TRC1306

Work Zone Capacity Estimation for High Truck Volume Routes in Arkansas:

Predicting Highway Capacity through Work Zones with High Truck Volumes and Reduced Lane Geometry Based Upon Local Conditions

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Final Report

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16. Abstract
Work zones on freeways are estimated to contribute to nearly 24 percent of non-recurring delay. Prior to 2010, the Highway Capacity Manual (HCM) provided limited guidance on vehicular capacity impacts for freeway work zones. Simplified methodologies estimated capacities for short and long term freeway work zones. Previous research (MBTC 2025) conducted by ARDOT during the 1999 Interstate Rehabilitation Program (IRP) found that there are many other factors influencing delay in freeway work zones. The need to consider factors such as truck percent, work times by time-of-day and day-of-week, presence of law enforcement, Intelligent Transportation Systems (ITS), work zone configuration and duration, and the intensity of construction activities, in estimating work zone capacities has long been recognized in the industry. Until 2016, existing analysis methodologies that estimate capacity through work zones did not specifically consider the impacts of high volumes of heavy vehicles. The recently published HCM 6th Edition, 2016, provides a more detailed methodology to estimate work zone lane capacities but has not been corroborated for Arkansas freeways, where high volumes of heavy vehicles are present. Title 23 CFR Subpart J – Work Zone Safety and Mobility requires that States develop procedures to address work zone delays.

The primary intent of this research was to establish a correlation between work zone lane capacity and the presence of high volumes of heavy trucks on Arkansas freeways. The secondary intent was to examine work zone traffic data collection methods, both existing at the time of research initiation, and evolving, to determine the feasibility of economically obtaining and utilizing work zone traffic volume and speed data. Lastly, applications for the use of this data in day to day traffic analysis functions by the Transportation Planning and Policy Division of ARDOT were investigated.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Acknowledgments

This document contains findings for research conducted for ARDOT under project TRC1306, Work Zone Capacity Estimation for High Truck Volume Routes in Arkansas Predicting Highway Capacity through Work Zones with High Truck Volumes and Reduced Lane Geometry Based upon Local Conditions. The authors are grateful for the assistance of those who took part in the research project, including ARDOT employees Andrew Brewer, Daniel Byram, Michael Henry, Jessie Jones, John Spears, Ben Faeth, Nicholas Vanhaute and Alexander Peta from the Transportation Planning and Policy Division, as well as those from the System Information and Research Division.

ABSTRACT

Work zones on freeways are estimated to contribute to nearly 24 percent of non-recurring delay[1]. Prior to 2010, the Highway Capacity Manual (HCM) provided limited guidance on vehicular capacity impacts for freeway work zones. Simplified methodologies estimated capacities for short and long term[2] freeway work zones. Previous research (MBTC 2025) conducted by ArDOT during the 1999 Interstate Rehabilitation Program (IRP) found that there are many other factors influencing delay in freeway work zones. The need to consider factors such as truck percent, work times by time-of-day and day-of-week, presence of law enforcement, Intelligent Transportation Systems (ITS), work zone configuration and duration, and the intensity of construction activities, in estimating work zone capacities has long been recognized in the industry. Until 2016, existing analysis methodologies that estimate capacity through work zones did not specifically consider the impacts of high volumes of heavy vehicles. The recently published HCM 6th Edition, 2016, provides a more detailed methodology to estimate work zone lane capacities but has not been corroborated for Arkansas freeways, where high volumes of heavy vehicles are present. Title 23 CFR Subpart J – Work Zone Safety and Mobility requires that States develop procedures to address work zone delays.

The primary intent of this research was to establish a correlation between work zone lane capacity and the presence of high volumes of heavy trucks on Arkansas freeways. The secondary intent was to examine work zone traffic data collection methods, both existing at the time of research initiation, and evolving, to determine the feasibility of economically obtaining and utilizing work zone traffic volume and speed data. Lastly, applications for the use of this data in day to day traffic analysis functions by the Transportation Planning and Policy Division of ArDOT were investigated.

[1] Temporary Losses of Highway Capacity and Impacts on Performance (ORNL/TM-2003/3), Oak Ridge National Laboratory, University of Tennessee, Knoxville, Tennessee, May 2002; and https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm

[2] The main distinction between short and long term work zones is the type of barrier separation.

1. Introduction and Problem Statement

Title 23 Code of Federal Regulations (CFR) Subpart J – Work Zones Safety and Mobility requires that all states develop procedures to address work zone delays. Accurate prediction of highway work zone capacity is necessary to estimate travel delays, vehicle speeds, and queuing patterns. The prediction of traffic flow and congestion through work zones is complex and with many variables. There are several reasons for inaccuracies in the estimation of highway work zone capacities. Highway work zone capacities are affected by the type of construction and maintenance activities, duration of lane closure, adverse weather conditions, and highway incidents.

The purpose of this research was to collect traffic count and vehicle classification data before and after interstate construction projects, to observe vehicle queuing dynamics during construction, and to develop a correlation between work zone capacity reductions and the presence of heavy vehicles. Until the HCM 6th Edition was published in 2016, limited research was available that documented the effects of high proportions of heavy vehicles through highway construction sites and truck impacts on work zone lane capacities.

Arkansas highways carry a disproportionately high volume of heavy vehicles, particularly on rural freeways, where trucks commonly comprise more than 40 percent of average daily traffic. In urban areas, heavy trucks can comprise up to 20 percent of the vehicle mix on an average day. High truck volumes combined with temporary alterations in roadway geometry and traffic flow characteristics specific to Arkansas can adversely affect the highway capacity through work zones, resulting in increased travel delays. With the implementation of the State's 2011 Interstate Rehabilitation Program, which rehabilitates approximately 455 miles of interstate highway in Arkansas, better methods to calculate work zone capacity are needed at a time when opportunities to observe highway work zone capacity for a variety of highway types will increase in both urban and rural settings.

Photo 1 – Interstate 40 Westbound in Conway (looking east)

This research focuses on highway work zone capacity and travel delay in relation to short term and long term work zones. The HCM 2010 associates short term work zones with the use of traffic drums or cones and long term work zones with temporary precast concrete barriers (PCCB). The Federal Highway Administration

(FHWA) identified major freight corridors as carrying more than 8,500 trucks per day.[3] The HCM 2010 look-up tables provided for a maximum input of 25 percent trucks.

Preliminary research data selection efforts concentrated upon corridors meeting or exceeding these criteria. Interstate 540 in Fort Smith was included in the data collection efforts because it had a unique work zone configuration and relatively high truck volumes for a small urban area. To establish base conditions and highway work zone capacity, field data comprised of vehicle classification counts were collected, and subsequent National Performance Management Research Data Set (NPMRDS) data was obtained to confirm travel speed estimates for individual time periods.

2. Background and Literature Review

Estimation of work zone capacity has been covered by several studies in the literature. Krammes and Lopez developed a model for estimation of freeway work zone capacity by using the data collected at 33 work zone sites in Texas between 1987 and 1991 (Krammes & Lopez, 1994). Kim et al. developed a multiple regression model that took into account the number of closed lanes, percentage of heavy vehicles, grade, and work intensity to estimate capacity for short-term freeway work zones (Kim, Lovell, & Paracha, 2001). Al-Kaisy and Hall examined the capacities of six reconstruction sites in Ontario, Canada, and then developed a generic multiplicative model to estimate the long-term work zone capacity (AL-Kaisy & Hall, 2003). The effects of heavy vehicles, driver population, weather, lane configuration, work intensity, and light conditions on capacity were examined, and it was found that heavy vehicles and driver population were the most significant factors affecting work zone capacity. In another study conducted by Heaslip et al., analytical models and procedures were proposed for estimating the long-term work zone capacity considering geometric, traffic, and work zone factors (Heaslip, Kondyli, Arguea, Elefteriadou, & Sullivan, 2009). Their analytical models were trained with simulation data from FHWA's Corridor Simulation model (CORSIM) and validated with field data. Weng and Meng proposed a decision tree-based model to estimate work zone capacity. Their model can be used easily by traffic engineers (Weng & Meng, 2011). Compared with other work zone capacity models, their model provides higher estimation accuracy of work zone capacity. There are also some nonparametric models based on field data, which can be applicable for estimating work zone capacity (Adeli & Jiang, 2003; Weng & Meng, 2012; Weng & Yan, 2014).

These studies put considerable effort into measuring work zone capacity data from a number of field sites, which is not an economical way to estimate work zone capacity. In addition, the measurement accuracy could be affected by the measurement methods (Edara, Kianfar, & Sun, 2012). Heaslip et al. adopted the traffic simulation method to estimate arterial work zone

[3] https://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/major.htm

capacity (Heaslip, Jain, & Elefteriadou, 2011). A few researchers adopted another method, which was first to determine the speed–flow relationship and then derive the capacity from speed–flow curves. For example, Benekohal et al. proposed a step-by-step method for estimating the operating speed and capacity in work zones (Benekohal, Kaja-Mohideen, & Chitturi, 2004). Using the data from eight long-term and three short-term work zones on interstate highways in Illinois, they developed a speed–flow curve under congested conditions that reflects operating conditions in work zones. They also developed a speed–flow curve for uncongested conditions through their judgment and information in the HCM (Transportation Research Board, 2000). Sarasua et al. derived the relationships between speed, density, and flow, assuming a linear relationship between density and speed (Sarasua, Davis, Chowdhury, & Ogle, 2006). In their study, the passenger car equivalent value for trucks varies with traffic speed. Racha et al. investigated the work zone speed–flow relationship by fitting a nonlinear model based on the data from 22 two-to-one-lane work zones in South Carolina (Racha, Chowdhury, Sarasua, & Ma, 2008). To estimate work zone capacity accurately, Avrenli et al. investigated the speed–flow relationship at work zones with no lane closure (Avrenli, Benekohal, & Ramezani, 2011). Two nonlinear models were fitted to depict the work zone speed–flow curves under uncongested and congested conditions, respectively (Weng & Yan, 2014).

Because uncertainty is associated with work zone capacity, it should be represented by a probability distribution rather than a crisp number. In addition, the effects of some significant factors, such as the number of construction sites per work zone, type of work being performed, traffic control devices, geometric alignment, environmental factors, and speed limit, on work zone capacity were not fully understood in previous studies. For example, because of safety considerations, drivers would like to travel at lower speeds on a curved road, and more construction sites present on the work zone could cause drivers to travel more cautiously (Kim, Lovell, & Paracha, 2001). This slow and cautious driving reduces the work zone capacity. In addition to the factor of geometrical alignment, the average traffic speed naturally depends on the speed limits (Tracz & Gaca, 2009). Although Weng and Meng developed a lane-based speed–flow model incorporating the factor of speed limit, they did not evaluate the effects of speed limit on the speed–flow relationship in the work zone merging areas because of data limits (Weng & Meng, 2011; Weng & Yan, 2014). (Bham & Khazraee, June 2011)

The Highway Capacity Manual, 6th Edition (HCM6), is the accepted standard for capacity evaluations. The HCM6 (Transportation Research Board, 2016) added methodology to estimate freeway work zone capacity. NCHRP Project 3-107 report informed HCM6 regarding work zone capacity (Project 3-107: Work Zone Capacity Methods for the Highway Capacity Manual Final Report, 2015). *NCFRP Report 31 – Incorporating Truck Analysis into the Highway Capacity Manual* presented techniques to better analyze level of service for trucks and to quantify truck impacts on other modes. These documents introduced new or revised methodology for calculating work zone capacities.

3. Research Objectives

The objectives of this research project included, but were not limited to, the following:

- Determine reliable field data collection methodologies to collect vehicle classification counts, traffic speeds, and duration of the heaviest traffic, and determine reasonable methods to collect data measuring queue length by the time of day.
- Collect traffic counts and estimate vehicle delay data in Arkansas work zones.
- Determine the traffic capacity, given the specific MOT strategy, within the work zone on different types of highway functional classifications - interstates, multi-lane highways, and two-lane highways, as possible, in Arkansas.
- Develop highway work zone capacities to use on high truck volume routes when planning construction activities within Arkansas.

Each of the research objectives is discussed in detail below.

Field Data Collection Methodologies

When TRC1306 was initiated, the primary traffic data collection methods available were use of either pneumatic tubes or in-pavement inductors. Both methods are highly problematic near construction zones where the devices are easily disturbed by construction equipment. Video data collection was ultimately selected for use in TRC1306.

In 2016, Statewide Automated Work Zone Information System (AWIS) data was explored as a source of construction work zone data. AWIS is a component of some construction projects. Data collected includes vehicle speed, classification, and lane occupancy (vehicle presence). Some of the devices are limited in their ability to accurately count vehicles in that the Doppler radar devices experience occlusion when two or more vehicles in parallel lanes pass at the same time. The Doppler radar devices, better at detecting vehicle speeds, are the most common type used in Arkansas work zones. Microwave traffic data collection devices provide more reliable vehicle classification counts but were not being routinely used at the time of this research. Furthermore, the AWIS data was not successfully retrieved from the vendor website. However, data has been archived and can potentially be made available for future research. With future work zones, AWIS systems with at least one microwave device could be used to collect work zone traffic count information.

Select Data Collection Methodology

Initially, traditional traffic count data collection methodologies were used. The proximity of the traffic counters to actual work zones remained problematic, and the number of sites with usable data was reduced. Subsequently, a video data collection vendor (Miovision) was used to collect traffic count data. Job BB0602 was added to the list of jobs, and traffic counts were collected over a seven day period at multiple locations.

Traffic Capacity for Various Facility Types and MOT Strategies

Due to time and budget constraints, data collection on the Interstate System was the focus of this study effort. Traffic counts were collected at work zones with both temporary Precast Concrete Barrier (PCCB) and with traffic drums. Temporary PCCB is typically associated with long term work zones and lane closures. Traffic drums are often used for short term lane closures and are easily removed to allow lanes to open during peak hour traffic conditions. National research efforts have shown that short term lane closures have lower capacity. However, peak hour traffic flows are better accommodated. Capacities based on MOT strategies will be discussed in the Conclusions and Recommendations section of this report.

Work Zone Capacities

Work zone capacity is the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions. Highway work zone capacity is typically defined in terms of passenger car equivalents (PCE). PCE is the number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under identical roadway, traffic, and control conditions. This value is expressed as E_T in the HCM.

Two values have been used to define work zone capacities: pre-breakdown flow rate and post-breakdown queue discharge rate. Pre-breakdown flow rate helps with predicting the onset of congestion in a work zone, while the post-breakdown queue discharge rate is used to estimate the operations and queuing patterns after breakdown has occurred.

Findings of work zone capacity and its relation to high volume truck routes will be discussed in following sections of this report. Data collected can be made available to contribute to the national knowledge base, aid with the development of work zone MOT strategies, incentive/disincentives for construction contracts, and analyze traffic during studies and road user cost calculations. Discussions of each research objective follow.

4. Benefits

The Multimodal and Project Planning Section (MPP) of ArDOT's Transportation Planning and Policy Division (TPP) uses highway work zone capacities and PCE factors in calculating road user costs (RUC) for work zones. The PCE for both peak hours and daily volumes is calculated by applying an equivalency factor (E_T) to the heavy vehicles counted in a traffic stream. Daily RUC are used to inform incentive/disincentive clauses for contract bidding. Hourly RUC are used for enforcing lane requirements and provide a means to charge lane use fees when contractors violate the lane closure recommendations of contract documents. Additionally, the methodology estimates queue lengths at bottlenecks for various traffic conditions, usually distinguished by time of day and the number of available travel lanes. Strategies to minimize work zone impacts during peak hours are intended to minimize queues and vehicle delays and improve safety through the work zone by keeping vehicles flowing.

The primary focus of this research was to determine highway work zone capacities where high volumes of heavy trucks are present, which is common on Arkansas' Interstate System. In nationwide research and documentation, work zone capacities as reported do not usually state the E_T or percent trucks used to calculate work zone lane closure and queue dissipation capacities.

The results from this research will be used by the ArDOT when conducting traffic studies and estimating work zone RUC. Verifying the accuracy of work zone lane capacity estimates will improve queuing prediction models and RUC estimates. Results may be used to calculate contract incentive/disincentive site use special provisions, inform the development of Transportation Management Plans (TMP), and Maintenance of Traffic (MOT) plans.

Other benefits of this research project include:

- Develop a better understanding of work zone and construction method impacts on highway capacity in Arkansas to inform future decision making.
- Establish performance metrics correlating lane closures with a number of factors, including vehicle mix, time of day, and speeds.
- Inform more efficient construction phasing plans, and innovative contracting and construction methods. Traffic data and road user cost calculations are currently being used for Accelerated Bridge Construction projects and for design/build strategies.

5. Data and Analysis

Eleven construction jobs were selected for this study, varying in work type, traffic volume, and roadway characteristics. Figure 1 shows data collection locations, and Table 1 lists construction jobs and their attributes. Data from nearby traffic count stations were compiled and checked for quality assurance.

In order to be deemed adequate to establish work zone capacity, traffic conditions had to demonstrate evidence of vehicle demand exceeding capacity during the data collection period. Data had to have been collected during known lane closure activities, and either slower traffic speeds or queuing delays within the work zone had to be observed.

After analyzing traffic count data and NMPRDS data, a subset of data that met the speed and/or queuing criteria was identified and used as part of the analysis. Jobs BB0105 on I-40 (Station 680025), BB0407 on I-540 (Station 650284), and BB0602 on I-30 (Station 620012) were analyzed in detail. Lane capacity, vehicle classification counts, number of freeway lanes open, and work zone type were analyzed. Work zone barrier type was noted. Vehicle counts in classes[4] 4 through 15 were multiplied by a truck equivalency factor E_T in order to obtain the total PCE volume. An E_T value of 2.0 was standard for this study, but for reference, the data were also analyzed with values E_T of 1.5, 2.5, and 3.0 for Jobs BB0105 and BB0407. The hourly volumes from the open lane in the direction of the lane closure were then plotted against time at hourly intervals for each day of the study. Curves (typically a 4th order polynomial) were fitted to the scatter plots, and capacity was derived from the maximum values of these curves. Curves with an R2 value of less than 0.7 were not used, as the data was not consistent enough to be statistically significant. Averaging the maximum volumes for each usable day from the relevant jobs yielded what can be considered a good estimate of the reduced capacity of the roadway with a lane closure. Detailed descriptions of the jobs and relative data analysis follow.

The purpose of **Job BB0105** was to reconstruct 7.8 miles of Interstate 40 (I-40) main lanes at Forrest City. Average Daily Traffic (ADT) on I-40 at the time the job was constructed was estimated to be 32,000 vehicles per day (vpd) with 56 percent heavy vehicles. The MOT scheme reduced the number of lanes from two to one in each direction. Temporary PCCB was in place from September 16th, 2013, until the end of the year. Traffic count data from Station 680025 was used to calculate work zone capacity.

[4] More information for FHWA's Vehicle Classification System can be found at https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_2013/vehicle-types.cfm

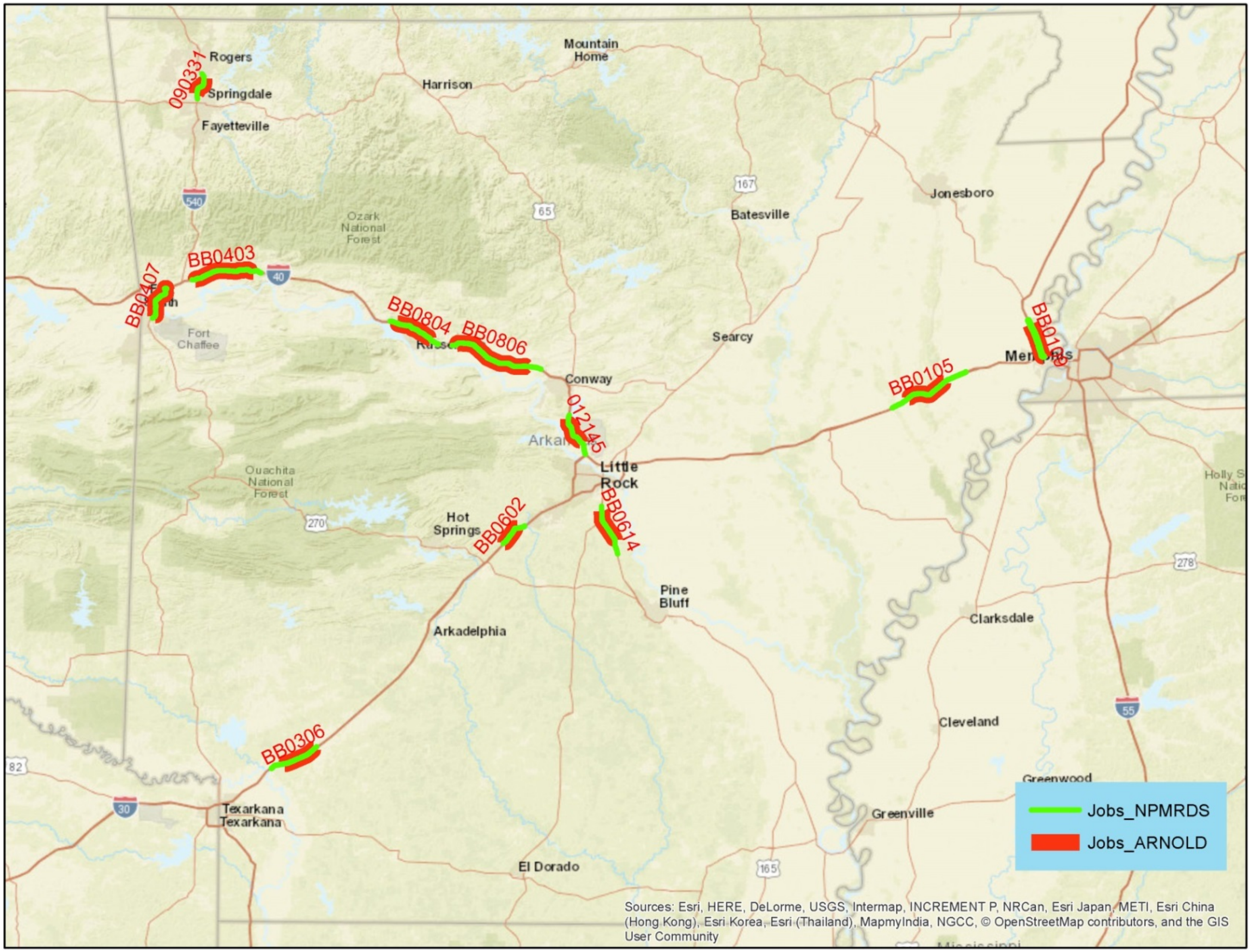

Figure 1 – Data Collection Sites and NPMRDS Data Limits

Table 1 – Preliminary Data Collection: Construction Job Sites and Attributes

Job Number	Route	Section	Job Name	Type of Work	MOT Scheme for Lane Configurations	Design Speed[1.]	Work Zone Speed[1.]	AADT	Truck Percent [2.]
012145	40	32, 33	Palarm Creek-Hwy. 365 (Widening) (F)	Major widening	Two per direction with PCCB	70	60	65,000	15%
090331	540	5	Wagon Wheel Rd. - Hwy. 264 (Widening) (S)	Major widening	Two per direction with PCCB	70	60	74,000	11%
BB0105	40	51	Forrest City-East (F)	Pavement reconstruction	Two to one (crossover)	70	60	32,000	56%
BB0109	55	11	I-40 - Jerico (S)	Pavement reconstruction; bridge deck hydrodemolition	Two to one with drums; PCCB at bridges	70	60	34,000	38%
BB0306	30	12	Sheppard - Hwy. 278 (S)	Pavement reconstruction	Two to one with drums	70	60	28,000	45%
BB0403	40	11, 12	Dyer - Cravens Creek (S)	Rehabilitation (mill & Inlay); bridge deck hydrodemolition	Two to one with drums; PCCB at bridges	70	60	30,000	36%
BB0407	540	1, 2	Hwy. 22 - I-40 (F)	Pavement reconstruction	Two to one (crossover)	65	55	46,000	12%
BB0602	30	22	Hwy. 70-West (Westbound Lanes) (F)	Pavement reconstruction	Two to one with PCCB	70	60	39,000 (two-way)	40%
BB0614	530	1, 2, 3	Bingham Rd. - Grant Co. Line (S)	Pavement rehabilitation (mill & Inlay); bridge deck hydrodemolition	Two to one (crossover)	70	60	20,000	12%
BB0804	40	22	Mill Creek - Hwy. 331 (F)	Pavement rehabilitation, replace 2 pairs of bridges; Cable median barrier	Two to one (crossover)	70	60	28,000	33%
BB0806	40	22, 31	Atkins - Plumberville (S)	Pavement rehabilitation (mill & inlay); bridge deck hydrodemolition	Two to one with drums; PCCB at bridges	70	60	32,000	28%

1. Speeds are taken from contract documents, with design speed from title sheet and work zone speed from MOT plans.
2. Truck percentages are taken from contract document title sheets.

For this job, the maximum capacity was estimated to be 1,400 passenger cars per hour per lane (pc/hr/lane) with an E_T of 2.0. For an E_T of 2.5, the estimated capacity was 1,650 pc/hr/lane; and for an E_T of 3.0, estimated capacity was 1,950 pc/hr/lane. This high variability in capacity under different E_T values can be attributed to the high truck percentage in this area. With a majority of the vehicles on the road being classified as heavy vehicles, increasing the E_T has a significant impact on the calculated capacity in terms of units expressed in PCEs. Since the terrain is relatively level at this location, an E_T of 2.0 is appropriate per HCM methodology to account for heavy vehicles in the traffic stream.

The purpose of **Job BB0407** on Interstate 540 (I-540) at Fort Smith was to rubblize and construct new pavement for 7.1 miles of roadway, replace nine structurally deficient bridges, modify/raise four bridges, and install sign support structures. ADT on I-540 at the time the job was constructed was estimated to be 46,000 vpd with 12 percent heavy vehicles. The MOT plans included reducing the number of lanes in the southbound direction from two to one for a few days in January 2015, and reducing the number of lanes in either the southbound or northbound directions for a few days in July 2016 starting at 7:30 PM each day. For this job, it was found that the maximum capacity was roughly 1,250 pc/hr/lane with an E_T of 2.0; 1,300 pc/hr/lane with an E_T of 2.5; and 1,400 pc/hr/lane with an E_T of 3.0. The effects of E_T on capacity are not dramatic here because the percentage of heavy vehicles in the traffic stream is low. I-540 is not a high truck volume route but there is a relatively high number of trucks for an urban area. This site was initially included to evaluate work zones in urbanized areas.

Job BB0602 was located on Interstate 30 (I-30) westbound lanes in Saline County. I-30 in the project area is a four-lane interstate with four 12-foot lanes, 10-foot outside shoulders, 4-foot inside shoulders and a grass or vegetated median. In 2016, the ADT was reported to be 37,000 vpd with 40 percent trucks. An exit ramp to Highway 70 (Hot Springs) is located adjacent to the job limits upstream of the work zone. Approximately 27 percent of traffic on I-30 in 2016 traveled between the east (Little Rock area) and the Hot Springs exit and includes commuters to central Arkansas' employment centers. The remainder is typical of rural interstate traffic. The job was 2.9 miles long. The work zone MOT plan extended about one mile east of the work zone and impacted only the westbound lanes. The scope of Job BB0602 was full-depth pavement replacement of the westbound I-30 main lanes and construction of cable median barriers on a portion of the alignment. Figure 2 shows the Job Title Sheet.

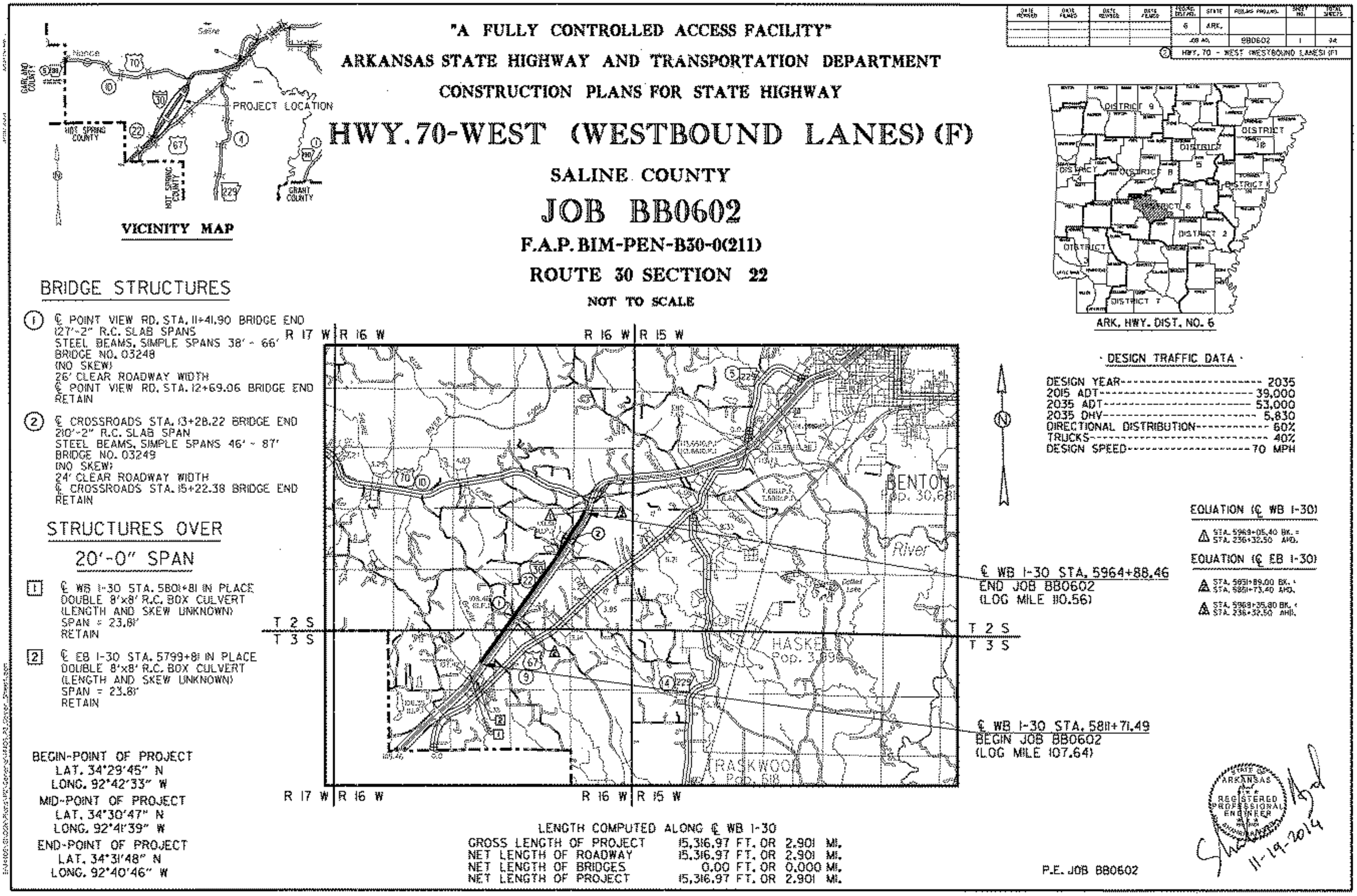

Figure 2 – BB0602 Title Sheet

The MOT plan generally closed one westbound lane downstream of the Highway 70 exit ramp and left one lane open to traffic. Temporary PCCB was installed to separate the work area from traffic. The outside lane upstream of the work zone was dropped at the Highway 70 exit ramp. The work zone incorporated AWIS technology for queue detection and traffic monitoring. Data collected through AWIS was not available for this study, although it is reported to be archived.

Photo 3 – I-30 westbound lanes approaching Job BB0602

Photo 2 – I-30 westbound lanes at Job BB0602; looking east at construction site

Photo 4 – I-30 westbound lanes approaching Job BB0602 within lane closure

Vehicle classification counts were collected along I-30 at four locations and on the Highway 71 westbound exit ramp from Thursday, January 12 to Wednesday, January 18, 2016 (seven days) using video data collection devices. Figure 3 shows the count stations. NPMRDS data for I-30 from the Alcoa exit in Saline County to the Highway 270 exit in Hot Spring County was retrieved. Also, vehicle crash data was retrieved for the period under study. Daily Work Reports and Traffic Management Plans submitted by the Resident Engineer office were also reviewed. The extensive data collection efforts afforded the opportunity to study the traffic data at a higher granularity for Job BB0602. Known events at the time of data collection were well documented. For this job, the vehicle class counts and NMPRDS data were organized in an excel spreadsheet by time-of-day (temporal) along the vertical axis and by NPMRDS segments (spatial) along the horizontal axis. This data was used to determine traffic speeds in relation to vehicle class counts at specific locations within the corridor. Table 2 shows an example of these data.

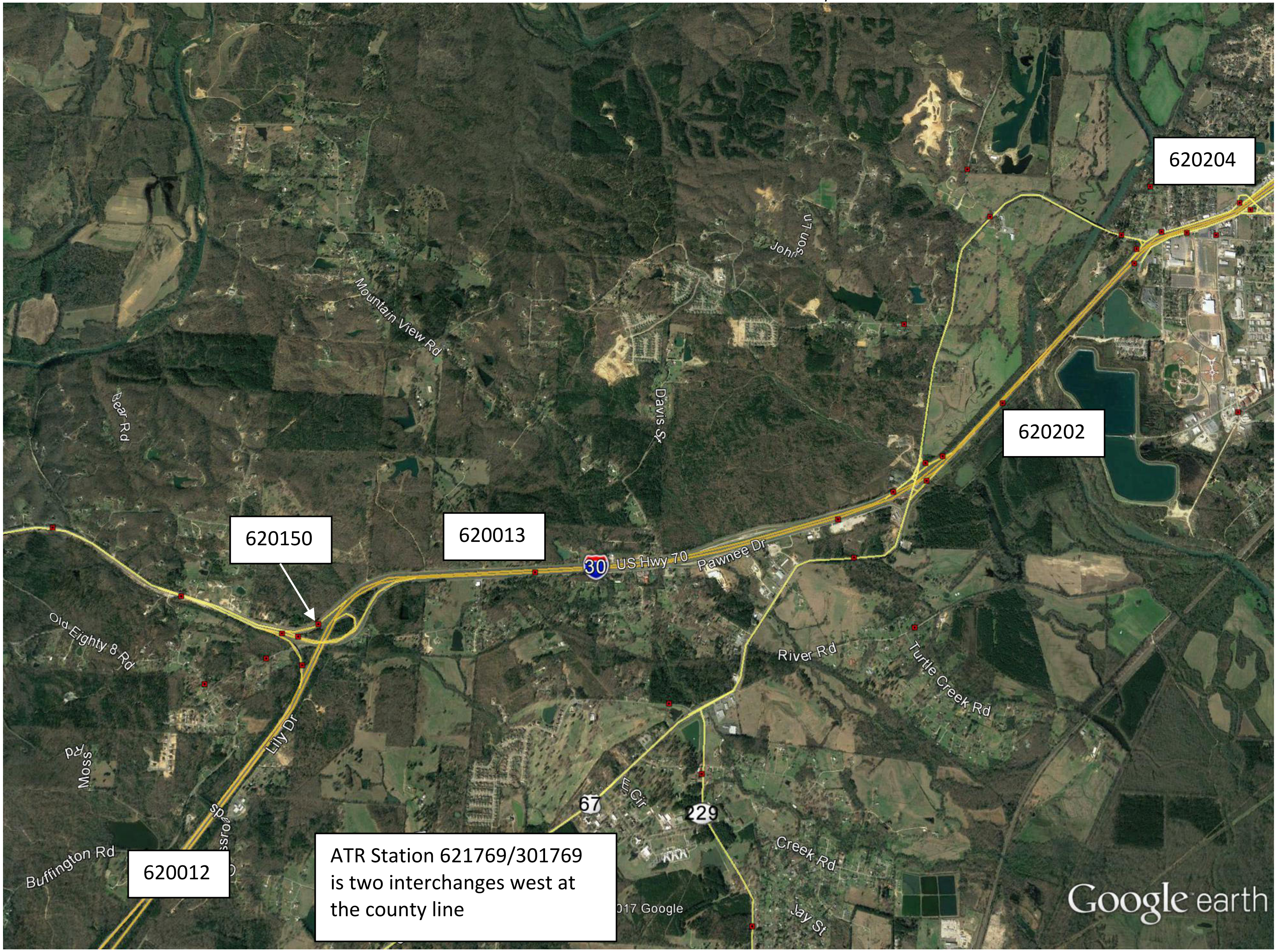

Figure 3 – BB0602 Traffic Count Stations

Table 2 – BB0602 Initial Data Screening

	US-270/GEORGE HOPKINS LOOP/EXIT 99	OLD MILITARY RD/EXIT 106		Sta. 620012 (within work zone)			US-70/EXIT 111		Sta. 620013 (upstream of work zone and Hwy. 71 WB exit ramp			US-67/EXIT 114		Sta. 620202			SEVIER ST/EXIT 116		Sta. 620204			AR-35/EXIT 117		CONGO RD/EXIT 118	
	113-12837	113N04476	113-04476	Total V	% TR	PCE (x	113N04477	113-04477	Total V	% TR	PCE (	113N04478	113-04478	Total V	% Truck	PCE (x	113N04479	113-04479	Total V	% Truck	PCE (x	113N04480	113-04480	113N04481	113-04481
1/13/2016 11:00	65.64	58.6	58.6	205	47.3%	302	58.99	58.99	309	40.1%	433	64.97	64.97	400	35.8%	543	64.33	64.33	402	33.1%	535	64.65	64.65	65.23	65.23
1/13/2016 11:15	64.65	59.96	59.96	205	49.3%	306	59.99	59.99	302	40.7%	425	63.32	63.32	404	31.7%	532	63.97	63.97	429	32.4%	568	64.97	64.97	66.53	66.53
1/13/2016 11:30	64.99	57.66	57.66	241	46.5%	353	58.99	58.99	309	34.3%	415	65.28	65.28	386	29.0%	498	64.99	64.99	383	29.2%	495	65.97	65.97	65.66	65.66
1/13/2016 11:45	64.33	56.99	56.99	206	47.1%	303	59.99	59.99	299	40.5%	420	62.97	62.97	368	34.2%	494	63.66	63.66	381	35.7%	517	64.65	64.65	63.33	63.33
1/13/2016 12:00	63.99	58.66	58.66	226	52.2%	344	56.95	56.95	315	42.5%	449	63.66	63.66	420	32.4%	556	63.66	63.66	432	31.3%	567	63.66	63.66	64.62	64.62
1/13/2016 12:15	64.65	58.28	58.28	241	50.2%	362	58.99	58.99	324	38.9%	450	64.33	64.33	427	32.3%	565	64.6	64.6	416	33.7%	556	65.32	65.32	66.33	66.33
1/13/2016 12:30	69.11	61.8	61.8	223	56.5%	349	62.32	62.32	322	39.8%	450	69.91	69.91	451	29.3%	583	67.44	67.44	453	27.4%	577	67.8	67.8	69.93	69.93
1/13/2016 12:45	67.02	58.66	58.66	226	54.0%	348	57.28	57.28	319	44.2%	460	63.32	63.32	422	37.9%	582	64.66	64.66	442	38.5%	612	63.96	63.96	62.83	62.83
1/13/2016 13:00	65.33	57.27	57.27	233	56.2%	364	51.61	51.61	346	39.3%	482	64.33	64.33	448	29.9%	582	62.55	62.55	451	30.6%	589	62.87	62.87	64.99	64.99
1/13/2016 13:15	65	58.33	58.33	250	48.8%	372	54.52	54.52	340	40.9%	479	61.6	61.6	410	34.4%	551	61.96	61.96	432	31.5%	568	64.31	64.31	63.66	63.66
1/13/2016 13:30	66.23	59.22	59.22	242	51.7%	367	46.96	46.96	368	34.0%	493	61.33	61.33	479	28.6%	616	64	64	462	29.2%	597	64	64	65.31	65.31
1/13/2016 13:45	66.17	56.99	56.99	235	51.5%	356	46.72	46.72	339	37.2%	465	63.31	63.31	443	29.1%	572	63.99	63.99	468	29.9%	608	65.32	65.32	64.96	64.96
1/13/2016 14:00	64.32	56.64	56.64	256	51.6%	388	56.62	56.62	363	37.7%	500	62.29	62.29	515	30.3%	671	63.64	63.64	484	30.2%	630	65.96	65.96	66.97	66.97
1/13/2016 14:15	63.33	58.31	58.31	262	51.1%	396	42.45	42.45	366	37.4%	503	62.99	62.99	477	27.7%	609	63.33	63.33	484	27.5%	617	65.64	65.64	64.99	64.99
1/13/2016 14:30	64.31	54.91	54.91	232	53.0%	355	38.32	38.32	362	37.0%	496	62.99	62.99	565	28.0%	723	64.33	64.33	546	29.9%	709	65.64	65.64	64.62	64.62
1/13/2016 14:45	68.28	58.66	58.66	223	48.0%	330	23.52	23.52	354	30.5%	462	62.31	62.31	493	21.9%	601	63.33	63.33	508	21.9%	619	63.32	63.32	62.09	62.09
1/13/2016 15:00	64.33	55.64	55.64	261	38.7%	362	29.94	29.94	391	29.7%	507	62.64	62.64	572	22.9%	703	63.2	63.2	560	23.9%	694	65.29	65.29	65.32	65.32
1/13/2016 15:15	65.64	40.08	40.08	226	44.7%	327	24.92	24.92	382	36.6%	522	61.33	61.33	571	27.1%	726	63.33	63.33	577	28.1%	739	64.65	64.65	65.32	65.32
1/13/2016 15:30	64	34.26	34.26	196	52.6%	299	17.25	17.25	337	32.9%	448	47.93	47.93	631	23.9%	782	60.97	60.97	599	25.7%	753	63.97	63.97	64.31	64.31
1/13/2016 15:45	65	32.34	32.34	204	47.1%	300	11.84	11.84	269	33.5%	359	23.54	23.54	541	20.3%	651	59.28	59.28	579	21.4%	703	64.97	64.97	62.86	62.86
1/13/2016 16:00	63.24	37.99	37.99	217	36.9%	297	15.56	15.56	266	33.8%	356	24.82	24.82	535	19.8%	641	29.79	29.79	630	19.2%	751	65.28	65.28	65.64	65.64
1/13/2016 16:15	60.27	51.88	51.88	223	45.7%	325	18.83	18.83	274	39.1%	381	26.35	26.35	507	20.3%	610	28.87	28.87	581	17.9%	685	65.64	65.64	65.91	65.91
1/13/2016 16:30	64.65	54.33	54.33	209	50.7%	315	24.63	24.63	357	31.9%	471	30.73	30.73	588	20.6%	709	29.59	29.59	590	18.1%	697	66.11	66.11	66.41	66.41
1/13/2016 16:45	65.96	55.56	55.56	233	47.6%	344	25.27	25.27	345	31.0%	452	34.74	34.74	624	16.7%	728	38.51	38.51	585	15.7%	677	62.65	62.65	64.99	64.99
1/13/2016 17:00	64.65	57.33	57.33	247	43.7%	355	34.61	34.61	339	28.0%	434	49.73	49.73	605	15.7%	700	59.6	59.6	564	15.6%	652	64.62	64.62	67.88	67.88
1/13/2016 17:15	63	57.96	57.96	253	37.2%	347	56.14	56.14	354	24.3%	440	63.66	63.66	576	14.4%	659	58.32	58.32	570	15.8%	660	65.28	65.28	67.23	67.23
1/13/2016 17:30	64.66	58.55	58.55	190	42.6%	271	61.33	61.33	300	28.0%	384	65.71	65.71	532	16.7%	621	64.81	64.81	551	15.8%	638	65.17	65.17	65.17	65.17
1/13/2016 17:45	70.73	59.39	59.39	186	41.9%	264	55.96	55.96	334	25.4%	419	62.97	62.97	568	17.1%	665	63.65	63.65	579	16.1%	672	64.65	64.65	63.99	63.99
1/13/2016 18:00	65.62	57.92	57.92	197	54.3%	304	44.84	44.84	405	34.3%	544	60.99	60.99	596	24.5%	742	61.32	61.32	615	26.2%	776	63.33	63.33	64.31	64.31
1/13/2016 18:15	66.33	49.54	49.54	217	52.5%	331	26.57	26.57	346	36.1%	471	62.66	62.66	581	23.4%	717	61.32	61.32	574	23.0%	706	64.97	64.97	62.58	62.58
1/13/2016 18:30	65.6	46.63	46.63	248	51.6%	376	32.59	32.59	339	31.9%	447	63.32	63.32	426	22.8%	523	64.29	64.29	424	21.9%	517	65.97	65.97	65.32	65.32

Key: | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | (mph)

Using average traffic speeds (shown with colored conditional formatting in Table 2), the absence or presence of queues upstream of the project area was determined. It was assumed that when speeds were less than 45 miles per hour (mph) over multiple segments, a queue was present. Thus, if speeds less than 45 mph were present for a duration of three or more 15-minute time periods on two or more NMPRDS segments, it was assumed that traffic demand had exceeded capacity. If the adjacent upstream NPMRDS segment exhibited similar speed decreases, it was assumed that effects of the queue extended into that segment. For times when an upstream queue was indicated, fifteen-minute vehicle class counts were analyzed to determine flow rates. Traffic count data is shown in the white and pink formatted cells in the example illustrated in Table 2. Slower traffic speeds are shown beginning 1/13/2016 at 13:30 hours. Prior to queue formation, the I-30 westbound lanes operated at capacity from 13:00 to 14:00 hours without breakdown.

Similar information was used to develop speed and volume profiles for the seven days that data was collected. Table 3 summarizes the findings for pre- and post-breakdown conditions in terms of average and maximum hourly work zone capacity, average and maximum saturated flow rates, and average truck percent.

Table 3 – Summary of Findings for BB0602

Date & Time		Measure	Pre-Breakdown 1-Hour [1.]	Pre-Breakdown Sat-Flow [2.]	Post-Breakdown 1-Hour [1.]	Post-Breakdown Sat-Flow [2.]	Truck%
from	**1/12/2016 14:00**	**Average:**	n/a	n/a	1,308	1,323	54.53%
to	**1/12/2016 16:45**	**Max:**	n/a	n/a	1,394	1,516	
from	**1/13/2016 13:00**	**Average:**	1,483	1,520	1,335	1,312	48.21%
to	**1/13/2016 17:00**	**Max:**	1,507	1,584	1,495	1,448	
from	**1/14/2016 14:30**	**Average:**	1,382	1,400	1,435	1,413	42.46%
to	**1/14/2016 17:00**	**Max:**	1,400	1,576	1,529	1,600	
from	**1/15/2016 12:00**	**Average:**	1,383	1,387	1,431	1,464	29.0%
to	**1/15/2016 16:45**	**Max:**	1,428	1,484	1,435	1,516	
from	**1/18/2016 10:15**	**Average:**	1,429	1,429	1,529	1,535	35.5%
to	**1/18/2016 11:45**	**Max:**	1,429	1,560	1,537	1,552	

1. Hourly flow rate is the sum of four 15-minute time periods, in pc/hr/ln assuming E_T = 2.0.
2. Saturated flow rate is the product of a single 15-minute time period multiplied by four, in units of pc/hr/ln assuming E_T = 2.0.

Maximum capacity typically occurs just prior to the breakdown of traffic flow. However, at this location, post-breakdown flow rates were often higher than pre-breakdown flow rates. The location of the lane drop at the Highway 70 westbound exit ramp is non-standard for a freeway lane closure segment and may have impacted the measured capacity. Therefore, pre-breakdown flow rates should be used with caution. Post-breakdown flow rates, on the other hand, likely provide a good indicator of queue dissipation capacity for a single lane. For Job BB0602, the average observed capacity for queue dissipation was estimated to be 1,400 pc/hr/lane if the passenger car equivalency factor (E_T) of 2.0 is assumed. The calculated capacities in terms of PCE would increase or decrease as a function of E_T if different values are assumed.

To correlate heavy truck impacts to capacity, truck percentages were plotted against pre- and post-breakdown hourly traffic capacity. E_T values of 2.0 and 3.0 were analyzed. Figure 4 shows the results of the scatter plot analysis for pre-breakdown capacity, and Figure 5 shows results for the post-breakdown (queue dissipation) capacity.

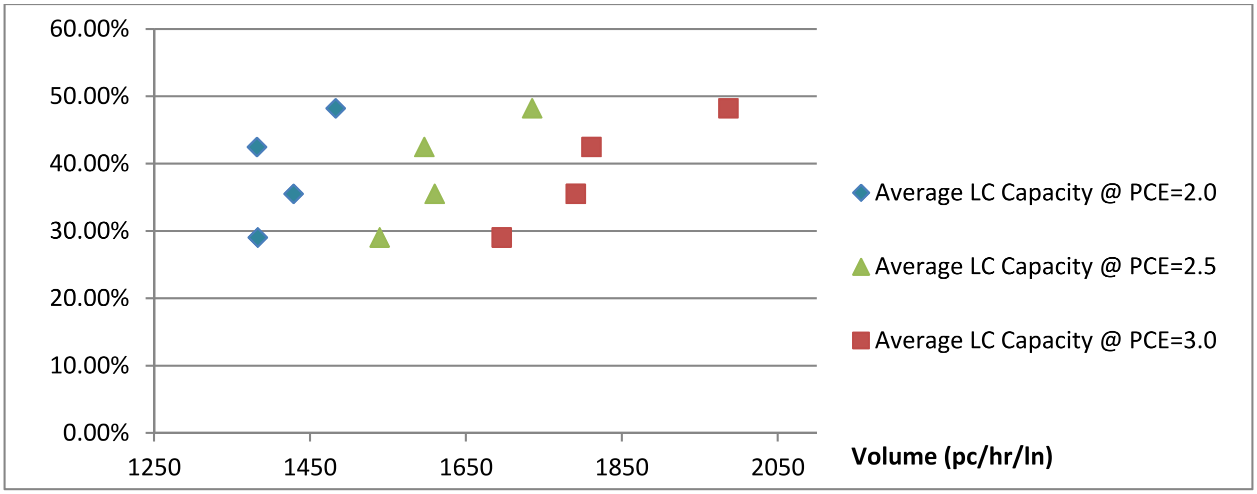

Figure 4 – Job BB0602 Average Lane Capacity Prior to Queued Conditions

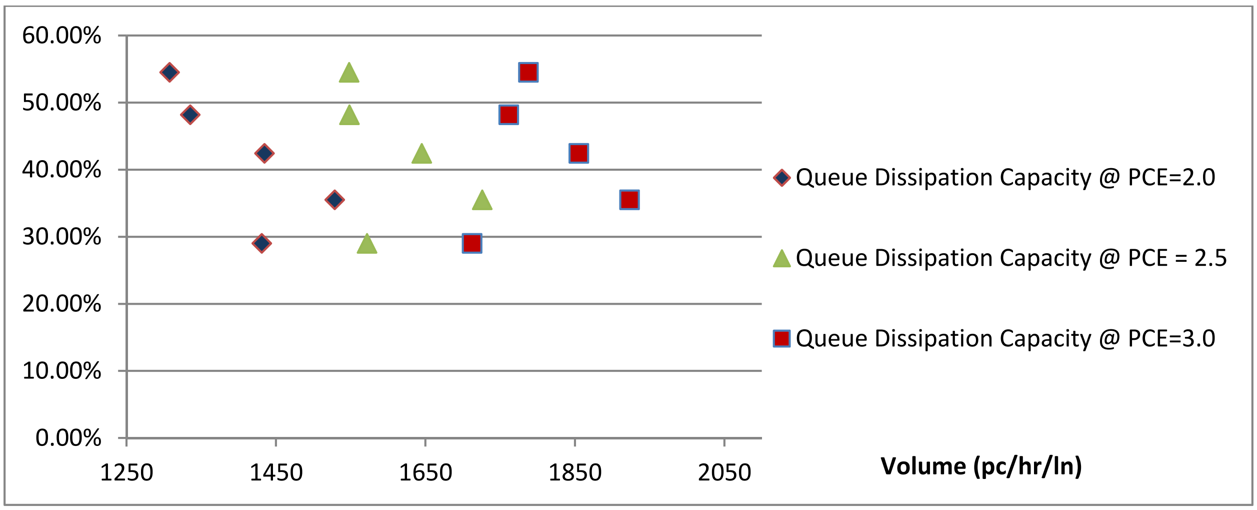

Figure 5 – Job BB0602 Average Lane Capacity for Queue Dissipation Conditions

Figure 4 suggests that an E_T of 2.0 may be appropriate for pre-breakdown flow conditions, as the range of capacity distribution is narrow. For queue dissipation capacity, a higher E_T may be appropriate due to heavy vehicle acceleration characteristics, headways, and length of vehicles. Insufficient data is available to conclusively recommend when an $E_T > 2.0$ may be beneficial for queue analysis in construction zones.

6. Conclusions and Recommendations

Data Collection Methodology

Collecting vehicle classification data in work zones presents obstacles in placing and maintaining traditional traffic counting equipment. Additionally, deploying staff for manual traffic counts is seldom practical, as traffic conditions fluctuate and capacity conditions (as indicated by queuing) may not be present. Data collected via AWIS may be useful in the future for tracking work zone capacity, especially if paired with Daily Work Reports and NPMRDS data.

In the analysis of traffic count data in work zones, field construction conditions that may impact capacity at the time data was collected should be known. For example, if heavy construction is occurring near traffic lanes, then traffic speeds and capacity tends to be lower. For this research, construction field data beyond that reported in the Daily Work Reports was not available. Many factors impact work zone capacity, including traffic patterns through the construction zone, work zone traffic control devices, changes in weather conditions, and construction activities. Pertinent factors should be systematically tracked at the time traffic data is recorded for a more complete assessment of work zone capacity and performance.

At the time this research was conducted, no single data collection methodology (i.e., induction loops, tubes, radar, or video traffic counters) had the ability to document all of the desired data parameters. Daily Work Reports contain much information, but often not at the granularity needed to determine exactly when queues are present or to suggest other factors that may contribute to slow traffic speeds and queuing.

Future efforts involving work zone traffic data collection should consider development of a database to document such factors as weather, pavement conditions, work zone MOT layout and devices, distance between construction operations and edge of traveled way, lane width, clear zone width, lighting conditions, travel speeds, public access points (roadways and/or driveways) within or adjacent to the construction zone, contractor access to work site, type of construction operations, visibility issues, and frequency of deliveries to the construction site.

Work Zone Capacity Findings

Traffic and speed data for twelve construction jobs were gathered as a component of this research. Data from three sites were validated as meeting criteria needed to establish work zone capacity. Queue dissipation capacity for those sites is shown in Table 4.

Table 4 – Summary of Work Zone Lane Closure Capacity Findings

Job Number	Route	Section	MOT Scheme for Lane Configurations	Capacity* (E_T = 2.0)	Capacity* (E_T = 2.5)	Capacity* (E_T = 3.0)	Percent Trucks
BB0105	40	51	Two to one (crossover)	1,400	1,650	1,950	56%
BB0407	540	1, 2	Two to one with traffic drums	1,250	1,300	1,400	12%
BB0602	30 WB	22	Two to one with PCCB	1,450	1,650	1,850	40%

*passenger car equivalents per hour per lane, calculated as saturated flow rate (15-minute volume x 4 periods)

The above findings are generally within expected ranges of work zone capacity on rural interstates. However, the documented capacity and known traffic flow characteristics for Job BB0407 (urban freeway with moderate truck volumes) are less consistent with expected urban interstate capacity values. This could be attributed to the work zone configuration or to the construction operations occurring at the time of traffic data collection. Not enough information was available to conclusively determine why BB0407 work zone lane closure capacity was lower than that of rural freeways with higher truck volumes.

The lane closure capacities and related E_T factors used to convert trucks to PCEs documented herein must be used with caution. Particularly, ramp operations and MOT treatments at ramps can have a large impact on traffic flow. None of the MOTs for jobs studied presented a simple lane closure reduction of two lanes to one lane on a basic freeway segment. All of the data points were impacted in some way by interchange traffic.

Data Analysis Qualifications

For Arkansas freeways, observed capacity in urban areas has been consistently less than that reported by the Highway Capacity Manual. This may not correlate with work zone data because the freeway segments studied do not necessarily have recurring congestion under normal operating conditions.

Because freeway capacity can fluctuate based upon site conditions, type of work adjacent to travel lanes and a number of other factors, these findings should be used as a guideline and do not replace engineering judgment. Additional data points are needed to accurately inform capacity analysis on other highway classification categories.

Implementation

Findings of this research may be used when conducting highway capacity analysis, queue length estimation, and travel time estimation. More field data is becoming available that will support lane closure capacity assumptions. However, caution must be used because each work zone configuration is unique. Particularly, each of the work zones carried forward for detailed evaluation in TRC1306 was impacted by the proximity of interchanges. Additional study is necessary to document work zone traffic capacity for varied MOT strategies and facility types.

HCM6 includes methodology to calculate heavy vehicle E_T values. This may be applied to work zones where bottlenecks are expected due to grade or alignment issues. NCHRP Report 3-107, Table A-7 suggests that an E_T of 2.4 be used for level terrain, and E_T of 3.0 be used for 3 percent 1-km upgrade. Additional testing of these values for conditions in Arkansas is warranted. HCM6 should be referenced to determine E_T for freeway segments on grades. Insufficient data is available to support an E_T that is different from HCM methodology.

Future in-house research efforts will strive to provide better documentation of traffic flow on highways with recurring congestion, as well as highway capacity in work zones.

References

Adeli, H., & Jiang, X. (2003). Neuro-Fuzzy Logic Model for Freeway Work Zone Capacity Estimation. *Journal of Transportation Engineering, 129*(5), 484–493.

AL-Kaisy, A., & Hall, F. (2003). Guidelines for Estimating Capacity at Freeway Reconstruction Zones. *Journal of Transportation Engineering, 129*(5), 572-577.

Avrenli, K., Benekohal, R., & Ramezani, H. (2011). Determining the Speed-Flow Relationship and Capacity for a Freeway Work Zone with No Lane Closure. *90th Annual Meeting of the Transportation Research Board.* Washington, D.C.: Transporation Research Board of the National Academies.

Benekohal, R., Kaja-Mohideen, A., & Chitturi, M. (2004). Methodology for Estimating Operating Speed and Capacity in Work Zones. *Transportation Research Board 1883*, 103-111.

Bham, G. H., & Khazraee, S. H. (June 2011). *Missouri Work Zone Capacity: Results of Field Data Analysis.* Rolla, MO: Missouri University of Science and Technology.

Edara, P., Kianfar, J., & Sun, C. (2012). Analytical Methods for Deriving Work Zone Capacities from Field Data. *Journal of Transportation Engineering, 138*(6), 809–818.

Heaslip, K., Jain, M., & Elefteriadou, L. (2011). Estimation of Arterial Work Zone Capacity Using Simulation. *The International Journal of Transportation Research, 2*, 123-134.

Heaslip, K., Kondyli, A., Arguea, D., Elefteriadou, L., & Sullivan, F. (2009). Estimation of Freeway Work Zone Capacity Through Simulation and Field Data. *Transportation Research Record 2130*, 16-24.

Kim, T., Lovell, D., & Paracha, J. (2001). A New Methodology to Estimate Capacity for Freeway Work Zones. *80th Annual Meeting of the Transportation Research Board.* Washington, D.C.: National Research Council.

Krammes, R., & Lopez, G. (1994). Updated Capacity Values for Short-Term Freeway Work Zone Lane Closures. *Transportation Research Record 1442*, 49-56.

Racha, S., Chowdhury, M., Sarasua, W., & Ma, Y. (2008). Analysis of Work Zone Traffic Behavior for Planning Applications. *Transportation Planning and Technology, 31*(2), 183–199.

Sarasua, W., Davis, W., Chowdhury, M., & Ogle, J. (2006). Estimating Interstate Highway Capacity for Short-Term Work Zone Lane Closures: Development of Methodology. *Transportation Research Record 1948*, 45-57.

Schoen, J. M., Bonneson, J. A., Safi, C., Schroeder, B., Hajababaie, A., Yeom, C. H., . . . Zou, Y. (April, 2015). *NCHRP Project 3-107 Work Zone Capacity Methods For The Highway Capacity Manual.* Washington, D.C.: Transportation Research Board.

Schoen, J. M., Bonneson, J. A., Safi, C., Schroeder, B., Hajababie, A., Yeom, C. H., . . . Zou, Y. (2015). *NCHRP Project 3-107 Work Zone Capacity Methods For The Highway Capacity Manual.* Washington, D.C.: Transportation Research Board.

Tracz, M., & Gaca, S. (2009). Influences of Various Restrictions on Speed-Flow Models. *Transportation Research Board 1901*, 167-177.

Transportation Research Board. (2000). *Highway Capacity Manual.* Washington, D.C.: National Research Council.

Transportation Research Board, J. M. (2015). *Project 3-107: Work Zone Capacity Methods for the Highway Capacity Manual Final Report.* Washington D.C.: Kittleson & Associates, in Association with: The Institue for Transportation Reseach and Education at North Carolina State University, The Uniersity of Washington.

Transportation Research Board. (2016). *Highway Capacity Manual 6th Edition.* Washington, DC: The National Academy of Sciences.

Weng, J., & Meng, Q. (2011). Modeling Speed-Flow Relationship and Merging Behavior in Work Zone Merging Areas. *Transportation Research Part C: Emerging Technologies, 19*(6), 985–996.

Weng, J., & Meng, Q. (2012). Ensemble Tree Approach to Estimating Work Zone Capacity. *Transportation Research Record 2286*, 56-67.

Weng, J., & Yan, X. (2014). New Methodology to Determine Work Zone Capacity Distribution. *Transportation Research Record 2461*, 25-31.

Weng, M., & Meng, Q. (2011). Decision Tree-Based Model for Estimation of Work Zone Capacity. *Transportation Research Record 2257*, 40-50.