HIGHWAY WORK ZONE CAPACITY ESTIMATION USING FIELD DATA FROM KANSAS

by

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Abstract

Although extensive research has been conducted on urban freeway capacity estimation methods, minimal research has been carried out for rural highway sections, especially sections within work zones. This study filled that void for rural highways in Kansas. This study estimated capacity of rural highway work zones in Kansas. Six work zone locations were selected. An average of six days' worth of field data was collected, from mid-October 2013 to late November 2013, at each of these work zone sites. Two capacity estimation methods were utilized, including the Maximum Observed 15-minute Flow Rate Method and the Platooning Method divided into 15-minute intervals. The Maximum Observed 15-minute Flow Rate Method provided an average capacity of 1469 passenger cars per hour per lane (pcphpl) with a standard deviation of 141 pcphpl, while the Platooning Method provided a maximum average capacity of 1195 pcphpl and a standard deviation of 28 pcphpl. Based on observed data and analysis carried out in this study, the recommended capacity to be used is 1500 pcphpl when designing work zones for rural highways in Kansas. This research provides the proposed standard value of rural highway work zone capacities so engineers and city planners can effectively mitigate congestion that would have otherwise occurred due to impeding construction/maintenance.

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Dedication

I would like to dedicate this thesis to my loving family. Without my wife's support, this goal of mine would have been much harder to have accomplished. Without my parents and siblings I would not be where I am at today. Thank you all, you have been my support throughout the years!

Chapter 1 - Introduction

1.1 Background

Highway transportation in the United States (U.S.) has been prevalent since the late 1700s. Some historical events that defined the nation's highway system include:

- In 1794, completion of the first turnpike, known as Lancaster Turnpike, connected two Pennsylvanian cities, Lancaster and Philadelphia.
- Construction of the highway system, encompassing 42,500 miles, began in 1956.
- The U.S. Department of Transportation (USDOT) was established in 1967.
- The Interstate highway system was completed in 1991.
- A 161,000-mile National Highway System (NHS) was approved in 1995.

An effective system is necessary to efficiently transport goods, commerce, trade, and military supplies and personnel. Currently, the highway transportation system provides primary modes of travel for recreation, work, eating out, and socializing. As the highway system becomes more relevant to individuals' daily routines, upkeep and various regulations must be established for system maintenance and assurance of safety to individuals.

Since 2009 the American Society of Civil Engineers (ASCE) has issued an annual report card of America's infrastructure. The 2013 report card established grades for various forms of transportation in the U.S., including aviation, bridges, inland waterways, ports, rail, roads, and transit (ASCE, 2013). No transportation grades were found to be better than a "C+." The grades and their corresponding equivalency are as follows: "A" equals excellent, "B" equals good, "C" equals mediocre, "D" equals poor, and "F" equals a failing condition. Reported grades pertaining to U.S. roads received a "D," meaning the roads are in poor condition. However, roads in the state of Kansas received a letter grade of "C+," indicating mediocre condition. Each statistic was found in ASCE's 2013 Report Card for America's Infrastructure (ASCE, 2013).

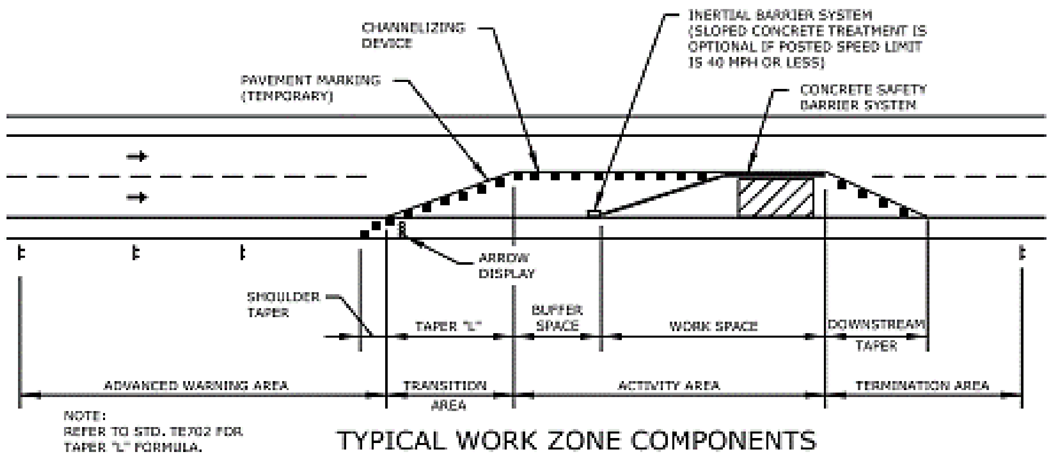
Many of these grades are the result of system deterioration due to lack of maintenance. These grades can increase only by re-building or rehabilitating the highway system. The ASCE report card helped emphasize the importance of change in America's infrastructure. Road rehabilitation throughout America, however, requires the establishment of various types of work zones and potential long-term construction with which motorists must contend in their daily routines. These work zones could potentially cause more vehicle crashes, considerable travel delays, and inconveniences to motorists on the roadway.

Mitigation of these three conditions have been considered by transportation authorities and many studies have been conducted, resulting in various standards established by USDOT. These standards, which help motorists understand upcoming work zone situations, have been adopted nationally. One of the most widely used standards followed by transportation engineers and city officials is the Highway Capacity Manual (HCM). This manual provides proven techniques for nationwide capacity estimation for various types of facilities. Methodologies for urban freeway systems have been established, but few studies have incorporated work zones, specifically in rural areas. This current study is intended to provide relevant data and information in regards to rural highway work zones and then provide a proposed standard to be used for future planning and design.

1.2 Problem Statement

For many years civil engineers have collected data and analyzed various highway facility types in order to gain a more thorough understanding of capacity estimation. As a result, estimation methods were developed, but they were primarily related to large facility types and very few of the methods pertained to work zones. This research focused on data and analysis provision for rural facility work zone sites, including state highway work zones and local arterial work zone sites. A typical work zone site is illustrated in Figure 1.1. As a result of this research, city planners and engineers can plan alternative routes during the design phase of the project to prevent roadway congestion. The primary concern for motorists in a work zone is additional time added to their daily commute. By mitigating congestion early in the design phase, a more efficient design with less severe crashes can be expected. This research also provides necessary supplementary data required by the HCM to address capacity estimation on rural highway work zones. Few states have produced such research; therefore, sufficient information is lacking for the HCM to state an accurate capacity estimation method for rural highway work zone sites.

Figure 1.1 – Typical work zone setup and components for Kansas work zones (KDOT, 2012)



Based on a typical work zone, highway safety may minimally influence capacity estimation due to delays created by a crash. Highway safety has become a relevant subject to engineers and city planners because of the growth of the highway transportation system. Two programs have partnered with the Federal Highway Administration (FHWA) to increase safety of various work zones during the rehabilitation of the highway system in America: the Highway Safety Improvement Program (HSIP) and the Highway Performance Monitoring System (HPMS) (Garber and Hoel, 2009). HSIP is divided into three phases: planning, implementation, and evaluation of the implemented countermeasure. HPMS investigates the extent, performance, condition, and operating characteristics of U.S. highways and evaluates the use of systems under review.

Based on the 2010 Kansas Traffic Accidents Facts Book, 69.7% of all fatal accidents occurred on a rural highway, as shown in Table 1.1 (KDOT, 2010). Since 2005, the number of accidents in a work zone setting on rural highways in Kansas has fluctuated. As shown in Table 1.2, a 16.8% increase in the amount of accidents in a work zone setting occurred in 2010 (KDOT, 2010). Information in these two tables demonstrates the significance of accurately determining a capacity estimation method for rural highway work zones in Kansas. With the provided information from other studies, engineers and city planners can accurately account for motorists who utilize the section of road under construction and potentially re-route the excess traffic on the roadway so less crashes occur because of frustrated motorists. Reducing the amount of crashes in work zone sites could possibly decrease the severity of crashes as well.

Table 1.1 – Rural and Urban Accidents for 2010 (KDOT, 2010)

Roadway Type	Accidents	% of All	Fatal Accidents	% of All
Rural Unknown	8	0.0%	1	0.3%
Rural Interstate	2,176	3.6%	16	4.3%
Rural Principal Arterial-Other	4,944	8.2%	78	20.7%
Rural Minor Arterial	3,842	6.3%	41	10.9%
Rural Major Collector	4,979	8.2%	57	15.2%
Rural Minor Collector	878	1.4%	12	3.2%
Rural Local Road	5,031	8.3%	57	15.2%
Rural Total	**21,858**	**36.0%**	**262**	**69.7%**
Urban Unknown	5	0.0%	0	0.0%
Urban Interstate	4,782	7.9%	19	5.1%
Urban Principal Arterial-Other Freewa	2,498	4.1%	15	4.0%
Urban Principal Arterial-Other	11,694	19.3%	34	9.0%
Urban Minor Arterial	8,658	14.3%	24	6.4%
Urban Major Collector	2,847	4.7%	7	1.9%
Urban Local Road	8,292	13.7%	15	4.0%
Urban* Total	**38,776**	**64.0%**	**114**	**30.3%**
Total	**60,634**	**100.0%**	**376**	**100.0%**

Table 1.2 – Work Zone Accident Summary since 2000 (KDOT, 2010)

Work Zone Accident Summary

	Accidents				People	
Year	Total	Fatal	Injury	PDO	Deaths	Injuries
2000	1,430	9	363	1,058	9	552
2001	1,551	13	398	1,140	15	632
2002	1,637	16	393	1,228	19	592
2003	1,896	12	417	1,467	14	607
2004	2,165	20	505	1,640	26	756
2005	1,404	7	325	1,072	8	463
2006	1,862	14	452	1,396	15	659
2007	1,632	6	382	1,244	7	546
2008	1,694	6	410	1,278	7	610
2009	1,294	1	339	954	1	513
2010	1,556	4	418	1,134	4	593
Total	**18,121**	**108**	**4,402**	**13,611**	**125**	**6,523**

1.3 Objectives

This research contains four objectives:

- To investigate work zone field data to identify capacity estimation approaches.
- To compare various capacity estimation methods.
- To identify the most suitable capacity estimation method for rural highway work zones.
- To estimate the capacity of rural highway sections using the identified method.

1.4 Definitions, Terminology, & Acronyms

The HCM does not specifically define work zone capacity, but it does define freeway capacity as the maximum sustained 15-minute rate of flow in passenger cars per hour per lane (pcphpl) able to be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction (HCM, 2010). The primary difference between work zone capacity and freeway capacity is that the HCM definition applies to freeway facility types and not rural state facility types. The HCM's definition of capacity does not mention work zone capacity but combines all conditions. Maximum sustained 15-minute flow rate is assumed to occur when congestion is present and all other situations are to be taken as the maximum observed 15-minute flow rate.

Other definitions pertinent to this study are listed in Appendix C and can be referenced when needed throughout this report. Definitions were obtained from (FHWA 2013) & (Garber and Hoel, 2009). Any terms not found within the two references were defined based on this study and should not discredit a definition obtained from another location. The following acronyms should be referenced when warranted.

KDOT	– Kansas Department of Transportation
DOT	– Department of transportation
USDOT	– United States Department of Transportation
SWZDI	– Smart Work Zone Deployment Initiative
HCM	– Highway Capacity Manual
FHWA	– Federal Highway Administration
AASHTO	– American Association of State Highway and Transportation Officials
ASCE	– American Society of Civil Engineering
HPMS	– Highway Performance Monitoring System
SHSP	– Strategic Highway Safety Plan
HSIP	– Highway Safety Improvement Program
FARS	– Fatality Analysis Reporting System
NEISS	– National Electronic Injury Surveillance System
MCMIS	– Motor Carrier management Information System
MUTCD	– Manual on Uniform Traffic Control Devices

1.5 Outline of Thesis

Objectives of this paper were completed by conducting a detailed literature review on methods pertaining to work zone capacity estimations throughout the United States. Next, data was collected on three rural work zones in Kansas. The data was analyzed and an estimated capacity was determined for each site under review for this study. Results were then compared to identify the most applicable methodology for rural highway work zone capacity estimations. Lastly, a final report was formed which details steps taken for this study, including choosing sites for review and analysis and capacity estimation for those sites. Once details for the final report were constructed, brief recommendations were made.

This report contains five chapters. Chapter 1 presents the introduction to this study. Chapter 2 provides a detailed literature review. Chapter 3 details data collection and methodology and Chapter 4 provides data analysis and results per site reviewed. Chapter 5 summarizes this study, provides a conclusion, and offers brief recommendations for future research.

Chapter 2 - Literature Review

This chapter investigates past research and respective recommendations related to highway work zone capacity estimation methods. A summary of relevant past research is presented in this chapter.

2.1 Capacity Estimation

In past studies, upper and lower limits of capacity in a work zone have been estimated using three distinct methods. Ramezani (2011) used the first method, known as the Platooning Method, to find the upper limit of capacity in a work zone when all platooning vehicles are counted. Results indicated that as the roadway operates at capacity, the upper observed capacity limit and lower observed capacity limit becomes closer to actual roadway capacity (Ramezani, 2011). The Platooning Method has two criteria: (1) if the headway is less than 4.0 seconds or (2) if the spacing is less than 250 ft. If neither of these criteria is met, the vehicle is considered free flowing. The other two methods, the 15-minute flow rate and the h-minus-n method, help establish the lower limit of the capacity in a work zone.

The 15-minute Flow Rate Method for this study found roadway capacity by analyzing 15-minute moving intervals and then determining maximum 15-minute flow rate from the observed data. The h-minus-n method is used when large gaps are discovered in the traffic stream when determining capacity estimation of a work zone. However, this method does not produce accurate results in high speed limit sections. These methods are suggested to be used for 45 to 55 miles per hour (mph) speed limit zones.

Adeli and Jiang (2003) used a computational approach in that every parameter had a defined variable. Those variables were placed in an elaborate equation that provided estimated capacity. Overall, Adeli and Jiang (2003) considered seventeen factors and variables in this approach. The factors ranged from the percentage of trucks to driver compositions (Adeli and Jiang, 2003). A statistical approach to calculating capacity is possible using fuzzy logic and neurocomputing concepts. Chosen variables for review must be carefully considered by the investigating engineer, and each variable must have a clear and concise definition or the results may be falsely interpreted.

Dr. Tom V. Mathew from the Indian Institute of Technology Bombay stated that capacity is not dependent on demand (NPTEL, 2006). Capacity is not the number of observed vehicles on a roadway on any given day; instead, capacity is the amount of vehicles a roadway can carry on any day while accounting for geometric conditions and types of travelers on that roadway (NPTEL, 2006). Capacity depends on many factors, including time and position. Therefore, coming up with an all-inclusive analytical method is nearly impossible in order to obtain the capacity of given roadways because data collection must occur before capacity can be found. Maximum flow rate can be found while observing the busiest 15-minute interval of peak hours. Freeway capacity is not the maximum flow rate observed but an expected value for that particular section of freeway (NPTEL, 2006).

A breakdown flow, which can occur at any flow rate, is not expected at the specific capacity of a roadway. A breakdown flow rate is defined as the flow rate observed immediately prior to a breakdown event (Lorenz and Elefteriadou, 2000). However, many breakdown events occur at a specific section of a roadway, so these values must be compared to similar flow rates at the same location where a breakdown did not occur. A breakdown flow rate can be found when three 20-second consecutive intervals occur immediately following the speed drop below the work zone speed limit (Lorenz and Elefteriadou, 2000). In general, roadways can accommodate traffic fluctuations without the occurrence of a breakdown event; however, an increased chance of breakdown events occurs in work zone areas.

When three analysts studied a rural highway in Iowa they found that when lane closures are present, capacity generally ranged from 1,400 passenger car equivalents to 1,600 passenger car equivalents (Maze, 1999). The analysts determined the maximum capacity of a rural highway with lane closure as the average volume of the ten highest volumes before and after queuing conditions.

2.2 Capacity Estimation Analysis

Certain criteria must be met in order for a breakdown minute to be established within a 5-minute breakdown flow rate (Bham, 2011). The first criteria is that an average flow rate at or above the speed limit must be met for one full minute, proceeded by five full 1-minute intervals of the average flow rate below the speed limit. The recovery stage is met when an average flow rate of the initial speed limit is sustained for five consecutive minutes. Then the process can be restarted. These two criteria are known as breakdown and recovery for the 5-minute Breakdown Flow Rate Method.

The next method, the maximum pre- and post- breakdown flow rates, may be applied after the Breakdown Flow Rate Method has been found (Bham, 2011). This method uses uncongested and congested conditions, also known as pre- and post- breakdown conditions of the breakdown flow rate. Each uncongested and congested event is justified before or after the 5-minute breakdown flow rate, respectively. All 1-minute intervals are classified as uncongested or congested, and any 5-minute period that cannot be classified is marked as queued periods. This method identifies three main components of capacity classification: maximum pre-breakdown flow, maximum queue discharge flow, and mean queue discharge flow. Once the three components are found, the data was used to establish whether or not a location was a bottleneck and, if so, then a capacity was found.

The maximum sustained flow rate can be established using various intervals. The interval used to calculate roadway capacity is typically the 15-minute interval (Bham, 2011). Based on 1-minute intervals, the data was divided into two categories: uncongested and congested. The work zone capacity was estimated using two methods: mean queue discharge and breakdown flow rate. This study shows that the mean queue discharge flow rate was less than the breakdown flow rate due in part to traffic flow not averaging congested queue conditions. The maximum sustained 15-minute flow rate was found to be conservative and should be adjusted in accordance with the mean queue discharge flow and breakdown flow rates.

Wayne A. Sarasua et al. estimated interstate highway capacities for short-term work zones in South Carolina (Sarasua et al., 2006). The study was conducted in two phases. The first phase monitored 23 work zone sites and the second phase monitored 12 additional sites, all within state limits of South Carolina. The ultimate goal of this project was to revise the policy of threshold limits for short-term interstate work zone lane closures. The threshold values were determined to be the 85th percentile speed for motorists traversing the respective work zones. Phase one focused on methods to measure capacity, data collection methods, and factors affecting freeway work zone capacity. Phase two analyzed data collected in Phase one to identify relationships regarding speed, density, flow, and headway which were then used to prove that the revision of threshold limits was warranted. Throughout Phase two, Greenshields Model was initially used to discover a linear relationship between the speed and density of a work zone. However, a multi-Regime model was found to be better suited for this data. At the end of this research, a 20% increase from threshold limits of the 85th percentile speed found in Phase one was proposed. The study also found that a capacity ranging between 1,200 and 1,400 pcphpl should be used to analyze work zones on interstates in South Carolina (Sarasua et al., 2006).

A study conducted in Illinois investigated 2 – to – 1 lane closures on interstate work zones to determine the capacity of that type of work zone. This study analyzed data from 11 collection sites in which as many parameters as possible were to remain the same. Three of the 11 sites were listed as short-term work zones while the remainder of the sites were listed as long-term work zones. This study also investigated vehicle headway and spacing and classified each vehicle as platooning or non-platooning. A vehicle was considered platooning if it had headway less than or equal to 4 sec or spacing less than or equal to 250 ft (Benekohal, 2004). If neither parameter was met then the respective vehicle was considered free flowing and not considered when estimating capacity in this study. After listing whether or not a vehicle was platooning, a methodology was established that allowed estimation of the capacity at a work zone. The capacity estimation used a model shown in Eq. 2.1, followed by parameter definitions (Benekohal, 2004).

$$C_{adj} = C_{Uo} * f_{HV} * PF \qquad \text{Eq. 2.1}$$

Where,

C_{adj} = Adjusted capacity (vphpl)

C_{U_o} = Capacity at operating speed U_o (pcphpl)

f_{HV} = Heavy-vehicle adjustment factor

PF = Platooning factor

The capacity estimation model was used with other models and speed-curves from the HCM to create a nine-step process in order to determine capacity in respective work zones.

CORSIM software (version 5.1) was used by Heaslip in 2009 to establish work zone capacities. This study was based on analytical models, HCM 2000 version, and an adjusted capacity equation to account for basic parameters observed in the field. Three work zone configurations were used, including 2 - to - 1, 3 – to - 1, and 3 – to - 2 lane closures on freeways in Jacksonville, Fla. The adjusted capacity Eq. 2.2 was:

$$C_{adj} = f_l * f_d * f_r * (C_{unadj} - V_R) \qquad \text{Eq. 2.2}$$

Where,

C_{adj} = Adjusted capacity (vphpl)

f_l = Adjustment for lighting conditions

f_d = Adjustment for driver population

f_r = Adjustment for rain

C_{unadj} = Calculated unadjusted capacity (vphpl)

V_R = Ramp volume (vph)

Each parameter was analyzed from the data collected. Standard deviation for average discharge flow was the lowest capacity measure. When the average pre-breakdown flow rate was lowest, the average maximum discharge flow rate was at its highest. In addition, no difference was observed in the lane closure (Heaslip, 2009).

A study conducted in two major cities of Canada, Toronto and Ontario, investigated the definition of freeway capacity as a function of breakdown potential on the freeway. The study analyzed 40 congested events which required nearly 20 days to collect data. This project, which utilized detector stations found on the 401 Freeway Toronto and Ontario, Canada, recorded average vehicle speeds (km/hr) and vehicle counts for upstream and downstream conditions. The detector stations recorded data in 20 sec intervals for 8 to 24 hours, depending on the required sample period. Collected data indicated a threshold boundary of approximately 90 km/hr. Recovery periods, number of breakdowns, and breakdown flow were all analyzed from the data. Breakdown was deemed a non-deterministic event, meaning that breakdown probability increased as flow rate increased. Finally, a new capacity definition was proposed for the HCM which implies that a percentage of obtaining a breakdown situation should be attached with the estimated capacity for a freeway site when under review (Lorenz and Elefteriadou, 2001).

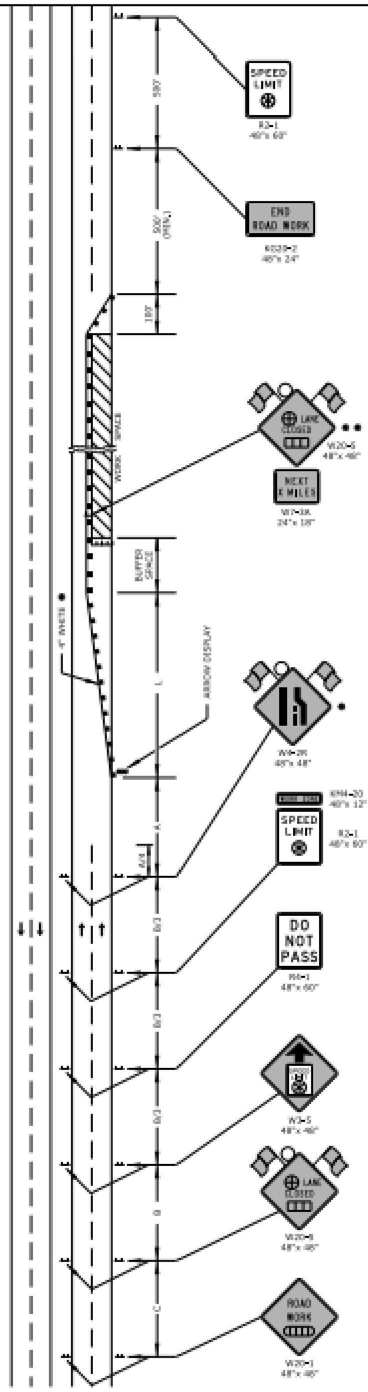
Chapter 3 - Data Collection & Analysis

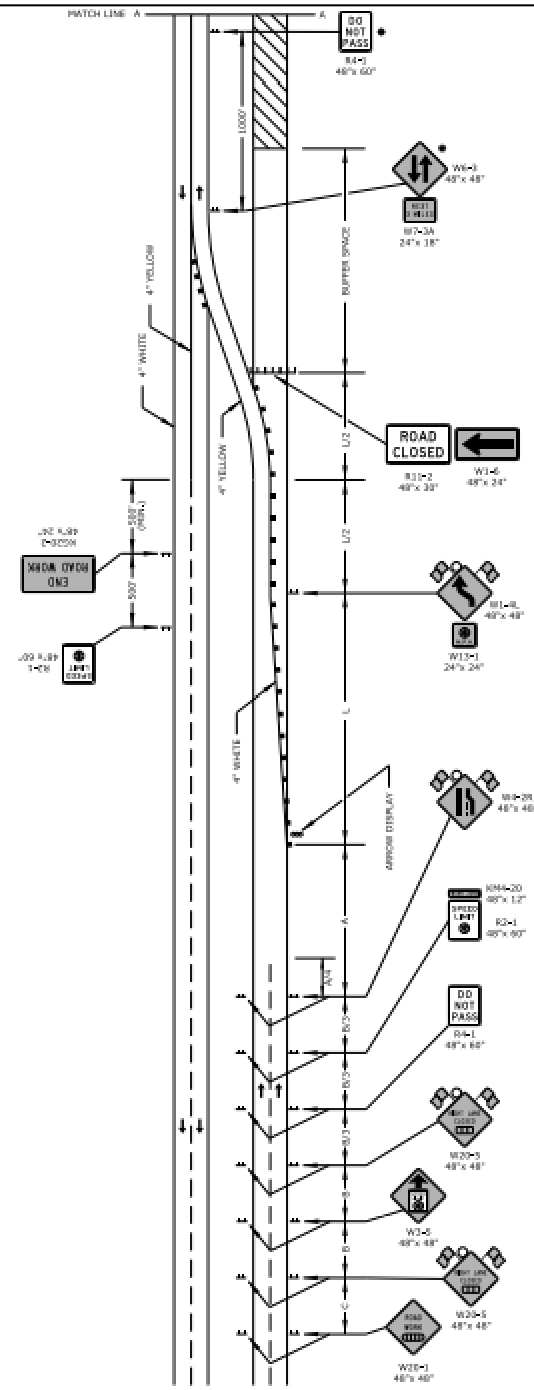
The Maximum Observed 15-minute Flow Rate Method and the Platooning Method were utilized in this study to estimate rural highway work zone capacities. The Maximum Observed 15-mintue Flow Rate Method can be viewed as the lower limit to capacity estimation and the Platooning Method can be viewed as the upper limit (Ramezani, 2010).

Three work zones were analyzed depending on site availability at the time of the project. Six days' worth of data were collected on average between mid-October 2013 and late November 2013. The three Kansas observation locations, K-18 in Riley County, K-10 in Johnson County, and US-56 in Johnson County, could be considered rural state highways. The setups were located at bottleneck situations which have previously provided the highest probability to produce capacity for the respective work zone.

Data collected for this study was obtained using Jarmar Technologies Trax 1 Plus traffic counters. The traffic counters were strategically placed in work zone areas in which bottleneck situations were identified. The standard work zone setup for Kansas is demonstrated in Figure 1.1. Standards are controlled by KDOT to maintain uniformity across the state. Standard traffic control setups for each work zone situation used for this study are shown in Figures 3.1 and 3.2.

Figure 3.1 – Standard traffic control setup for a 4-lane divided median 2 – to – 1 lane closure (KDOT, 2012)	**Figure 3.2 – Standard traffic control setup for a 4-lane divided median one roadway closed crossover (KDOT, 2012)**





An estimation of capacity for the respective work zone was completed based on collected data. Capacities for each work zone site were compared to one another. Chapter 5 discusses the most suitable method for estimating capacities on rural highway work zones in Kansas. Chapter 5 also provides the base range to be used when estimating capacities on rural highway work zones in Kansas.

3.1 Rural Facility Types

Rural facility type highways are located outside of urban cities and comprise the rural road system. Roadways in a rural highway system are classified into five types of roadways: principal arterial streets, minor arterial streets, major collectors, minor collectors, and local roads (Garber and Hoel, 2009).

Principal arterial streets generally control traffic that circulates within an urban setting and smaller rural cities. An urban setting refers to locations with a population greater than 25,000 people. Similar to the urban principal arterial system, the rural principal arterial system is divided into freeways and other principal arterial streets. The difference between freeways and other principal arterial streets is that freeways have controlled access and no intersections at-grade.

Rural minor arterial systems connect cities, towns, or resorts with principal arterial streets. Minor arterial roads generally have a high speed limit, such as 45 to 65 mph, with limited entry points to the roadway. The rural collector system carries traffic within counties and generally guides traffic to arterial streets. The collector system is divided into two types of roads: major collector roads and minor collector roads. Motorists typically use the collector system in a rural setting as a short-term option to getting to the arterial system in the town. The last category for rural facility types is the local road system. These roads connect adjacent land with collector roads within the rural city.

3.2 Criteria for Site Selection

Work zone characteristics can be categorized in two categories: physical characteristics and geometric conditions. Both categories can cause significant changes in capacity estimation. Physical characteristics can change the way motorists perceive the upcoming work zone. Physical characteristics considered in this research include:

1) Duration of the project
2) Number of open lanes
3) Type of work activity in the work zone
4) Position of the closed lane(s)
5) Intensity of the work activity (low, medium, high)
6) Length of the lane closure
7) Traffic control devices being utilized
8) Weather conditions

Geometric conditions of the roads in a roadway work zone can also drastically change capacity estimation. Geometric specifications to remain similar for this study include:

1) 2 – to – 1 (one directional) lane closure
2) Rural setting
3) Level terrain
4) Lane width(s)
5) Shoulder width(s)

Because geometric conditions remained similar, each data collection site was compared with each other. Physical characteristics and geometric characteristics of the sites utilized for data collection are listed in Table 3.1, 3.2, and 3.3 for each rural work zone site under review.

Table 3.1 – Geometric conditions obtained per site

Site	# of Lanes Open	Position of Closed Lanes	Length of Lane Closure (ft)	Traversable Lane Width (ft)	Type of Work Activity	Intensity of Work Activity (low/med/high)	Duration of Work Activity (short term or long term)	Weather Conditions
K-18 EB	1	Outside	15,600	11	Road Reconstruction	High	Long Term	Clear
K-18 H-H EB	1	H-H	15,600	11	Road Reconstruction	High	Long Term	Clear
K-18 H-H WB	1	H-H	15,600	11	Road Reconstruction	High	Long Term	Clear
K-10 EB	1	Outside	2,640	11	Bridge Repair	Medium	Long Term	Clear w/ some rain
US-56 EB	1	Inside	3,400	12	Bridge Repair	Low	Long Term	Clear w/ some rain
US-56 WB	1	Inside	3,000	12	Bridge Repair	Low	Long Term	Clear w/ some rain

Table 3.2 – Geometric conditions obtained per site (continued)

Site	Operation of Lanes in Work Zone	Work Zone Setting	Traversable Lane Widths (ft)	Outside Shoulder Width (ft)	Inside Shoulder Width (ft)	Median Divided or Non-Divided
K-18 EB	2 - to - 1	Rural	11	10	6	Divided
K-18 H-H EB	2 - to - 1	Rural	11	10	0	Non-Divided
K-18 H-H WB	2 - to - 1	Rural	11	6	0	Non-Divided
K-10 EB	2 - to - 1	Rural	11	10	6	Divided
US-56 EB	2 - to - 1	Rural	12	10	0	Non-Divided
US-56 WB	2 - to - 1	Rural	12	10	0	Non-Divided

3.3 Work Zone Sites Selection Process

Based on maintaining geometric conditions, the temporary traffic control engineer at KDOT obtained rural highway work zone locations found in Kansas to aid in this study. However, weather in Kansas limits a typical construction season to the beginning of March to early November. Consequently, weather was the major concern for data collection. Since data parameters to be collected were not established until early September, an efficient plan had to be developed that allowed for a maximum amount of data to be collected simultaneously while retaining accuracy. Three work zone locations were chosen to be analyzed. Those three sites included K-10 and Kill Creek Bridge, K-18 in between Manhattan and Ogden, and US-56 in Gardner. Each of these sites was in a rural setting and had similar geometric conditions. The work zone locations are discussed in more detail in the proceeding sections of this chapter.

Speed, volume, classification of vehicles, and gaps of traffic flow in work zones were collected at each site. Each variable was determined to be helpful in finding various breakdown effects in previous studies, typically leading to capacity estimation for the roadway.

Six rural data collection sites were observed on the three established work zones, as shown in Figures 3.3 and 3.4. The six sites for data collection included:

- K – 18

  One data collection site, at a head-to-head section of the work zone, collected data from eastbound traffic.

  One data collection site, at a head-to-head section of the work zone, collected data from westbound traffic.

  One data collection site, at the west end of the work zone, collected data at a 2 – 1 in the eastbound direction.

- K-10 and Kill Creek Bridge

  One data collection site was at a 2 – 1 in the eastbound direction.

- US – 56 and Gardner

  One data collection site was at a 2 – 1 in the eastbound direction.

  One data collection site was at a 2 – 1 in the westbound direction.

Averages of six days of raw data were collected among the sites. The Maximum Observed 15-minute Flow Rate Method and Platooning Method were chosen for capacity estimation on these rural highway work zone sites, and each site had standard highway work zone traffic control setup, as previously shown in Figures 3.1 and 3.2. In addition to the standards, Figures 3.5 and 3.6 provide an accurate schematic of each site setup. The traffic control devices used on each site was chosen based on the Manual on Uniform Traffic Control Devices (MUTCD). Because the traffic control setup was known, a similar setup of traffic counters was determined prior to arrival at the site, thus allowing for appropriate safety measures to be taken prior to entering the work zone.

Each data collection site was analyzed for 24-hour intervals to determine maximum flow rate, maximum volume, mean speeds at 2 mph and 5 mph, regular posted speed limit, work zone speed limit, breakdown flow rate, percentage of cars, percentage of buses, percentage of heavy vehicles, peak hour factor, and the date of data collection. Once a peak hour was determined, a peak time period was established by adding and subtracting an hour from that peak hour. Each parameter was analyzed based on a 15-minute interval.

Rain, which occurred during the K-10 and US-56 data collection process, was documented but only affected the speed collected for the work zone site. (The pneumatic tubes were un-adhered to the roadway but not spliced, so the volume, classification, and gap were determined to be accurate based on other data collected at this site.) Data obtained at the US-56 sites included 3-day data collection counts instead of the average six days due how weather affected the pneumatic tubes on the roadway. Tubes in the westbound direction were pushed away from the roadway due to the adhesive tape’s loss of bonding strength to the surface of the roadway, and the tubes in the eastbound direction were spliced due to damage from the traffic during inclement weather. Speed data obtained during the time of the rain for each site was eliminated due to data inconsistencies. Although the volume, classification, and gap counts were accurate, they were also eliminated for the maximum observed 15-minute flow rate method because no correlation could be made between mean speed and flow rate on the roadway during the rainy days.

Motorcycle percentages were excluded from this study due to lack of motorcyclists at each site. The highest percentage of motorcyclists at any site in a 24-hour period was 70%, which was an average of 64 motorcycles. Small cars and light trucks were classified as passenger cars, buses were classified as buses, and everything else was considered heavy trucks. This information was needed for the conversion from vphpl to pcphpl, which is discussed later in this chapter. The make-up of vehicles on the roadway during the time of data collection played a small role in the data collection site selection process due to the necessity of heavy vehicles on the roadway for an accurate measure of capacity for the respective site.

Figure 3.3 – Aerial map of Kansas with data collection sites pinned

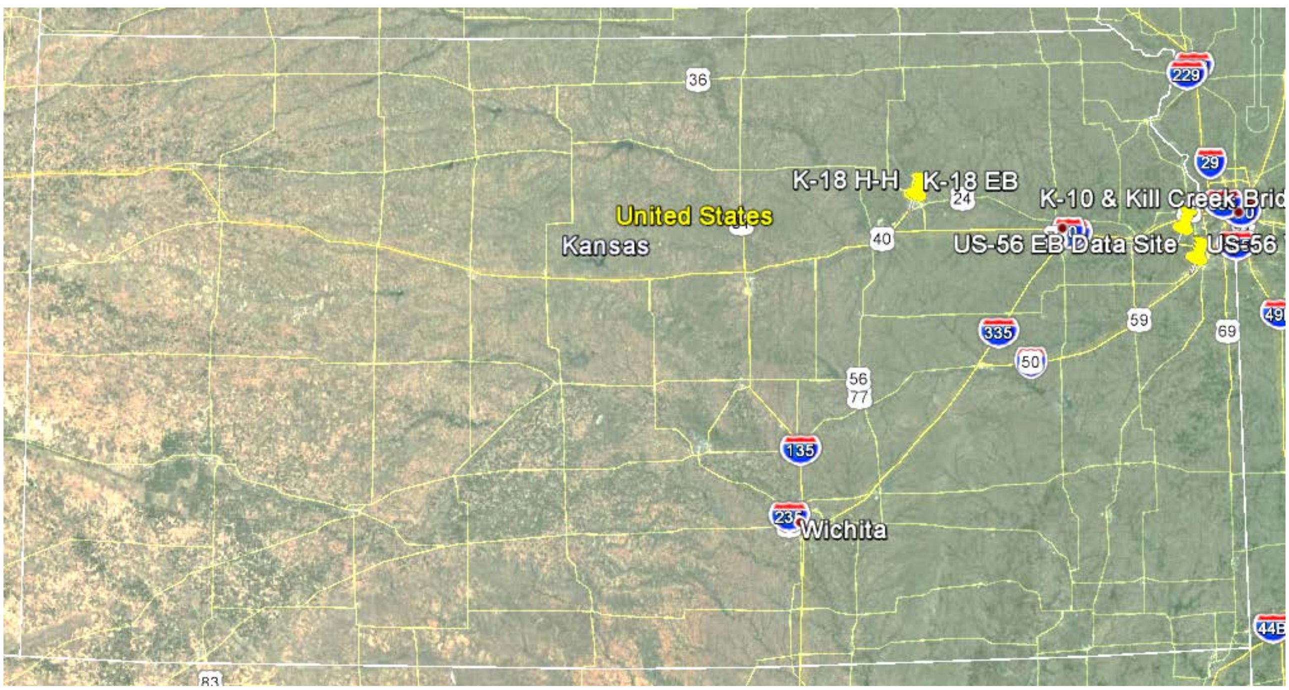


Figure 3.4 – Zoomed-in aerial map of data collection sites

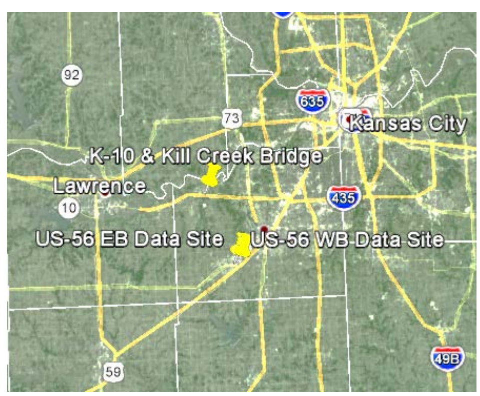


Figure 3.5 – K-10 EB, K-18 EB, & K-18 H-H Typical Schematics

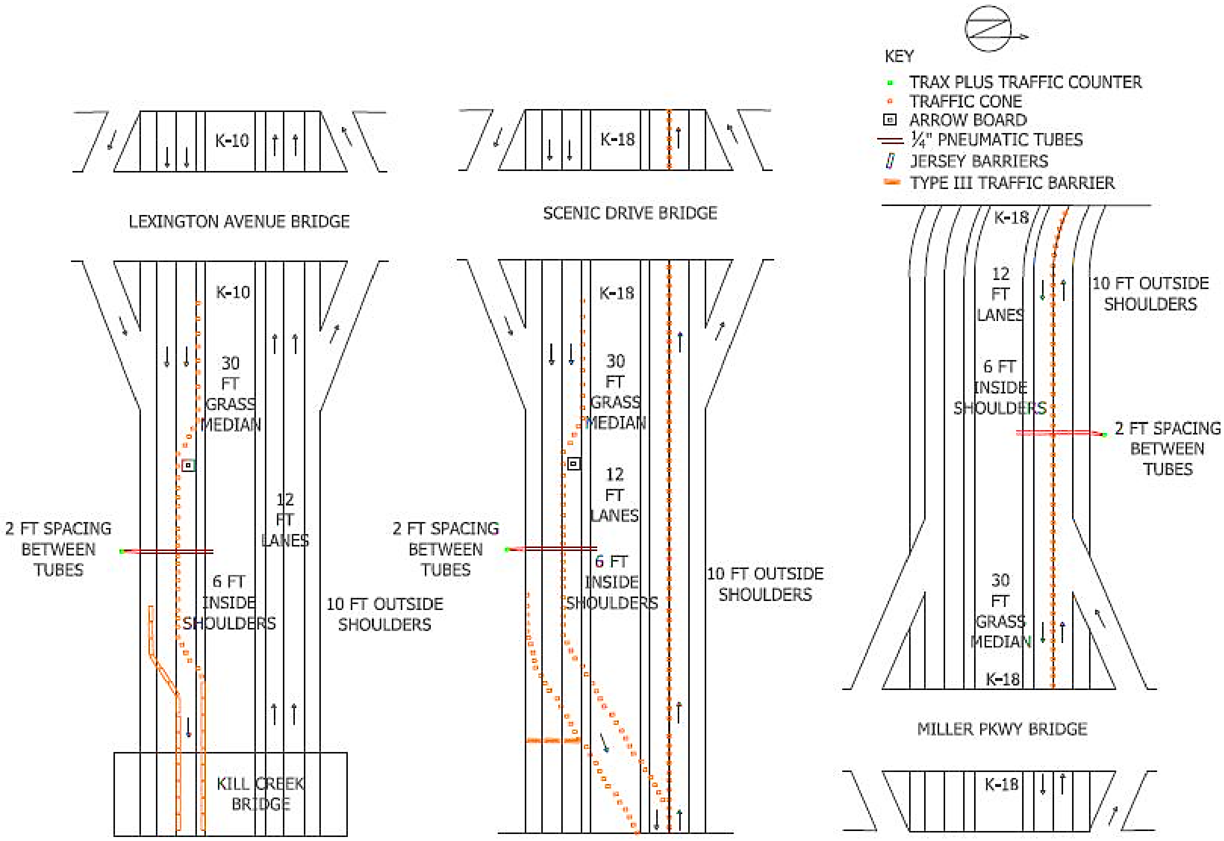
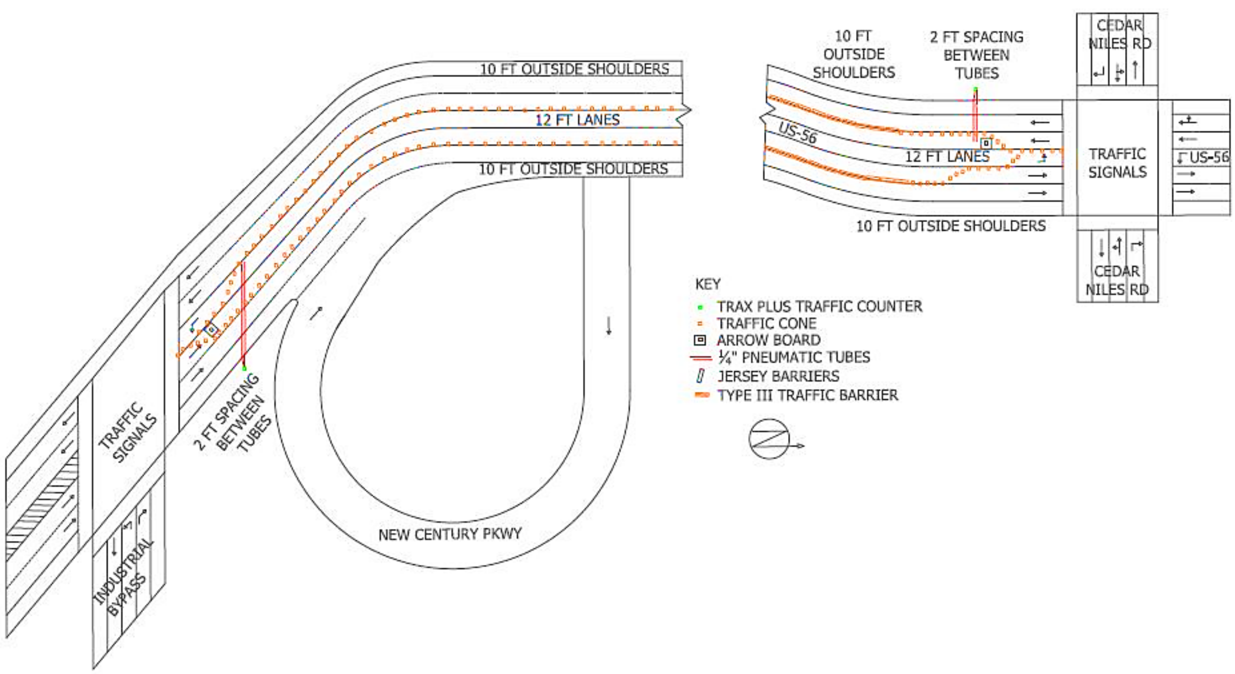


Figure 3.6 – US-56 EB & WB Typical Schematic



3.4 Equipment Used

Traffic counters used, called TRAX 1 Plus traffic counters made by Jamar Technologies, can obtain the speed, classification, gap, and volume of a roadway (Jamar, 2008). Several types of pneumatic tubes could be used to gather data for these counters but tubes used for this research were round mini-tubes with an inside diameter of 0.187 in and an outside diameter of 0.365 in. The tubes were cut into 50-ft sections. The L6 layout was used which sends a signal from two pneumatic tubes lying across two roadways to the traffic counter which warns the processor that two vehicles could simultaneously cross the tubes at any one time in the same or opposite directions. If layout L6 is the chosen, then the unit assumes that two-directional traffic on the roadway could be under study and data counts for both lanes must be recorded separately. This function can collect needed data for each work zone location. TRAX Pro software analyzed the collected data and exported it to Excel files based on chosen parameters.

The HCM states that under standard conditions and ideal geometric conditions, a 2 – to – 1 lane closure on a freeway would have a capacity of 1600 pcphpl (HCM, 2000). Heavy vehicles on the roadway drive at a slower pace and can cause queues; therefore, the heavy vehicles should be multiplied by a passenger car equivalent factor (PCE) to obtain accurate data analysis. The PCE values were obtained from table 9.25 in the textbook "Traffic and Highway Engineering" by Garber and Hoel in 2009. Garber and Hoel state that for level terrain on basic freeway sections, the PCE factor for recreational vehicles should be 1.2 and the PCE factor for heavy vehicles should be equal to 1.5 (Garber and Hoel, 2009). These PCE values were also used in several similar studies. The most referenced study was by Bham and Khazraee in 2011.

Work zone features are another parameter in capacity determination on rural highways. The work zone features include eight geometric conditions, as listed in Table 3.1. This table provides relevant data for this study. The table consists of the number of open lanes, position of closed lane(s), length of lane closure, lane width, type of work activity, intensity of work activity (low/medium/high), traffic control devices used, and weather conditions. Each geometric parameter can affect the estimated capacity so the geometric parameters must be accurately recorded. Two major reductions found in the HCM include a 14% reduction in capacity for a 2-ft lane drop and an 11% reduction in capacity for a high percentage of heavy vehicles in the traffic stream (HCM, 2000).

Equipment used for this study included Jamar Technologies TRAX 1 Plus traffic counters, Jamar Technologies TRAXPro software, mini pneumatic tubes, adhesive tape, metal bracket (located on the side of the road to create tension on the tubes to ensure an accurate reading), a hammer, a class II safety vest, a tape measure, pen and paper, and a camera.

Jamar Technologies TRAX 1 Plus traffic counters use two half-round or D-shaped pneumatic tubes to perform three methods of data collection:

1) Basic function
2) Volume-Only function
3) Binned function

The basic function allows the user to obtain speed, volume, classification and/or gaps of vehicles in a traffic stream. This function uses real time to stamp data into a count file until the unit is shut off. In this function tubes should be spaced no less than 2 ft apart in order to accurately record speed. Spacing of 2 feet is the recommended function because it is much easier to determine why the data was not obtained correctly in the event it does not load into the software (JAMAR, 2008). TRAX 1 Plus pneumatic tubes have several settings, but in order to obtain necessary data using the basic method, tubes should be set in layouts L5, L6, L10, L11, or L12. Layout L6 is the most common layout because it is designed for a standard two-lane roadway with traffic traveling in opposite directions. Layout L5 is the second most common layout because it mimics the L6 layout but is designed for two lanes of traffic traveling in the same direction.

The volume-only function only obtains the volume and gaps of vehicles. This function can use layouts L1, L2, L3, L4, L7, L8, L9, L13, or L14. This method of data collection is beneficial if the study required Average Daily Traffic (ADT) only. However, to estimate capacity on a roadway in a work zone, more data than just volume must be gathered.

The binned function obtains the classification, speed and/or gaps, depending on what data is required. This data is sorted and stored in specific categories or bins. The binned function can use any layout the basic function uses, but the L5 or L6 layout is recommended for data collection (Jamar, 2008).

Other outputs obtained from the Jamar Technologies TRAX 1 Plus traffic counter include mean speed, pace, 85th percentile, ADT, vehicle classification distribution, and the percentage of vehicles exceeding speed limits. Pneumatic tubes use air pulses provided by vehicles to obtain stamped raw data. The stamped raw data is then analyzed with TRAXPro software provided by the manufacturer to produce intended outputs. This software produces queries and graphs of selected data stored within the traffic counter memory. The software also allows the user to extract data into Excel files, thus allowing the user to run analysis separate from the analysis that the software provides. Photos of the traffic counter used for this study are shown in Figure 3.7.

In knowing the gaps, through simple arithmetic, headway and speed can be found. For example, if vehicle speeds are 60 mph (88ft/s) and the gap recorded between two vehicles is 3 sec, then the vehicle's headway is 3.18 sec. If the assumption is made that average vehicle length is equal to 16 ft. If an average vehicle is 16 ft in length and the vehicle travels at 88 ft/s, the gap is 0.1818 sec. Based on basic rounding methods, the gap value is not significant and therefore is assumed to equal the headway between vehicles in this study.

Figure 3.7 – TRAX I Plus Traffic Counter Photos

(A) (B)

3.5 Data Collection Sites and Setups

This section details individual data collection sites and how those respective sites were set up in the field. Each site detailed has corresponding figures and schematics to help define the counter setup.

3.5.1 K-10 EB

The K-10 EB work zone site was located in DeSoto, Kansas near Kill Creek Bridge, approximately 1,500 ft east of Lexington Avenue Bridge, as shown in Figure 3.5. This site is considered a long-term work zone site because of bridge repair that occurred during the construction phase of the roadwork. KDOT standard temporary traffic control was followed in all facets. Traffic control barriers, or jersey barriers, were used to ensure the safety of the construction crew. Due to the amount of space the jersey barriers occupy, the traversable roadway was moved to the edge of the inside shoulder to maximize the lane width available to motorists when passing through the work zone. Photographs of the site are shown in Figure 3.8. During data collection, the site experienced rain for three days, thus causing a discrepancy in speed data. Therefore, this data was discarded before any analysis was performed. With the exception of the rainy days, the site had clear skies with temperatures in the 50's and 60's, during the data collection period.

Figure 3.8 – K-10 EB Site Setup Photos

3.5.2 K-18 EB

The K-18 EB site was located 2,500 ft east of Scenic Drive Bridge in Manhattan, Kansas, as shown in Figure 3.5. Photographs of the data collection setup are shown in Figure 3.9. The temporary traffic control for this work zone site followed KDOT road reconstruction project standard setup, including the use of an arrow board and channelizing devices spaced at approximately 50 ft. The location of the counter setup preceded the point at which directional traffic had to merge to a head-to-head situation. This work zone had a typical 2 – to – 1 lane closure, and the traffic counter was placed at a location considered a bottleneck situation. This site had a 10-ft outside shoulder width with two 12-ft lanes, followed by a 6-ft inside shoulder width. The weather during the data collection process for this site was clear with temperatures in the 50's and 60's. Although this site had no adjacent workers, it had an approximate 30-ft grass median dividing the eastbound and westbound traffic lanes.

Figure 3.9 – K-18 EB Site Setup Photos

3.5.3 K-18 H-H EB & WB Directions

The K-18 head-to-head (H-H) EB and WB data collection setup was approximately 1,500 ft west of Miller Parkway Bridge in Manhattan, Kansas, as shown in Figure 3.5. Photographs of the site are shown in Figure 3.10. This is the only setup that incorporated an H-H situation, but this site also used standard KDOT temporary traffic control setup. Construction was occurring approximately 30 feet adjacent to the traversable lanes. The lanes were divided by tubular markers spaced at approximately 120 ft with two reflective devices equally placed between the markers. Although heavy machinery was adjacent to the traversable lane, the heavy machinery was out of the clear zone of the motorists and did not pose a threat to the motorists. Therefore, very little interruption was due to construction traffic. This site had a standard 10-ft outside shoulder with two 12-ft lanes adjacent to the shoulder, followed by a 6-ft outside shoulder. Due to H-H, no inside shoulders were available at this location. As with the other K-18 eastbound data collection site, clear skies and temperatures in the 50’s and 60’s prevented the weather from being a factor during the data collection process for this site.

Figure 3.10 – K-18 H-H EB and WB Site Setup Photos

3.5.4 US-56 EB

The US-56 EB data collection site was approximately 600 ft east of the Industrial Bypass stoplight in Gardner, Kansas, as shown in Figure 3.6. The traffic control was a standard KDOT temporary traffic control setup for a work zone site with no median and a 2 – to – 1 lane closure. One on-ramp was approximately 350 ft east of the data collection location. Setup for this site is shown in Figure 3.11. This site had clear skies and temperatures ranging from 55 to 65 degrees Fahrenheit during the last three days of the collection process. During the first four days, the site encountered rainy conditions. Due to the rain, the adhesive tape used to stick mini-pneumatic tubes to the surface of the roadway gave way and caused too great of stresses on the tubes, causing them to splice. A second round of mini-tubes was placed on the traffic counter once the weather cleared, and data was obtained for the last three days of the data collection process. Setup at this site varied from the other sites because there was no median splitting the 60 ft impervious driving lanes. Due to the roadway constraints, the use of typical Jamar Technology equipment to tie down the end of the mini-tubes which were not attached to the traffic counter had a slightly different setup. Due to the absence of a median, additional adhesive tape had to be used to adhere the mini-tubes to the road surface.

Figure 3.11 – US-56 EB Site Setup Photos

3.5.5 US-56 WB

The US-56 WB site was located approximately 750 ft west of Cedar Niles Road intersection in Gardner, Kansas, as shown in Figure 3.6. The westbound setup was similar to the eastbound setup. No median tied down the mini-tubes so additional adhesive tape was used to ensure accurate data was collected. The weather was rainy for the first four days and clear for the last three days of data collection. Unlike the EB site, mini-tubes for the WB site did not splice but were pushed to the outside shoulder and did not need to be replaced when re-set. All data during rainy conditions was discarded due to data inconsistencies. Traffic counters were set up in the transition zone of the standard KDOT temporary traffic control setup. An arrow board blocked the closed lane, consequently guiding motorists to the open lane. Channelizing devices were approximately 40 ft apart throughout the transition zone. Site setup is shown in Figure 3.12.

Figure 3.12 – US-56 WB Site Setup Photos

3.6 Maximum Observed 15-minute Flow Rate Method

The Maximum Observed 15-minute Flow Rate Method utilizes four parameters to establish estimated capacity of a work zone. The four parameters include the volume, maximum 15-minute flow rate, 15-minute mean speed, and 15-minute breakdown flow rate. If no three consecutive 15-minute intervals occur in which the flow rate falls below the threshold value, then a capacity for the site cannot be estimated. This constraint ensures that a single maximum 15-minute flow rate cannot become the capacity for a site and also assists in identifying the peak time period within a day. Peak time period specification also provides a more accurate comparison between the two methods under review.

The maximum observed 15-minute flow rate can be found by first obtaining 15-minute volumes per day per site, which is then converted to flow rates by multiplying the 15-minute volume by four, as shown in Eq. 3.1:

$$q = V * 4 \qquad \text{Eq. 3.1}$$

Where,

q = the flow rate in vehicles per hour per lane (vphpl)

V = the 15-minute volume

Once flow rates are obtained for each 24-hr period for a site, the peak time period must be established.

The next piece of information that is needed to run the maximum observed 15-mintue flow rate method is the mean speeds for the corresponding 15-minute intervals where the volumes were being considered. Once mean speeds are divided into 15-minute intervals, corresponding peak time period mean speeds can be graphed and compared against the same peak time period flow rates. If capacity is observed at the site, a correlation between the flow rate and mean speed under review should be evident. As flow rate increases, the mean speed should decrease. As the flow rate hits its peak, mean speed should become equal. As flow rate begins to decrease, mean speed should begin to increase again. If the pattern is not evident, the correlation is not met and a capacity cannot be determined for the respective site.

Correlation between flow rate and mean speed proves capacity if and only if at least three consecutive 15-mintue intervals can be found below the threshold limit (Bham, 2011). As defined, the threshold limit for this study was the work zone speed limit for the site under review.

After determining estimated capacity per day, vphpl must be converted to pcphpl. The conversion equation is listed as Eq. 3.2:

$$Q = (P_c * q) + ((P_r * q) * E_R) + ((P_t * q) * E_T) \qquad \text{Eq. 3.2}$$

Where,

Q = flow rate in pcphpl

q = flow rate in vphpl

P_c = percentage of passenger cars observed during a 24-hr period

P_r = percentage of recreational vehicles during a 24-hr period

P_t = percentage of heavy vehicles during a 24-hr period

E_R = Passenger Car Equivalent factor for recreational vehicles (1.2)

E_T = Passenger Car Equivalent factor for heavy vehicles (1.5)

The common method listed in the HCM was not used in this study because the percentages of vehicles for each site were known based on field data collection. The only values that needed to be determined were PCE values for recreational vehicles and heavy vehicles which were both obtained from table 9.25 in the textbook "Traffic and Highway Engineering" by Garber and Hoel in 2009. The PCE values were also used in several similar studies. The most referenced study was by Bham and Khazraee in 2011. As shown in equation 3.2 the PCE factor for recreational vehicles to be used in this study is 1.2 while the PCE factor for heavy trucks in this study is 1.5. The large geometric factor that played a role in this decision was that each site was positioned in a level type of terrain. Converting flow rates to pcphpl allows capacity comparisons from one site with capacities from another site no matter the vehicle compositions.

The final parameter to be established in the maximum observed 15-minute flow rate method is the 15-minute breakdown flow rate. This parameter is always less than the maximum observed 15-minute flow rate, because it sets one more parameter on flow rate values. The breakdown flow rate is considered for vehicles that have headway less than or equal to 4 sec. A true breakdown of traffic flow can be found by applying this parameter. If the 15-minute breakdown flow rate correlates with the maximum observed 15-minute flow rate, the estimated capacity is accurate. If the breakdown flow rate is greater than the maximum observed 15-minute flow rate, the observed data must be re-examined. If no correlation exists between the two parameters, the obtained data must also be re-examined. If either of these parameters have a negative correlation twice, capacity cannot be found from this method for the site.

3.7 Platooning Method

The Platooning Method utilizes two parameters to determine whether or not a vehicle is free flowing or in-platoon. Parameters for capacity estimation with this method include 4.0 sec or less of headway or 250 ft or less of spacing. If either of these parameters is true, the vehicle is in-platoon. After identifying in-platooning vehicles, average 15-minute headways can be identified. Once the new headways are found, capacity on the roadway can be estimated using Eq. 3.3.

$$C_p = 3600 / h_p \qquad \text{Eq. 3.3}$$

Where,

C_p = Potential Capacity (vphpl)

h_p = the average headway of all in-platoon vehicles (sec)

Potential capacity is the primary distinction from the maximum observed 15-minute flow rate method and the Platooning Method for this study. This capacity estimation approach causes capacity values to be greater than what was found when using the Maximum Observed 15-minute Flow Rate Method because an average of 4 sec was used, whereas this method uses realistic observational data for headway values. However, just as the values were converted in the Maximum Observed 15-minute Flow Rate method they will be converted here. The conversion from a flow rate in vphpl to a flow rate in pcphpl can be seen Eq. 3.4.

$$Q = (P_c * C_p) + ((P_r * C_p) * E_R) + ((P_t * C_p) * E_T) \qquad \text{Eq. 3.4}$$

Where,

Q = flow rate in pcphpl

C_p = flow rate in vphpl

P_c = percentage of passenger cars observed during a 24-hr period

P_r = percentage of recreational vehicles during a 24-hr period

P_t = percentage of heavy vehicles during a 24-hr period

E_R = Passenger Car Equivalent factor for recreational vehicles (1.2)

E_T = Passenger Car Equivalent factor for heavy vehicles (1.5)

Once the potential capacity is found then it is converted an estimated operating capacity as shown in, Eq. 3.5. This equation must be utilized to accurately account for the platooning factor for the site.

$$CE_E = C_p * f_p \qquad \text{Eq. 3.5}$$

Where,

CE_E = the estimated operating capacity in passenger cars per hour per lane (vphpl)

C_p = potential capacity (vphpl)

f_p = is the platooning factor

After the estimated capacity is found based on the platooning factor for the site it gets converted into an estimated flow rate in pcphpl. The conversion equation for this step can be seen in Eq. 3.6.

$$Q = (P_c * CE_E) + ((P_r * CE_E) * E_R) + ((P_t * CE_E) * E_T) \qquad \text{Eq. 3.6}$$

Where,

Q = Estimated flow rate in pcphpl

CE_E = Estimated capacity in vphpl

P_c = percentage of passenger cars observed during a 24-hr period

P_r = percentage of recreational vehicles during a 24-hr period

P_t = percentage of heavy vehicles during a 24-hr period

E_R = Passenger Car Equivalent factor for recreational vehicles (1.2)

E_T = Passenger Car Equivalent factor for heavy vehicles (1.5)

In a study by Ramezani (2010), four platooning factors were considered when using the Platooning Method: a platooning factor of 1.0 for any data set with queuing conditions, a platooning factor of 0.95 for long-term and short-distance work zones, a platooning factor of 0.90 for long-term and long-distance work zones, and a platooning factor of 0.85 for all short-term work zones (Ramezani, 2010).

However, since an abundant amount of data was obtained for this study, platooning factors were found separately per site per day. Values were based on the amount of platooning vehicles divided by the total amount of vehicles on the roadway for the 15-minute time interval during the peak time period chosen for that day. Once these values were determined, the average of the variables during the peak time period under review for the respective 24-hr period was found. This approach provided realistic results for platooning factors per site because the factors were analyzed from observed data and not assumed. The previous study combined similar data collection sites together, potentially causing distorted results because no two roadways are identical. Once platooning factors for each site were chosen, the capacity estimation Eq. 6 was utilized and an estimated capacity per day was obtained.

Chapter 4 - Data Analysis & Results

Results showed that the occurrence of breakdown events did not always lead to capacity of the respective work zone. The breakdown event is typically caused by a simultaneous influx of vehicles in the bottleneck location which can be classified as the capacity of that roadway. However, a breakdown event can also be caused by a slow driver, therefore requiring the speed distribution graph to be analyzed with the frequency distribution graph to notice if a correlation can be observed. Typical observed correlation is when a drastic decrease in vehicle mean speeds occurs at high frequencies of flow rates, thus proving capacity of the roadway. The maximum observed 15-minute flow rate often occurred after the breakdown, and the capacity was found as traffic regained speed until reoccurrence of event or the roadway managed traffic flow.

Sites at US-56 WB and EB may not provide accurate capacity data due to nearby controlled intersections. However, other sites provided sufficient data to prove capacity of a rural highway work zone in Kansas. For example, K-10 and Kill Creek Bridge gave the most accurate results and clearly provided maximum flow rate, breakdown flow rate, mean speed, and breakdown mean speed.

4.1 Expected Capacity per Work Zone Site

Based on previous research, the Maximum Observed 15-minute Flow Rate Method was expected to produce the lower limit of the capacity while the Platooning Method was expected to produce the upper limit. From the two limits, a range of capacity was expected to be formed. After completing the analysis using each method, a comparison of the accuracy of the two methods would be determined and the more accurate method would be established.

4.2 Maximum Observed 15-minute Flow Rate Method Results

PCE values for recreational vehicles and heavy vehicles which were both obtained from table 9.25 in the textbook “Traffic and Highway Engineering” by Garber and Hoel in 2009. The PCE values were also used in several similar studies. The most referenced study was by Bham and Khazraee in 2011. As shown in equation 3.2 the PCE factor for recreational vehicles to be used in this study is 1.2 while the PCE factor for heavy trucks in this study is 1.5. Average speed was found by averaging 24-hr periods of data obtained at each site. By using equations discussed and studying collected data, a maximum flow rate, maximum volume, and maximum breakdown flow rate was chosen per site. Each variable led to the capacity for each work zone. The capacity for each site was selected based on the largest maximum observed flow rate for that respective site. Values were selected based on the concept that when the capacity of a roadway is met, excess vehicles traversing the roadway will be delayed.

4.2.1 K-10 EB

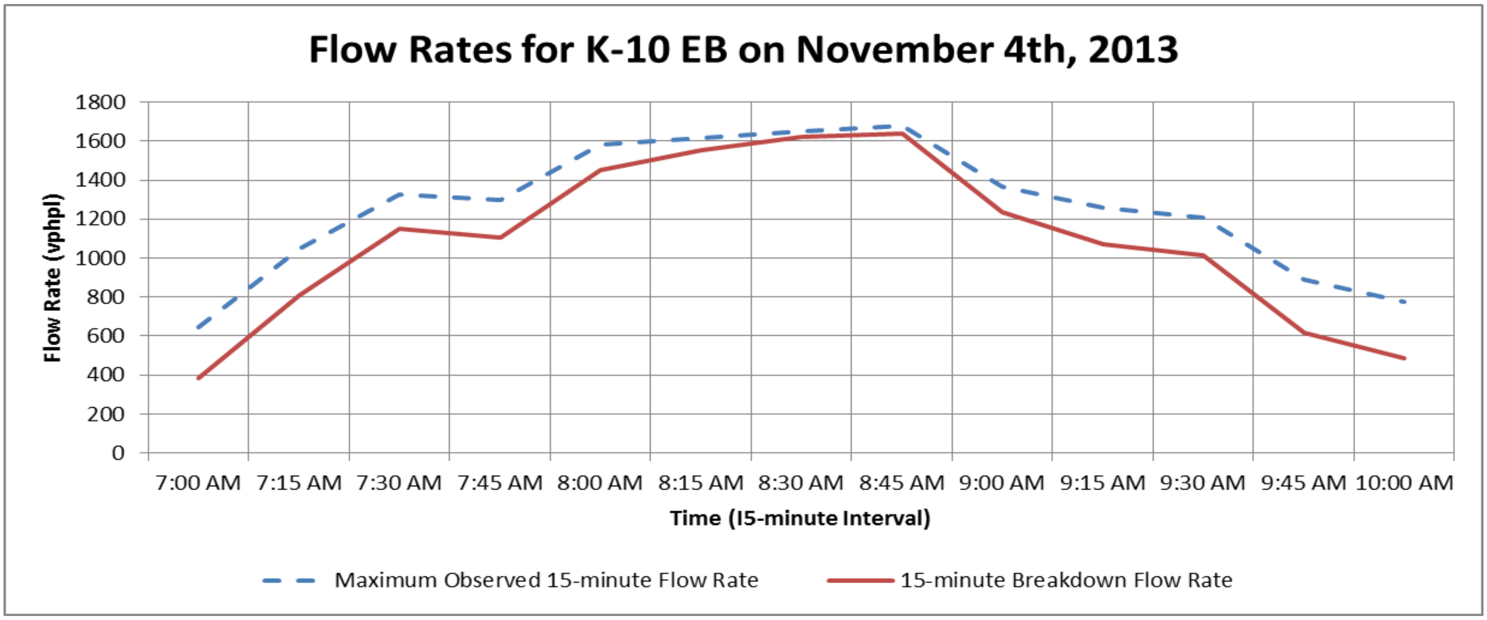
Even though rain caused three days' worth of speed data to be discarded, the work zone site located on K-10 near Kill Creek Bridge provided the strongest evidence of capacity compared to all the data collection sites. As shown in Table 4.1, obtained capacity for the K-10 EB site equaled 1730 pcphpl with a standard deviation of 46.82 pcphpl. The normal speed limit for this site was 70 mph while the work zone speed limit was found to equal 60 mph. The average and the average standard deviation were both based on the peak time period of the site. The correlation between flow rate and mean speed for the peak time period is shown in Figure 4.1. The mean speed for the entire data collection on this site was 60.3 mph, as shown in Figure A.1 in Appendix A. The three days' worth of data that was discarded was collected from October 29* thru October 31, 2013*. Due to the splicing of pneumatic tubes and failure to maintain 2-ft separation, the counter recorded vehicle pulses while the tubes varied from a few inches apart to a few feet apart. This drastically threw the values off as it can be seen on the three days mention from Table 4.1. Maximum flow rates for those three days are drastically larger than any other maximum flow rates recorded.

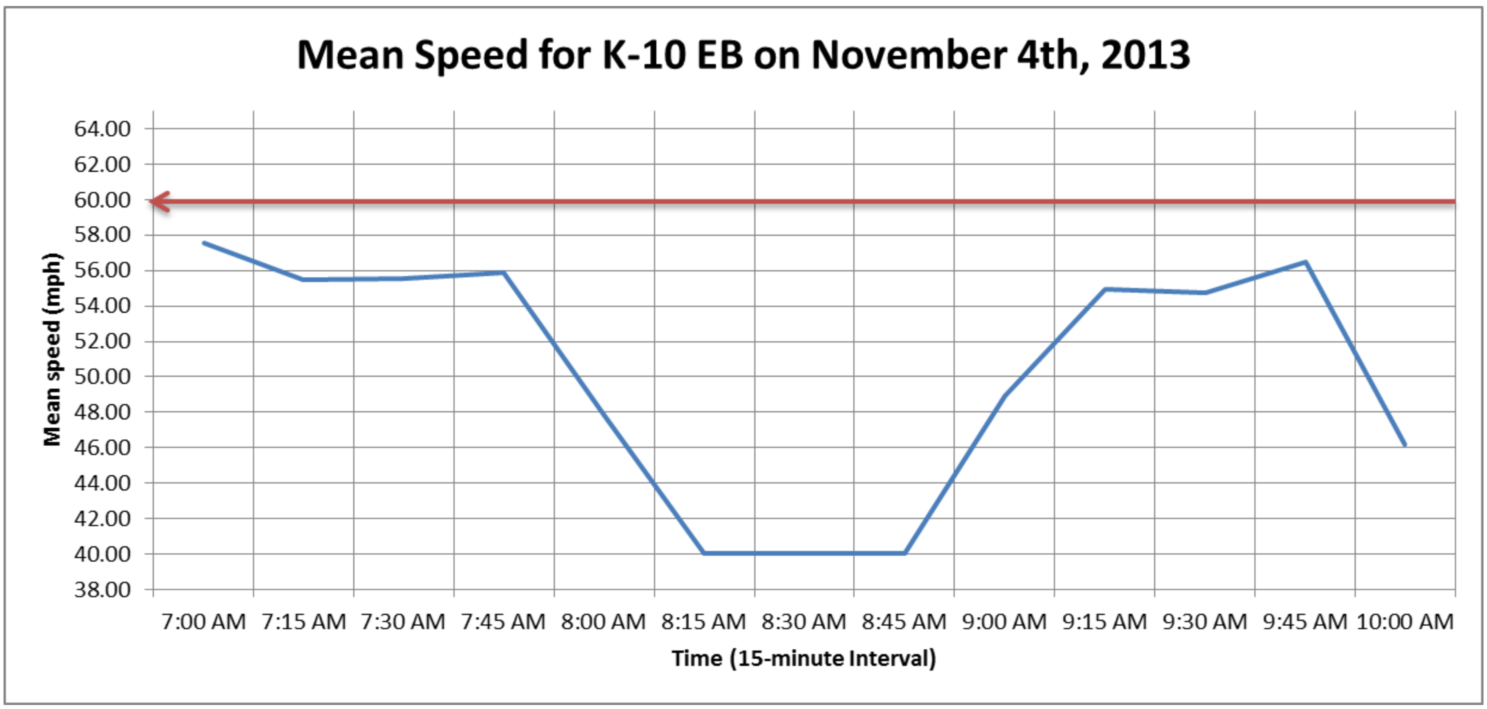
Table 4.1 – K-10 EB site for Maximum Observed 15-minute Flow Rate Method

K-10 EB Site								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate(pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/28/2013	10:00 am to Midnight	58.26	92.10%	0.91%	6.99%	1522	1396	1356
10/29/2013*	24 hrs	61.29	57.39%	1.98%	40.63%	1917	1805	1878
10/30/2013*	24hrs	67.71	39.48%	16.20%	44.32%	2036	1910	1986
10/31/2013*	24hrs	63.52	44.12%	43.99%	11.89%	1836	1738	1804
11/1/2013	24hrs	57.06	93.68%	0.63%	5.69%	1730	1641	1656
11/2/2013	24hrs	59.63	96.85%	0.18%	2.97%	1157	1093	942
11/3/2013	24hrs	59.95	97.43%	0.08%	2.49%	1191	1030	992
11/4/2013	Midnight to 11:00 am	55.23	93.62%	0.64%	5.74%	1730	1681	1689
TOTAL/AVERAGE*		58.03	94.74%	0.49%	4.78%	1466	1368.2	1327
AVG STANDARD DEVIATION*		---	---	---	---	46.82	50.38	47.84

* It rained heavily during the days 10/29/13 to 10/31/13.

Figure 4.1 – K-10 EB Site Peak Time Period Flow Rate VS. Mean Speed Graphs





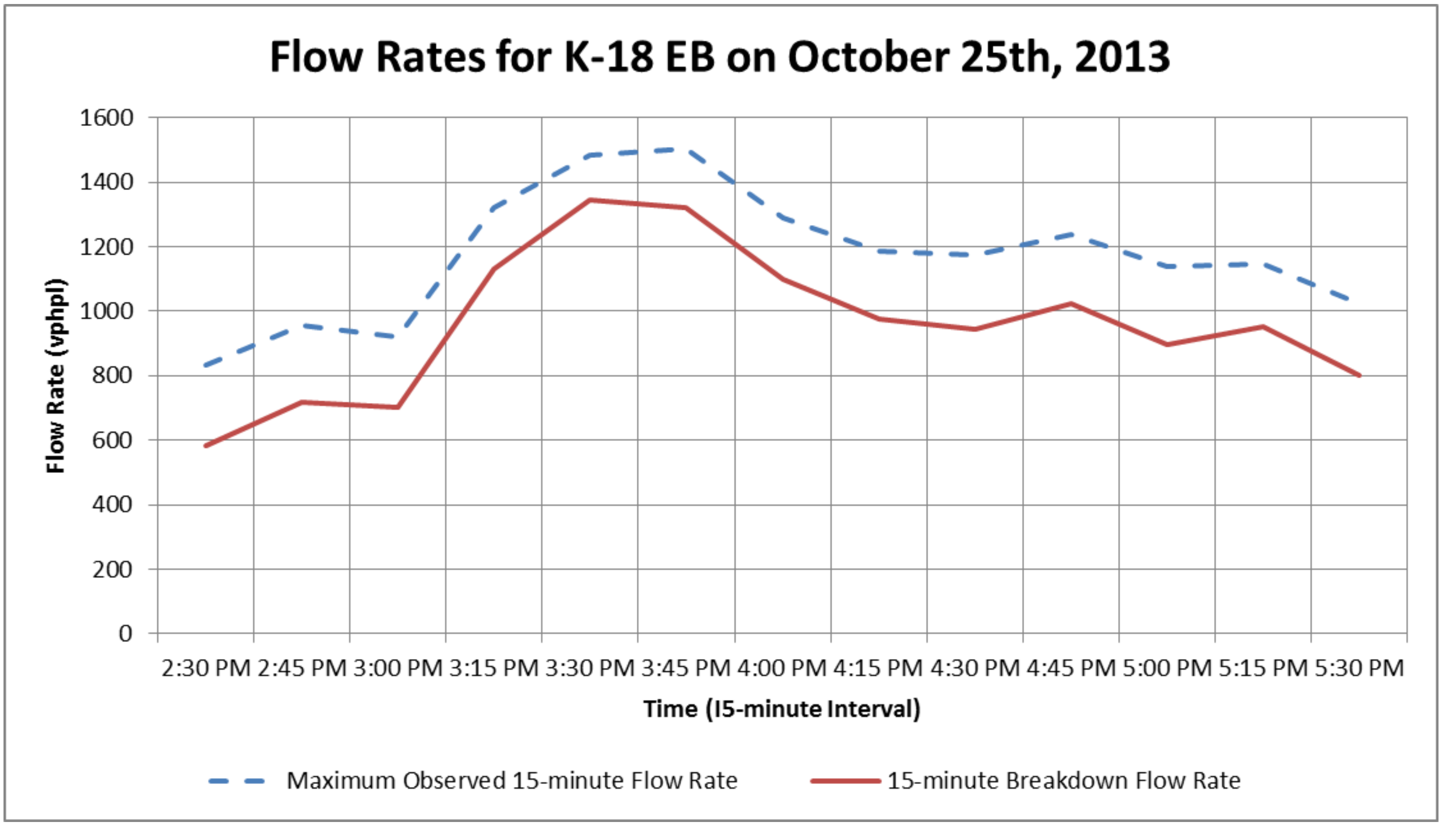
4.2.2 K-18 EB

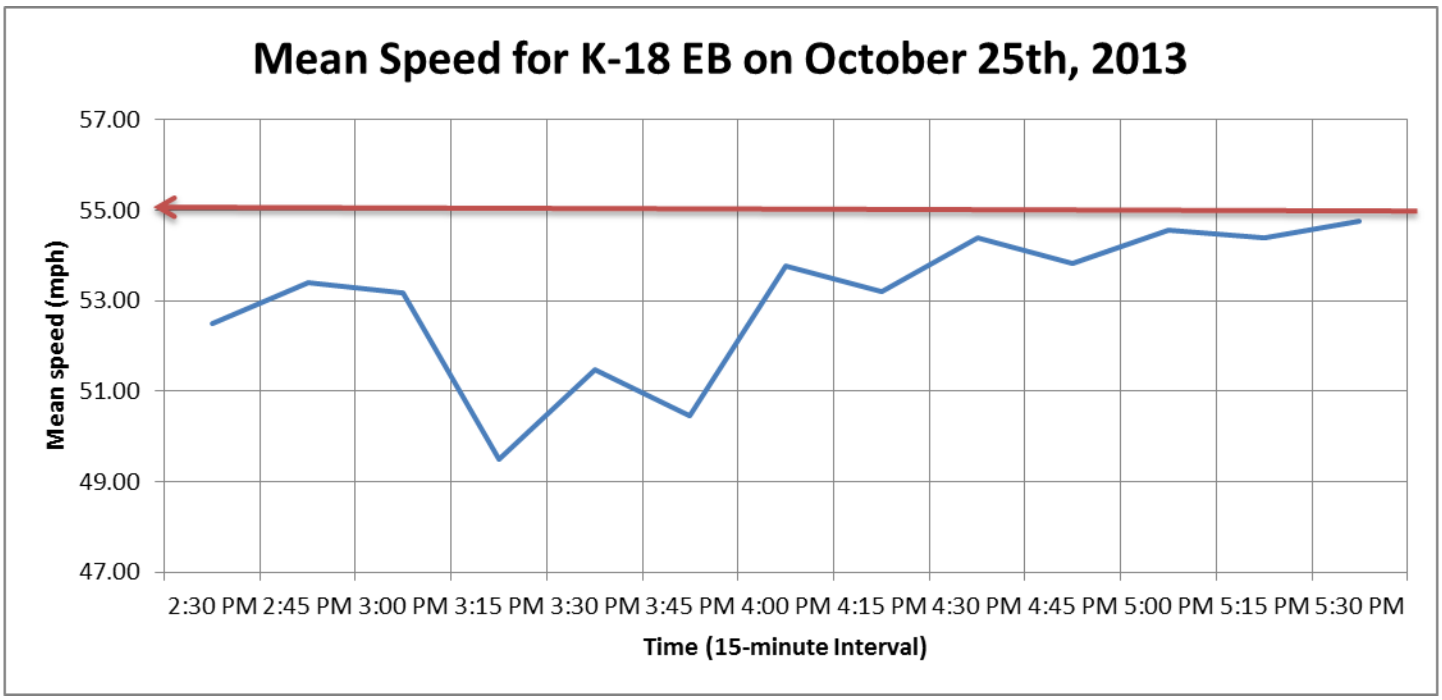
Capacity found using the maximum observed 15-minute flow rate method for the K-18 EB data collection site was found to be 1551 pcphpl with a standard deviation of 233.06 pcphpl, as shown in Table 4.2. The normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The weather during data collection for this site had clear skies and temperatures ranging from 55 to 65 degrees Fahrenheit. The correlation during the peak time period for one 24-hr period is shown in Figure 4.2. The mean speed of the entire data collection was equal to 53 mph, as shown in Figure A.2 in Appendix A. The average and the average standard deviation were both based on the peak time period of the site.

Table 4.2 – K-18 EB site for Maximum Observed 15-minute Flow Rate Method

K-18 EB Site								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate (pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/19/2013	3:15 pm to Midnight	55.82	97.16%	0.50%	2.34%	847	830	648
10/20/2013	24 hrs	56.10	98.02%	0.08%	1.90%	731	715	477
10/21/2013	24hrs	54.99	93.17%	0.40%	6.43%	1368	1265	1264
10/22/2013	24hrs	55.58	91.61%	0.48%	7.91%	1423	1344	1203
10/23/2013	24hrs	55.55	92.73%	0.36%	6.90%	1255	1203	1015
10/24/2013	24hrs	55.46	92.20%	0.37%	7.43%	1490	1278	1316
10/25/2013	24hrs	55.29	93.49%	0.47%	6.04%	1551	1443	1386
10/26/2013	24hrs	56.70	96.26%	0.27%	3.47%	1278	1187	1079
10/27/2013	Midnight to 10:15 am	57.06	96.34%	0.19%	3.47%	419	350	191
TOTAL/AVERAGE		55.69	94.33%	0.37%	5.30%	1243	1158	1049
AVG STANDARD DEVIATION		---	---	---	---	233.06	217.09	248.72

Figure 4.2 – K-18 EB Site Peak Time Period Flow Rate VS. Mean Speed Graphs





4.2.3 K-18 H-H EB & WB

Two data collection sites that had slightly different setups than the other data collection sites were the K-18 H-H EB and WB sites. The EB site provided accurate capacity values throughout the duration of the data collection process. Maximum capacity for the K-18 H-H EB site was equal to 1530 pcphpl with a standard deviation of 156.77 pcphpl, as shown in Table 4.3. EB correlation graphs representing flow rates and mean speeds during the peak time period are shown in Figure 4.3. The normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The average and the average standard deviation were both based on the peak time period of the site. The mean speed for entire data collection at the EB site was 55.6 mph, as shown in Figure A.3 in Appendix A.

Analysis of capacities per day for the WB direction did not provide as accurate of results as the EB direction. The WB direction did not provide sufficient evidence that capacity could be determined. The mean speed must fall below the threshold value for three consecutive 15-minute time intervals, but this was not met in the observed data. Potential maximum capacity for the WB direction was 1292 pcphpl with a standard deviation of 124.14 pcphpl which is reasonable but possibly not accurate. Table 4.4 provides results for the K-18 WB data observation. Figure 4.4 displays the unmet parameter; therefore, no correlation between flow rates and mean speed for the K-18 WB data collection site could be made. Like the EB direction the normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The average and the average standard deviation were both based on the peak time period of the site. The mean speed for the entire data collection in the WB direction was 57.3 mph, as shown in Figure A.4 in Appendix A.

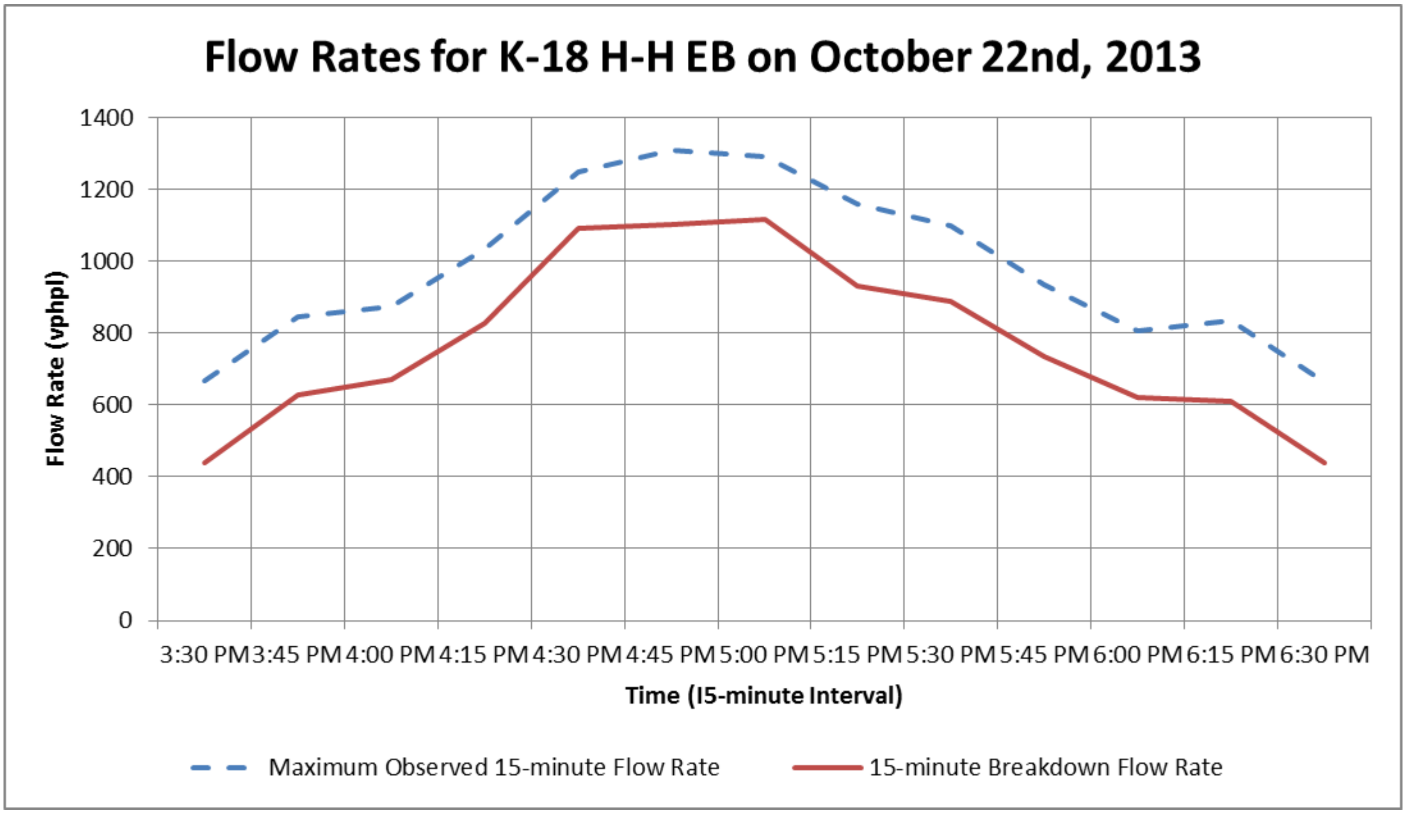
Table 4.3 – K-18 H-H EB site for Maximum Observed 15-minute Flow Rate Method

K-18 H-H EB Site								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate (pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/19/2013	2:15 pm to Midnight	55.76	89.08%	0.66%	10.26%	964	851	762
10/20/2013	24 hrs	56.98	92.57%	0.11%	7.32%	751	725	535
10/21/2013	24hrs	55.78	86.57%	0.50%	12.93%	1436	1274	1257
10/22/2013	24hrs	55.69	86.64%	0.62%	12.74%	1393	1333	1188
10/23/2013	24hrs	55.35	86.94%	0.42%	12.64%	1247	1199	1047
10/24/2013	24hrs	55.19	86.52%	0.46%	13.02%	1249	1255	1245
10/25/2013	24hrs	55.58	86.60%	0.60%	12.81%	1530	1376	1359
10/26/2013	24hrs	55.61	90.54%	0.35%	9.11%	1335	1204	1151
10/27/2013	Midnight to 10:00 am	57.45	92.75%	0.32%	6.93%	369	318	178
TOTAL/AVERAGE		55.74	88.18%	0.47%	11.35%	1238	1152	1068
AVG STANDARD DEVIATION		---	---	---	---	156.77	146.36	162.04

Table 4.4 – K-18 H-H WB site for Maximum Observed 15-minute Flow Rate Method

K-18 H-H WB Site								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate (pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/19/2013	2:15 pm to Midnight	56.73	93.84%	0.72%	5.44%	979	906	741
10/20/2013	24 hrs	57.65	95.17%	0.20%	4.63%	815	758	581
10/21/2013	24hrs	57.24	89.30%	0.46%	10.24%	968	768	741
10/22/2013	24hrs	56.99	88.70%	0.77%	10.53%	1029	936	789
10/23/2013	24hrs	56.65	88.51%	0.58%	10.91%	1009	928	777
10/24/2013	24hrs	56.94	89.14%	0.44%	10.42%	990	922	767
10/25/2013	24hrs	56.55	89.81%	0.48%	9.71%	966	914	751
10/26/2013	24hrs	57.44	93.53%	0.25%	6.23%	1292	1260	1127
10/27/2013	Midnight to 10:00 am	58.00	94.32%	0.27%	5.41%	543	408	325
TOTAL/AVERAGE		57.02	91.00%	0.49%	8.51%	1006	924	784
AVG STANDARD DEVIATION		---	---	---	---	124.14	140.67	132.07

Figure 4.3 – K-18 H-H EB Site Peak Time Period Flow Rate VS. Mean Speed Graphs



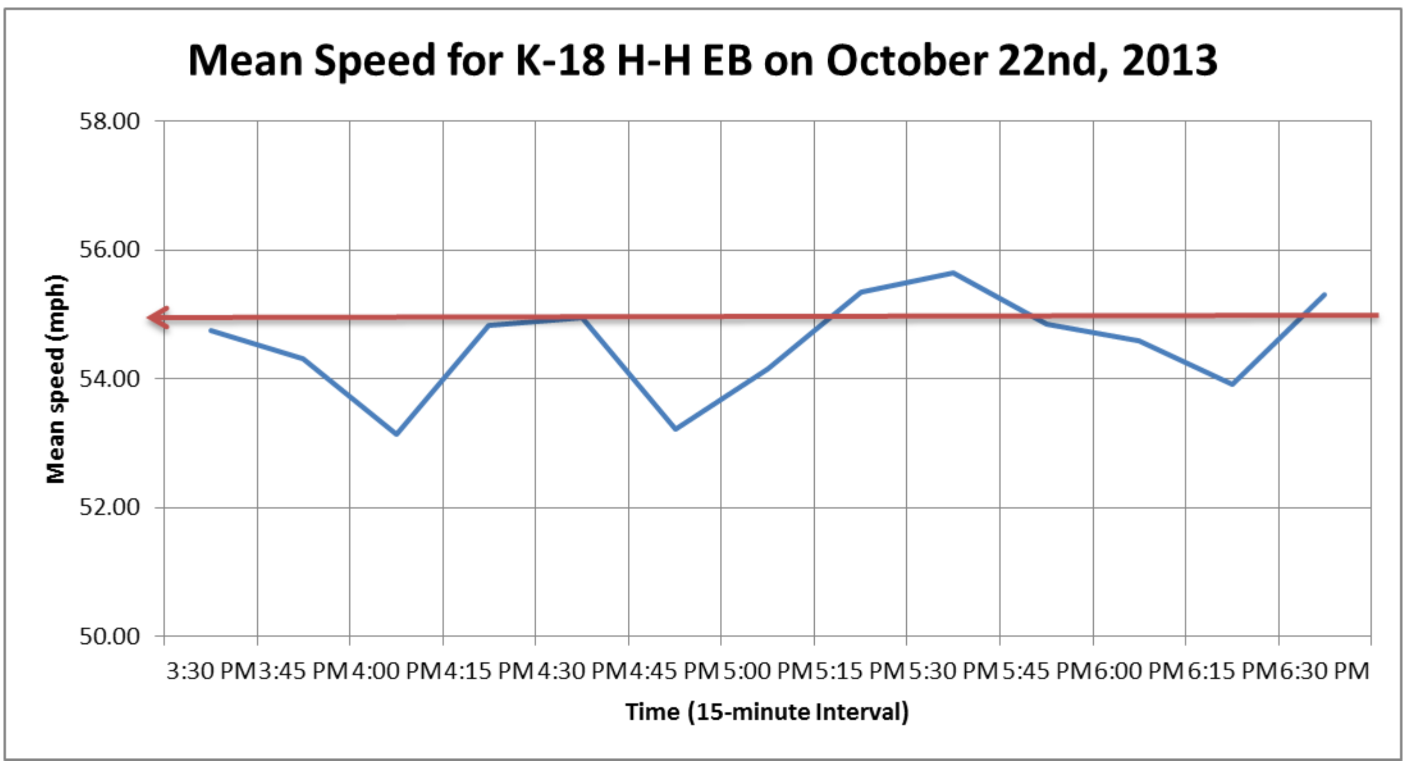
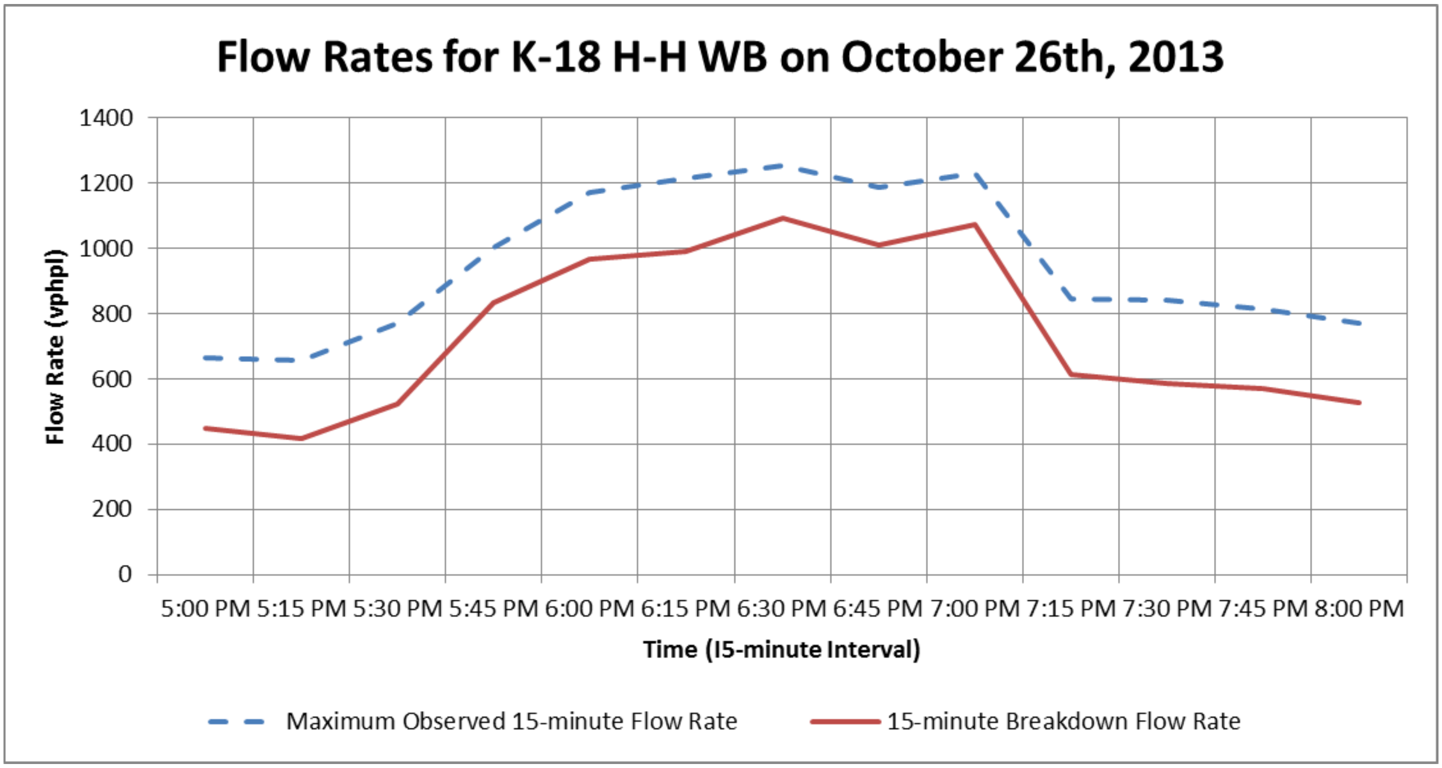
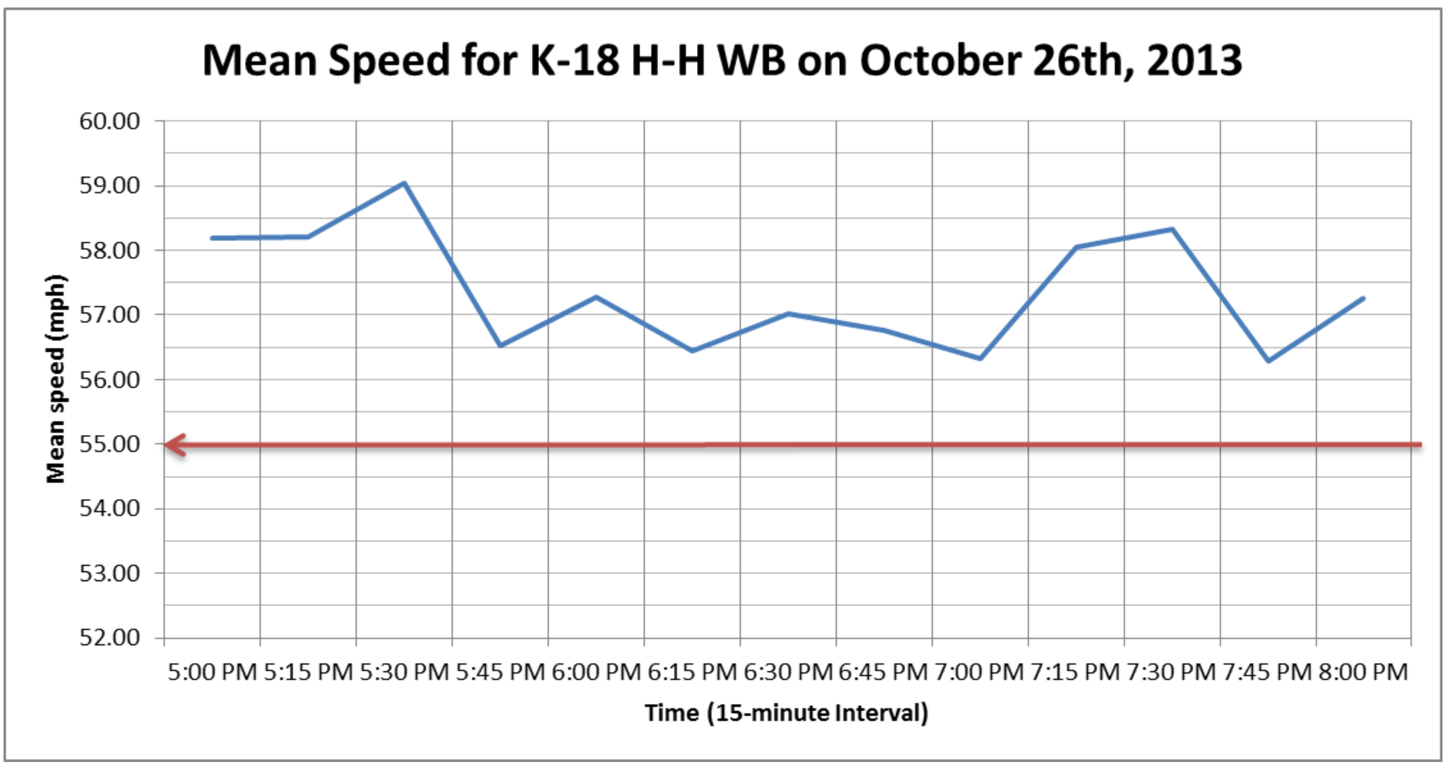


Figure 4.4 – K-18 H-H WB Site Peak Time Period Flow Rate VS. Mean Speed Graphs





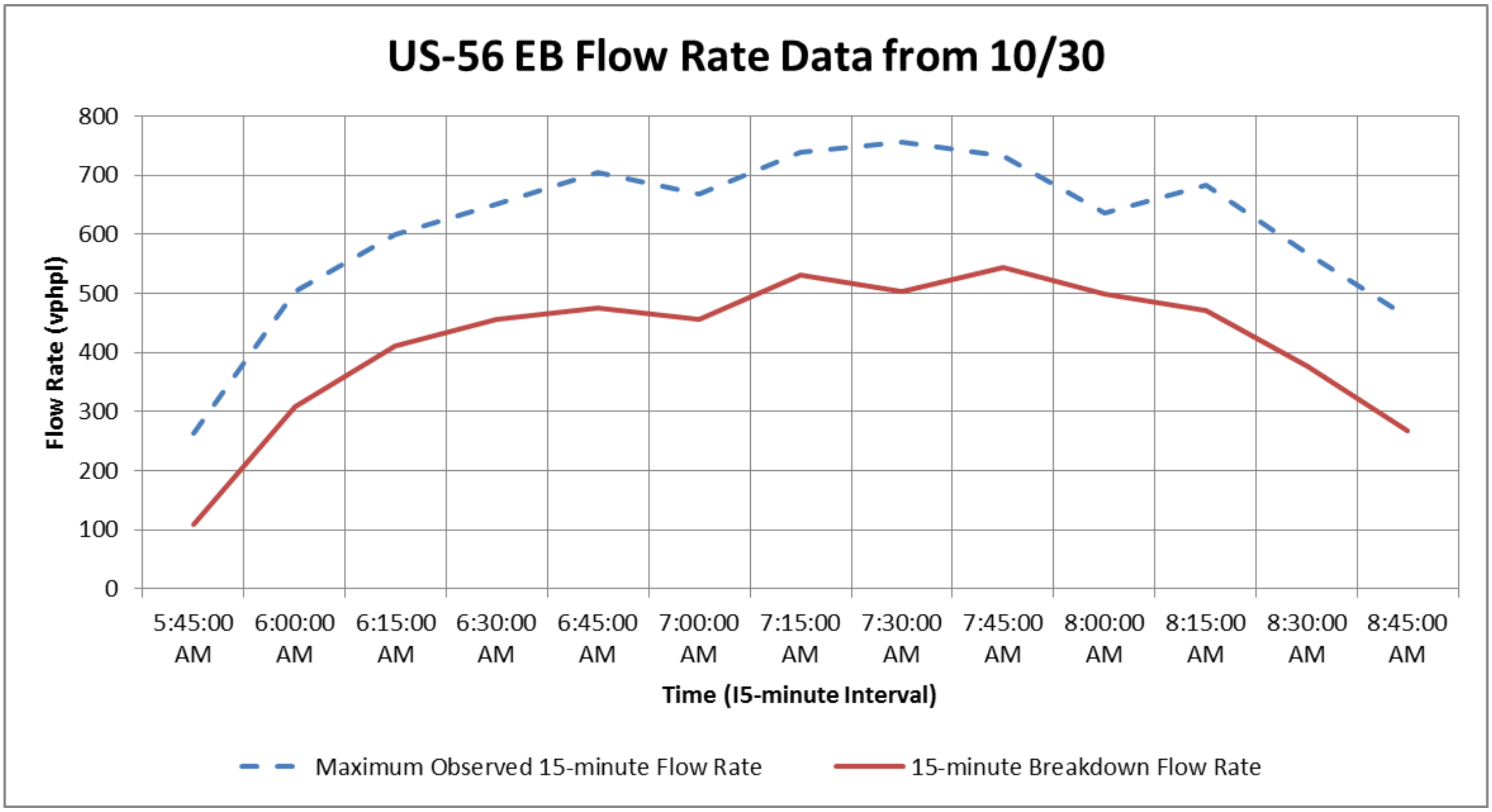
4.2.4 US-56 EB

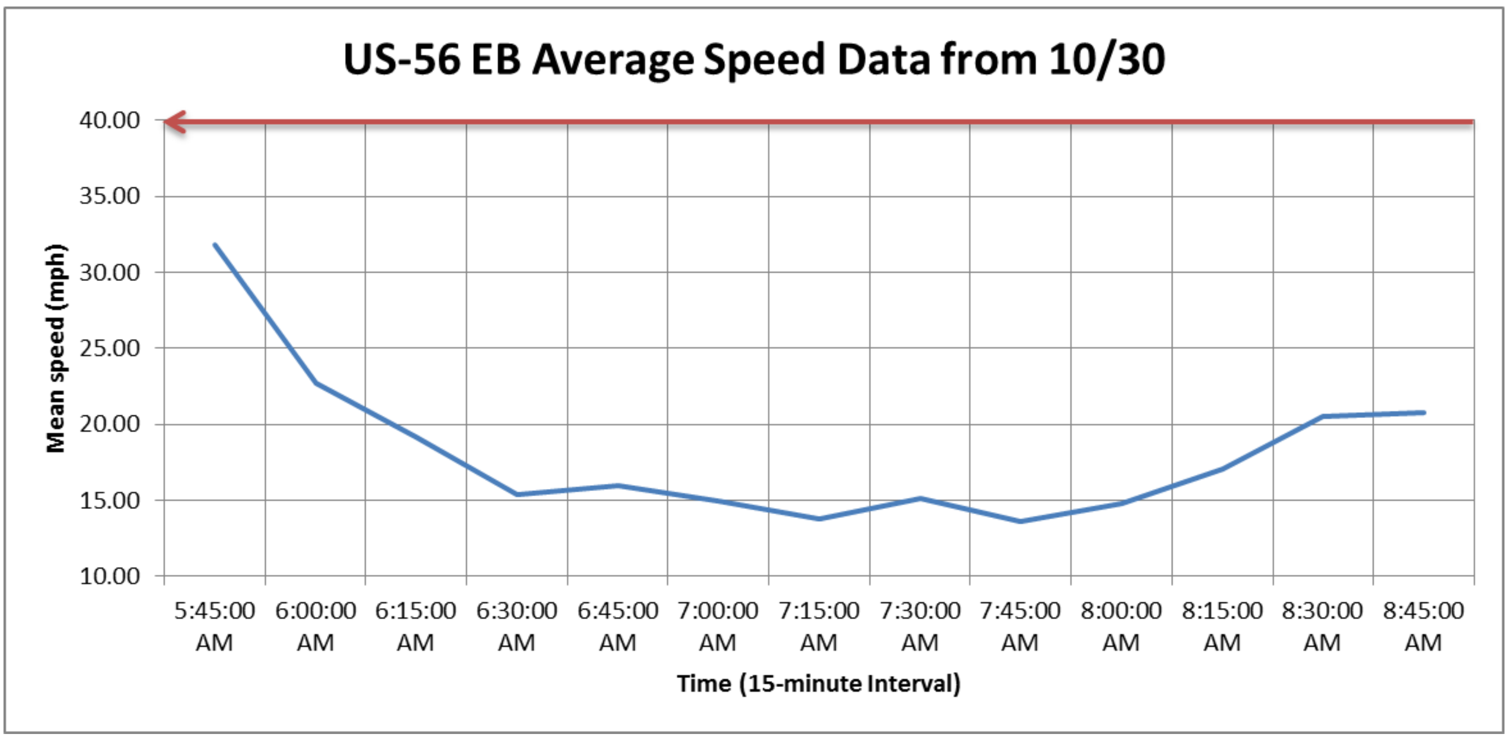
Data obtained at the US-56 EB data collection site was thought to have been lost due to a bad pin in the VGA adaptor which transfers data to the software program for analysis. However, after sending the traffic counter to Jamar Technologies for service, obtained data was extracted and determined to be accurate. Filtering out traffic breaks due to the stoplight-controlled intersection approximately 650 ft west of the data collection point was another challenge for estimating capacity at this site. The last obstacle to overcome was weather interference for this site. Maximum capacity at the site was 1036 pcphpl with a standard deviation of 132.56 pcphpl, as shown in Table 4.5. The only full 24-hr period of collected data can be found on October 29th, 2013. The normal speed limit for this site was 50 mph while the work zone speed limit was found to equal 40 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure 4.5 shows the correlation between mean speed and maximum observed 15-minute flow rate. This correlation proves that the capacity obtained from the site is accurate. The mean speed for the entire data collection at the site was 24.4 mph, as shown in Figure A.5 in Appendix A.

Table 4.5 – US-56 EB site for Maximum Observed 15-minute Flow Rate Method

US-56 EB Site for the Maximum Observed 15-minute Flow Rate Method								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate (pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/28/2013	10:30 am to Midnight	29.25	91.85%	1.19%	6.96%	560	529	398
10/29/2013	24 hrs	24.40	93.27%	0.67%	6.05%	1036	857	805
10/30/2013	Midnight to 10:30 am	29.47	93.96%	0.44%	5.65%	778	745	560
TOTAL/AVERAGE		27.71	93.03%	0.77%	6.22%	791	710	588
AVG STANDARD DEVIATION		---	---	---	---	132.56	90.03	119.17

Figure 4.5 – US-56 EB Site Peak Time Period Flow Rate VS. Mean Speed Graphs





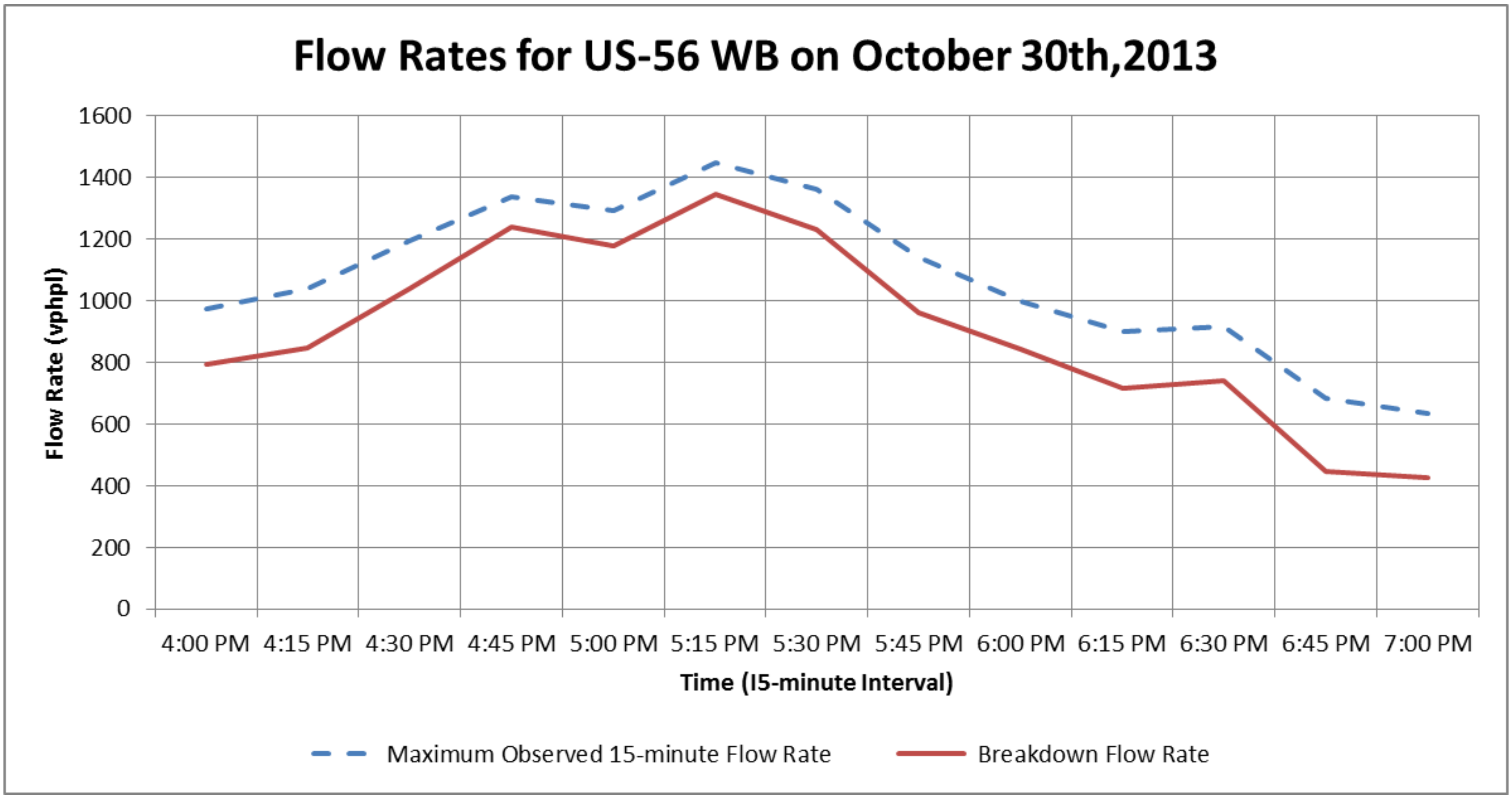
4.2.5 US-56 WB

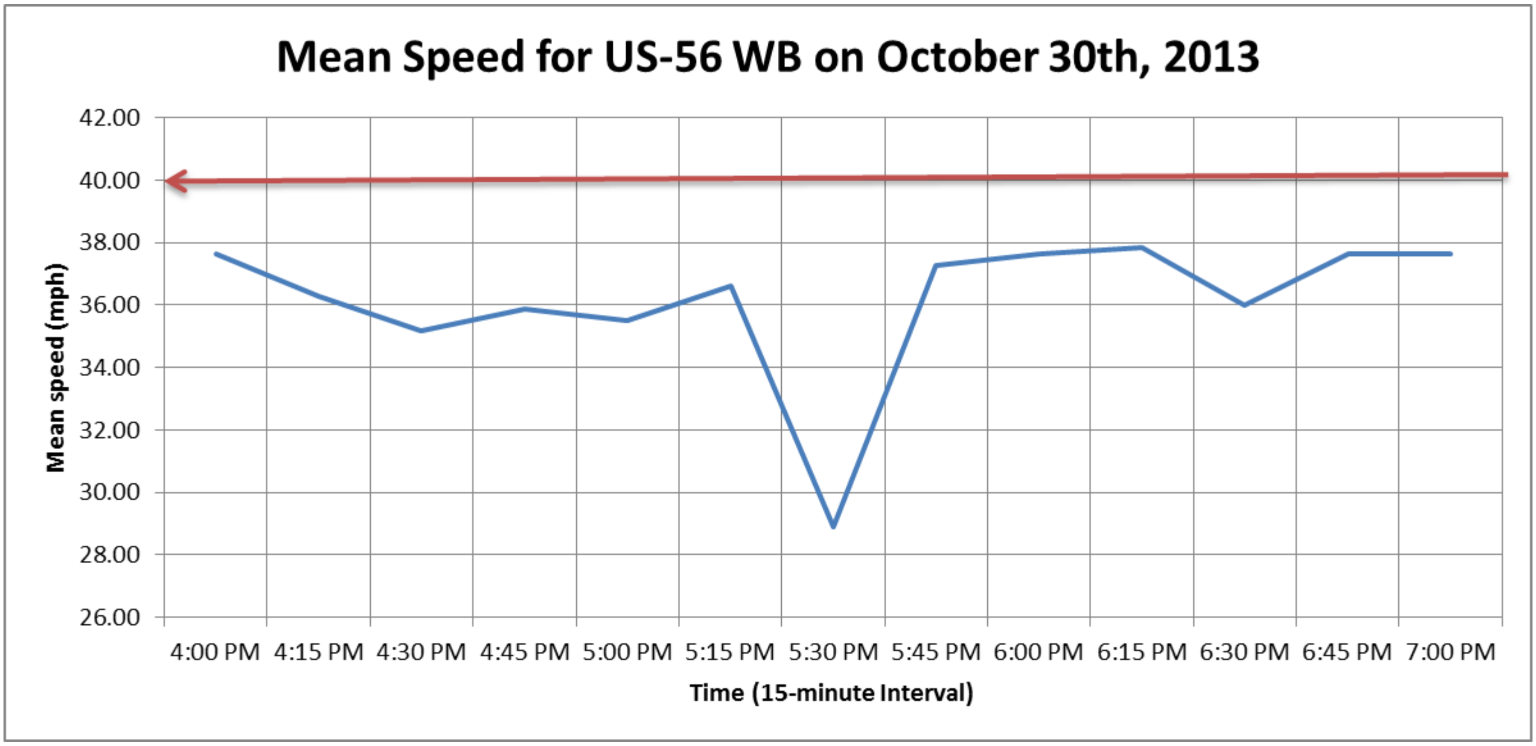
Similar to the US-56 EB direction, the US-56 WB direction also encountered rain for the first four days of the data collection process. Data from the rainy days were discarded due to data inconsistencies, but one full 24-hr period of data collection was obtained in which the peak time period was found. Maximum capacity identified during the peak time period was 1496 pcphpl with a standard deviation of 132.36 pcphpl, as shown in Table 4.6. The normal speed limit for this site was 50 mph while the work zone speed limit was found to equal 40 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure 4.6 provides graphs to observe the correlation which proves that capacity was met on this site. Determined mean speed for the data collected at the site was 38.05 mph, as shown in Figure A.6 in Appendix A.

Table 4.6 – US-56 WB site for Maximum Observed 15-minute Flow Rate Method

US-56 WB Site								
Date	Time Period	Average Speed (mph at 2 mph intervals)	Percent Cars	Percent Buses	Percent Trucks	Maximum Flow Rate (pcphpl)	Maximum Volume (pcphpl)	Breakdown Flow Rate (pcphpl)
10/28/2013	11:00 am to Midnight	39.65	89.92%	0.32%	9.76%	1465	1372	1339
10/29/2013	24 hrs	37.77	93.31%	0.19%	6.50%	1496	1404	1388
10/30/2013	24 hrs	36.93	90.45%	0.15%	6.52%	1201	1096	1056
TOTAL/AVERAGE		38.12	91.23%	0.22%	7.59%	1387	1291	1261
AVG STANDARD DEVIATION		---	---	---	---	132.36	138.27	146.33

Figure 4.6 – US-56 WB Site Peak Time Period Flow Rate VS. Mean Speed Graphs





4.3 Platooning Method

The Platooning Method provided evidence that estimated capacities found in the Maximum Observed 15-minute Flow Rate Method were accurate. However, based on obtained data, justification of an upper limit existing with the Platooning Method and a lower limit existing with the Maximum Observed 15-minute Flow Rate Method was not established in this study. Instead, the opposite was found to be true. Various reasons can be identified for this difference, but the overall determination can be made that since platooning factors were not assumed but practically found for each site, the platooning method is a more accurate approach than previous studies.

Overall analysis per site for the Platooning Method is provided in the following subsections. Additional details on data collected at each site with respect to the Platooning Method are provided in Appendix B. Summary tables and graphs for each site are also shown and explained in Appendix B. The graphs in Appendix B show the peak time period for the maximum 24-hr period per site. The platooning factor per site was multiplied by the maximum potential capacity to discern the maximum estimated capacity per site.

In the Platooning Method, potential capacity per site can only be found if more than five platooning vehicles are found per interval for three consecutive time intervals. This approach eliminates high values for capacities during non-peak hours of the day/night. When only one to three vehicles are seen in-platoon, average headways amount to smaller values and therefore provide larger estimated capacities.

4.3.1 K-10 EB

The K-10 EB observed data is provided in Table 4.7 and the setup is shown in Figure 4.7. As discussed, data collected during rainy days were discarded from the analysis, identified by italics and underlining in Table 4.7. Excluding those three days, the maximum estimated capacity for this site was found to equal 1358 pcphpl with a platooning factor of 0.8 and a standard deviation of 31.06 pcphpl. This was due to the amount of vehicles found in-platoon during the peak time period from the respective day where the maximum estimated capacity could be seen.

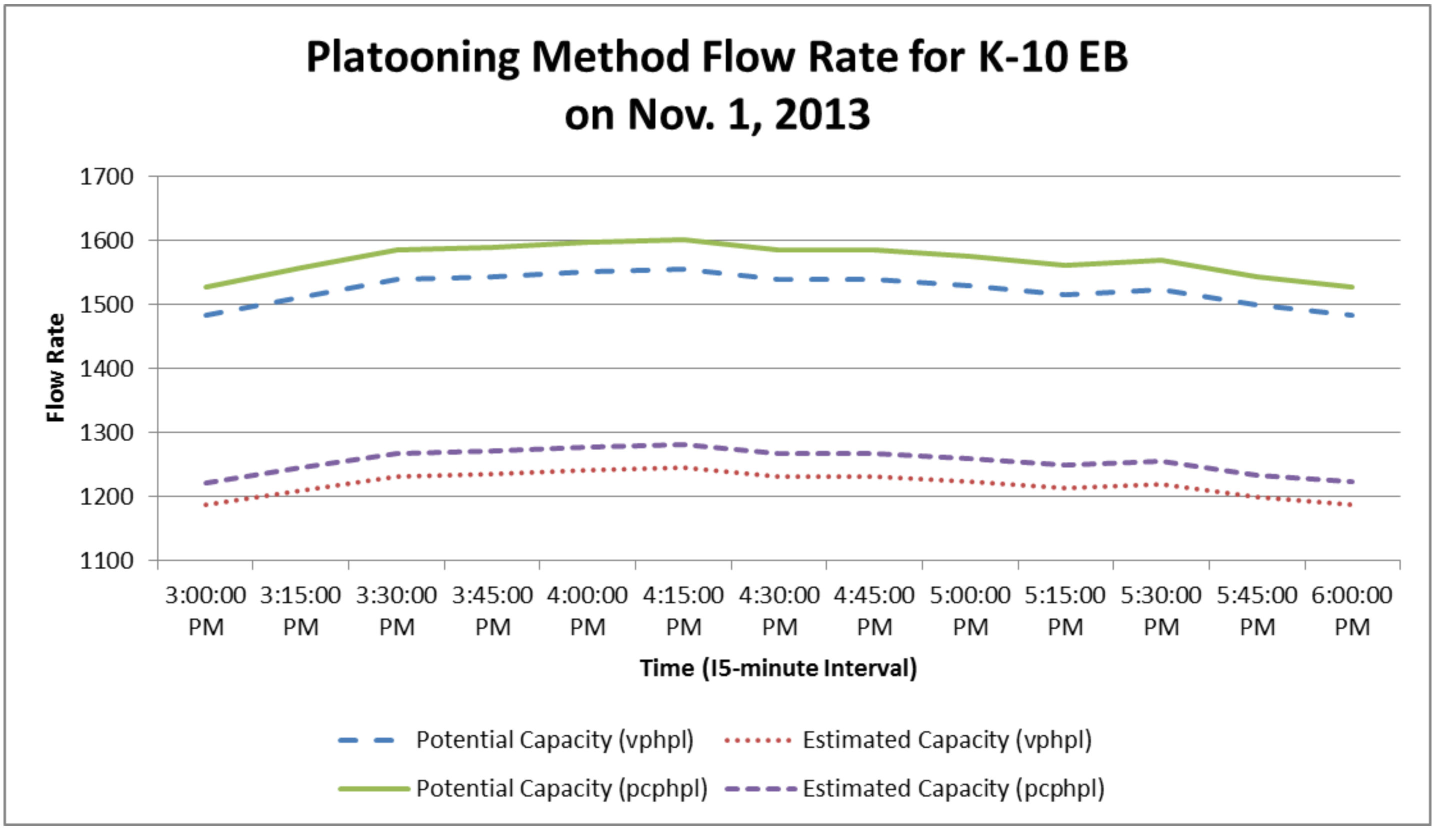
This platooning factor was relatively high compared to other sites but this site was also the most traversed highway under review. The average speed in 2 mph intervals over the provided peak time periods was found to equal 58.03 mph. The normal speed limit for this site was 70 mph while the work zone speed limit was found to equal 60 mph. The average and the average standard deviation were both based on the peak time period of the site. The full set of observed data for the site is provided in Figure B.1 in Appendix B.

Table 4.7 – Results for K-10 EB site using Platooning Method

K-10 EB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/28/2013	10:00 am to Midnight	92.10%	0.91%	6.99%	0.80	1530	1224	1586	1269
10/29/2013*	24 hrs	57.39%	1.98%	40.63%	0.80	1504	1203	1815	1452
10/30/2013*	24hrs	39.48%	16.20%	44.32%	0.80	1560	1248	1956	1565
10/31/2013*	24hrs	44.12%	43.99%	11.89%	0.80	1517	1214	1741	1393
11/1/2013	24hrs	93.68%	0.63%	5.69%	0.80	1556	1245	1602	1282
11/2/2013	24hrs	96.85%	0.18%	2.97%	0.80	1468	1174	1490	1192
11/3/2013	24hrs	97.43%	0.08%	2.49%	0.80	1452	1162	1470	1176
11/4/2013	Midnight to 11:00 am	93.62%	0.64%	5.74%	0.80	1648	1318	1697	1358
TOTAL/AVERAGE*		94.74%	0.49%	4.78%	0.80	1531	1225	1569	1255
AVG STANDARD DEVIATION*		---	---	---	---	37.76	30.21	38.82	31.06

* It rained heavily during the days 10/29 to 10/31.

Figure 4.7 – K-10 EB Site Peak Time Period Flow Rate Graph



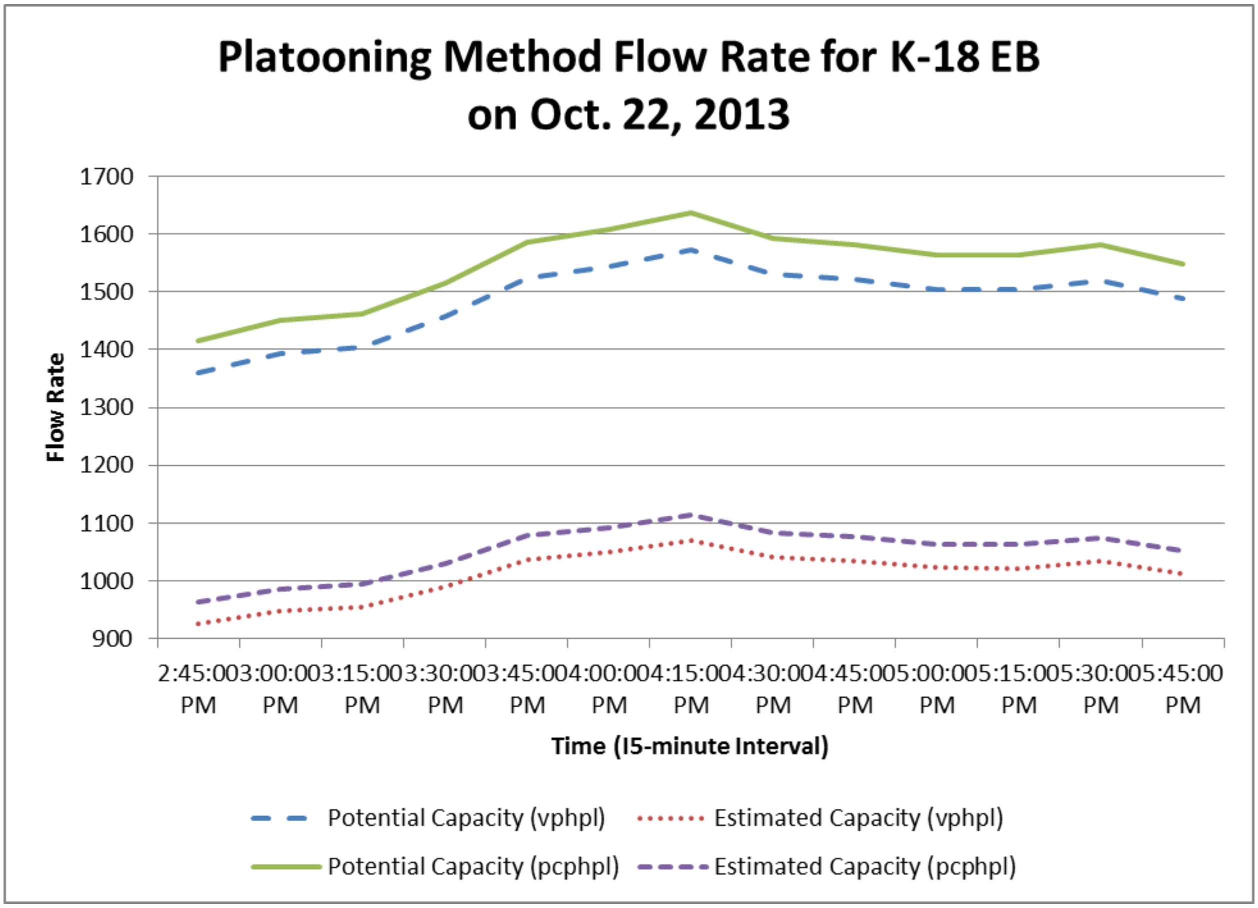
4.3.2 K-18 EB

The K-18 EB observed data is shown in Table 4.8 and Figure 4.8. The table provides estimated capacities per day. The maximum estimated capacity for this site was found to equal 1113 pcphpl with a standard deviation of 25.57 pcphpl. The estimated capacity is low for this site because the platooning factor was found to equal 0.68. This value was low due to the amount of vehicles that seen in-platoon. Although this site is traversed frequently, construction had been underway for the past several months leading up to the data collection process for this report. Many motorists may have found a more direct route to their final destination, thus reducing vehicle volume on the roadway, and decreasing the flow rate on the roadway, and leading to a lower platooning factor. The average speed in 2 mph intervals over the provided peak time periods was found to equal 55.84 mph. The normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The average and the average standard deviation were both based on the peak time period of the site. The full set of observed data for the site is presented in Figure B.2 in Appendix B.

Table 4.8 – Results for K-18 EB site using Platooning Method

K-18 EB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/19/2013	3:15 pm to Midnight	97.16%	0.50%	2.34%	0.68	1526	1038	1545	1051
10/20/2013	24 hrs	98.02%	0.08%	1.90%	0.68	1525	1037	1540	1047
10/21/2013	24hrs	93.17%	0.40%	6.43%	0.68	1564	1064	1616	1099
10/22/2013	24hrs	91.61%	0.48%	7.91%	0.68	1573	1070	1637	1113
10/23/2013	24hrs	92.73%	0.36%	6.90%	0.68	1498	1019	1551	1055
10/24/2013	24hrs	92.20%	0.37%	7.43%	0.68	1534	1043	1592	1083
10/25/2013	24hrs	93.49%	0.47%	6.04%	0.68	1541	1048	1589	1081
10/26/2013	24hrs	96.26%	0.27%	3.47%	0.68	1522	1035	1549	1053
10/27/2013	Midnight to 10:15 am	96.34%	0.19%	3.47%	0.68	1519	1033	1546	1051
TOTAL/AVERAGE		94.55%	0.35%	5.10%	0.68	1534	1043	1574	1070
AVG STANDARD DEVIATION		---	---	---	---	36.58	24.88	37.60	25.57

Figure 4.8 – K-18 EB Site Peak Time Period Flow Rate Graph



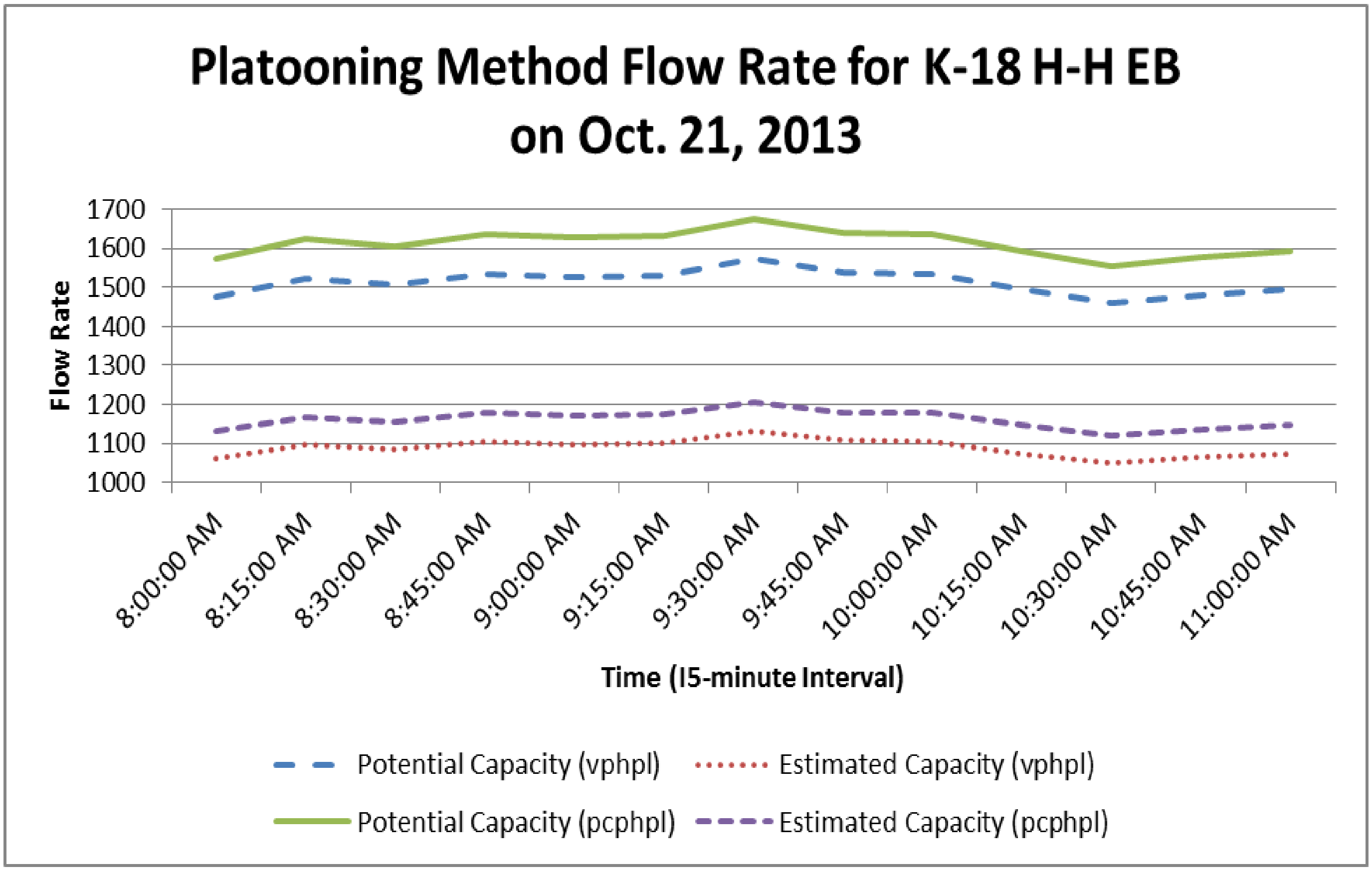
4.3.3 K-18 H-H EB

The maximum estimated capacity for the K-18 H-H EB site was found to equal 1207 pcphpl with a standard deviation of 26.82 pcphpl, as shown in Table 4.9. The platooning factor for this site was 0.72 which was the average of each site and thereby considered the most accurate due to motorist usage during peak time periods. Traffic on the roadway in this section had to manipulate a head-to-head section while accounting for large construction trucks entering and leaving the construction location. However, the traversable lane was approximately 30 ft from the construction so traffic flow was generally not disrupted due to large volumes in the work zone. Figure 4.9 provides the peak time period flow rate graph for the peak 24-hr period on this site. The average speed in 2 mph intervals over the provided peak time periods was found to equal 55.93 mph. The normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure B.3 shown in Appendix B provides the full observed data on this site.

Table 4.9 – Results for K-18 H-H EB site using Platooning Method

K-18 H-H EB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/19/2013	2:15 pm to Midnight	89.08%	0.66%	10.26%	0.72	1591	1146	1675	1206
10/20/2013	24 hrs	92.57%	0.11%	7.32%	0.72	1586	1142	1644	1184
10/21/2013	24hrs	86.57%	0.50%	12.93%	0.72	1573	1133	1676	1207
10/22/2013	24hrs	86.64%	0.62%	12.74%	0.72	1569	1130	1671	1203
10/23/2013	24hrs	86.94%	0.42%	12.64%	0.72	1544	1112	1643	1183
10/24/2013	24hrs	86.52%	0.46%	13.02%	0.72	1555	1120	1658	1194
10/25/2013	24hrs	86.60%	0.60%	12.81%	0.72	1541	1110	1641	1182
10/26/2013	24hrs	90.54%	0.35%	9.11%	0.72	1545	1112	1616	1164
10/27/2013	Midnight to 10:00 am	92.75%	0.32%	6.93%	0.72	1624	1169	1681	1211
TOTAL/AVERAGE		88.69%	0.45%	10.86%	0.72	1570	1130	1656	1193
AVG STANDARD DEVIATION		---	---	---	---	35.47	25.54	37.25	26.82

Figure 4.9 – K-18 H-H EB Site Peak Time Period Flow Rate Graph



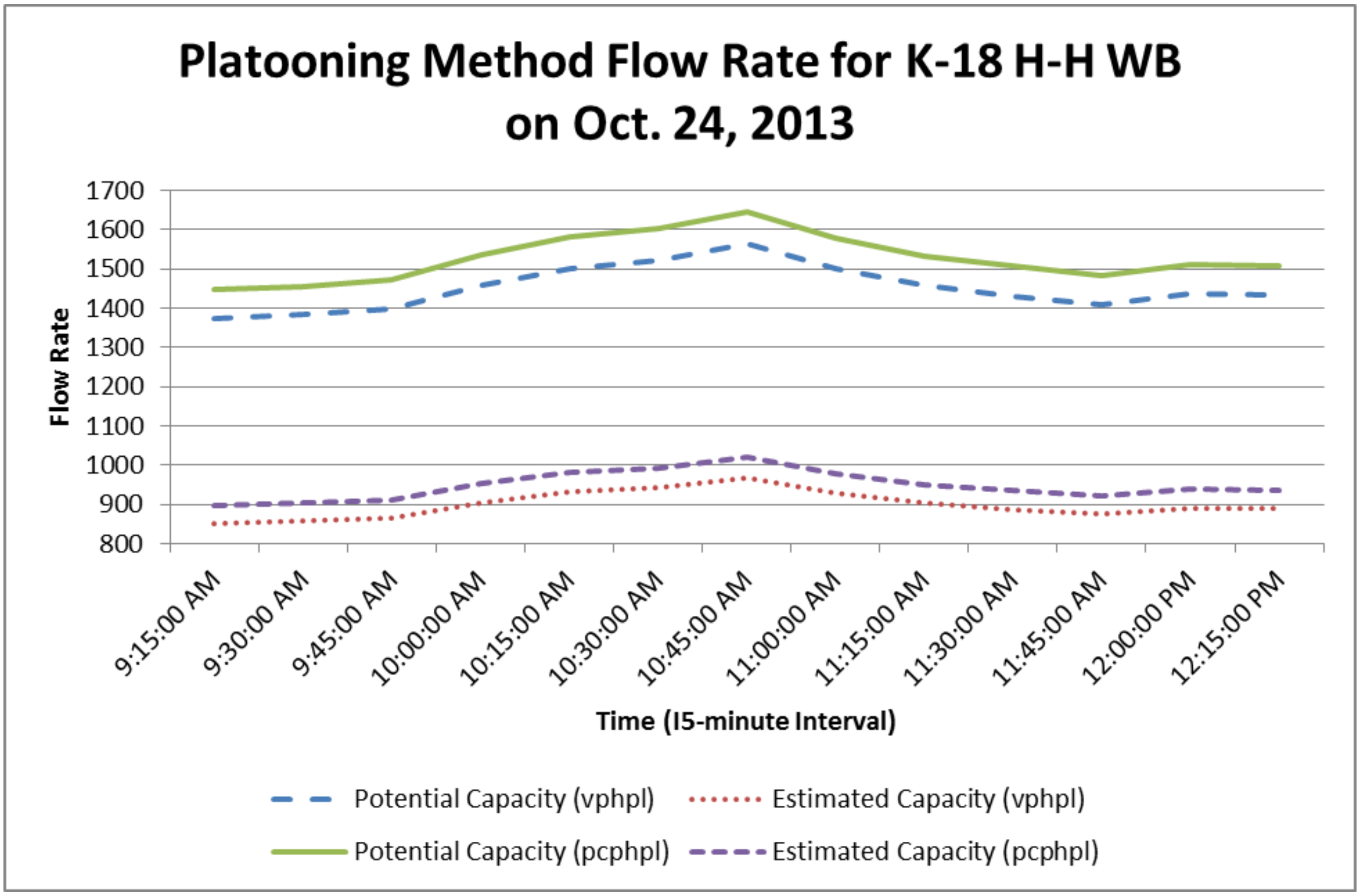
4.3.4 K-18 H-H WB

The K-18 H-H WB site was under the same conditions as the EB direction but had a maximum estimated capacity of 1020 pcphpl with a standard deviation of 19.71 pcphpl, as shown in Table 4.10. Similar to the K-18 EB site, estimated capacity can be seen to be lower than potential capacity due to the platooning factor of 0.62 for this site. Motorists could use several alternative routes to avoid this site, possibly causing the low platooning factor. If some of the passenger cars chose alternative routes, traffic volume on the roadway would decrease, leading to less in-platoon vehicles. Since estimated capacity accounts for the platooning factor and the platooning factor accounts for the amount of in-platoon vehicles, the estimated capacity would be lower than expected in this situation. The peak time period flow rate graph for the maximum 24-hr period for this site is shown in Figure 4.10. The average speed in 2 mph intervals over the provided peak time periods was found to equal 57.13 mph. The normal speed limit for this site was 65 mph while the work zone speed limit was found to equal 55 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure B.4 in Appendix B provides the full observed data from this site.

Table 4.10 – Results for K-18 H-H WB site using Platooning Method

K-18 H-H WB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/19/2013	2:15 pm to Midnight	93.84%	0.72%	5.44%	0.62	1490	924	1533	950
10/20/2013	24 hrs	95.17%	0.20%	4.63%	0.62	1498	929	1533	951
10/21/2013	24hrs	89.30%	0.46%	10.24%	0.62	1498	929	1576	977
10/22/2013	24hrs	88.70%	0.77%	10.53%	0.62	1485	921	1565	971
10/23/2013	24hrs	88.51%	0.58%	10.91%	0.62	1503	932	1587	984
10/24/2013	24hrs	89.14%	0.44%	10.42%	0.62	1563	969	1646	1020
10/25/2013	24hrs	89.81%	0.48%	9.71%	0.62	1512	937	1587	984
10/26/2013	24hrs	93.53%	0.25%	6.23%	0.62	1489	923	1536	952
10/27/2013	Midnight to 10:00 am	94.32%	0.27%	5.41%	0.62	1478	916	1519	942
TOTAL/AVERAGE		91.37%	0.46%	8.17%	0.62	1502	931	1565	970
AVG STANDARD DEVIATION		---	---	---	---	30.51	18.92	31.79	19.71

Figure 4.10 – K-18 H-H WB Site Peak Time Period Flow Rate Graph



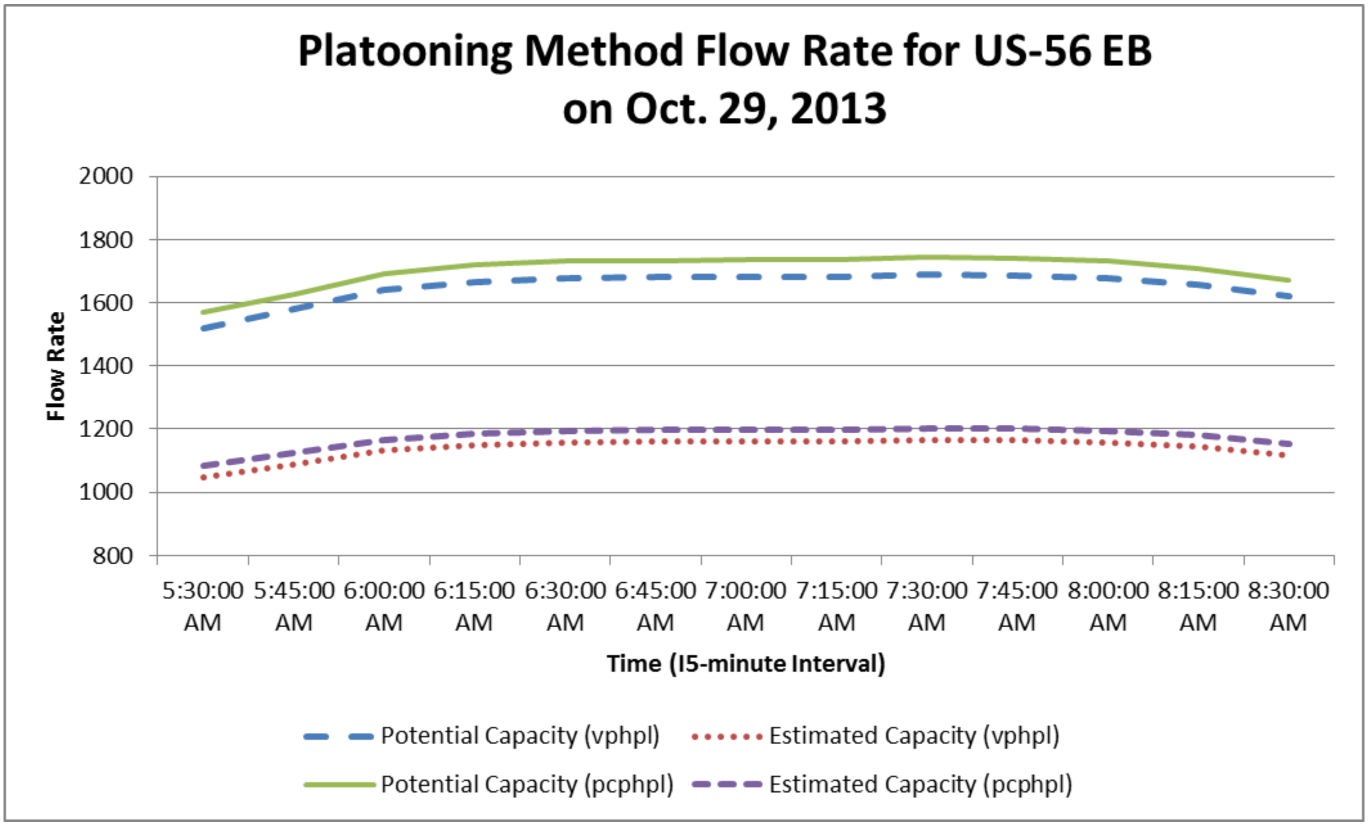
4.3.5 US-56 EB

The traffic signal upstream from the US-56 EB data collection site may have occasionally controlled the platooning factor, thus causing the platooning factor of 0.69 for the US-56 EB site. Due the low platooning factor, a low estimated capacity can be expected. The maximum estimated capacity for the US-56 EB site was equal to 1204 pcphpl with the standard deviation equal to 33.4 pcphpl, as shown in Table 4.11. This site was also affected by rainy days and, therefore, only three days' worth of data was available to analyze. Figure 4.11 provides the peak time period flow rate graph for the site. The average speed in 2 mph intervals over the provided peak time periods was found to equal 27.71 mph. The normal speed limit was found to equal 50 mph while the work zone speed limit was found to equal 40 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure B.5 provides the full observed data at this site, as shown in Appendix B.

Table 4.11 – Results for US-56 EB site using Platooning Method

US-56 EB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/28/2013	10:30 am to Midnight	91.85%	1.19%	6.96%	0.69	1638	1130	1699	1172
10/29/2013	24 hrs	93.27%	0.67%	6.05%	0.69	1691	1167	1744	1204
10/30/2013	Midnight to 10:30 am	93.96%	0.44%	5.65%	0.69	1643	1134	1692	1167
TOTAL/AVERAGE		93.02%	0.77%	6.22%	0.69	1658	1144	1712	1181
AVG STANDARD DEVIATION		---	---	---	---	46.8	32.3	48.4	33.4

Figure 4.11 – US-56 EB Site Peak Time Period Flow Rate Graph



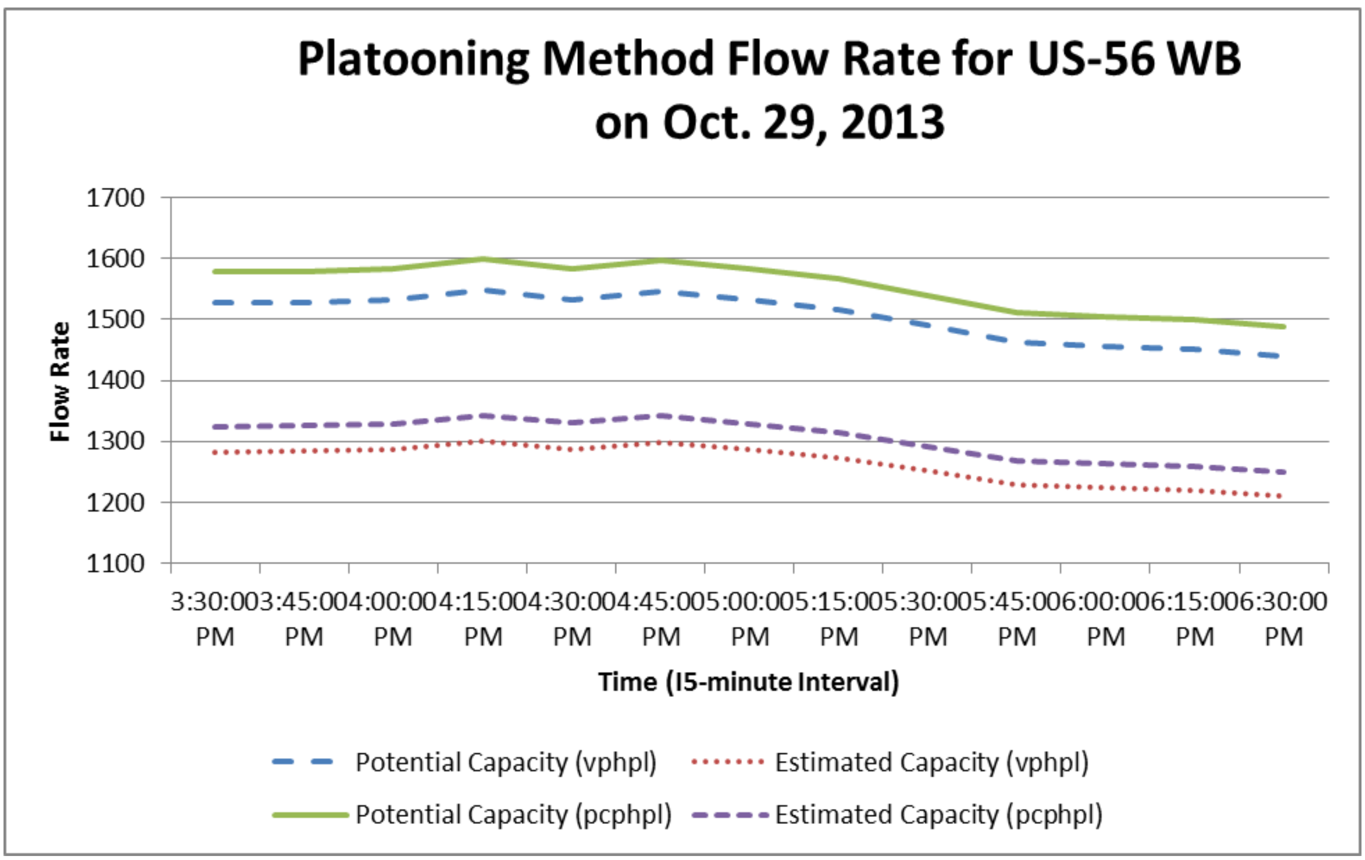
4.3.6 US-56 WB

The US-56 WB site also had an upstream traffic signal which, similar to the US-56 EB site, may have controlled traffic flow so that the platooning factor became inaccurate. However, the platooning factor for this site was found to be 0.84, thus proving that the stoplight had no control over platooning vehicles for this site. The US-56 WB site had an anticipated high volume on the roadway due to the location to Interstate 35. In addition, an intermodal system is located in Gardner which could have led to an increased percentage of heavy trucks entering the work zone site, thereby leading to more in-platoon vehicles. Maximum estimated capacity for the US-56 WB site was equal to 1387 pcphpl with a standard deviation of 30.99 pcphpl, as shown in Table 4.12. The peak time period flow rate graph in Figure 4.12 provides the graph for the maximum 24-hr flow rate on this site. The average speed in 2 mph intervals over the provided peak time periods was found to equal 38.12 mph. The normal speed limit for this site was 50 mph while the work zone speed limit was found to equal 40 mph. The average and the average standard deviation were both based on the peak time period of the site. Figure B.6 shown in Appendix B provides the graph of the full observed data for this site.

Table 4.12 – Results for US-56 WB site using Platooning Method

US-56 WB Site for the Platooning Method									
Date	Time Period	Percent Cars	Percent Buses	Percent Trucks	Platooning Factor	Potential Capacity (vphpl)	Estimated Capacity (vphpl)	Potential Capacity (pcphpl)	Estimated Capacity (pcphpl)
10/28/2013	11:00 am to Midnight	89.92%	0.32%	9.76%	0.84	1573	1321	1651	1387
10/29/2013	24 hrs	93.31%	0.19%	6.50%	0.84	1548	1300	1599	1343
10/30/2013	24 hrs	90.45%	0.15%	6.52%	0.84	1483	1246	1489	1251
TOTAL/AVERAGE		91.23%	0.22%	7.59%	0.84	1535	1289	1580	1327
AVG STANDARD DEVIATION		---	---	---	---	35.59	29.90	36.89	30.99

Figure 4.12 – US-56 WB Site Peak Time Period Flow Rate Graph



4.4 Findings

This section states the findings for each site setup. The following paragraph details the average capacity per method and provides a range to be used if necessary.

4.4.1 Maximum Observed 15-minute Flow Rate Method

Maximum observed 15-minute flow rate capacities were found for five of the six data collection sites. For the sixth site, since no breakdown events occurred, capacity could not be established. Capacities that were found are presented below:

- K-10 EB Capacity = 1730 pcphpl
  - Standard deviation = 46.82 pcphpl
- K-18 EB Capacity = 1551 pcphpl
  - Standard deviation = 233.06 pcphpl
- K-18 H-H EB Capacity = 1530 pcphpl
  - Standard deviation = 156.77 pcphpl
- K-18 H-H WB Capacity = Unknown
  - Standard deviation = Unknown
- US-56 EB Capacity = 1036 pcphpl
  - Standard deviation = 132.56 pcphpl
- US -56 WB Capacity = 1496 pcphpl
  - Standard deviation = 132.36 pcphpl

Based on the Maximum Observed 15-minute Flow Rate Method, the average capacity was 1468.6 pcphpl with an average standard deviation of 140.31 pcphpl. When determining work zone capacity on a rural highway in Kansas while using the Maximum Observed 15-minute Flow Rate Method, the recommended capacity value of 1500 pcphpl should be used with a standard deviation of 141 pcphpl.

4.4.2 Platooning Method

The 15-minute breakdown flow rate method provided capacities for all six sites for the observed data. The capacities were:

- K-10 EB Capacity = 1282 pcphpl
  - Standard deviation = 31.06 pcphpl
- K-18 EB Capacity = 1113 pcphpl
  - Standard deviation = 25.57 pcphpl
- K-18 H-H EB Capacity = 1207 pcphpl
  - Standard deviation = 26.82 pcphpl
- K-18 H-H WB Capacity = 1020 pcphpl
  - Standard deviation = 19.71 pcphpl
- US-56 EB Capacity = 1204 pcphpl
  - Standard deviation = 33.4 pcphpl
- US -56 WB Capacity = 1343 pcphpl
  - Standard deviation = 30.99 pcphpl

Based on the Platooning Method, the average capacity was 1194.83 pcphpl with an average standard deviation of 27.92 pcphpl. When determining work zone capacity on a rural highway in Kansas while using the Platooning Method, the recommended capacity value of 1200 pcphpl should be used with a standard deviation of 28 pcphpl.

4.5 Comparison of Two Capacity Estimation Methods

A comparison between the Maximum Observed 15-minute Flow Rate Method and the Platooning Method were conducted with the intention of identifying which method should be used to estimate capacity on rural highway work zones in Kansas. The Maximum Observed 15-minute Flow Rate Method does not require much data to accurately provide estimated capacity for the work zone under review. However, the Platooning Method requires a substantial amount of data in order to utilize the method. If enough data is not obtained, the proportion of in-platooning vehicles will be low and capacity cannot be determined.

If even a small amount of data is obtained per site, the maximum observed 15-minute flow rate is the recommended capacity estimation method. If the amount of data collected at the site is abundant, the Platooning Method should be used. The Platooning Method is a more accurate method when properly accounting for the platooning factor. However, in order to obtain an accurate platooning factor, a large amount of in-platooning vehicles must be present.

In this study, the Maximum Observed 15-minute Flow Rate Method provided greater values for capacities per site than was expected, while the Platooning Method provided much lower capacities than expected. Overall, the expected capacities were found to be comparable to other studies with respect to work zone capacity estimation. The overall capacity that should be used in the event no data is to be collected is the most conservative approach of 1500 pcphpl with a standard deviation of 141 pcphpl. Although the Platooning Method has a much lower average standard deviation, it would not be the most conservative choice because the average capacity is far lower than that of the Maximum Observed 15-minute Flow Rate Method's average capacity. As previously discussed, both of these values are respectable based on past research in this field and either approach would be warranted for design.

Chapter 5 - Summary, Conclusions, & Recommendations

5.1 Summary

As stated in Chapter two, Bham and Khazraee determined that the mean queue discharge flow rate was less than the breakdown flow rate due in part to traffic flow failing to average congested queue conditions (Bham and Khazraee, 2011). Maximum sustained 15-minute flow rate was found to be conservative and should be adjusted in accordance with the mean queue discharge flow and breakdown flow rates. Based on these findings, a study had to be conducted that would exploit breakdown events on rural highway work zones in order to estimate the capacity of such roadway conditions. Therefore, the study analyzed the effects of breakdown flow rates on threshold speed for specific work zones.

Currently, capacity for this research is defined as the maximum observed 15-minute flow rate in pcphpl that a rural work zone can sustain under prevailing traffic and roadway conditions in one direction. Capacity was observed in 5 out of 6 rural work zone locations when using the Maximum Observed 15-minute Flow Rate Method. Average capacity found per site equaled 1469 pcphpl with a standard deviation of 141 pcphpl. Capacity was observed in 6 out of 6 rural work zone locations when using the Platooning Method. Average capacity found per site equaled 1273 pcphpl with a standard deviation of 28 pcphpl. The proposed capacity to be used for rural highway work zones is 1500 pcphpl with a standard deviation of 141 pcphpl.

5.2 Conclusions

In conclusion, the Maximum Observed 15-minute Flow Rate Method included four parameters that estimated capacity of a work zone site: volume, maximum 15-minute flow rate, 15-minute mean speed, and 15-minute breakdown flow rate. If the observed flow rates did not fall below the threshold value for three consecutive 15-minute intervals, a capacity for the site could not be estimated. The platooning factor included three set parameters to ensure the vehicle was platooning and not free flowing. The three analyzed parameters included headway less than or equal to 4 sec or spacing between the vehicles of 250 ft or less. Once those parameters were analyzed, the third parameter was accounted for to ensure a platooning condition was possible during the specified time. This parameter required at least three consecutive 15-minute intervals with more than five vehicles considered platooning. Once the three parameters were satisfied, a peak time period of 3 hrs was found per day to provide a realistic analysis of capacity on the roadway during the peak hour. The first two parameters were replicated based on research conducted by Ramezani (2010). The third parameter had to be accounted for due to mass amount of data obtained during this study. No previous studies have been conducted with this parameter; however, by utilizing the third parameter, capacity on the roadways can be compared to results from the Maximum Observed 15-minute Flow Rate Method. In previous studies the Platooning Method was considered an upper limit and the maximum sustained 15-minute flow rate was considered the lower limit with capacity range between the two values (Ramezani, 2010). Findings from the two methods under review for this study provide a more precise estimation of capacity due to similar capacity estimations per site.

Based on the expected comparison shown in Section 4.1, the platooning factor yields a consistent result when estimating capacity for a rural highway work zone in Kansas. However, in order to obtain consistent results, significant data is required for this method to be accurately measured for any given site. The Maximum Observed 15-minute Flow Rate capacity can produce respectable capacity values with less data. The other considerable piece of information is “how” the data is obtained. If the data is obtained with any form of capacity-counting device, the device could provide the investigator with an abundant amount of data, but if obtained data was found by roadway inspection during specific time intervals then the required data may not be available to run the Platooning Method. These criteria determine the analysis method for estimating capacity on a roadway if an inspector was used for data collection.

For research analyzed with Kansas work zone data, the determination was made that the most suitable course of action is to use the most conservative approach in finding the capacities which is to use the Maximum Observed 15-minute Flow Rate Method to estimate capacity on rural highway work zones in Kansas. Use of this method for obtained data averaged over every site yielded a result of 1469 pcphpl with a standard deviation of 141 pcphpl. The estimated capacity, rounded to the nearest hundred to maintain consistency with the HCM, then yielded a capacity estimation of 1500 pcphpl. This capacity can be used for any rural highway work zone site in Kansas with similar geometric conditions to sites reviewed for this study. These descriptions are provided in Section 3.3.

Due to the amount of raw data obtained from this research, another analysis was performed which yielded an estimated capacity of 1332 pcphpl with an average standard deviation of 84.05 pcphpl. Again, rounding to the nearest hundred provided an estimated capacity of 1400 pcphpl. This capacity was found by averaging maximum estimated capacities for both methods for each site. This method would not be as accurate if less data had been obtained. However, it would still yield accurate capacities for the sites under review for this study when averaging both methods together.

In conclusion, for rural highway work zones in Kansas a capacity estimation method should be determined based on the amount of data obtained prior to site construction. Based on observed data and analysis of this study, a capacity of 1500 pcphpl with a standard deviation of 141 pcphpl should be used as a base condition when estimating capacity for a rural highway work zone in Kansas. Geometric conditions should be similar to those shown in Section 3.3 for base conditions to yield an accurate result for the roadway under review.

5.3 Recommendations

Four recommendations are made for future research with regard to work zone capacity estimation in rural highway settings. The first recommendation is to pre-emptively establish a definition for rural highway work zone capacity. The second recommendation is to use a different type of traffic counter or find an alternate way of collecting necessary data to run study analysis. The third recommendation is to use more than two capacity estimation methods to determine the most suitable method for design. Finally, the last recommendation is to run a statistical analysis on the results to produce concrete evidence for the conclusion.

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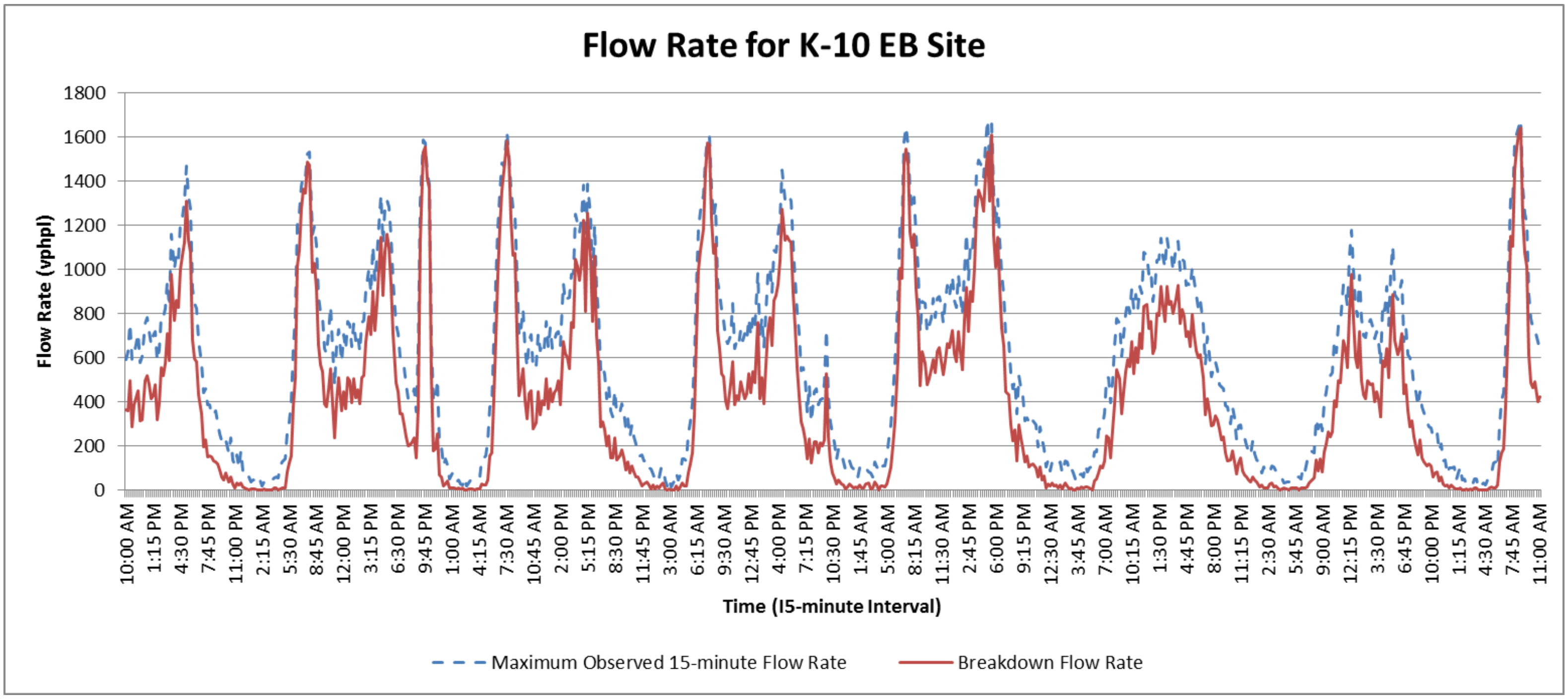
Appendix A - Maximum Observed 15-minute Flow Rate Method Graphs

Figure A.1 – K-10 EB Complete Flow Rate VS. Mean Speed Graphs



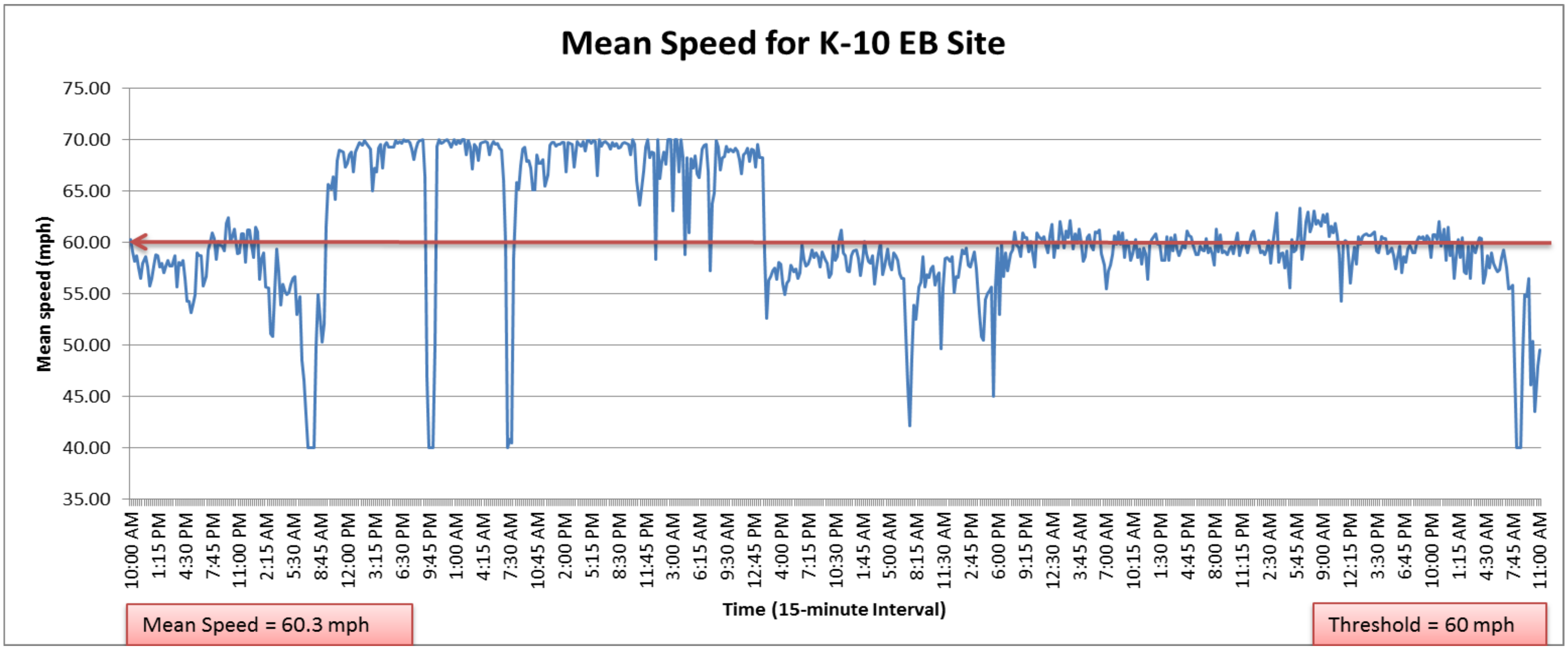
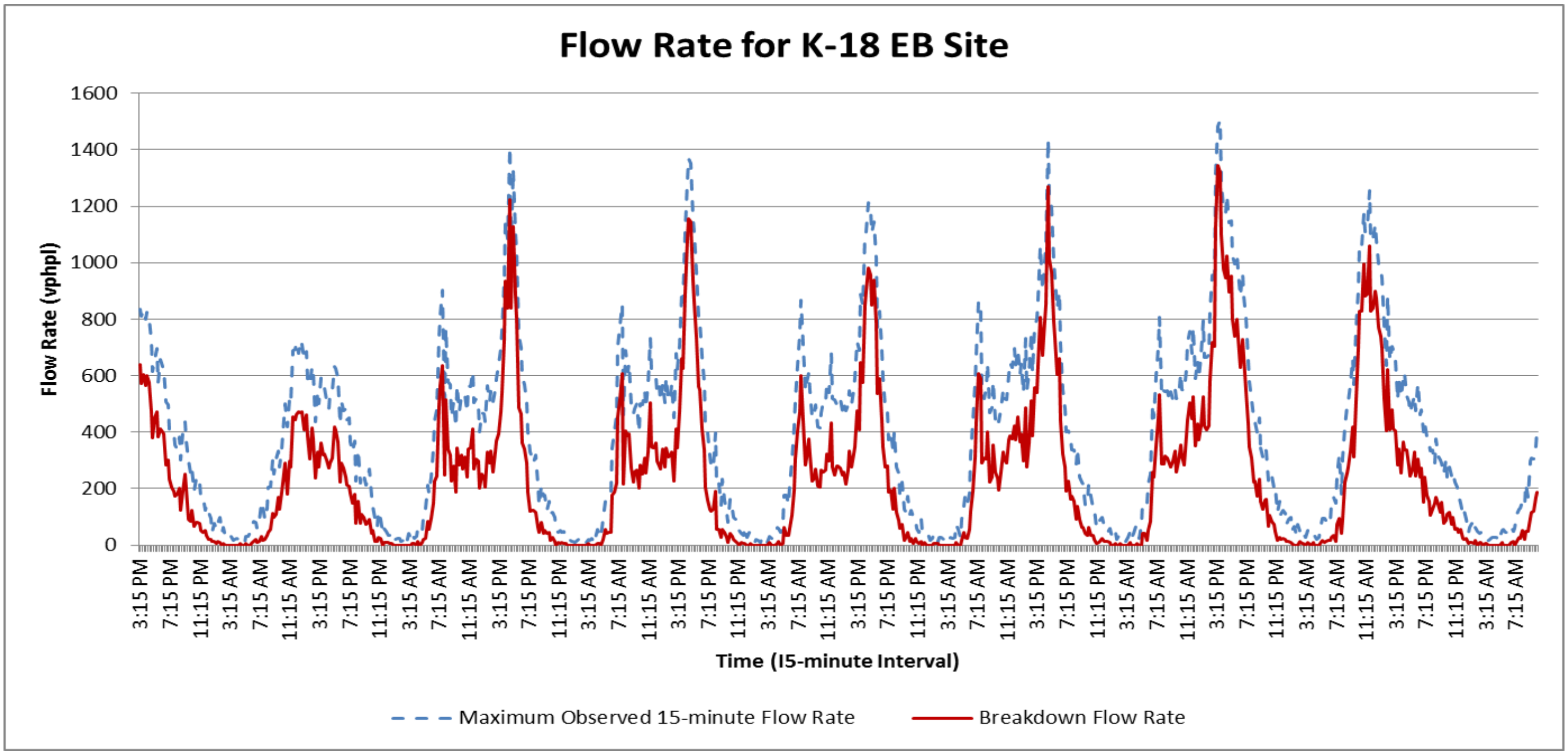


Figure A.2 – K-18 EB Complete Flow Rate VS. Mean Speed Graphs



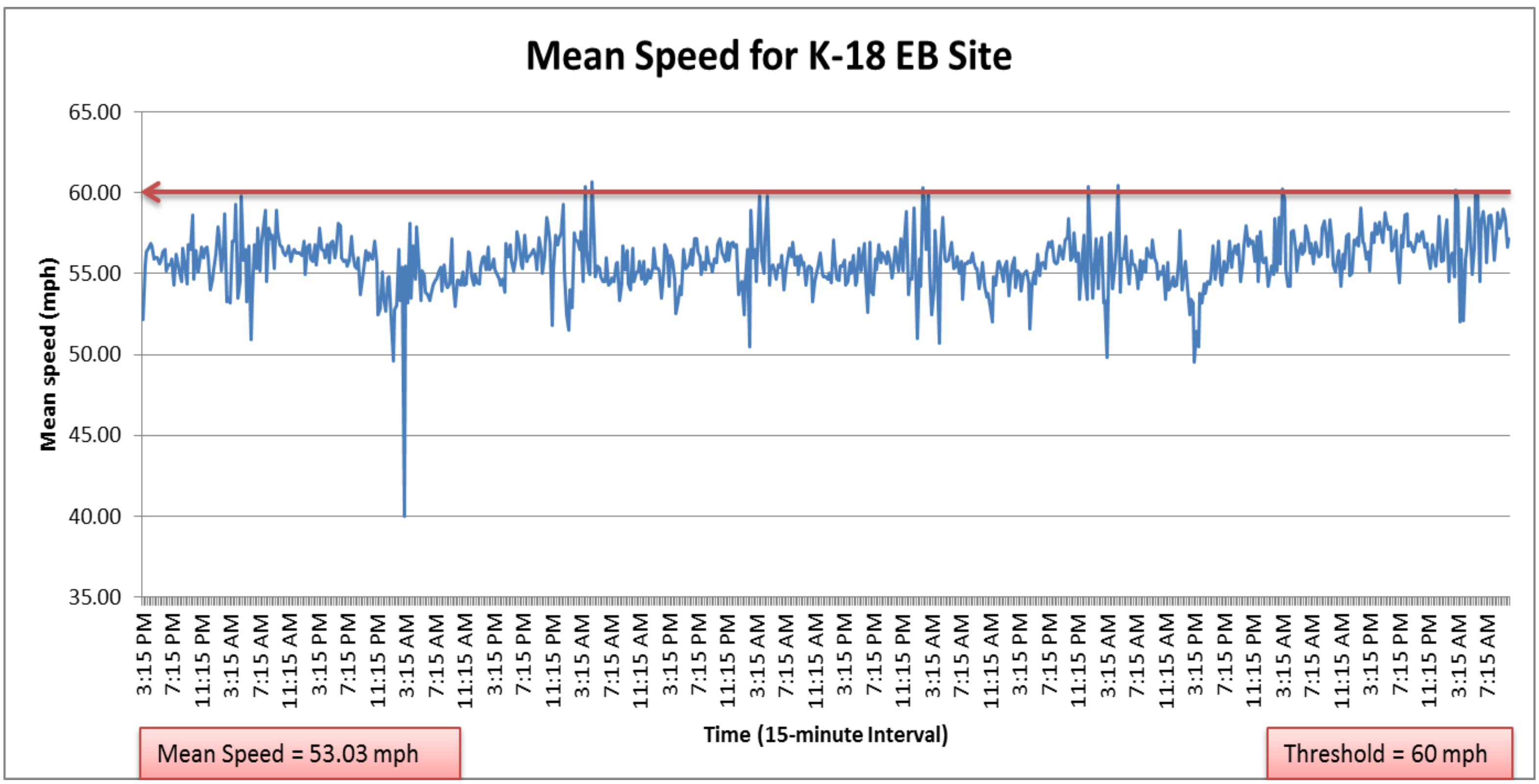
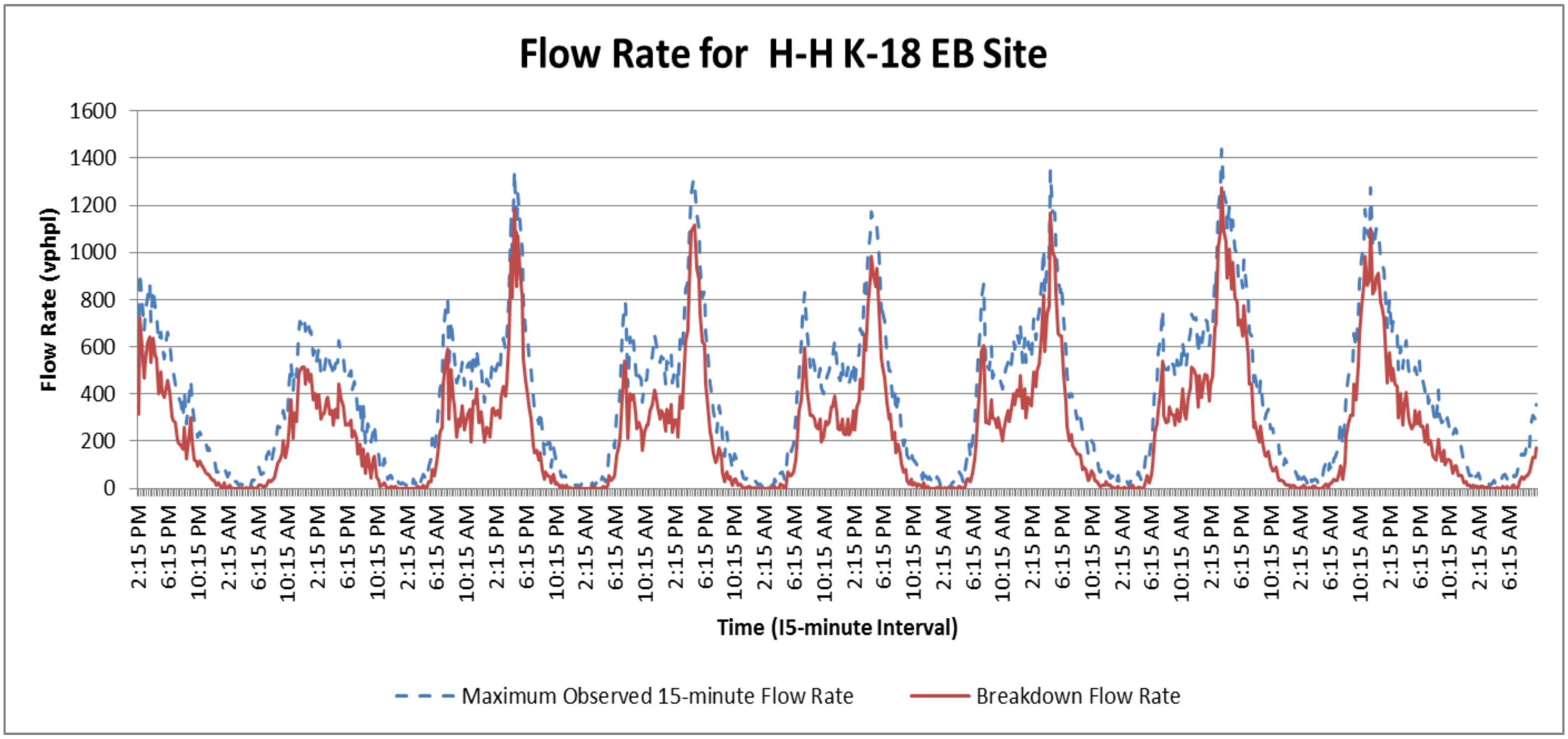


Figure A.3 – K-18 H-H EB Complete Flow Rate VS. Mean Speed Graphs



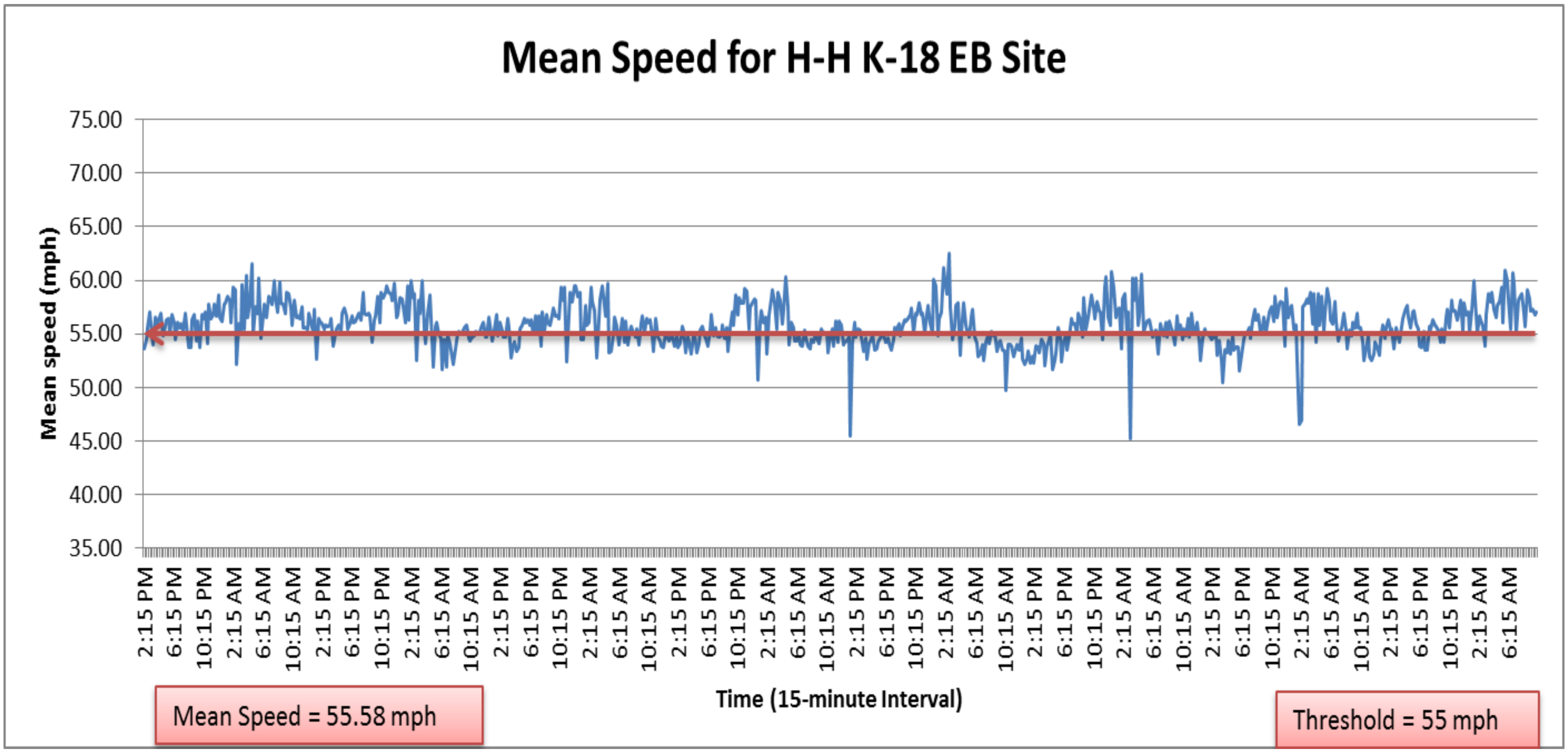
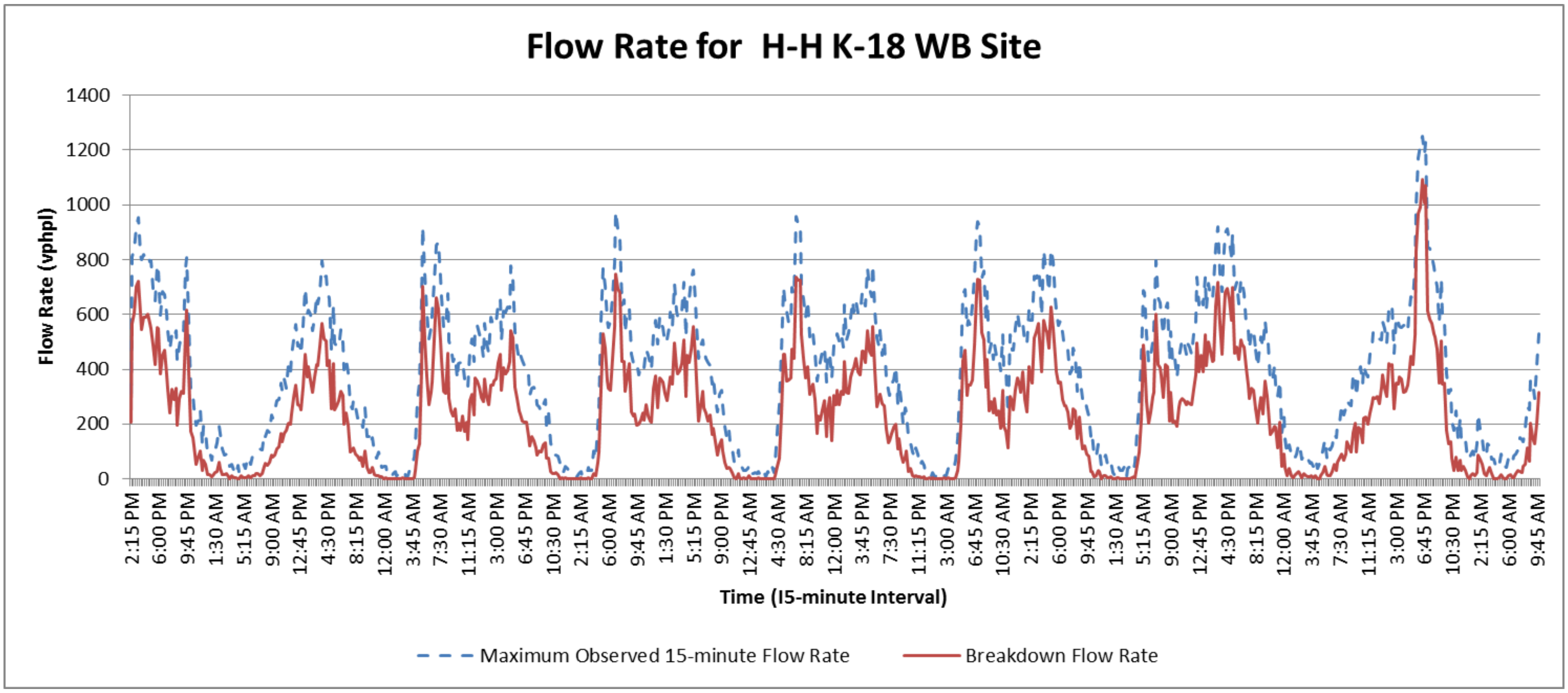


Figure A.4 – K-18 H-H WB Complete Flow Rate VS. Mean Speed Graphs



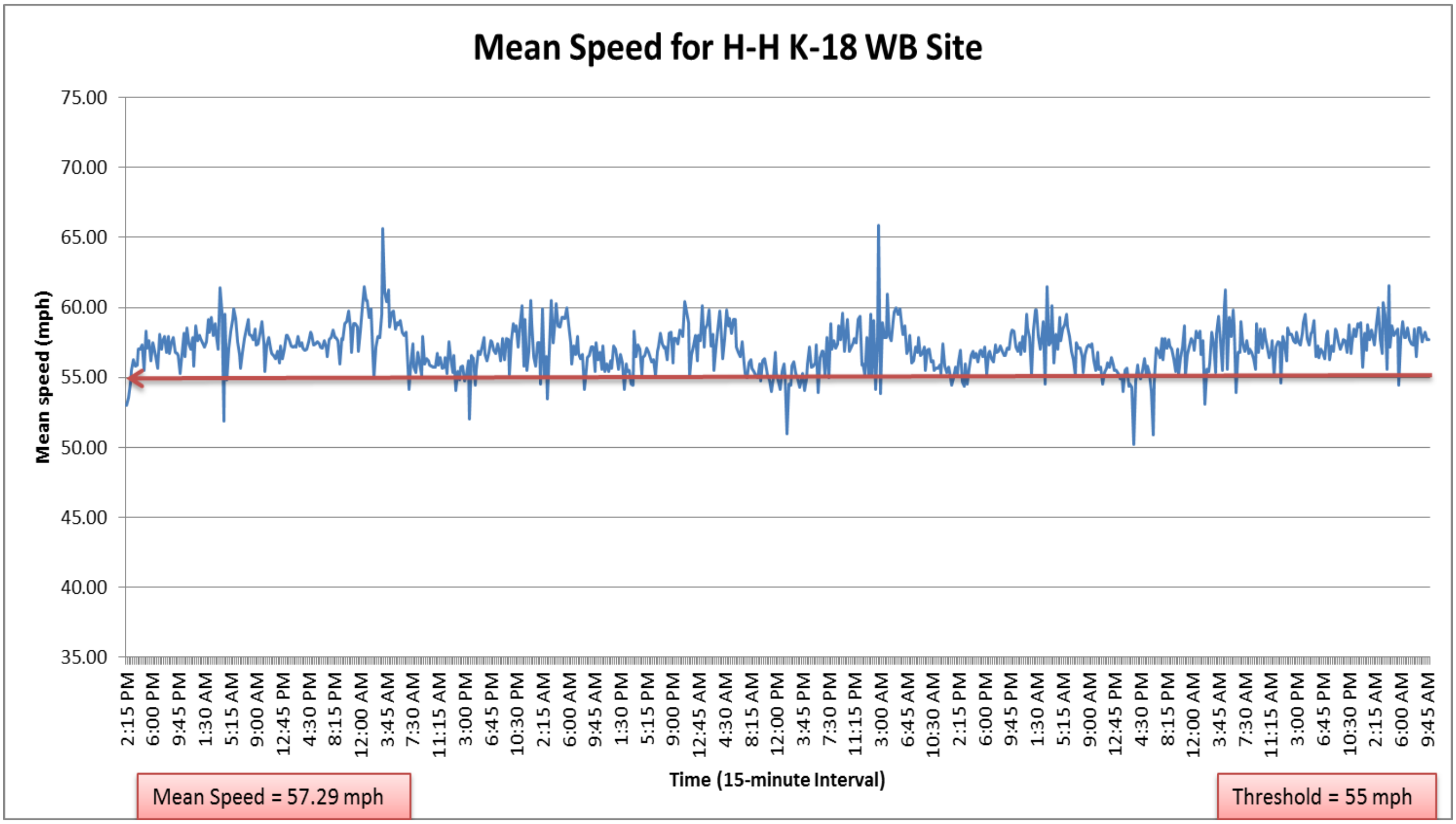


Figure A.5 – US-56 EB Complete Flow Rate VS. Mean Speed Graphs

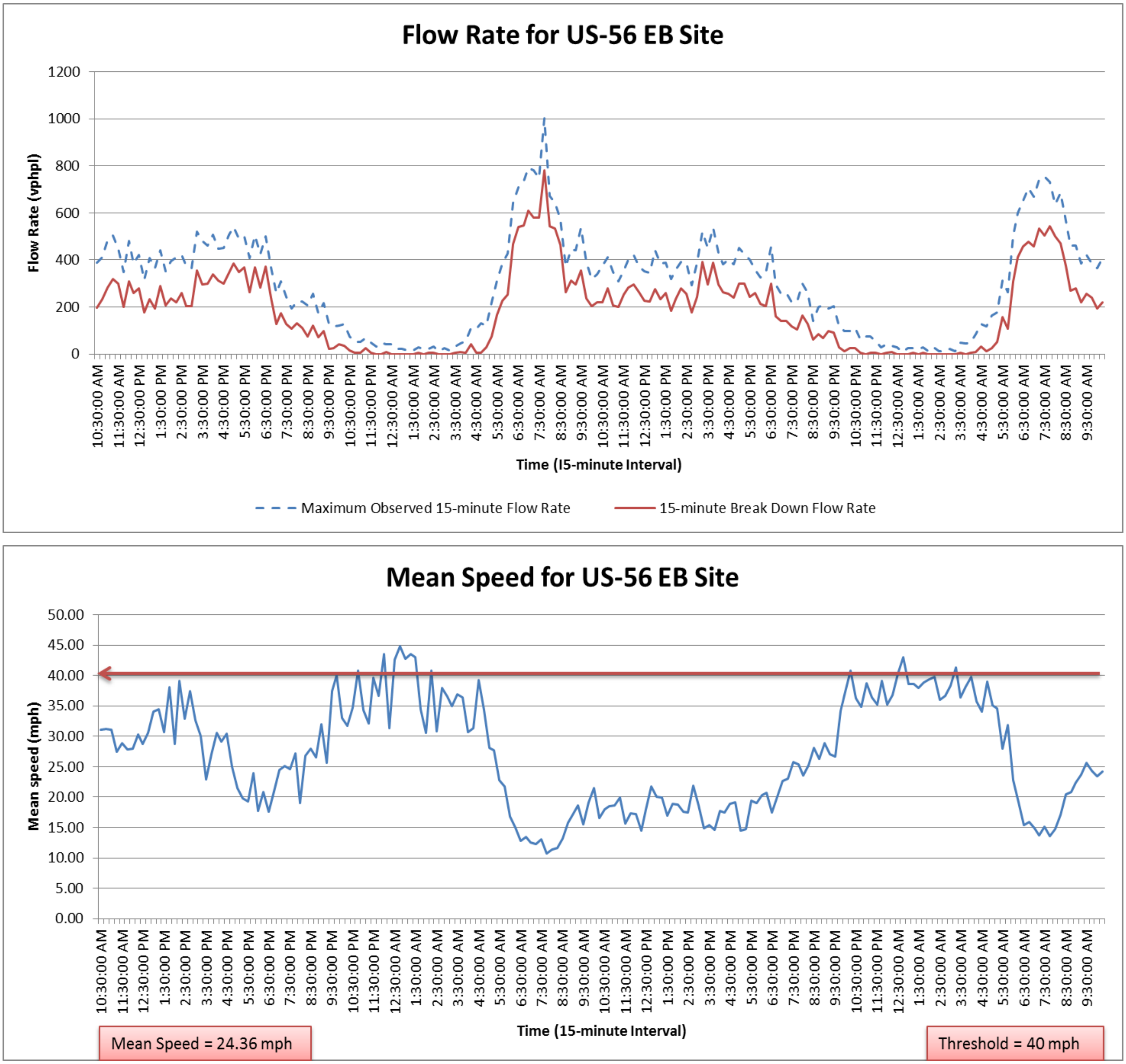
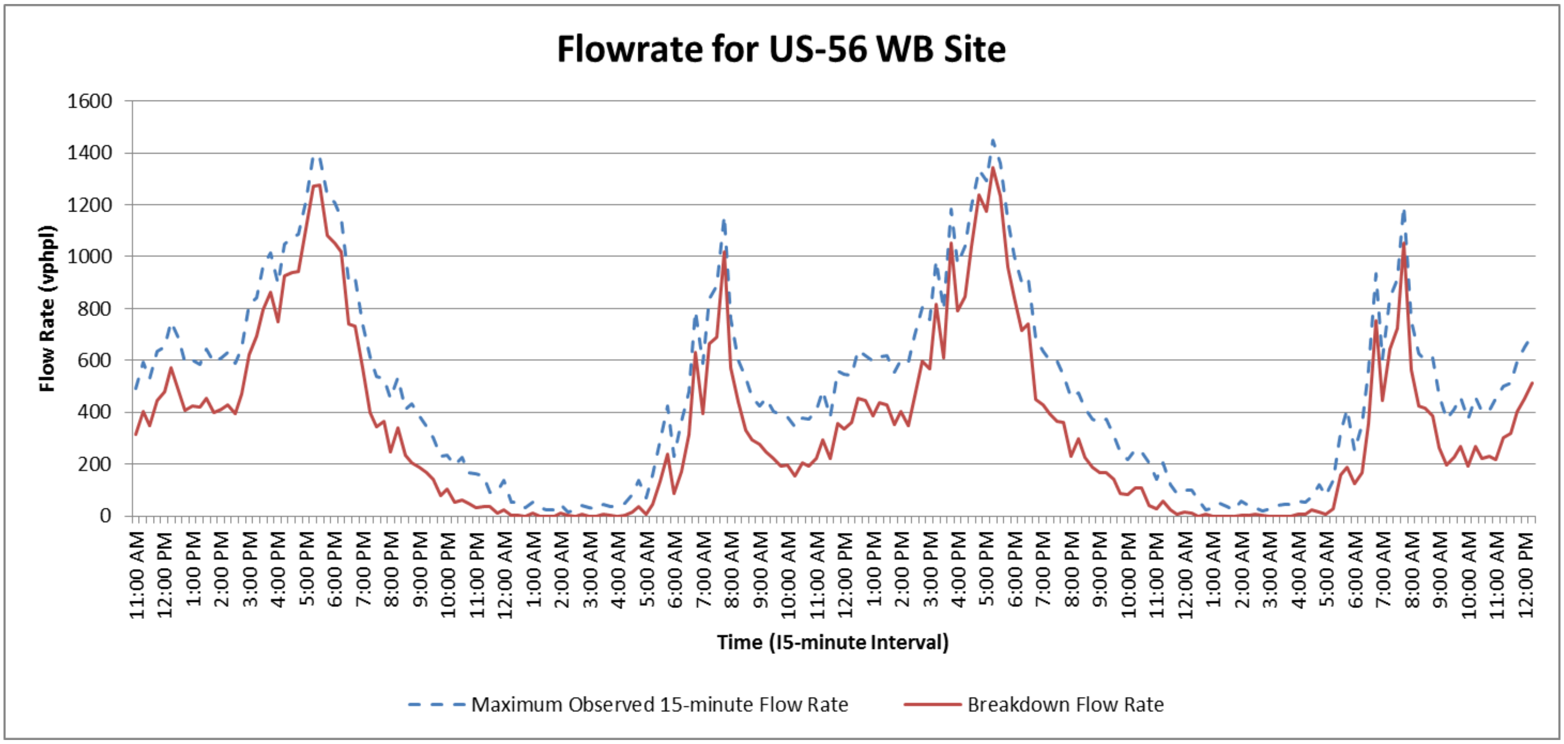
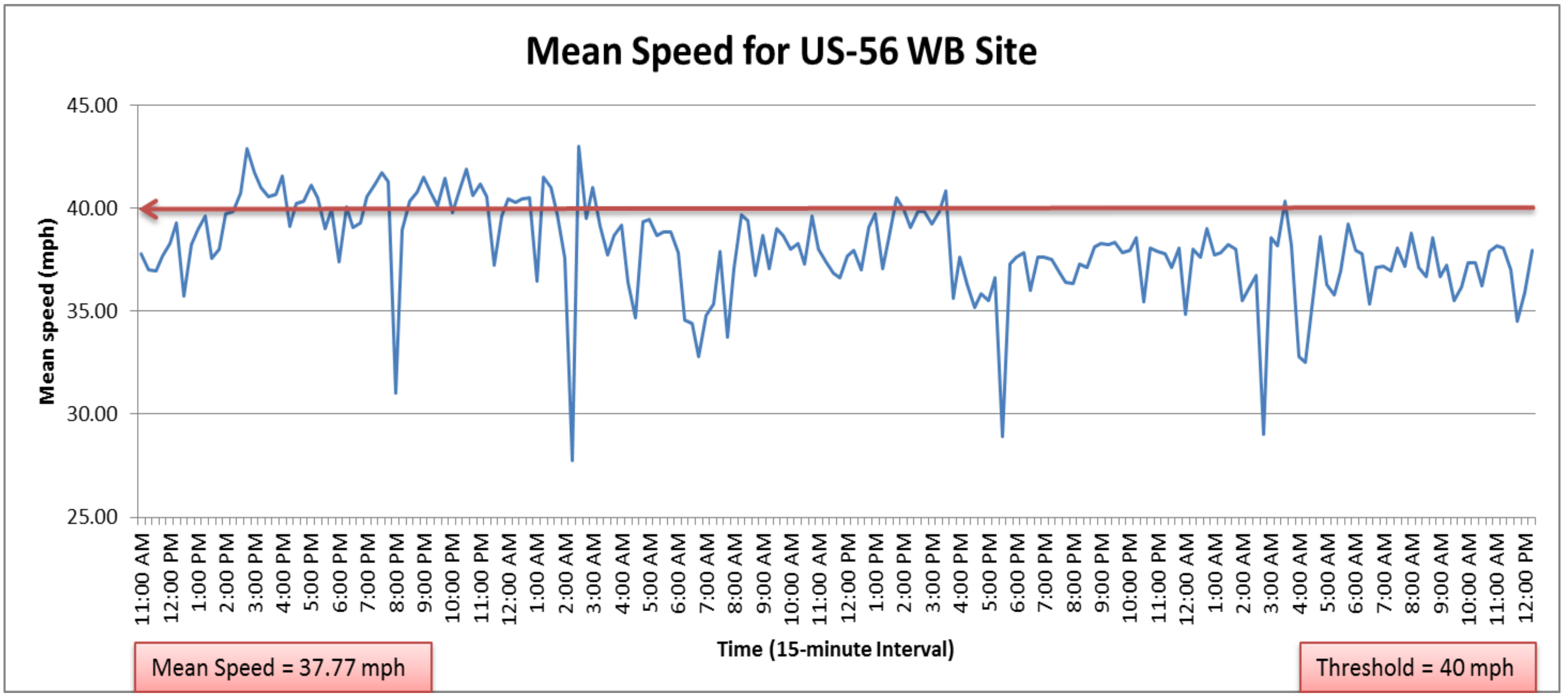


Figure A.6 – US-56 WB Complete Flow Rate VS. Mean Speed Graphs





Appendix B - Platooning Method Graphs

Figure B.1 –K-10 EB Flow Rate Graph of Complete Observed Data

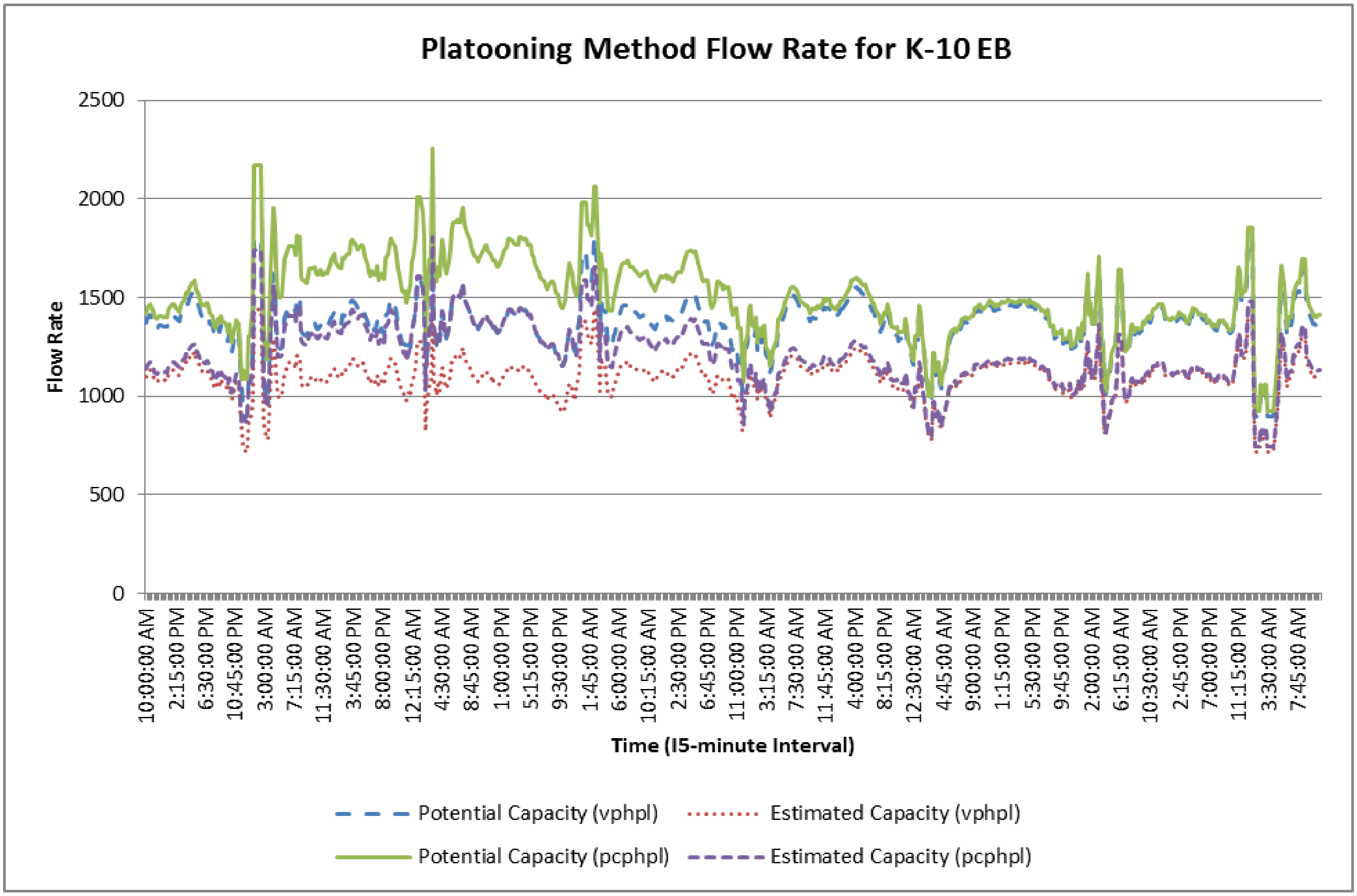


Figure B.2 –K-18 EB Flow Rate Graph of Complete Observed Data

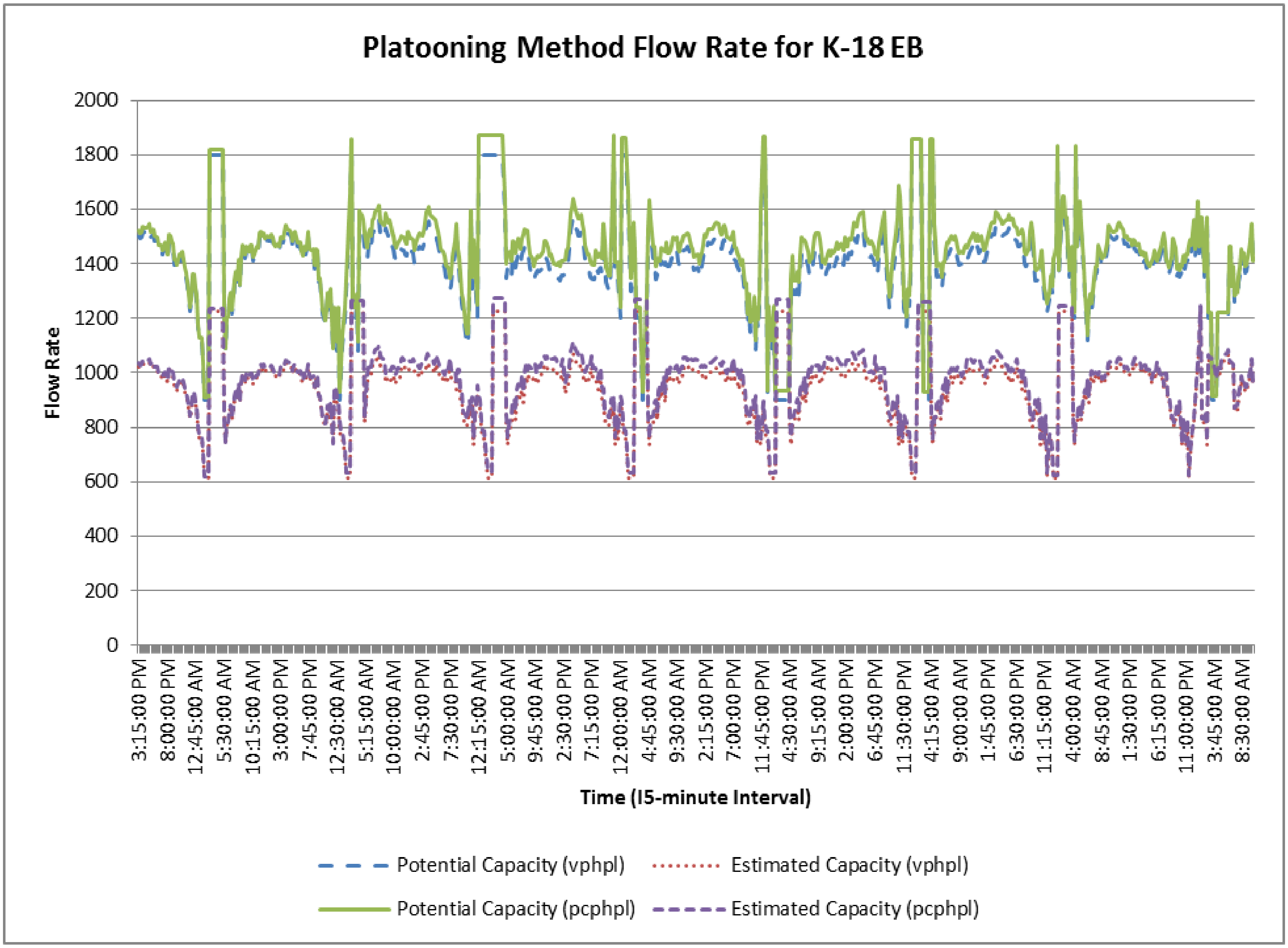


Figure B.3 –K-18 H-H EB Flow Rate Graph of Complete Observed Data

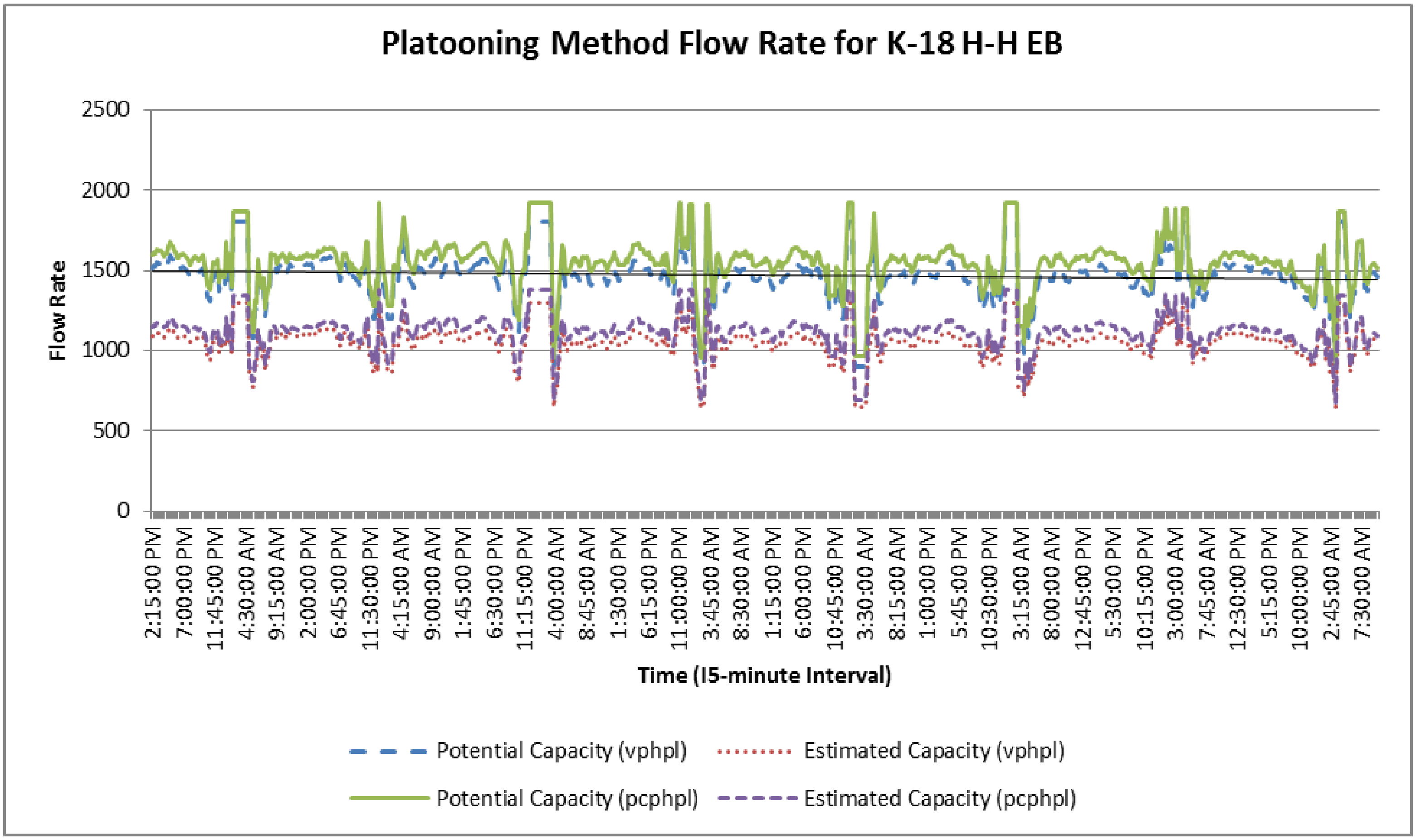


Figure B.4 –K-18 WB Flow Rate Graph of Complete Observed Data

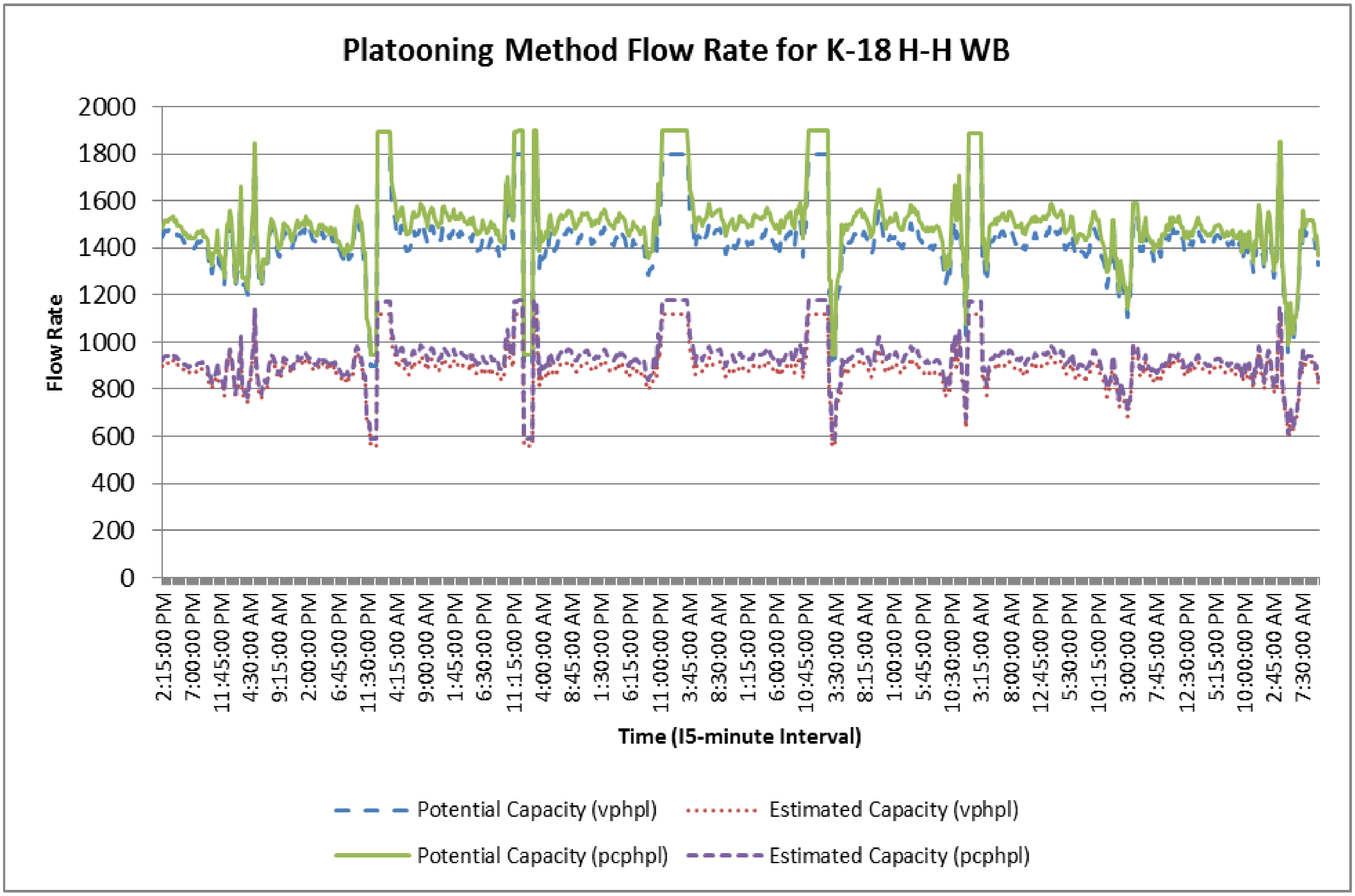


Figure B.5 –US-56 EB Flow Rate Graph of Complete Observed Data

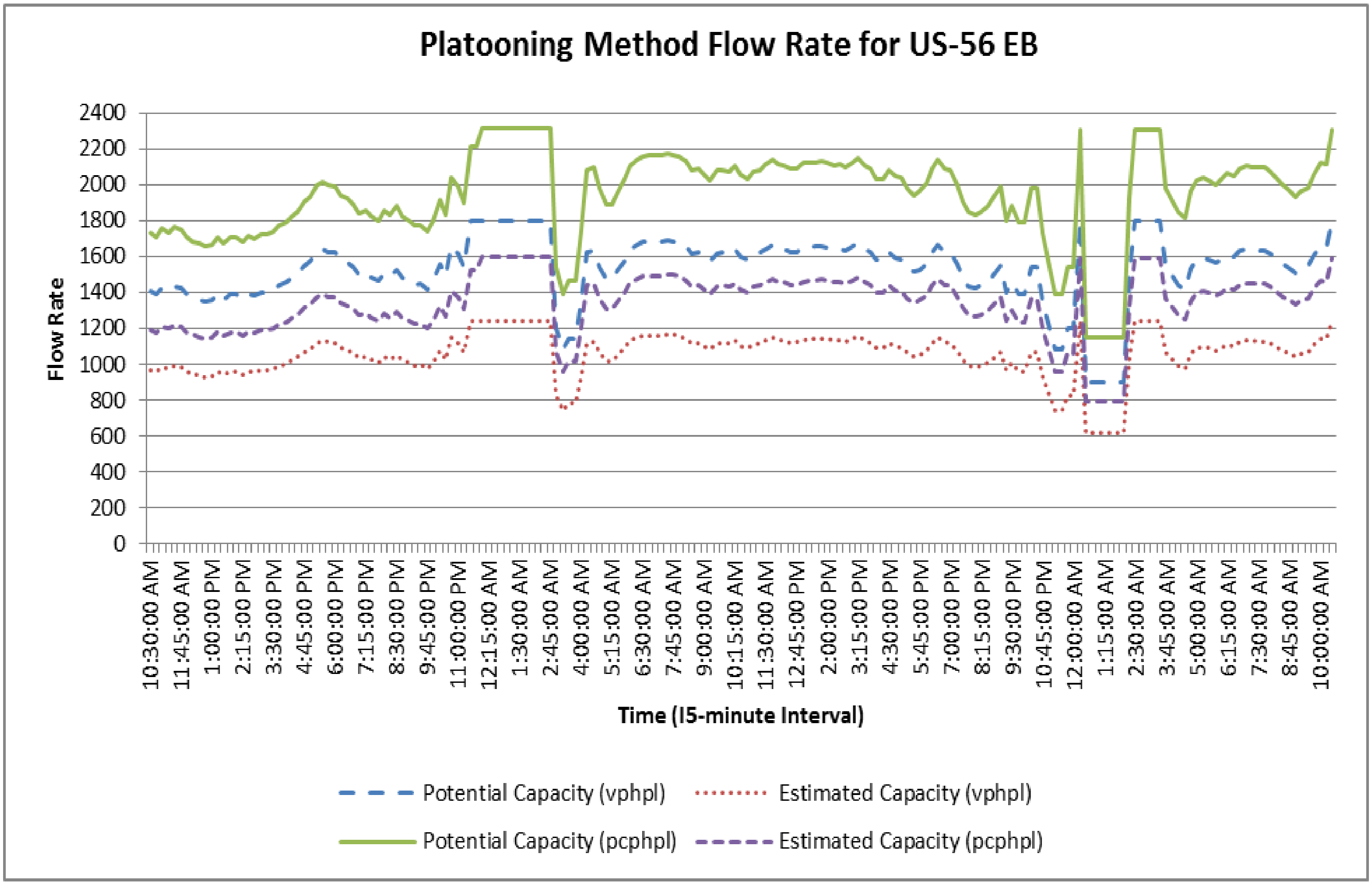
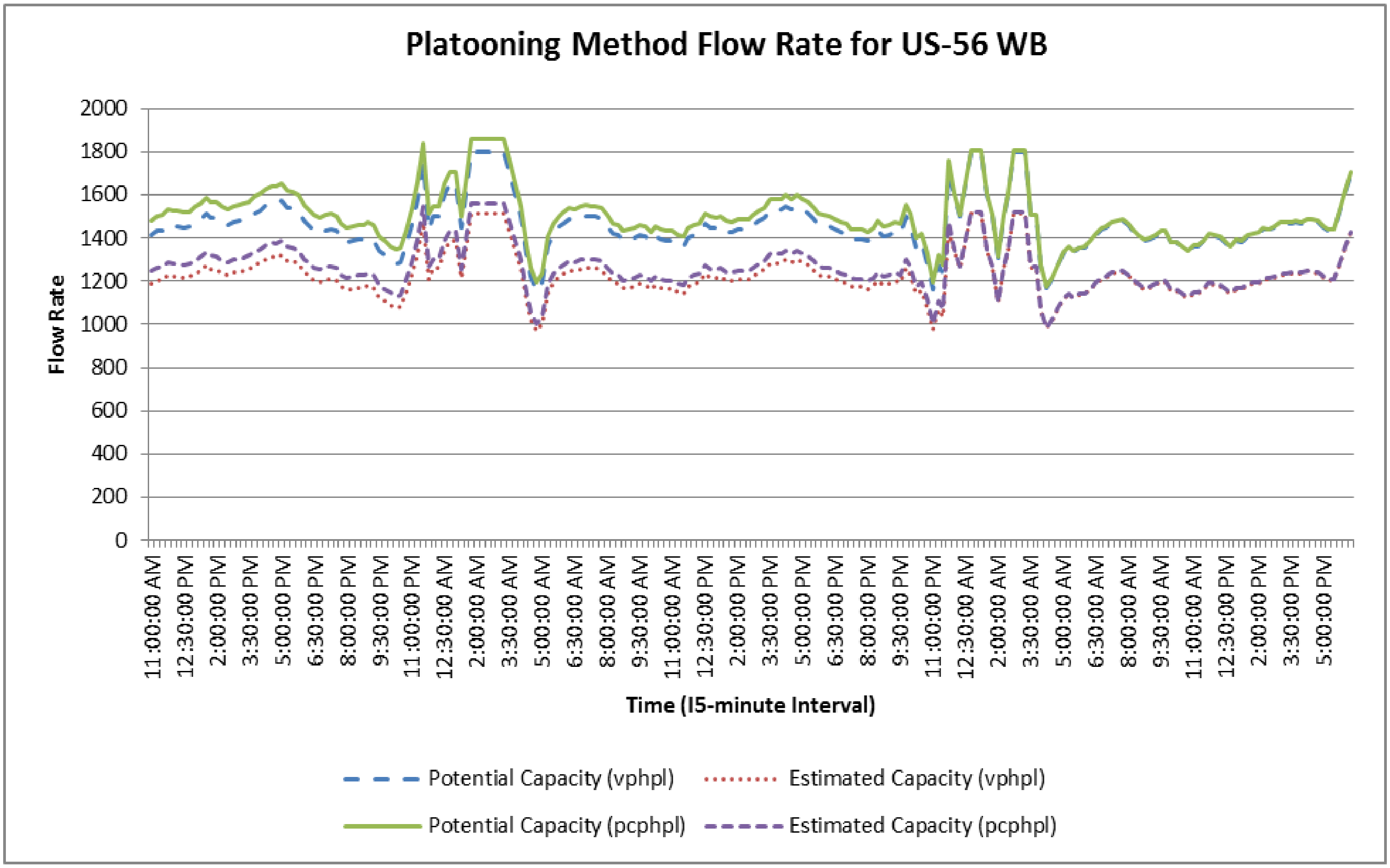


Figure B.6 –US-56 WB Flow Rate Graph of Complete Observed Data



Appendix C - Definitions and Acronyms

Work Zone – A segment of highway in which maintenance and construction operations impinge on the number of lanes available to traffic or affect operational characteristics of traffic flowing through the segment. A work zone typically is marked by signs, channelizing devices, barriers, pavement markings, and/or work vehicles. It extends from the first warning sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle to the END ROAD WORK sign or the last temporary traffic control device.

Work Zone Capacity – The maximum sustainable flow rate at which vehicles can pass a given point or uniform segment of a lane or roadway in a work zone during a specified period under prevailing roadway, traffic, and control conditions. Capacity usually is expressed as passenger cars per hour per lane (pcphpl) or vehicles per hour per lane (vphpl).

Facility Types – Various roadway systems in the United States.

Geometric Conditions – A term used to describe physical characteristics of a roadway approach or a section, including the number and width of lanes, grades, and the allocation of lanes for various uses, including designation of a parking lane.

Flow Rate – Equivalent hourly rate at which vehicles pass a point on a highway during a period of time less than 1 hr and is then converted to 1-hr intervals.

Breakdown Flow Rate – Traffic flow rate immediately prior to the onset of congestion.

Queue – A line of vehicles, bicycles, or persons waiting to be served by the system in which the flow rate from the front of the queue determines the average speed within the queue. Slow-moving vehicles or people joining the rear of the queue usually are considered part of the queue. Internal queue dynamics can involve starts and stops. A fast-moving line of vehicles often is referred to as a moving queue.

Queue Delay – Additional time necessary to travel through the queue under restricted traffic flow.

Hourly Traffic Demand – 24-hr hourly distribution of vehicles passing through the work zone in a single direction under normal operating conditions.

Congestion – Traffic condition in which an excess amount of vehicles suddenly have a decreased rate of speed and long wait time.

Bottleneck Locations – Locations in which vehicles are funneled into fewer lanes due to construction.

Platooning Vehicles – Vehicles that can be seen trailing one another and have headway less than or equal to 4 seconds or have spacing less than or equal to 250 ft (Ramezani, 2011).

Mean Speed – Arithmetic mean of the speeds of vehicles passing a point on a highway during an interval of time.

Threshold Value – Work zone speed limit under review.

Volume – The amount of vehicles traversing a site for any specified time period.

Density – Number of vehicles traveling over a unit length of highway at an instant in time. This can also be known as concentration.

Gap – Headway in a major stream, evaluated by a vehicle driver in a minor stream who wishes to merge into the major stream. It is expressed either in units of time (time gap) or in units of distance (space gap).

Space Headway – Distance between the front of a vehicle and the front of the following vehicle. Usually expressed in feet.

Time Headway – Difference between the time the front of a vehicle arrives at a point on the highway and the time the front of the next vehicle arrives at that same point (usually expressed in seconds).

Free Flow – A condition in which a traffic flow is unaffected by upstream or downstream conditions.

Average Annual Daily Traffic (AADT) – The total volume of traffic passing a point or segment of a highway facility in both directions for one year divided by the number of days in the year.

Peak Time Period – 3-hr time frame that houses the peak hour for the particular work zone site for a given day.

Peak Hour Volume (PHV) – Maximum number of vehicles that pass a point on a highway during a period of 60 consecutive min.

Passenger Car – Defined as vehicle classes 1 through 3 in the FHWA Traffic Monitoring Guide. Includes automobiles (small, medium, or large), pickup trucks, and vans.

Single Unit Truck – Defined as vehicle classes 4 through 7 in the FHWA Traffic Monitoring Guide. Includes six-tire trucks and trucks on a single frame with three or more axles.

Passenger Car Equivalents (PCE) – The number of passenger cars displaced by a single heavy vehicle of a particular type under specified roadway, traffic, and control conditions.

Percent Trucks and Buses (e_t) – Percentage of heavy vehicles traversing a site.

Percent Recreational Vehicles (e_r) – Percentage of recreational vehicles traversing a site.

Temporary Traffic Control – Setup of various work zones by using devices to control motorists’ actions. The operations are standardized by local agencies for situations encountered in the design phase.

Pre-breakdown Flow – Flow rate prior to the onset of a breakdown event.

Maximum Queue Discharge Flow – Maximum flow rate released from a queued condition.

Mean Queue Discharge Flow Rate – Average traffic flow during congested queued conditions.

Traffic Counter – A device that collects data by obtaining pulse readings from pneumatic tubes and sends it back to the device for storage.

Pneumatic Road Tubes – Measures the pulse from vehicles as they cross the tubes and sends recorded data to the counter to be stored.

Construction Season – Months within the year in which construction can be performed without deviation from local agencies standard specifications due to weather.

Head to head (H-H) – Section of a roadway is a 2-lane highway with one traveling lane for each direction. This situation may arise due to various reasons. In this study, the reason for H-H sections were due to construction closing one-half of the highway.

Eastbound (EB) – The direction traffic is moving on a roadway.

Westbound (WB) – The direction traffic is moving on a roadway.