of vehicles dropped by about 10 mph for a lane width of 10 ft. Given the 50mph speed limit of the work zone studied, the 40 mph speed threshold seemed reasonable, and it was used in the definition of breakdown described below.

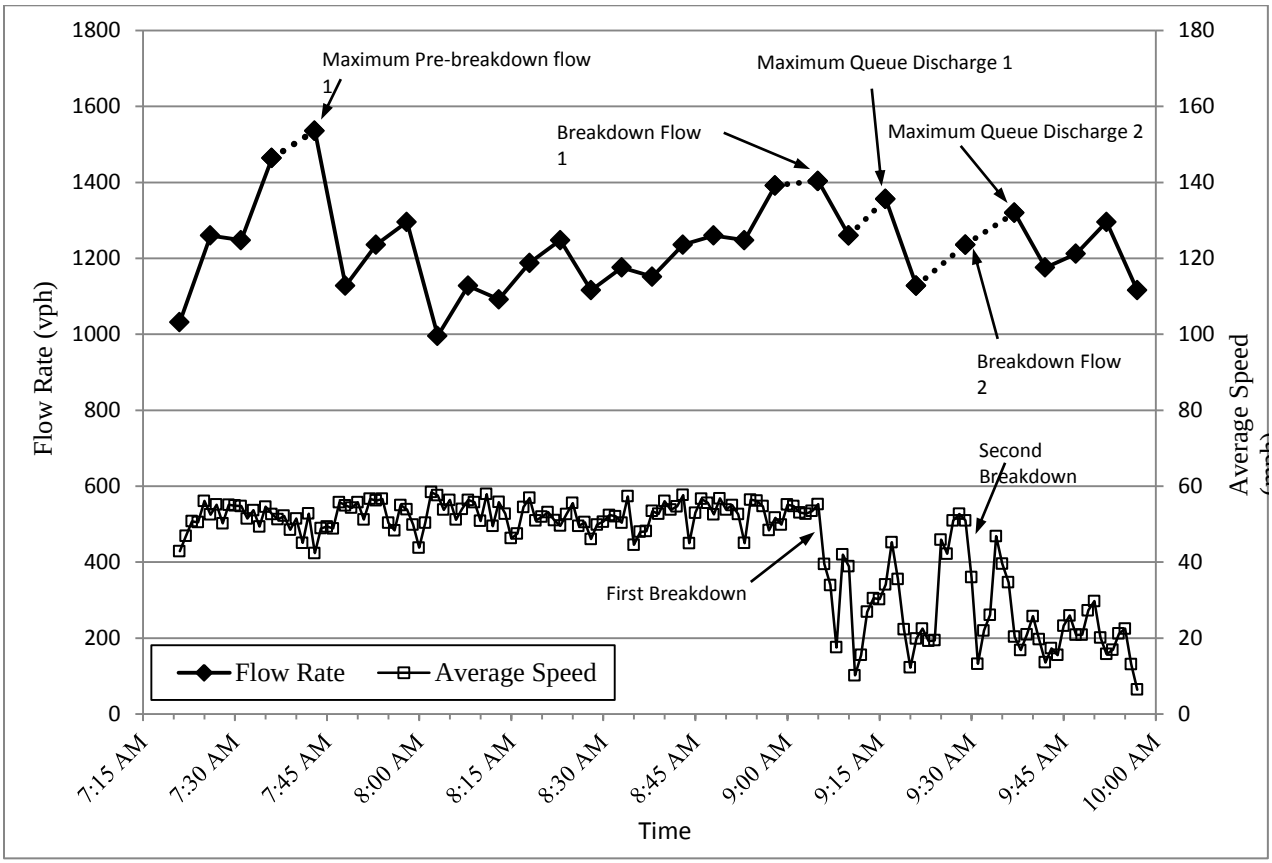

Figure 4.1 Speed and Flow Rate Profile for Westbound Site, June 24th, 2010

4.2.2 Definitions of Traffic Flow Breakdown and Recovery

Speed profiles similar to one presented in Figure 4.1 were examined. Occasionally, speed decreased to below 40 mph for a very short time period, but such decrease did not always result in a traffic breakdown. Since the traffic stream recovered from small disturbances in most cases,

only those disturbances that caused the average speed to drop below 40 mph for a period of five minutes or more (five consecutive one-minute intervals) were considered breakdowns. The same criterion was used for recovery periods, those periods when average speeds recovered to over 40 mph. A period of higher speeds was not considered a recovery period unless speeds over 40 mph were maintained for more than five minutes (i.e., five consecutive one-minute intervals).

A considerable number of borderline cases were observed, and the five-minute criterion was applied to these. For example, on June 24, as shown in Figure 4.1, after the traffic initially broke down at around 9:05 a.m., a twenty-minute period of congestion was followed by a brief period (five minutes) of recovery, and then by a second sustained period of congestion. Although one could argue that this pattern constitutes a single event, the five-minute criterion identifies two separate breakdown events. In order to keep the analysis consistent for both directions and the daily data samples, the five-minute criterion was applied consistently.

4.2.3 Definition of Breakdown Flow Rates

This project defines the breakdown flow rate as the five-minute flow rate (expressed as an equivalent hourly rate) observed immediately prior to breakdown. The procedure for finding the breakdown flow rate begins with identification of the minute during which the average speed is above 40 mph, followed by at least five consecutive one-minute periods with average speeds of less than 40 mph. The minute with such characteristics is labeled as the breakdown minute. The traffic count corresponding to this minute is then added to the sum of the minute counts of the preceding four minutes to yield the five-minute volume immediately prior to breakdown. This five-minute volume is then converted to an equivalent hourly rate and expressed as the breakdown flow rate.

A true recovery after the initial breakdown is identified when the average speed of traffic remains above 40 mph for five consecutive minutes. Once this criterion is met, the same method applies for identification of a second breakdown, if any, and the procedure continues. Selection of five-minute intervals for calculation of breakdown flow rates is consistent with the five-minute criterion used for identification of breakdown and recovery, and it ensures that the five consecutive minutes immediately prior to breakdown have uncongested characteristics (i.e., an average speed greater than 40 mph). This method of breakdown identification is also in accordance with Jiang's (10) definition of breakdown flow rate as the flow rate immediately before a sharp drop in speed. However, identification of breakdown flow rates using one-minute speed profiles yields more accurate results than breakdown flow using five-minute interval speed plots.

4.2.4 Maximum Pre- and Post-Breakdown Flow Rates

Once the breakdown events are identified, the pre- and post-breakdown periods can be easily distinguished. Pre- and post-breakdown flows generally address uncongested and congested conditions, respectively. Uncongested periods are those either before the initial breakdown event or between a traffic recovery event and another breakdown event following it. All breakdown and recovery events are identified according to the five-minute criterion explained above. Periods of time not classified as uncongested are considered congested, and are also referred to as *queued periods*. Based on this method, one-minute intervals are classified as either congested or uncongested.

Once the uncongested and congested periods of each data sample are determined, maximum pre-breakdown flow and maximum queue discharge flow are obtained using a moving time window of five minutes over the uncongested and congested time periods, respectively.

Finally, the mean queue discharge flow is computed by averaging all the one-minute flow rates during the congested period.

Figure 4.1 identifies two breakdown events and indicates their position on the speed profile. The flow rate profile indicates the maximum pre-breakdown flow, breakdown flow, and maximum queue discharge, all determined using a moving window of five-minute intervals. None of the five-minute-aggregated flow profiles would indicate these flow rates at the same time unless the aggregation of one-minute intervals was adjusted. In Figure 4.1, the sections of the flow profile shown by dotted lines indicate the intervals at which this adjustment was made. At each dotted line in the flow profile, a number of minutes (between 1 and 4) were omitted so that the next point in the series would indicate the flow rate of interest (maximum pre-breakdown flow, breakdown flow, or maximum queue discharge).

Each of the four characteristic flow rates, the maximum pre-breakdown flow, the breakdown flow, the maximum queue discharge flow, and the mean queue discharge flow, was obtained for each breakdown event. Data collection for multiple days at a particular bottleneck enabled researchers to study the variability of these four different measures of capacity. Chapter 5 summarizes the field data analysis.

Chapter 5 Analysis of Field Data

This section presents the analysis of data obtained for each day on I-44 near Pacific, Missouri. Westbound and eastbound data were analyzed separately.

5.1 Westbound Data

Table 5.1 presents the maximum sustained flow rates for the site based on different intervals.

Table 5.1 Maximum Sustained Flow Rate (Pacific Site, I-44 Westbound)

Date	15-minute		10-minute		5-minute	
	vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl
Jun. 9th	1249	1427	1265	1457	1349	1532
Jun. 16th	1157	1301	1187	1324	1277	1433
Jun. 24th	1436	1585	1476	1636	1572	1772
Aug. 12th	1388	1544	1446	1628	1542	1698
Average	1307	1464	1343	1511	1435	1609
Std. Deviation	127.89	127.77	139.90	149.66	144.43	154.27

Figures 5.1 to 5.4 present the speed profiles for the four days of data. As shown in Figure 5.1, on June 9, the traffic stream was uncongested for the entire duration of data collection. At times, the average speed fell below 40 mph, but this lower speed was not sustained for more than five minutes.

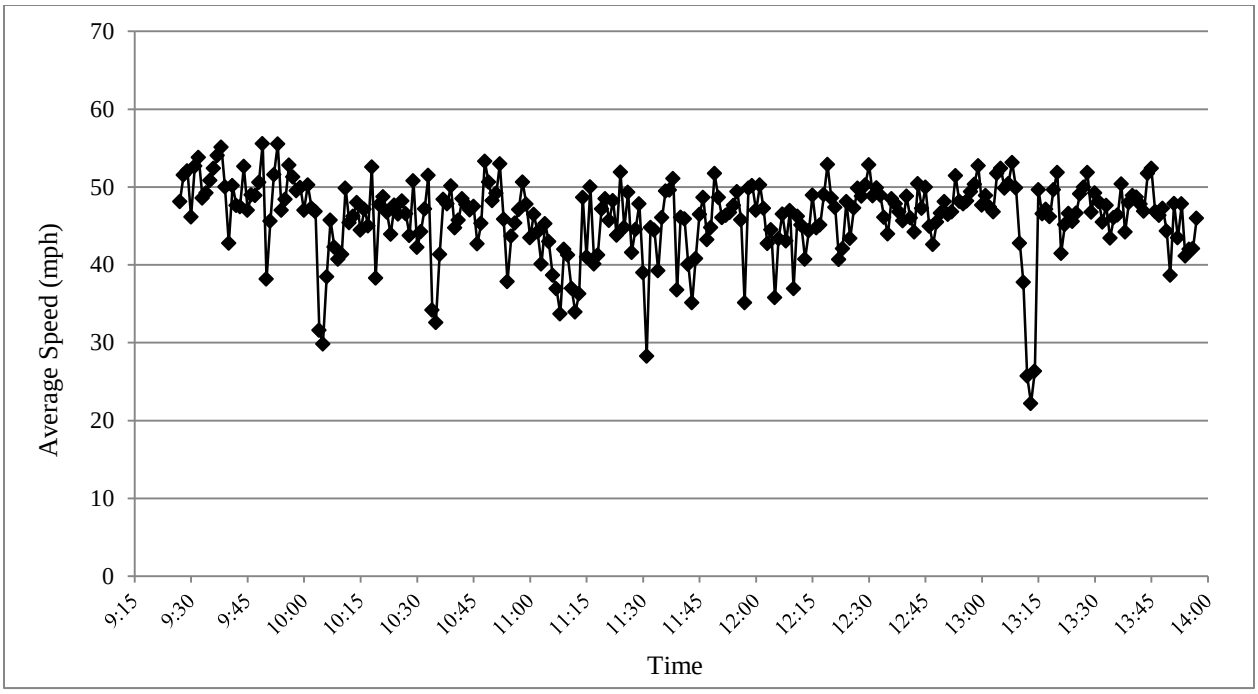

Figure 5.1 Speed Profile, 6/9/2010, Westbound

In Figure 5.2, for June 16, the single breakdown event is easily identifiable. Speed dropped significantly at 8:08 a.m., and once the traffic broke down, it never fully recovered before the end of the data collection period.

Speed profiles for June 24 and August 12 data are quite similar. As shown in Figures 5.3 and 5.4, on both days the traffic initially broke down at around 9:00 a.m., recovered after approximately twenty minutes, and underwent a second breakdown shortly thereafter. The second breakdown was followed by a sustained period of congestion towards the end of the data collection period. Although the recovery periods were very short (five to ten minutes), application of the five-minute criterion resulted in identification of two breakdown events each day.

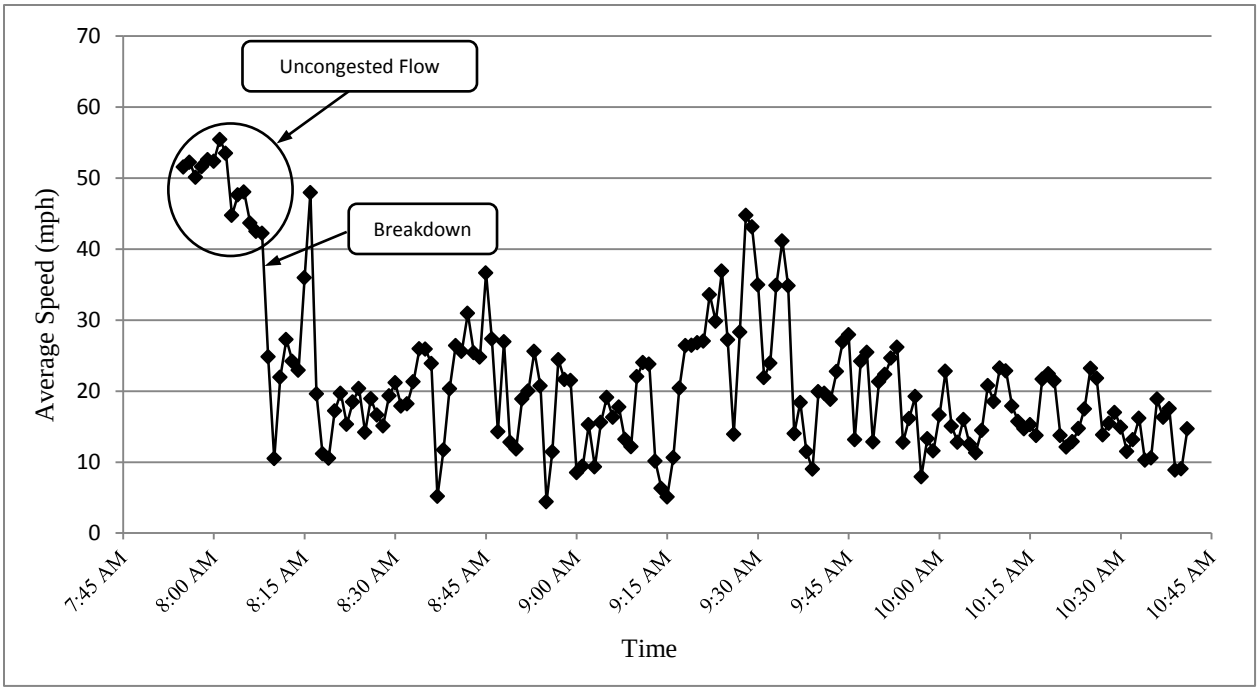

Figure 5.2 Speed Profile, 6/16/2010, Westbound

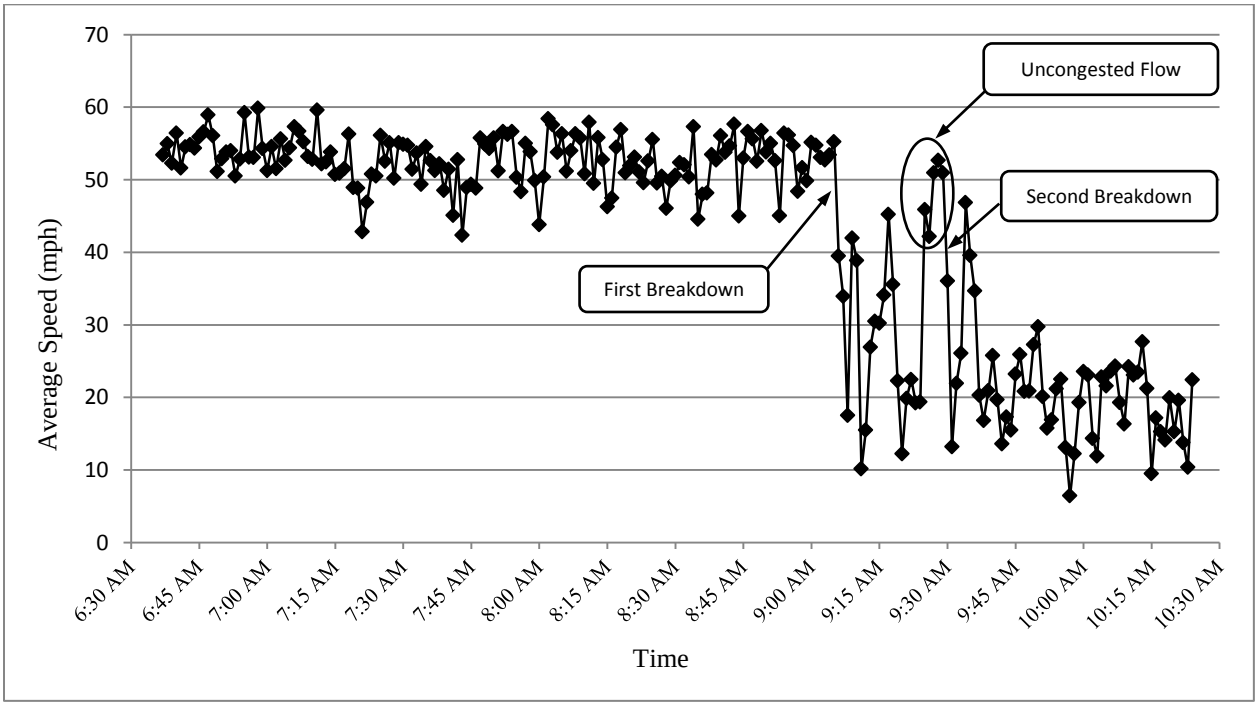

Figure 5.3 Speed Profile, 6/24/2010, Westbound

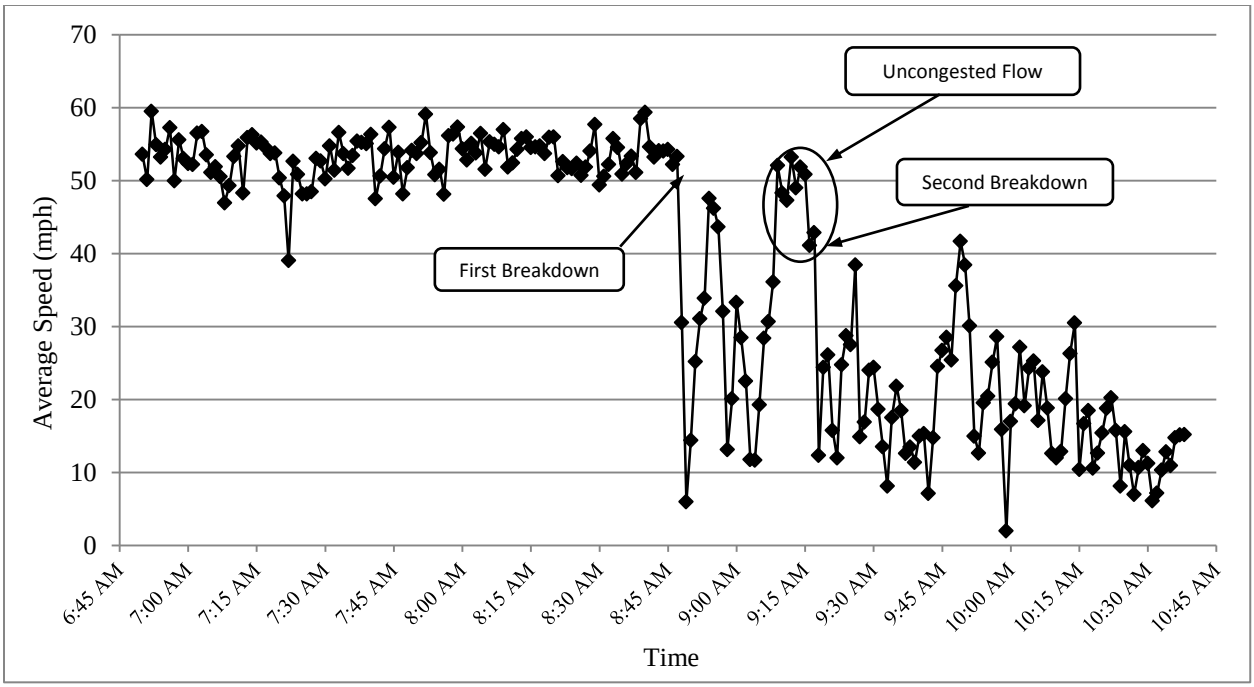

Figure 5.4 Speed Profile, 8/12/2010, Westbound

Table 5.2 Capacity-Related Measures for Each Breakdown (I-44 Westbound)

Breakdown Events	Date	Maximum Pre-Breakdown Flow		Breakdown Flow		Maximum Queue Discharge Flow		Mean Queue Discharge Flow	
		vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl
1	6/16/2010	1272	1422	1272	1422	1260	1380	1034	1158
2	6/24/2010	1536	1656	1404	1596	1356	1500	1222	1320
3	6/24/2010	1236	1416	1236	1416	1320	1464	1175	1320
4	8/12/2010	1524	1644	1368	1524	1200	1320	1051	1200
5	8/12/2010	1344	1488	1296	1452	1296	1440	1059	1200
Average		1382	1525	1315	1482	1286	1421	1108	1240
Standard Deviation		140.3	117.5	69.2	76.8	59.6	71.3	84.6	75.4
Coefficient of Variation		14.24	9.04	3.65	3.98	2.76	3.58	6.45	4.58

Table 5.2 presents the values of four predefined flow rates for each of the five breakdown events observed for the westbound direction. It also indicates that the maximum pre-breakdown flow rate was, on average, greater than the maximum post-breakdown flow rate (maximum

discharge flow). Further, the maximum pre-breakdown flow shows greater variation than either the breakdown flow or the maximum discharge flow. Importantly, breakdown flow rates are usually greater than maximum discharge flow rates, indicating that traffic congestion reduces the capacity of work zones. Previous research has also shown that when congestion occurs the flow is no longer at its maximum, but is governed instead by the queue discharge rate, which is usually lower than the expected maximum flow. As an example, Dehman et al. (3) observed a significant loss of capacity following weekday peaks at the onset of oversaturated (i.e., queuing) conditions; he claimed that the capacity drop was mainly due to queue formation.

The coefficient of variation was used to compare the variation in each of the flow rates before and after conversion to equivalent passenger cars per hour. Generally, converting flow rates into passenger cars per hour reduces the variation in characteristic flow rates because this conversion takes into account the effect of heavy vehicles. However, as shown in Table 5.2, expressing flows in passenger cars per hour reduces the variation in the maximum pre-breakdown and average discharge flows, but slightly increases the variation in the breakdown and maximum discharge flows.

Table 5.3 presents the traffic composition in general and truck composition specifically for westbound data. It shows that the percentage of heavy vehicles travelling through the work zone was relatively high, around 26%. The effect of heavy vehicles on traffic flow is therefore significant.

Table 5.3 Vehicle and Truck Composition (Westbound)

Vehicle Class	Date				Average
	Jun. 9th	Jun. 16th	Jun. 24th	Aug. 12th	
Passenger Cars	69.2%	71.2%	74.1%	73.1%	71.9%
Trucks	28.7%	26.8%	24.3%	24.9%	26.2%
RVs	1.5%	1.0%	1.2%	1.4%	1.3%
Buses	0.2%	0.2%	0.1%	0.3%	0.2%
Motorcycles	0.3%	0.8%	0.3%	0.3%	0.4%
Truck Composition					
Single Unit (short trucks)	8.9%	12.2%	15.0%	15.6%	12.9%
Single Trailer	86.4%	84.2%	78.9%	79.0%	82.1%
Double Trailer	4.7%	3.5%	6.1%	5.4%	4.9%

5.2 Eastbound Data

Data were collected for the eastbound direction on two days, June 9 and August 12. Table 5.4 presents the maximum sustained flow rates for this direction. A comparison between Table 5.1 and 5.4 indicates that the average maximum sustained flow rate in the westbound direction is slightly higher than that in the eastbound (at each length of interval).

Table 5.4 Maximum Sustained Flow Rate (Eastbound)

Date	15-min		10-min		5-min	
	vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl
Jun. 9th	1322	1477	1350	1498	1446	1573
Jun. 24th	1490	1654	1518	1681	1566	1722
Average	1406	1565.5	1434	1589.5	1506	1647
Std. Deviation	118.79	125.16	118.79	129.40	84.85	105.36

Figures 5.5 and 5.6 present the speed profiles for these two days. As shown in Figure 5.5, on June 9, a rare and interesting traffic pattern occurred in the work zone. The traffic stream broke down and recovered quickly multiple times over a three hour period. Application of the

five-minute criterion resulted in identification of six breakdown events, each shown on the speed profile in Figure 5.5. The average speed also fell below 40 mph at 10:26 a.m. and did not exceed 40 mph until 10:34 a.m. Although speeds remained below 40 mph for more than five minutes, this event was not considered a breakdown because no vehicle queues developed and traffic never became congested.

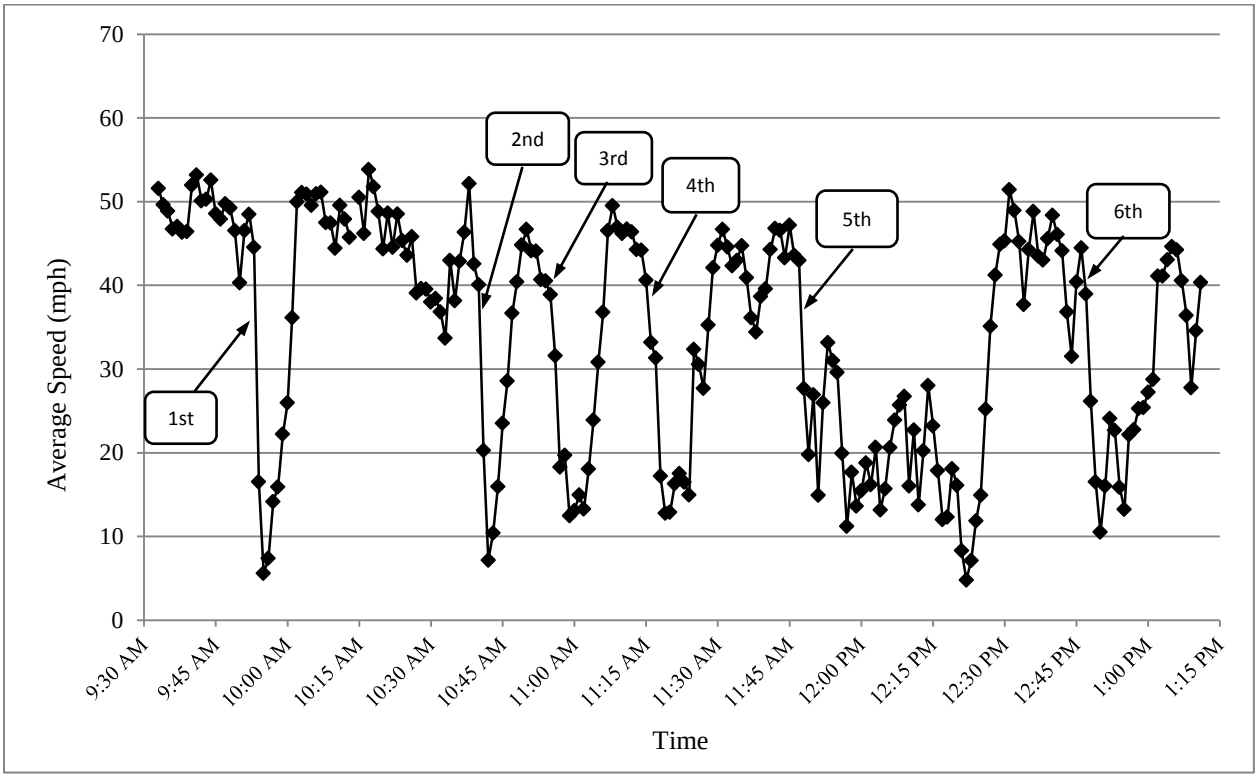

Figure 5.5 Speed Profile, 6/9/2010, Eastbound

On June 24, as shown in Figure 5.6, traffic was free flowing throughout the data collection period, and no breakdown occurred.

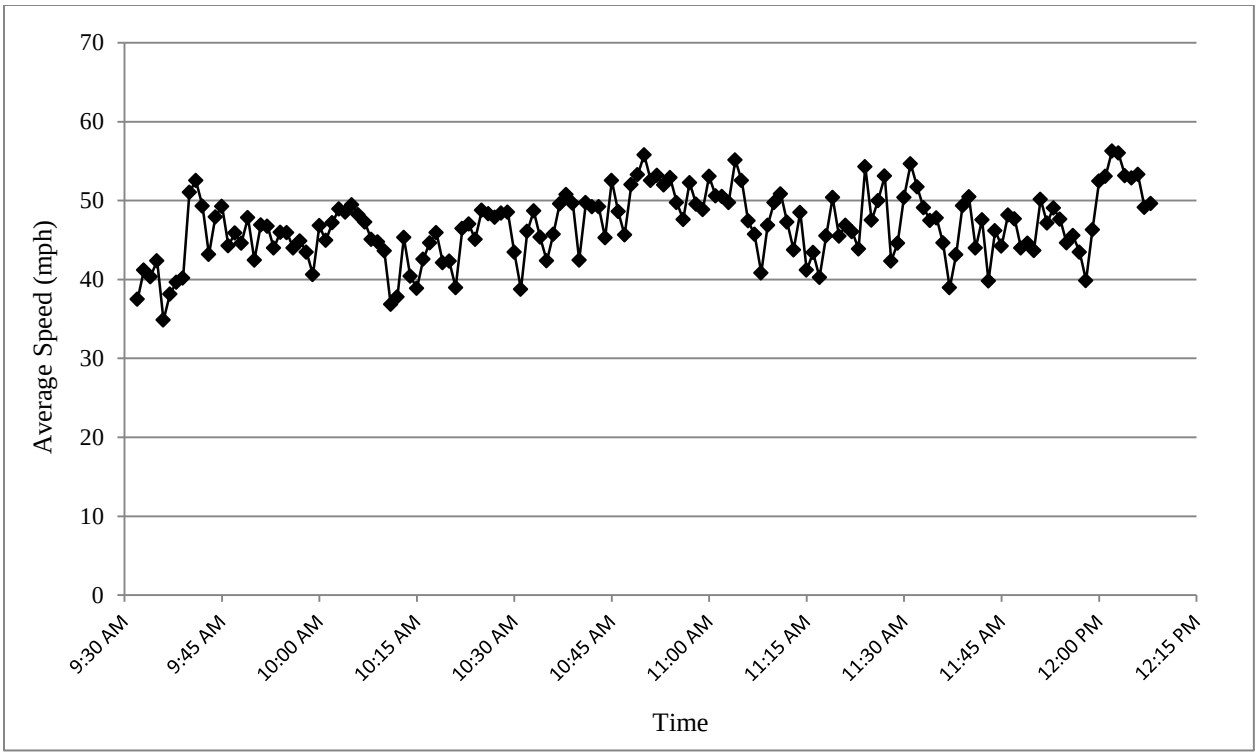

Figure 5.6 Speed Profile, 6/24/2010, Eastbound

Table 5.5 presents the four predefined flow values for each of the six breakdown events observed during the data collection period for the eastbound site. As noted above, all breakdown events in the eastbound direction were observed on June 9. As shown in Table 5.5, the six breakdown flow rates were similar; ranging between 1194 to 1362 vphpl. Conversion of vehicles per hour to equivalent passenger cars per hour significantly reduced the variance of breakdown flows. This result was expected. As for the westbound direction, the maximum pre-breakdown flow rate was on average greater than the breakdown flow rate, which on average was greater than the maximum discharge flow.

Table 5.5 Capacity-Related Measures for Each Breakdown Event (Eastbound)

Breakdown Events	Date	Maximum Pre-Breakdown Flow		Breakdown Flow		Maximum Queue Discharge Flow		Mean Queue Discharge Flow	
		vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl	vphpl	pcphpl
1	6/9/2010	1446	1536	1362	1470	1026	1152	925	1032
2	6/9/2010	1350	1500	1326	1464	1050	1212	995	1140
3	6/9/2010	1302	1409	1302	1409	1182	1344	1133	1260
4	6/9/2010	1254	1416	1194	1344	1038	1164	992	1122
5	6/9/2010	1314	1488	1230	1419	1290	1428	1050	1170
6	6/9/2010	1326	1440	1254	1436	1302	1428	1139	1266
Average		1320	1452	1278	1424	1148	1288	1039	1165
Standard Deviation		76.5	72.8	63.0	45.8	127.8	128.1	85.0	88.8
Coefficient of Variation		4.44	3.65	3.11	1.48	14.22	12.73	6.95	6.77

Table 5.6 presents the traffic composition for each day of eastbound data. The vehicle composition for eastbound direction was similar to that for the westbound direction.

Table 5.6 Vehicle and Truck Composition (Eastbound)

Vehicle Class	Date		Average
	Jun. 9th	Jun. 24th	
Passenger Cars	72.9%	75.8%	74.3%
Trucks	24.7%	21.8%	23.3%
RVs	1.6%	1.5%	1.6%
Buses	0.3%	0.3%	0.3%
Motorcycles	0.5%	0.6%	0.5%
Truck Composition			
Single Unit (short trucks)	10.8%	11.9%	11.4%
Single Trailer	85.1%	85.0%	85.1%
Double Trailer	4.0%	3.1%	3.6%

5.3 Summary and Discussion of Results

In addition to the conventional method of maximum sustained flow used in determining work zone capacity, this study used average speed and flow profiles to determine four other variables related to capacity: the traffic breakdown, the maximum pre-breakdown, maximum, and mean queue discharge flow rates. Two of these variables were used to define work zone capacity. A review of the literature indicated that work zone capacity is most often defined either as mean queue discharge or breakdown flow. Each definition has certain applications. For instance, mean queue discharge is most appropriate for estimation of user delay under congested conditions, whereas breakdown flow is best used to schedule lane closures to avoid traffic breakdown. Maximum pre- and post-breakdown flow rates were determined mainly to show that breakdown flow is not always the highest flow rate attained by traffic and can be exceeded either before or after the onset of congestion.

As Tables 5.2 and 5.5 indicate, the maximum pre-breakdown flow rates exceeded their respective breakdown flow rates for eight out of the eleven breakdown events, implying that traffic does not necessarily break down once it reaches the peak flow rate (capacity). Breakdown flow rates presented in Tables 5.2 and 5.5 were also compared to their respective maximum queue discharge flow rates after breakdown. Except for one breakdown event on June 24 in the westbound direction, no other breakdown flow rate was exceeded by flow rates that occurred during congested traffic conditions (queue discharge). This finding indicates that congested traffic can occasionally flow at rates greater than the breakdown flow rate. Work zone studies in Indiana and Iowa (10, 11) indicated the same phenomenon.

Comparison of the maximum queue discharge and maximum pre-breakdown flow rates indicate that flow rates exceeding breakdown flow are more likely to occur before breakdown

than after; out of a total of eleven breakdown events for both directions, eight were exceeded by flow rates before breakdown, and only one was exceeded after breakdown. Therefore, it is reasonable to conclude that once traffic breaks down, flow rates usually remain below the breakdown flow. This phenomenon has been documented by many research efforts (e.g., 19, 21, 22), and it is recognized by the HCM 2000 (1).

To test whether the breakdown flow rates for the eastbound and westbound directions were different, the possibility of combining data from the eastbound and westbound directions was considered. This was carried out since no noticeable differences in geometry or work intensity was observed for the two directions during the data collection period. A statistical test, an analysis of variance (ANOVA) (23), was carried out to confirm that such a comparison would be valid. The null hypothesis, H_0, was that the mean breakdown flow rate for the eastbound direction (μ_e) would be equal to that for the westbound direction (μ_w). The alternative hypothesis, therefore, was expressed as $\mu_e \neq \mu_w$. Type I error was controlled at $\alpha = 0.05$, and $F_{0.95,\,1,\,9} = 5.12$ with 1 and 9 as the degrees of freedom were associated with the factor level and the error term. Table 5.7 presents the results, and considering the flow rates in vphpl, the ANOVA test statistic was calculated to be 0.87. ($F^* = MST^1/MSE^2 = 3774.1/4339.2 = 0.87$).

Since F* (0.87) is less than $F_{0.95,\,1,\,9}$ (5.12), the difference between the mean breakdown flow in the two directions was not statistically significant. As a result, the mean breakdown flow values for both directions were combined into a single dataset. To reflect the minor differences in the breakdown flow rates of eastbound and westbound directions, however, Table 5.7 presents the individual values (means and confidence intervals) for each direction.

[1] Mean Square Treatment
[2] Mean Square Error

Table 5.7 ANOVA Results of Breakdown Flow Rates (vphpl)

Direction	Count	Mean	Standard Deviation	95% Confidence Interval	
Eastbound	6	1278	63.0	(1228, 1328)	
Westbound	5	1315	69.2	(1255, 1375)	
Source of Variation	SS	df	MS	F*	P-value
Direction (EB, WB)	3774.1	1	3774.1	0.87	0.3754
Error	39052.8	9	4339.2		
Total	42826.9	10			

The breakdown flow rates ranged from 1194 to 1404 vphpl with a mean value of 1295 vphpl and a standard deviation of 65.4 vphpl. Due to the similarity of work zone characteristics between westbound and eastbound sites, queue discharge flow rates for eastbound and westbound directions were combined. Figure 5.7 presents the distribution of queue discharge flow rates. In this distribution, one-minute intervals classified as congested flow rates were used, and 105 and 329 minutes of congested flow rates for the eastbound and westbound directions were observed, respectively. As shown in Figure 5.7, the queue discharge flow rates varied over a wide range, with mean and median values of approximately 1072 and 1100 vphpl, respectively. Comparison of the mean values of breakdown and queue discharge flow rates (mean and median) indicates a clear drop in traffic flow rates after the onset of congestion.

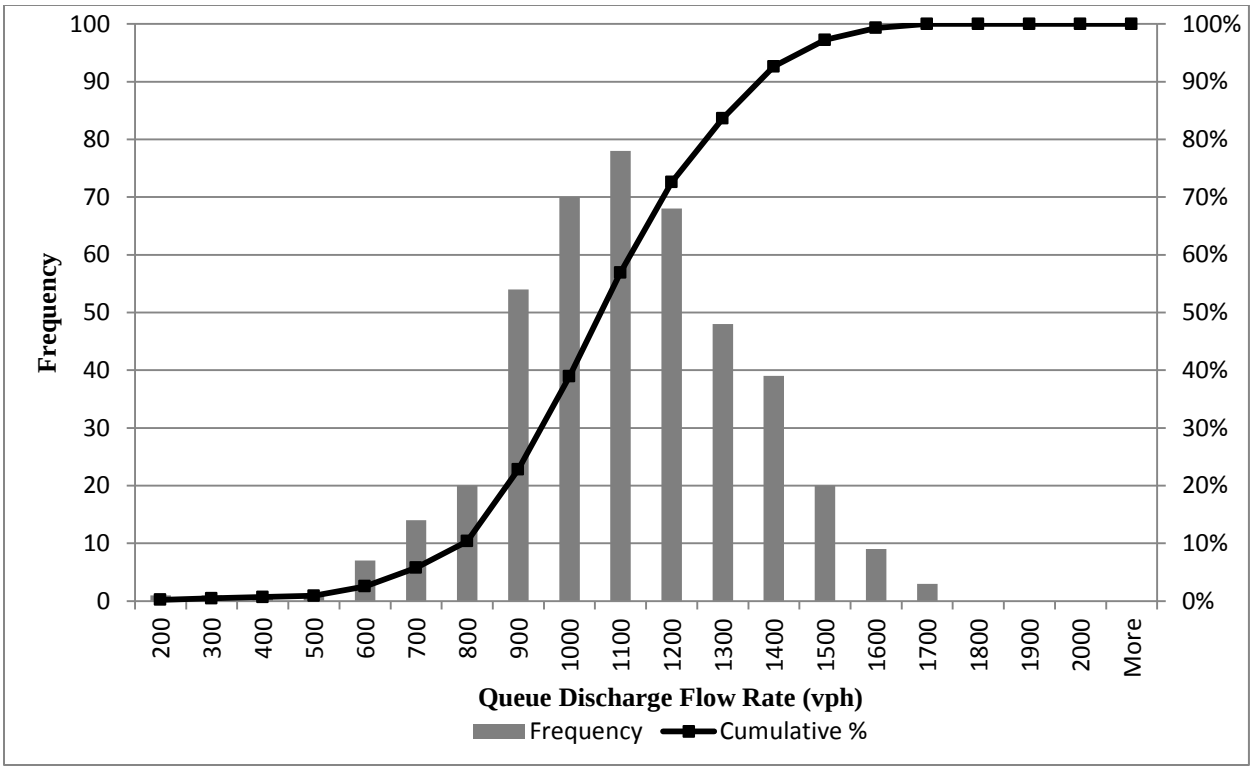

Figure 5.7 Histogram of Queue Discharge Flow Rate (EB and WB directions combined)

5.3.1. Comparison of Results with Missouri DOT Capacity Values

The Missouri DOT work zone guidelines (16) suggest capacity values for various open- and closed-lane scenarios. A freeway with a two-to-one lane configuration (one lane closed) has a capacity value of 1240 vphpl. Missouri DOT also uses a spreadsheet developed by the University of Missouri-Columbia (24) to estimate the queue length and quantify the travel delay caused by work zones. This spreadsheet uses capacity values from the Missouri DOT guidelines (16) and the results are based on the demand-capacity model from the HCM 2000 (1).

The HCM 2000 (1) demand-capacity model is analytical and assumes that traffic operates at its maximum flow (capacity) once demand reaches capacity. This model is simple and easy to use, but has certain limitations. While capacity is apparently a stochastic variable, it is reasonable to assume that traffic breaks down once demand reaches a fixed value of capacity. The results of

the current study, however, clearly indicate that the mean queue discharge rate is mostly lower than the breakdown flow rate. In this study the average breakdown flow rate was 1295 vphpl and the mean queue discharge rate was 1072 vphpl. Other studies have shown that when demand exceeds capacity and queues form, the traffic flow is no longer at its maximum, but is governed instead by the queue discharge rate that is usually lower than the maximum flow rate (2, 3).

The current spreadsheet can, therefore, be refined by separating the flow rate at which the traffic breaks down (breakdown flow) and the traffic flow under congested conditions (queue discharge). The average breakdown flow found in the current study (1295 vphpl) is slightly higher than the capacity value (1240 vphpl) suggested by MoDOT's work zone guidelines, whereas the mean queue discharge rate (1072 vphpl) is considerably lower than the recommended capacity value—all values are for a two-to-one lane closure. A stochastic model that considers variability in the value of capacity is, nevertheless, preferred over a deterministic model.

In addition, the results of this study indicated that capacity values show less variation when converted to passenger cars per hour per lane units. This conversion takes into account the significant effect of heavy vehicles. Therefore, it is recommended that the Missouri DOT expresses capacity values in passenger cars per hour units.

5.3.2. Comparison of Results with HCM 2000 Capacity Values

The results of this study were compared to the HCM 2000 (1) guidelines for estimation of work zone capacity. The HCM 2000 (1) divides the work zones into two categories: short-term maintenance work zones and long-term construction zone lane closures. The primary distinction between short-term and long-term work zones is the nature of the barriers used to separate the activity area from the traffic. According to the Manual on Uniform Traffic Control Devices (25),

long-term construction zones generally have portable concrete barriers, whereas short-term work zones use standard channeling devices (traffic cones, drums). The HCM 2000 (1) recommends different capacity values for short- and long-term work zones.

The work zone studied in this project lasted about four months. Figure 3.1 shows the work area was demarcated using traffic cones characteristic of short-term work zones. Furthermore, the middle lane was opened regularly to traffic during peak hours. Consequently, for the sake of comparison with the HCM capacity values, the work zone in this study is considered a short-term work zone.

As indicated earlier, the HCM 2000 (1) proposes a model for estimation of short-term work zone capacity based on studies in Texas (5, 6). The authors of those studies defined work zone capacity as the mean queue discharge rate at a freeway bottleneck. The average short-term work zone capacity value in HCM's model is 1600 pcphpl. Based on mean queue discharge, the present study found work zone capacity to be 1072 vphpl. This value was converted to passenger car equivalents using the equivalency factors prescribed by the HCM 2000 (1) for flat terrain (E_T = 1.5 and E_T = 1.2). The resulting flow, 1199 pcphpl, is 25% lower than the HCM capacity value. The HCM 2000 (1) recommends that a 2-ft reduction in lane width can account for up to 14% reduction in capacity, which is less than the 25% of capacity reduction observed in the current study. The low capacity values can also be attributed to the high percentage of heavy vehicles in the traffic stream (around 25%). Al-Kaisy and Hall (26) have shown the HCM passenger equivalency factor for flat terrain (E_T = 1.5) to significantly underestimate the adverse effects of heavy vehicles in congested traffic conditions.

Chapter 6 Conclusions and Recommendations

To determine work zone capacity, in addition to the traditional method of maximum sustained flow rate, a detailed capacity analysis was carried out based on identification of breakdown events. Maximum sustained flow rates were determined based on five-, ten-, and fifteen-minute intervals. The average maximum fifteen-minute sustained flow rate in the eastbound direction was higher than that in the westbound direction; the average flow rates were 1406 and 1307 vphpl for the eastbound and westbound directions, respectively.

For a detailed capacity analysis, the data collection period was divided into uncongested and congested periods based on one-minute intervals at breakdown. Work zone capacity was estimated using two definitions: mean queue discharge and breakdown flow rate. Breakdown flow is the traffic flow rate immediately prior to the onset of congestion, and mean queue discharge flow is the average traffic flow during congested queued conditions. Breakdown flow rate is a useful measure of capacity that can be used for predicting traffic congestion.

Traffic breakdown occurred over a range of flow rates (1194 to 1404 vphpl). A total of eleven breakdown events were observed, with an average flow rate of 1295 vphpl and a standard deviation of 65 vphpl. This study found the mean queue discharge rate for the work zone studied to be 1072 vphpl, considerably lower than the average breakdown flow rate observed.

For all breakdown events except three, the maximum pre-breakdown flows were higher than the respective breakdown flows, indicating that traffic does not necessarily break down once it reaches a maximum value traditionally known as capacity. Further, breakdown flow rates are generally not exceeded during queued conditions. Thus, the breakdown flow rate is more likely to be exceeded before occurrence of breakdown rather than after.

The Missouri DOT currently uses a spreadsheet to calculate queue length and delay based on the HCM 2000 (1) analytical demand-capacity model, and considers the capacity of a two-to-one lane closure to be 1240 vphpl. The model assumes that flow is at a maximum (capacity) during queued condition. This study, however, found that the mean queue discharge rate was lower than the average breakdown flow rate—that is, once traffic breaks down the flow usually remains below the breakdown flow.

Work zone capacity based on mean queue discharge rate converted into passenger car equivalent units using the HCM 2000 (1) prescribed equivalency factors for level terrain (E_T = 1.5 and E_T = 1.2), resulted in a value of 1199 pcphpl, which is 25% less than the average work zone capacity of 1600 pcphpl prescribed by the HCM 2000. This reduction can be attributed to reduced lane width (10 ft) and the high percentage of heavy vehicles in the traffic stream (around 25%).

This study makes the following recommendations:

- The present definition of capacity in HCM 2000 (1) is subjective. It varies from one study to another, and capacity values measured by different methods should be compared carefully. It is important to distinguish between rates of breakdown flow and mean queue discharge flow, and between the applications of each definition. An incorrect definition and use of inappropriate capacity value may cause significant error.
- Similar studies should be conducted for work zones with different geometric, environmental, traffic and control characteristics. Traffic data should be collected with multiple breakdown events, as in the present study, to capture the breakdown probability distribution that is of interest in traffic management and control. A

generic estimation model can be developed provided that sufficient data are collected for various conditions. Such a model will help traffic engineers analyze the risk of traffic breakdown under various conditions.

- Missouri DOT can refine their spreadsheet for calculation of queue length and delay by differentiating between the flow rates at which traffic breaks down (breakdown flow rate), and at which traffic operates under congested conditions (queue discharge rate). Further, it is recommended that work zone capacity is reported in passenger car equivalent units as well. Reporting capacity values in vehicles per hour underestimates the significant effect of heavy vehicles on traffic flow, especially in work zones with only a single open lane that prevents passenger vehicles from passing the slow-moving heavy vehicles.
- Work zone specific equivalency factors should be explored to improve the accuracy of work zone capacity estimation.

References

1. Highway Capacity Manual. 2000. Transportation Research Board, National Research Council, Washington, D.C.
2. Persuad, B. N., and V. F. Hurdle. 1991. "Freeway Capacity: Definition and Measurement Issues." In *Proceedings of the International Symposium on Freeway Capacity and Level of Service*. Karlsruhe, Germany.
3. Dehman, A., A. Drakopoulos, and E. Örnek. 2008. "Temporal Capacity Traits at Long-Term Urban Work Zone Bottlenecks." Transport Chicago Conference, Illinois.
4. Kermode, R. H., and W. A. Myyra. 1970. "Freeway Lane Closures." *Traffic Engineering* 40.5: 14-18.
5. Dudek, C. L., and R. H. Richards. 1981. *Traffic Capacity through Work Zones on Urban Freeways*. Report FHWA/TX-81/28+228-6. Texas Department of Transportation, Austin, Texas.
6. Krammes, R. A., and G. A. Lopez. 1992. *Updated Short-Term Freeway Work Zone Lane Closure Capacity Values*. Report No FHWA/TX-92/1108-5. Prepared by the Texas Transportation Institute for the Federal Highway Administration and for the Texas Department of Transportation, Austin, Texas.
7. Highway Capacity Manual. 1994. Transportation Research Board, National Research Council, Washington, D.C.
8. Dixon K. K., J. E. Hummer, and A. R. Lorscheider. 1995. *Capacity for North Carolina Freeway Work Zones*. Report No 23241-94-8. North Carolina Department of Transportation by the Center for Transportation Engineering Studies. Raleigh: North Carolina State University.

9. Hall, F. L., V. F. Hurdle, and J. H. Banks. 1992. "Synthesis of Recent Work on the Nature of Speed-Flow Occupancy (or Density) Relationships on Freeways." *Transportation Research Record: Journal of the Transportation Research Board* 1365: 12-18.

10. Jiang, Y. 1999. "Traffic Capacity, Speed, and Queue-Discharge Rate of Indiana's Four-Lane Freeway Work Zones." *Transportation Research Record: Journal of the Transportation Research Board* 1657: 7-12.

11. Maze, T. H., S. D. Schrock, and A. Kamyab. 2000. "Capacity of Freeway Work Zone Lane Closures." In *Mid-Continent Transportation Symposium Proceedings* 178-183. Aimes: Iowa State University.

12. Heaslip, K., A. Kondyli, D. Arguea, L. Elefteriadou, and F. Sullivan. 2009. "Estimation of Freeway Work Zone Capacity Using Simulation and Field Data." *Transportation Research Record: Journal of the Transportation Research Board* 2130: 16-24.

13. Sarasua, W. A., W. J. Davis, D. B. Clarke, J. Kottapally, and P. Mulukutla. 2004. "Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures." *Transportation Research Record: Journal of the Transportation Research Board* 1877: 85-94.

14. Al-Kaisy, A., and F. L. Hall. 2000. "Effect of Darkness on the Capacity of Long-Term Freeway Reconstruction Zones." Transportation Research Circular E-C018, Transportation Research Board, 164-174.

15. Autoscope Software Suite Version 8.30 User Manual: Econolite Control Products. 2006.

16. Missouri Department of Transportation (MoDOT). 2004. *MoDOT Work Zone Capacity Guidelines*. http://www.modot.mo.gov/business/documents/MoDOTWorkZonesGuidelines2.pdf.

17. Persaud, B. N., and V. F. Hurdle. 1991. “Freeway Capacity: Definition and Measurement Issues.” In *Proceedings of the International Symposium on Freeway Capacity and Level of Service*. Karlsruhe, Germany.

18. Elefteradiou, L., and P. Lertworawanich. 2003. “Defining, Measuring and Estimating Freeway Capacity.” Presented at the 80th Annual Meeting of the Transportation Research Board Meeting, Washington D.C.

19. Lorenz, M., and L. Elefteriadou. 2001. “Defining Freeway Capacity as Function of Breakdown Probability.” *Transportation Research Record: Journal of the Transportation Research Board* 1776: 43-51.

20. Benekohal, R., and M. V. Chitturi. 2005. “Effects of lane widths on speeds of cars and Heavy vehicles in work zones.” *Transportation Research Record: Journal of the Transportation Research Board* 1920: 41-48.

21. Banks, J. H. 1991. “Two-Capacity Phenomenon: Some Theoretical Issues.” *Transportation Research Record: Journal of the Transportation Research Board* 1320: 234-241.

22. Banks, J. H. 1991. “Two-Capacity Phenomenon at Freeway Bottlenecks: A Basis for Ramp Metering?” *Transportation Research Record: Journal of the Transportation Research Board* 1320: 83-90.

23. Christensen, R. 1998. *Analysis of Variance, Design and Regression*. Chapman & Hall/CRC.

24. Edara. P. 2009. *Evaluation of Work Zone Enhancement Software Programs*. Report No OR10-006. Missouri Department of Transportation, Columbia, MO.

25. Manual on Uniform Traffic Control Devices. 2009. Federal Highway Administration, U.S. Department of Transportation.

26. Al-Kaisy, A., and F. L. Hall. 2002. "Guidelines for estimating Freeway Capacity at Long Term Reconstruction Zones." Presented at the 81st Annual Meeting of the Transportation Research Board Washington, D.C.

Appendix A: Data Collection Sites and Analysis

In 2009, data were collected over four days at three different construction zones on I-44. Unfortunately, no traffic breakdown was observed at any of these sites; therefore, no analysis similar to that described in the main report was possible. The following section describes the additional study sites, speed and flow profiles, and vehicle composition for these data sets.

Data Collection Sites

All sites were located on I-44 highway in Missouri. The location of the sites, date and time of data collection, and work zone speed limits are given in Table A.1. Two of the data sets (collected on October 2 and October 9) refer to the same work zone setup, but at different locations. At all sites, one of the lanes was closed due to construction activity, and the other lane was open. In order to eliminate the effect of driver population on capacity estimates, all data collection efforts were scheduled and carried out on weekdays.

Table A.1 Summary of work zones in this study

Location	Mile Post	Speed Limit (mph)	Duration (Term)	Date and Time of Data Collection
Doolittle, WB	179	60	Short	Sept. 11, 2009 11:45AM to 1:15PM
Rolla, WB	185	60	Long	Oct. 2, 2009 12:00AM to 4:30PM
	184	60	Long	Oct. 9, 2009 11:15AM to 5:00PM
Cuba, WB	202	60	Short	Nov. 6, 2009 11:30AM to 4:30PM

Field Data

Apart from work zone location, work zone features may be broadly classified into two categories: physical characteristics and traffic patterns. Physical characteristics of a work zone include:

i. Number of open lanes
ii. Position of closed lane(s)
iii. Length of lane closure
iv. Lane width
v. Type of work activity
vi. Intensity of work activity (Low/Medium/High)
vii. Traffic control devices used
viii. Weather conditions

Table A.2 summarizes these characteristics for all three work zones addressed here. Qualitative judgments of work intensity were based on factors such as amount and size of construction equipment, number of workers, length of work activity area, and proximity of work activity to the travel lanes in use.

Table A.2 Physical Characteristics of Work Zones

Location	Total No. of Lanes	No. of Open Lanes	Position of Closed Lane	Length of Lane Closure (mile)	Lane Width (ft)	Type of Work Activity	Work Intensity	Traffic Control Devices	Weather Conditions
Doolittle	2	1	Left	2	12	None	-	Tubular Markers	sunny
Rolla (Oct. 2nd)	2	1	Right	10	10	Pavement Rehabilitation	Medium	Tubular Markers	windy
Rolla (Oct. 9th)	2	1	Right	10	12	None	-	Tubular Markers	rainy
Cuba	2	1	Left	2	12	Rumble Striping	Low	Tubular Markers	sunny

Results

Doolittle Site

There was no construction activity at the Doolittle site during the data collection period. The camera was set up on the overpass bridge at mile marker 179. The site was on a flat and straight segment of highway. Figure A.1 shows the location of the data collection with a snapshot from the video. Figure A.2 presents the flow rate and average speed of traffic over time.

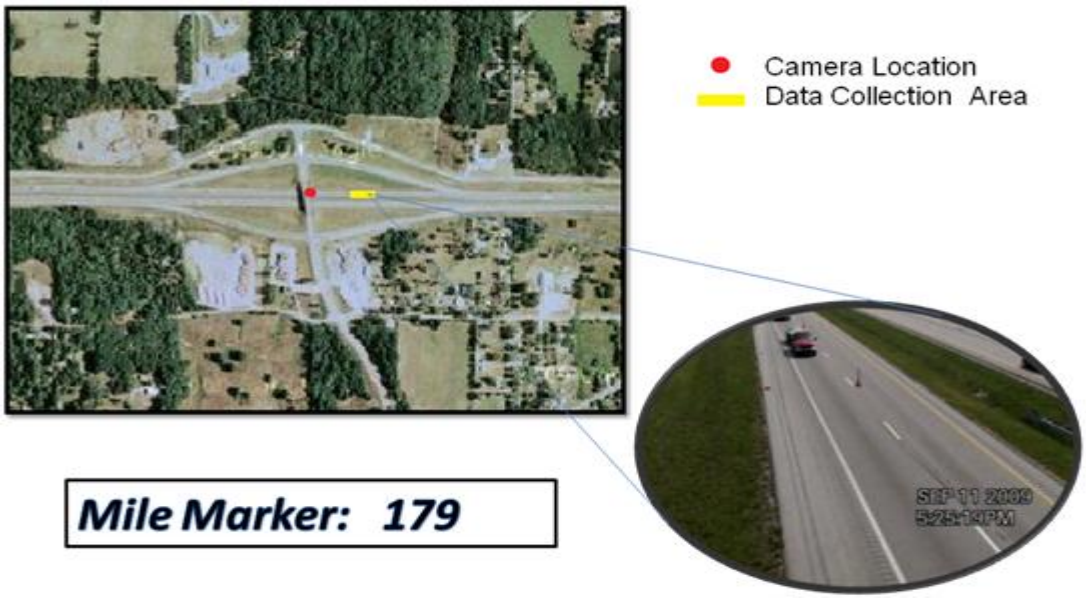

Figure A.1 Doolittle Data Collection Location

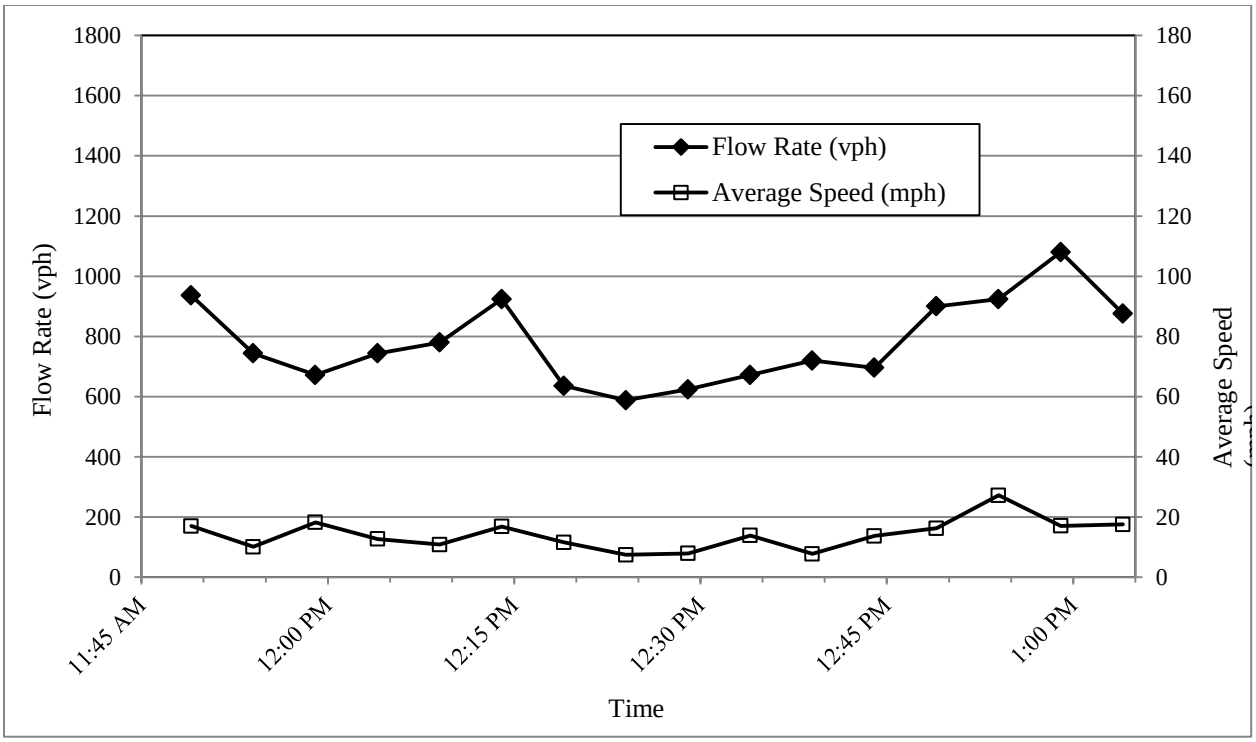

Figure A.2 Doolittle Site (Sept. 11) Flow Rate and Average Speed Profiles

The traffic had already broken down and long queues had formed at the time of data collection. As shown in Figure A.2, the average speed of vehicles was very low, usually less than 20 mph due to the congested traffic conditions. Further, the work zone setup at the Doolittle site was removed after one hour and twenty minutes of data collection due to congestion resulting from lane closure. The traffic was congested throughout the data collection period, and mean queue discharge was 850 vphpl (equivalent to 904 pcphpl). Table A.3 presents the maximum sustained flow rates. Table A.4 shows the percentages of vehicles in each class.

Table A.3 Capacity as Maximum Sustained Flow Rate (Doolittle Site)

Unit	15-min	10-min	5-min
vphpl	1066	1132	1160
pcphpl	1138.40	1208.40	1262.40

Table A.4 Vehicle and Truck Composition (Doolittle Site)

Vehicle Class	Percentage
Passenger Cars	75.3%
Trucks	21.3%
RVs	2.2%
Buses	0.6%
Motorcycles	0.6%
Truck Composition	
Single Unit (short trucks)	9.3%
Single Trailer	81.3%
Double Trailer	9.3%

Rolla Site

The work zone near Rolla was a long-term resurfacing project that began in September 2009 and lasted about two months. Traffic data were collected on October 2 and October 9. The nature of the activity at the Rolla site did not allow removal of lane closures during the peak hour and when queues were formed.

1) October 2

On October 2, data were collected from the overpass bridge at mile marker 185 as the bridge was closest to the construction area. Figure A.3 shows the location of the data collection

site with a snapshot of the video. Figure A.4 presents the flow rate and average speed of traffic over time.

No traffic breakdown was observed at this site during the 4.5 hours of data collection; however, the average speed of vehicles was well below the speed limit of 60 mph. The moderate speed of vehicles was probably due to the considerable lane width reduction (about 2 ft) and work activity adjacent to the data collection area. Table A.5 presents the maximum sustained flow rates. Since traffic never broke down at this site, these values cannot represent capacity values, and the only valid conclusion must be that capacity is higher than these sustained flow rates.

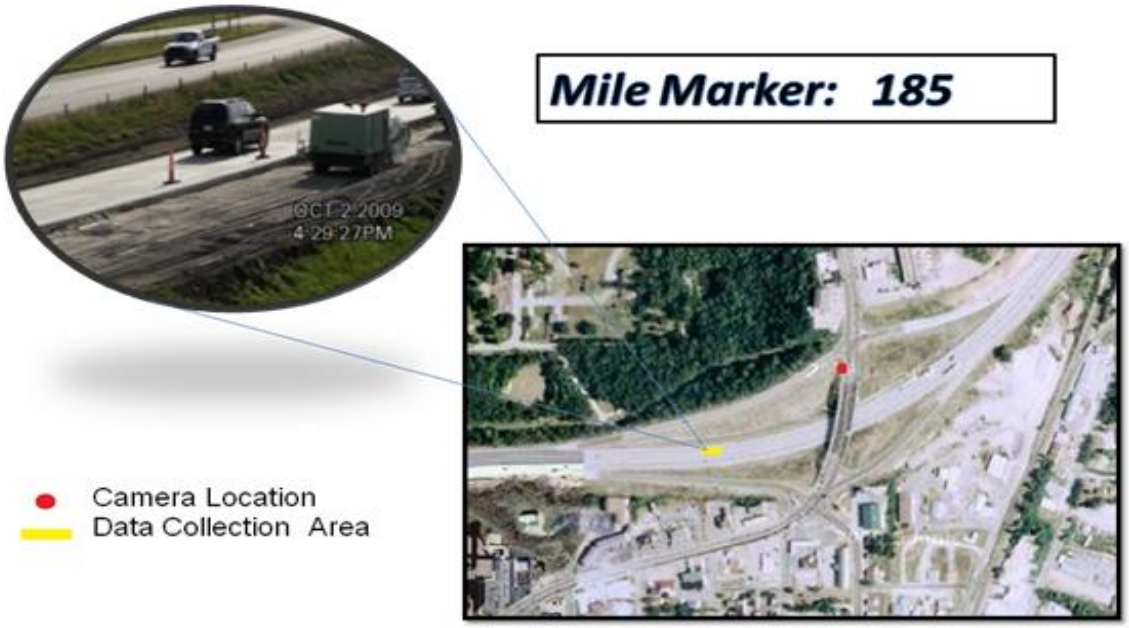

Figure A.3 Rolla Data Collection Location (Oct. 2)

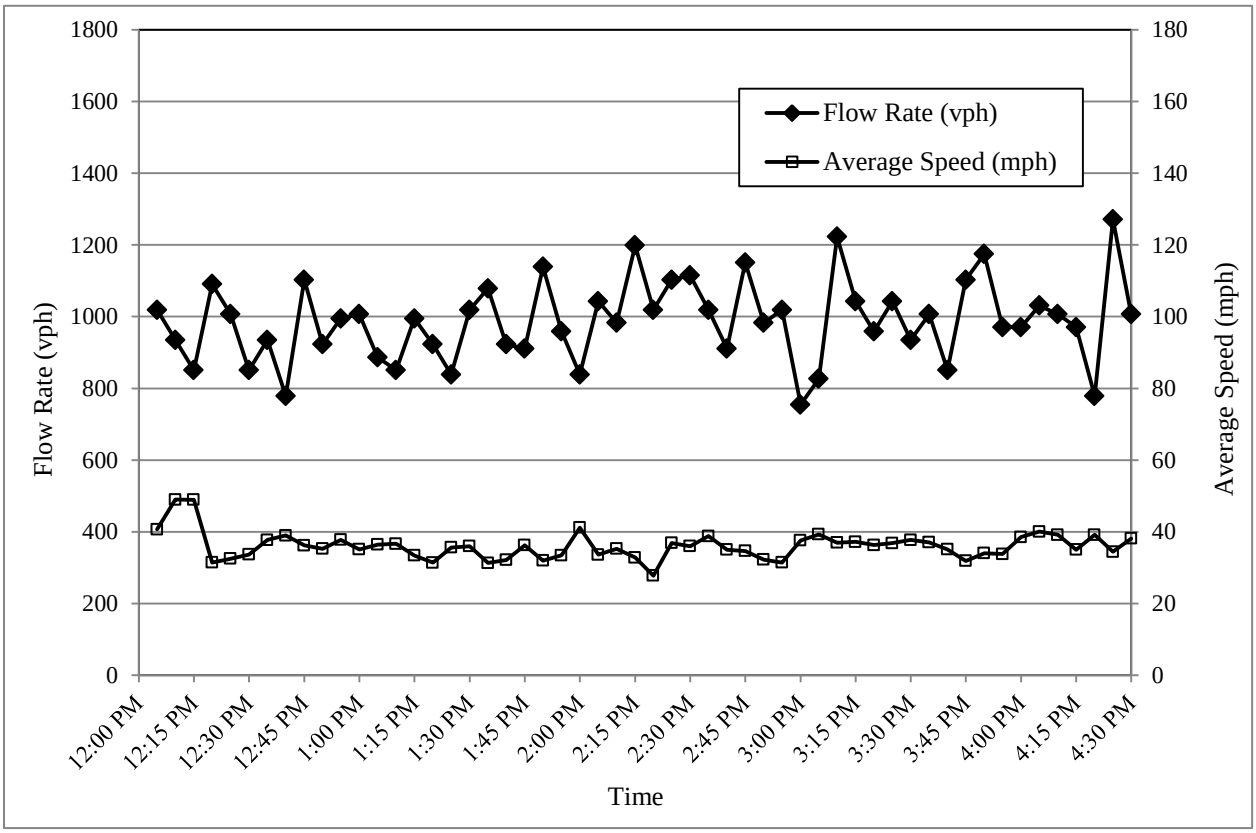

Figure A.4 Rolla Site Flow Rate and Average Speed profiles (Oct. 2)

Table A.5 Capacity as Maximum Sustained Flow Rate (Rolla site, Oct 2)

Unit	15-min	10-min	5-min
vphpl	1068	1110	1236
pcphpl	1160	1223	1308

2) October 9

On October 9, data were collected from a hill in Rolla. A section of highway between Exits 184 and 185 was selected for data collection because it was closest to the stationary construction equipment. No construction activity was observed due to rainy weather. Figure A.5 shows the location of the data collection site with a snapshot of the video.

Figure A.5 Rolla Data Collection Location (Oct. 9)

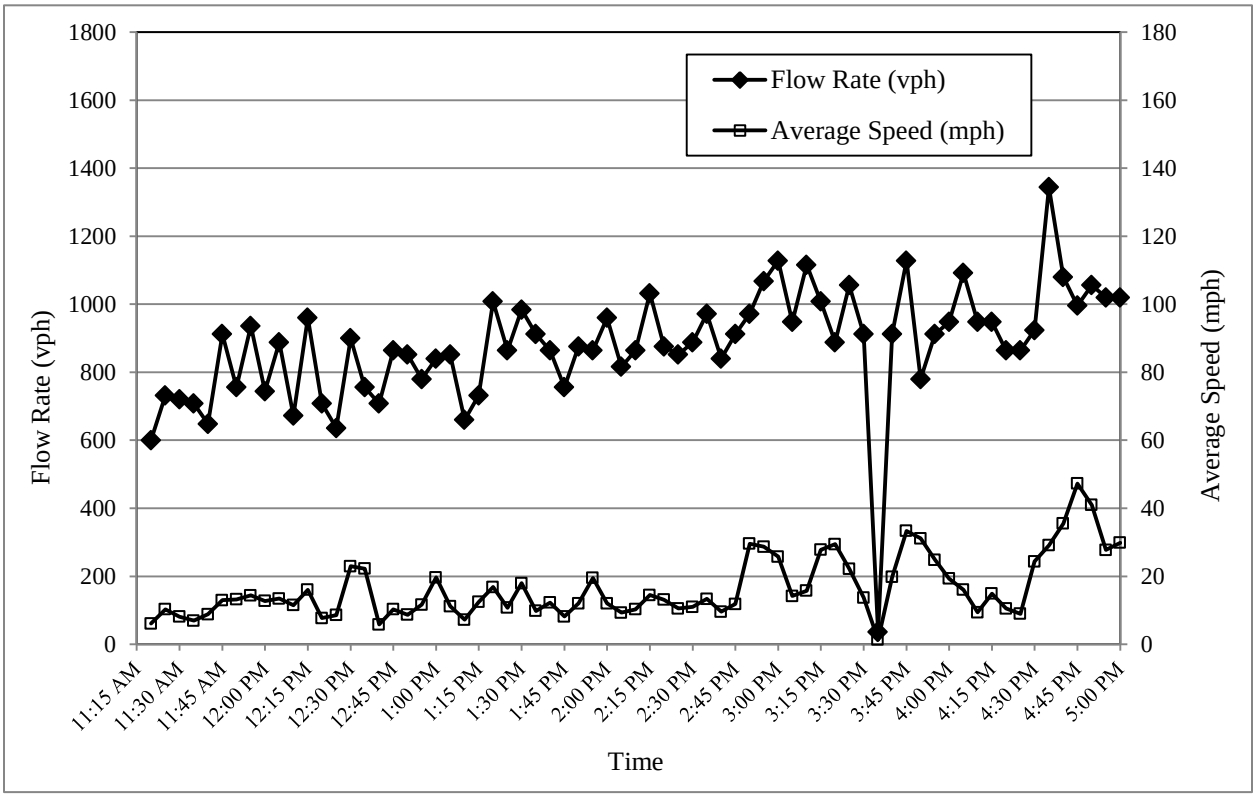

Figure A.6 Rolla Site Flow Rate and Average Speed profiles (Oct. 9th)

Figure A.6 presents the flow rate and average speed over time for this section of the highway. As on September 11 in Doolittle, the traffic stream had already broken down and queues were observed during the time of data collection. The average speed of the vehicles was very low, usually less than 25 mph, due to the congested traffic conditions. Traffic was congested throughout the data collection period, with a mean queue discharge of 879 vphpl, which is equivalent to 970 pcphpl. Table A.6 presents the maximum sustained flow rates. Table A.7 shows the percentages of vehicles of each class for the Rolla site (on both Oct. 2 and Oct. 9).

Table A.6 Capacity as Maximum Sustained Flow Rate (Rolla Site, Oct. 9)

Unit	15-min	10-min	5-min
vphpl	1140	1212	1344
pcphpl	1223	1300	1436

Table A.7 Vehicle and Truck Composition (Rolla Site)

Vehicle Class	Date	
	Oct. 2	Oct. 9
Passenger Cars	79.8%	77.8%
Trucks	17.8%	19.6%
RVs	1.6%	2.3%
Buses	0.3%	0.2%
Motorcycles	0.4%	0.2%
Truck Composition		
Single Unit (short trucks)	5.1%	4.0%
Single Trailer	87.3%	86.7%
Double Trailer	7.7%	9.3%

Cuba Site

At the Cuba site, a trailer with a 30-ft long boom was set up on the outer road and used to collect video at the end of a merge area within the work zone. This work zone was short-term, with light construction activity. Figure A.7 shows the location of the data collection area with a snapshot of the video.

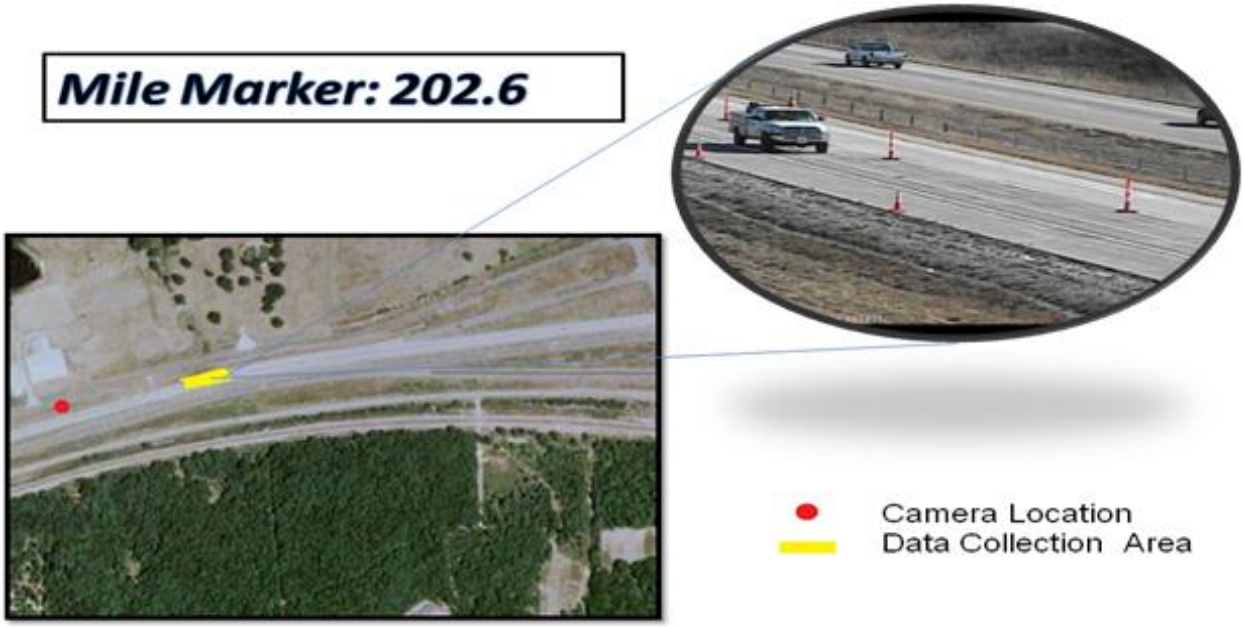

Figure A.7 Cuba Site Data Collection Location'

Figure A.8 presents the flow rate and average speed over time for this section of the highway.

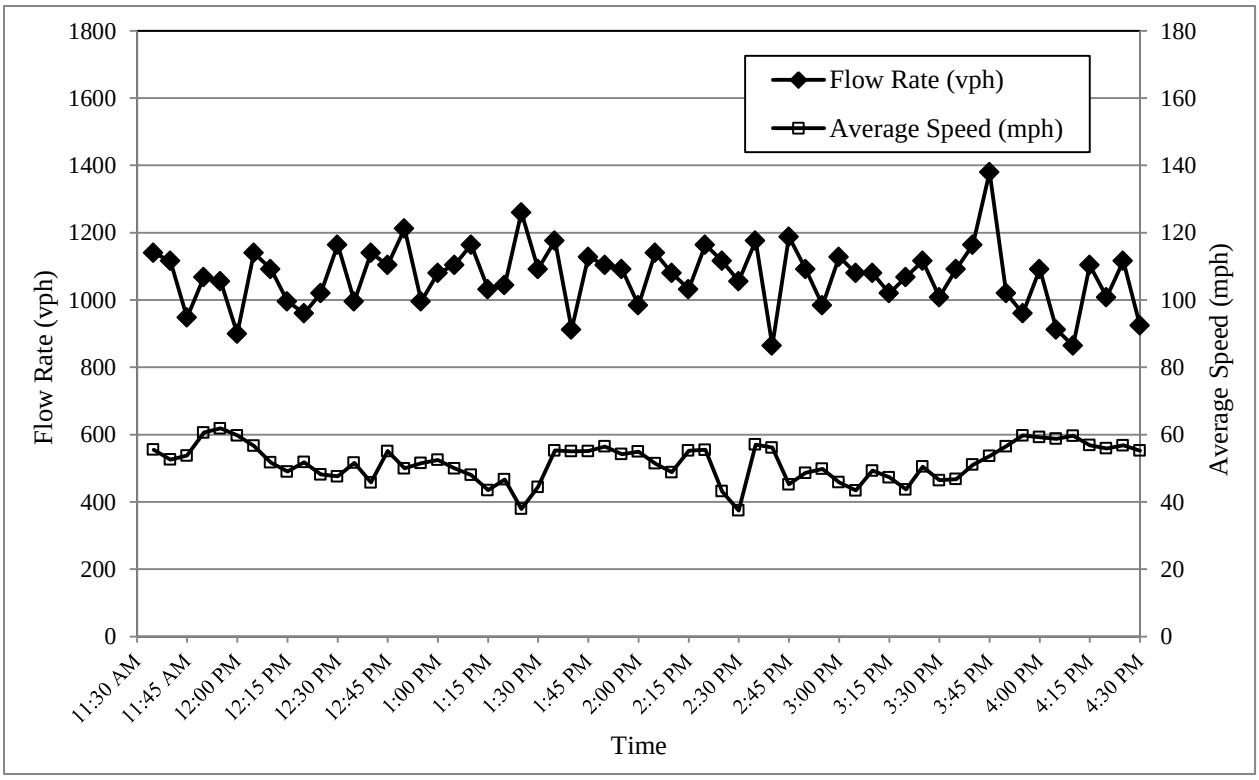

Figure A.8 Cuba Site Flow Rate and Average Speed profiles

As shown in Figure A.8, no traffic breakdown occurred at this site during data collection. The average speed of vehicles was usually between 45 and 60 mph. Table A.8 shows the maximum sustained flow rates. Since traffic never broke down at this site, these values cannot represent capacity values, and the only valid conclusion must be that capacity is higher than these sustained flow rates. Table A.9 shows the percentage of each class of vehicle in the traffic stream.

Table A.8 Capacity as Maximum Sustained Flow Rate (Rolla Site, Oct. 9)

Unit	15-min	10-min	5-min
vphpl	1212	1272	1380
pcphpl	1332	1388	1470

Table A.9 Vehicle and Truck Composition (Cuba Site)

Vehicle Class	Percentage
Passenger Cars	75.5%
Trucks	21.4%
RVs	2.2%
Buses	0.5%
Motorcycles	0.4%
Truck Composition	
Single Unit (short trucks)	7.3%
Single Trailer	84.9%
Double Trailer	7.8%