# *Louisiana Transportation Research Center*

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# Evaluation of DOTD's Existing Queue Estimation Procedures

by

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13. Abstract

Louisiana Department of Transportation and Development (DOTD) requests that freeway lanes should not be closed for construction work during hours when capacity exceeds 1,309 pcphpl. It is not known how accurate this 1,309 pcphpl value is when compared to actual queuing related to real world work zones in Louisiana. This study provided literature on how work zone capacities have been defined by different researchers and practitioners, and what factors affect such capacities. It further provided an overview of the HCM 2000 work zone capacity model and how that was used as basis for the 1,309 pcphpl threshold. A nationwide survey revealed that approximately half the number of states that responded enforced a similar threshold for lane closures, ranging from 1,100 – 2,000 pcphpl. A statewide survey revealed that majority of DOTD districts regularly performed queue analysis for work zone lane closures on freeways but perceived the 1,309 pcphpl threshold to be too high. This study determined an average field observed work zone capacity of 1,310 pcphpl, corresponding to an average queue duration of 120 minutes, and an average queue length of 1.30 miles. HCM 2016's work zone capacity model slightly overestimates (average 6%) the capacity at Louisiana work zones but will provide representative ranges in the absence of field collected data. The study further determined a new threshold of 1,052 pcphpl as corresponding to 30 minutes of queueing conditions.

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Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

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# Implementation Statement

The findings from the survey will provide DOTD a review of the state of practice of work zone lane closure procedures statewide and nationally. DOTD administrators can use results of the survey to develop targeted educational material at its districts. Additionally, useful lessons can be learned from documented procedures from other states. The analysis from field data evaluated the effectiveness of DOTD's existing queue estimation procedures. Currently, when determining when to close lanes for work zone related works, lanes shall not be closed during hours when lane capacity exceeds a threshold of 1,309 pcphpl. Often, lengthy queues exist even before this threshold is attained, and this study observed an average of 120 minutes' delay to correspond to a field observed capacity of 1,310 pcphpl. The study estimated a new reduced threshold of 1,052 pcphpl, corresponding to delays of no more than 30 minutes. DOTD administrators can use findings from this study to develop a revised threshold criterion that will provide bearable queues during work zone lane closures. However, a separate study may be needed to evaluate how implementing a statewide revised threshold criterion may impact stakeholder travel time and economic competitiveness of the region.

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# Introduction

The United States has extensive transportation infrastructure connecting different parts of the country. With this widespread transportation system comes the need for periodic maintenance and repairs with as many as 3,000 active work zones across state-maintained highways at any given time [1]. The Manual on Uniform Traffic Control Devices (MUTCD) defines a work zone as an area of a highway with construction, maintenance, or utility work activities. 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 zones may result in lane closures or detours, often causing mobility and safety issues [2]. Lane drops and merges arising from work zones account for nearly 24 percent of non-recurring congestion, or 482 million vehicle hours lost in a year due to traffic delays at work zones [3].

Aside causing congestion, work zones also have a significant safety impact on the roadways. In 2018 alone, there were 25,162 crashes in work zones nationally, involving 161 fatalities and 684 severe injuries. Majority of the fatalities (84%) were directly between motorists and/or their passengers. In 2018, Louisiana work zones recorded four fatal crashes, with a previous 3-year average of eight fatalities [4].

One of the reasons crashes happen in work zones is because motorists upstream are not aware of traffic conditions downstream in the work zone and therefore do not slow down enough prior to approaching the work zone. This often is a dangerous predicament and results in rear end collisions, which in turn, may give rise to secondary crashes. Federal Highway Administration (FHWA) requires all state departments of transportation (DOTs) to develop a Transportation Management Plan during the design phase of road construction and maintenance projects [5]. As a result, state DOTs conduct work zone traffic analyses to select appropriate lane closure strategies, based on maintaining flows below the capacity of the work zone, in a bid to reduce delays in the transportation network. Lane closures are usually scheduled when the demand is lowest and queue lengths are predicted to be the shortest.

FHWA recommends utilizing the Highway Capacity Manual (HCM) as a guideline in computing capacity and quality of service of highway facilities. Currently in the state of Louisiana, the Engineering Directives and Standard Manual (EDSM) requires that queue analysis be performed for all lane closures on interstates with ADTs equal to or greater than 25,000, using 7-day 24-hour volumes for the section of interest.

In the past, Louisiana Department of Transportation and Development (DOTD) utilized an HCM-based spreadsheet tool to estimate queuing for proposed projects, but more recently, has been using a flat reduced construction zone capacity of 1,309 pcphpl for its freeways. Lanes are not to be closed where a queue analysis determines lane capacity exceeds 1,309 pcphpl. In the case, where lanes must still be closed, special authorization for police presence at the site may be required. It is not known how accurate the estimation is when compared to actual queuing related to real world work zones in Louisiana.

This study seeks to document work zone lane closure policies practiced within the various DOTD districts as well as what other state DOTs practice. Additionally, the study aims to validate the flat capacity of 1,309 pcphpl currently being used. Since lane closures on interstates for construction, maintenance, and permit projects impact stakeholder travel time, economic competitiveness, safety, and expense of road works, results of this study will provide DOTD with a robust justification of its current practices of queue analysis or a basis to revise it thereof.

# Literature Review

This section reviewed published literature to document the concept of work zone capacity and how it can be estimated.

## Definitions of Capacity

Researchers have defined capacity using different criteria such as breakdown, sustained maximum flow rate, probability, and queue discharge rate. The definitions vary based on the purpose for the capacity estimation. For example, if an agency desires to estimate capacity in order to schedule lane closures to avoid traffic congestion, then pre-breakdown flow may be the suitable definition to use because it can predict the onset of congestion. If capacity estimation is desired in order to estimate delays or user cost, then the queue discharge rate is the most appropriate definition because once congestion occurs and queues form, that is the flow rate at which the work zone is likely to operate [6].

The Highway Capacity Manual 2016 defines capacity as “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” [7]. Dudek and Richard in 1982 defined capacity as the hourly traffic volume under congested traffic conditions. For their research, the authors counted full-hour volumes at lane closures with traffic queued upstream [8]. A study by Brilon in 2005 defined capacity as the volume at which traffic breaks down from fluent to congested conditions [9]. In 2005, Cassidy and Rudjanakanoknad presented capacity as the sustained flow that a freeway discharges from all exits that are unblocked by spill-over queues from downstream while the freeway entrances are queued [10].

Research conducted by Elefteriadou and Lertworawanich (2003) defined capacity in three different ways. First, the study defined capacity as 5 or 15-minutes flow immediately before the breakdown. The authors gave a second definition as the maximum 5 or 15-minutes flow observed before the breakdown. Lastly, the study also defined capacity as the maximum 5 or 15-minutes flow during oversaturated conditions or the condition when demand exceeds the capacity [11]. Prior to this research, Lorenz and Elefteriadou (2001) had defined capacity by incorporating the probabilistic nature of the freeway breakdown process. The study defined capacity as the rate of flow along a uniform freeway segment corresponding to the expected probability of breakdown deemed acceptable under prevailing traffic and roadway conditions in a specified direction. This definition opens the possibility to quantitatively describe the influence of traffic control systems on traffic flow [12]. Dixon and Hummer (1996) defined work zone capacity as the flow rate at which traffic behavior quickly changes from uncongested conditions to queued conditions or congested conditions [13].

## Factors Affecting Capacity in Work Zones

Weng and Meng (2013), in their study, found some factors that affect work zone capacity such as work zone configurations, roadway conditions, work activity characteristics, and environmental conditions [14]. Dixon et al. 1996 analysed data from 24 short term work zones and presented capacity values for both rural and urban freeways and concluded that capacity varies by work intensity, rural, and urban location [13].

A study done by Adeli and Jiang (2003) showed that lower work zone speeds could decrease capacity, albeit improving safety [15]. Karim and Adeli (2003), on the other hand, found that work zone capacity decreases as work intensity increases. The timing of work was also found to affect the capacity, with nighttime work zones decreasing capacity due to reduced driver attention [16]. In addition, long term work zones were found to have greater capacities than short term work zones, presumably due to the fact that frequent travelers may become acquainted with the work zone configuration [17]. HCM 2016 also considers different factors like barrier type, area type, lateral distance from work zone, ramp density, and lighting conditions affecting the capacity of the work zone [7].

## Estimating Capacity from HCM 2016

The HCM 2016 methodology sought to bridge the gap in capacity models that were insensitive to geographic regions, work configurations, or both. A new capacity model was proposed for freeway work zones using nationwide field data. The model estimates work zone capacity as a function of lane closure severity, barrier type, area type, lateral clearance, and many other factors. The model predicts the average QDR for the work zone, which then must be converted to work zone capacity using the percentage drop factor. Conditions considered during the analysis include the lane closure severity index, lateral distance from the edge of travel lane, the time of day, speed ratio, work zone speed limit and the total ramp density. HCM 2016 uses the following equation to come up with the QDR.

$$QDR_{wz} = 2093 - 154 \times LCSI - 194 \times f_{BR} - 179 \times f_{AT} + 9 \times f_{LAT} - 59 \times f_{DN} \qquad [1]$$

where,
$QDR_{wz}$ = average 15-minute queue discharge rate (pcphpl) at the work zone bottleneck,
$f_{BR}$ = indicator variable for barrier type,
$f_{AT}$ = indicator variable for area type,
$f_{LAT}$ = lateral distance from the edge of travel lane adjacent to the work zone to the barrier, barricades, or cones,
$f_{DN}$ = indicator variable for daylight or night, and
LCSI = lane closure severity index (described below).

$$LCSI = \frac{1}{OR \times N_o} \qquad [2]$$

where,
OR = ratio of the number of open lanes during road work to the total number of lanes; and
$N_o$ = number of open lanes in the work zone.

Equation 1 is a predictive model for freeway work zone queue discharge rate as a function of work zone configuration. The capacity for work zones is then estimated from the queue discharge flow rate as follows:

$$C_{wz} = \frac{QDR_{wz}}{100-\alpha_{wz}} \times 100 \qquad [3]$$

where,
$C_{wz}$ = work zone capacity (pre-breakdown flow rate) (pc/hr/ln), and
$\alpha_{wz}$ = percentage drop in pre-breakdown capacity at work zones due to queuing conditions.

Studies have shown that at non-work zones and work zones, there is an average queue discharge drop of 7% and 13.4%, respectively. These values can be used as defaults when there is minimal local information available.

## Estimating Capacity from HCM 2000

The HCM 2000 suggests a capacity of 1,600 pcphpl for short-term freeway work zones regardless of the lane closure configurations. This recommendation is based on a study conducted in 33 work zones in Texas using 45 hours of capacity counts. The base value can further be adjusted for intensity of work activity, the effect of heavy vehicles, and the presence of ramps. The research suggested that the capacity be adjusted by up to ± 10% to cater for the number of workers on site, the number and size of construction vehicles and the proximity of work zones to the travel lanes. The heavy vehicle adjustment factor, $f_{HV}$, accounts for the effects of heavy vehicles travelling through the work zone. The heavy vehicle adjustment factor is calculated as shown in Equation 4.

$$f_{HV} = \frac{1}{1+P_T(E_T-1)} \qquad [4]$$

where,
$f_{HV}$= heavy-vehicle adjustment factor,
$P_T$ = proportion of heavy vehicles, and
$E_T$ = passenger car equivalent factor for heavy vehicles (1.5).

For ramps 150 meter downstream of the beginning of a full lane closure, the ramp will have an evident effect on the capacity of the work zone. The following equation is used to compute the decreased capacity.

$$C_a = (1600 + I - R) * f_{HV} * N \qquad [5]$$

where,
$C_a$ = adjusted mainline capacity (vehicles per hour or vph),
$f_{HV}$ = adjustment for heavy vehicles as defined in Equation 4,
$I$ = adjustment factor type, intensity, and location of the work activity,
$R$= adjustment for ramps, and
$N$ = number of lanes open through the short-term work zone.

## Origin of 1,309 pcphpl

DOTD has been using a flat capacity of 1,309 pcphpl as basis for keeping lanes open during work zone lane closures. This figure is based on an adjustment of the HCM 2000 capacity value of 1,600 pcphpl. DOTD assumes a 10% work zone intensity adjustment, 20% heavy vehicles composition, and assumes a passenger car equivalent factor ($E_T$) for heavy vehicles as 1.5.

Using Equation [4];

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)}, P_T = 20\%, E_T = 1.5$$

$$f_{HV} = 0.909$$

$C_a = 1{,}600 \times 90\%$ x $0.909 = 1{,}308.96 \approx 1{,}309$ pcphpl

## Estimation of Capacity from Field Data

Common methods researchers have used to calculate the upper and lower capacity limits in work zones include the 15-minute flow rate method, platooning method, and the h-minus-n (h-n) method. Each is described below.

### Maximum 15-Minute Flow Rate

The 15-minute flow rate represents the maximum flow rate for continuous 15-minute intervals, advanced by 1-minute increments. For example, the flow rate from minute 1 to 15 is computed, the flow rate from minute 2 to 16 is also computed, and so on. This process is repeated until the last minute of the data. The maximum value is used to estimate the flow rate after it has been adjusted by a passenger car equivalency factor. Although the procedure is straightforward, it does not give an accurate reflection of the actual capacity because traffic counts could have large gaps/headways within the 15-minute interval. Previous studies found that the method returns feasible results only when traffic demand is high enough and close to capacity conditions. Large headways result in lower traffic volume and therefore lower capacity values.

### “h-minus-n” Method

To account for the large gaps in the traffic counts, the h-n method was proposed by researchers. The concept is that, at high volumes that are not close to capacity, some vehicles maintain large gaps. These large gaps constitute time that is not used in the analysis, referred to as underutilized time. The underutilized time is excluded from computation and the flow rate is computed using time that is efficiently utilized.

$$\text{Underutilized time} = \begin{cases} 0 & \text{if h<8 seconds} \\ h - n & \text{otherwise} \end{cases} \quad [6]$$

where,
h = headway in second, and
n = headway threshold for free flow traffic which is 4 seconds.

Under high and moderate speed conditions, vehicles whose headways are equal to or greater than 4 seconds are assumed to be moving under free flow conditions [18].

### Platooning Method

The platooning method computes capacity by eliminating all free-flowing vehicles from the traffic stream. The capacity must then be computed based on the average headway of the remaining vehicles. It is important to note that the lead vehicle in the traffic stream is in free flow and not considered to be in platoon. To determine whether a vehicle is in platoon one of the following criteria must be met; the headway must be less than four seconds or the spacing must be less than 250 feet. If a vehicle fails to meet any of these two criteria, they are considered to be in free flow. A study conducted by Avrenli et al. in 2011 utilized this method and concluded that as the roadway operates at capacity, the upper and lower observed capacities converge and closely reflect actual roadway capacity [19].

$$\text{Capacity (vphpl)} = \frac{3600}{h_{p>4}} \quad [7]$$

where,
$h_{p>4}$ = average headway of vehicles in platoons that had more than four vehicles.

## Capacity Modelling

### Capacity Modelling Using Field Data

Modelling capacity from field data can be grouped into parametric and non-parametric approaches. The parametric approach assumes that the sample data is collected from a population that follows a probabilistic distribution based on a fixed set of parameters. To model the data after certain probability distributions, some assumptions are made about the population. When these assumptions are true, the models will predict more accurate estimates than non-parametric methods. The caution is that the more assumptions that are made about the data, the greater the possibility of failing. Some researchers ( [20], [18], [19], [17]) have used multi-regression models derived from speed-flow relationships to estimate capacity.

The non-parametric approach on the other hand does not solely rely on parameters of probability distributions. In analyzing work zones, there may be some nonlinear relationships that can hide effects of work zone capacity. For this reason, parametric methods may be limiting in providing accurate estimates. The dissimilarity in nonparametric and parametric models is that the structure of the model is not fixed in the former, but rather it is determined from observation or experience. The neural-fuzzy logic approach, decision tree approach, and ensemble tree approach are all examples of non-parametric approaches [21].

Parametric and non-parametric approaches are both data driven approaches and therefore rely heavily on the accuracy of the data collected. Poor data collection adversely affects the estimates.

### Capacity Modelling Through Simulation

To formulate solutions for the problems that arise out of congestion related to work zones, the simulation models must closely reflect real life conditions. Some relevant factors that must be considered in simulating models are the geometric features, traffic composition, and driver behaviour [22]. These factors have direct bearing on the capacity of the highway. Geometric features and lane configurations are easy to input into the model. However, the traffic composition and driver behaviour require some effort. A study by Dhamaniya and Chandra (2017) presented the effect of mixed traffic on the capacity of urban arterial roads [23]. The operating and physical characteristics of different vehicles vary and thus affect the speed flow characteristics of the stream, consequently affecting the capacity of the roadway. The authors proposed a mathematical model to determine capacity of a six-lane divided urban arterial at different composition of various categories of vehicles present in the traffic stream. Microscopic simulation software VISSIM was used for the simulation. Field data was studied and used to calibrate the software.

Car following models replicate driver behaviour in simulation models and are widely used in the development of traffic simulation models, and in analysis of safety and capacity. Examples of these car-following models include Gipps, Intelligent Driver Model (IDM), Krauss Model, and Das and Asundi. Asaithambi et al. (2018) evaluated different car following models in mixed traffic conditions. Their performance was evaluated based on measure of effectiveness (MoE) using field data collected from a four-lane divided urban arterial road. Speed-concentration and flow-concentration relationships for different vehicle-following models were developed and analysed for different compositions. The study revealed that capacity is higher when the proportion of smaller size vehicles is higher, since these vehicles use longitudinal and lateral gaps more effectively [24].

## HCM Validation Efforts in Literature

Validation of the Highway Capacity Manual is a practice that has been long in existence. Usually the HCM provides models based on nation-wide data and it is expedient to modify these models to reflect field conditions and provide reliable local estimates. Many studies have found that the estimates provided in the HCM differs from local estimates.

Delaware Department of Transportation used field data for validation of the HCM 2000 work zone methodology. The study assessed traffic flow on multilane signalized roadways at 25 work zone sites across the state, to evaluate the variability of work zone capacity. A new methodology was proposed to calculate capacity based on probabilistic speed-flow density. Findings revealed that the average work zone capacity was 1,475 vphpl for the sustained flow, almost 19% more than the HCM predicted value of 1,240 vphpl [25].

Iowa State University also conducted a study at six work zone locations on rural highways in Kansas, utilizing the platooning method and the maximum observed 15-minute flow rate method in their capacity estimation. The average capacities from the two methods was 1,500 pcphpl, which was about 7% less than the 1600 pc/hr/ln value predicted by the HCM [26].

Furthermore, Missouri Department of Transportation collected several days of traffic data at work zones with a speed limit of 50 mph. Eleven breakdown events were recorded using average speed profiles. The study found the work zone capacity to be 25% lower than the HCM predicted value of 1,600 pcphpl at 1,199 pcphpl [6].

Jehn and Turochy in 2019 used VISSIM models to modify key parameters in the HCM 2016 methodology. Their study noted that the HCM 2016 methodology is limited by the fact that its output is deterministic while in real life scenarios, traffic flow breakdowns are stochastic in nature. The study posited that well-calibrated microsimulation models stand a better chance of predicting work zone capacities more accurately. Their results indicated the field measured distribution and truck characteristics were important variables in determining capacity [27].

These varying capacity values lend weight to the need to validate the HCM 2016 methodology using local data from Louisiana.

## Queue Length Estimation

### Using Conventional Data

Traditionally, devices such as loop detectors and video cameras have been used to collect traffic volumes for analysis. Although accurate, they have some limitations. For instance, loop detectors have high maintenance costs, while cameras may not be effective at night time or in adverse weather conditions. A study was conducted using event-based advance detector data to estimate real-time queue lengths at signalized intersections. The research developed a real-time maximum queue length estimation method using single channel detection, and resulted in queue estimation improvements [28].

Point detector has proven to be effective at signalized intersections. Research conducted using low resolution point detector data showed that spill backs can be predicted with up to 85% accuracy. Detector data upstream of the intersection was used to modify the volume data downstream when long queues occurred. The shockwave theory was then used to estimate the spillover [29]. Other methods of collecting traffic data for traffic management include Automatic Number Plate Recognition and Automatic Vehicle Identification Systems.

### Using Probe Data

Advances in data collection technologies have produced data sources such as trajectory data. Trajectory data logs the location of objects in motion and is beneficial in providing solutions for traffic issues [30]. Vehicles that collect this type of data are known as probes. There have been a number of research studies aimed at estimating traffic volumes and queue lengths at intersections using probe data.

One such study proposed a novel method in estimating queue lengths and traffic volumes at signalized intersections. The authors estimated penetration rates of the probe vehicles from the distribution of their stopping positions at the intersections. The number of probe vehicles in the queues and in traffic were then scaled up, taking into account the estimated penetration rate. This gives an estimate of the total queue length and the total traffic volume. Validation of the method through simulation and real-field data yielded positive results and showed promise for field applications [31].

Another such study using probe data utilized the Bayesian approach in estimating queue lengths at signalized intersections. Queue lengths were estimated from a distribution obtained from several neighboring cycles via a maximum a posteriori method. The proposed approach produced an accurate result at even a probe vehicle penetration rate of 2% [32].

Lastly, a combination of Kalman Filtering and shockwave theory was proposed as queue length estimation method for low penetration mobile sensor data. Validation of the method using DiDi mobile sensor data showed a mean absolute percentage error of 11.2% [33]. The use of probe data in queue length estimation holds much promise for traffic management systems.

## Queue Warning Systems

Warning motorists of changes in traffic conditions can be beneficial in reducing crashes and ensuring smooth operations in a work zone. Queue detection and warning systems comprise real time sensors or detectors, communication channels, and display devices that relay traffic information to motorists. This technology is usually applied in work zones where decreased capacity often results in congested traffic conditions. Rear end crashes often occur when vehicles travelling at high speeds rapidly reduce their speeds. This creates a transition point between rapidly forming queues and vehicles travelling upstream where motorists are unaware of the impending speed change [34]. Traditionally, static signs have been used to inform motorists about queues ahead of the location and nature of the work zone [35]. However, they have been inadequate in relaying real-time downstream congestion information that can improve traffic safety. Intelligent transportation systems (ITS) applications in work zones, bridges this gap through smart work zone systems. These systems collect real-time traffic flow data using roadside sensors, processes the data and displays relevant traffic information on portable message signs placed along the freeway (Smart Work Zone Systems). Several sensors upstream of the work zone detect the upstream end of the queue in order to give motorists adequate warning time. For example, a remote traffic microwave sensor may be placed immediately upstream of the construction area and another the end of the work area. The location of the back end of the queue can be estimated from this data. This information is then relayed to a portable changeable message sign and displayed at the upstream location. There are, however, many approaches and tools used in detecting and warning motorists of queues in work zones. Some may be as simple as a radar message sign that detects and immediately displays a warning such as “SLOW DOWN” if speeds detected by the radar are above the speed limit of the work zone [36]. Others may collect traffic data from sensors, transfer it to traffic management centers (TMC) through fiber optics, wireless data, or even cellular data and may require some analysis before sending the warning to appropriate variable message signs located through the system. Others still may collect the traffic data through sensors, analyze the data onsite using complex algorithms, and then display the warning message where appropriate.

As a component of queue detection systems, real-time measurement of queue parameters can be obtained through cameras or sensors. For cameras, vehicle motion is detected through image processing [37]. Queues are estimated through algorithms and then transferred to appropriate display channels. Acoustic (Doppler) sensors, wireless magnetic sensors, and radar traffic microwave sensors can be used in place of video cameras [38].

Another important factor is the effectiveness of the queue detection system. False warnings can be a setback when using queue detection systems. Motorists may disregard the authority of the system when false warnings are rampant [39]. However, when used accurately, queue detection systems have been known to reduce rear-end crashes by as much as 66% in some cases. Texas Department of Transportation evaluated the effectiveness of queue detection systems after deploying nighttime lane closures. Crashes reduced by 18 - 45% as compared to if no system had been deployed. Severe rear-end crashes were reduced, saving up to $1.8 million in societal crash costs. It was estimated that with each night of deployment, there was a societal crash cost saving between $6,600 and $10,000 [40]. Illinois Department of Transportation measured and ranked the effectiveness of safety measures in a state survey [41]. The most effective measures were:

1. Police Patrols
2. Truck-Mounted Attenuators (TMA)

3. Portable Speed Monitoring Displays (PSMD)
4. Portable Changeable Message Signs (PCMS)
5. Temporary Rumble Strips
6. Intrusion Alarms

In a national survey, the rankings were as follows:

1. Truck-Mounted Attenuators
2. Portable Changeable Message Signs
3. Police Patrols
4. Mobile Barriers
5. Temporary Rumble Strips
6. Portable Speed Monitor Displays
7. Automated Flagger Assistance Devices
8. Intrusion Alarms
9. Radar Drones

About 78% of the states that participated in the survey reported their ranking based on the use of portable speed monitor displays, portable changeable message signs, temporary rumble strips, truck mounted attenuators, and police patrol [41]. There have, however, been some motorist complaints and non-compliance especially when delay estimations are not accurate enough for public approval. In Arkansas, complaints were lodged when delay estimates were within 5 minutes of actual delay. This was mitigated by displaying more generic messages like “EXPECT DELAYS” [42].

## NPMRDS Data Set

National Performance Management Research Data Set (NPMRDS) consists of speed and travel time data at 5-minutes intervals on over 400,000 roadway segments that covers the whole national highway system. The data set, procured and sponsored by the FHWA, are available for passenger vehicles, trucks, and trucks and passenger vehicles combined. CATT lab provides the data set in its Regional Integrated Transportation Information

System (RITIS) platform and is responsible for validating the data set. INRIX currently provides the speed and travel time data in the NPMRDS data set.

Unlike the typical probe data, NPMRDS is not a real-time data set. It is updated within five business days after each month ends, is available every 5 minutes, and if not present at some instances or locations, is tagged as “null’ instead of using an imputed data [43]. Access to the data source is restricted to only registered members.

The RITIS platform provides different tools like congestion scan, trend map of roadway conditions, performance charts, user delay cost analysis, Moving Ahead for Progress in the 21st Century Act (MAP-21) performance reporting tools, and coverage map. For the purpose of this study, the congestion on the stretch of a roadway during the period of data collection was analyzed in detail using the congestion scan tool. By submitting the queries on the roadway, range of date, data sources, and required roadway segments, the tools generate the visualization or plot of the data metrics (e.g. speed) along the selected roadway segment. The color threshold set at different speeds help to determine the traffic conditions at different time frames along the roadway segments with a queue.

# Objective

The primary purpose of this study is to evaluate the effectiveness of DOTD's existing queue estimation procedures. Specifically, tasks performed to meet the objectives are to:

- Provide a review of the state of practice of work zone lane closure analysis nationally and statewide.
- Identify work zones and collect data on traffic flows.
- Analyze traffic flow to determine breakdown capacities, queue duration, and queue lengths.
- Determine if the flat construction work zone capacity of 1,309 pcphpl is a valid assumption.
- Replicate HCM 2016 model using Louisiana data.
- Compare field values with HCM 2016 recommended values.

# Scope

Sites were selected for data collection using the Louisiana 511 System and Content Manager of DOTD’s Project and Highway Information. Future and current work zone projects, along with their percentage of work complete, were retrieved. However, the percentage of work complete did not always reflect actual work zone conditions, which meant that a site selected could actually have no work zone at the time it was scheduled for data collection. Existing DOTD cameras were also found insufficient for the data collection effort due to inadequate range of the cameras at the specific work zone sites. Subsequently, a contractor was appointed to collect data through Remote Traffic Microwave Sensors (RTMS). Overall, speed and volume data were collected for ten sites across Louisiana. It was impossible to observe queue lengths from the data collected, hence data from the NPMRDS was used to estimate queue lengths.

# Methodology

## National Survey Design

One of the primary objectives of this research was to determine work zone lane closure procedures practiced by other state Departments of Transportation (DOTs). Contact information of traffic engineers from nationwide state DOTs were collected from their corresponding DOT websites. A national survey was developed and sent to these traffic engineers, who either could complete them or could designate to a more appropriate person to complete.

The survey consisted of five questions and a brief description of the project. There was a 16% response rate at the end of the first week. Weekly reminders were issued for six (6) consecutive weeks and then discontinued. In the end, 31 (out of 49) states participated in the survey by responding to at least one of the survey questions, resulting in approximately 63% response rate.

The national survey comprised the following questions:

1. Do you require a minimum capacity (vehicles per hour open lane) to be maintained when determining if short-term work zone lane closures can be allowed? If so, please state the value.
2. Do you undertake queue analysis for applicable interstate short-term lane closures? YES/NO
3. If you answered YES to Q2, what tools or software programs do you use in estimating queues and delays?
4. If you answered NO to Q2, how do you determine lane closure times?
5. Do all the districts in your state use the same tools/software programs? If no, please list all the other tools/software programs used by the different districts if possible.

## Louisiana Statewide Survey

Another objective was to also find out the work zone lane closure procedures administered by the various DOTD districts. Particularly, the survey was to determine the methodology and tools that the nine districts within DOTD use for traffic analysis prior to lane closures on the interstate. A survey was developed and issued to all District Traffic Operations Engineers (DTOE) in all nine DOTD districts. Only District 58 (Chase, LA) could not participate because there are no interstate roadways within the district's roadway network. All remaining eight districts participated, resulting in a response rate of 100%.

The statewide survey comprised the following questions:

1. Do you undertake queue analysis, as per attached, for applicable interstate lane closures?
2. If you don't, do you determine lane closure times by referencing traffic counts from the Interstate Speed Study GIS Map developed by Arcadis (sample spreadsheet attached)?
3. If you do, what tools or software programs do you use in estimating queues and delays?

## Field Data Collection

Ten different work zone locations were selected in Louisiana for the field data collection. All the work zones were located on an interstate (I-10, I-12, I-20, and I-210) and had at least one lane closed. Figure 1 shows location of the sites. The sites differed from one another in terms of lane closure configuration, types of barrier, area types, work zone speed limits, ramp density, and Annual Average Daily Traffic (AADT). RTMS devices were installed just before the start of the work zone to collect speed and flow data comprising traffic volumes, speed, and truck percentage in 5-minute increments. The device classified all vehicles over 20 ft. long as trucks.

**Figure 1. Location of data collection sites**

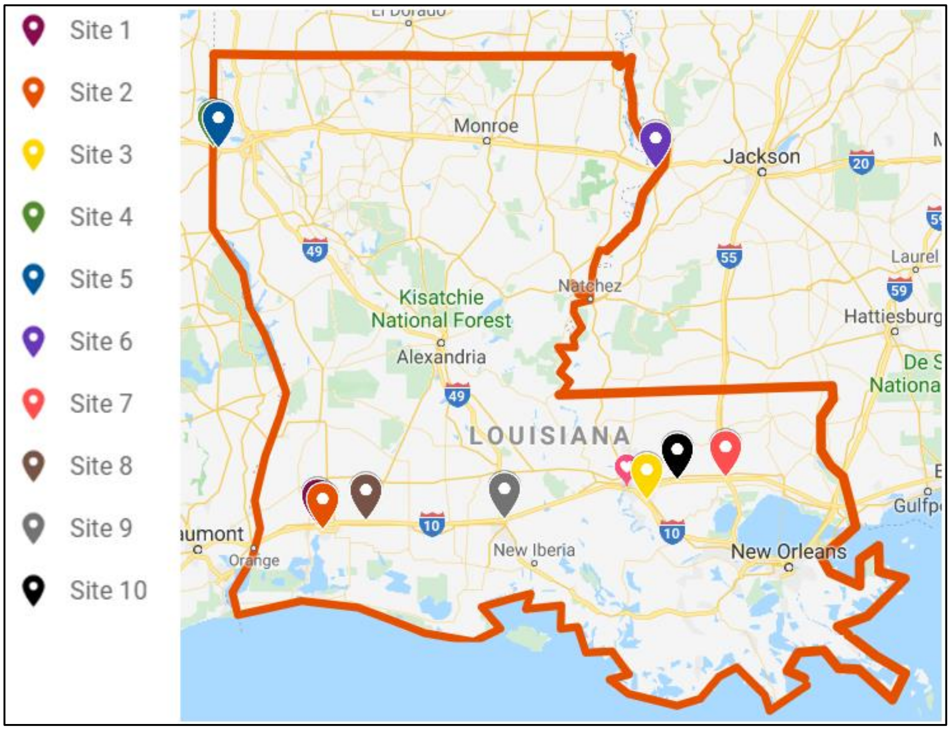


Figure 2 describes the characteristics of the work zone sites in percentages. From the figure, 60% of the sites were in rural areas while 40% were in urban areas. Most of the sites had posted speed limits of 60 miles per hour (mph). Eighty percent (80%) of the work zones were located on a linear roadway segment while 20% were located on horizontal curved sections of the roadway. All the work zones had soft barriers, such as drums and cones, with the length of the work zones ranging from 0.5 miles to 6.3 miles.

**Figure 2. Summary of site characteristics**

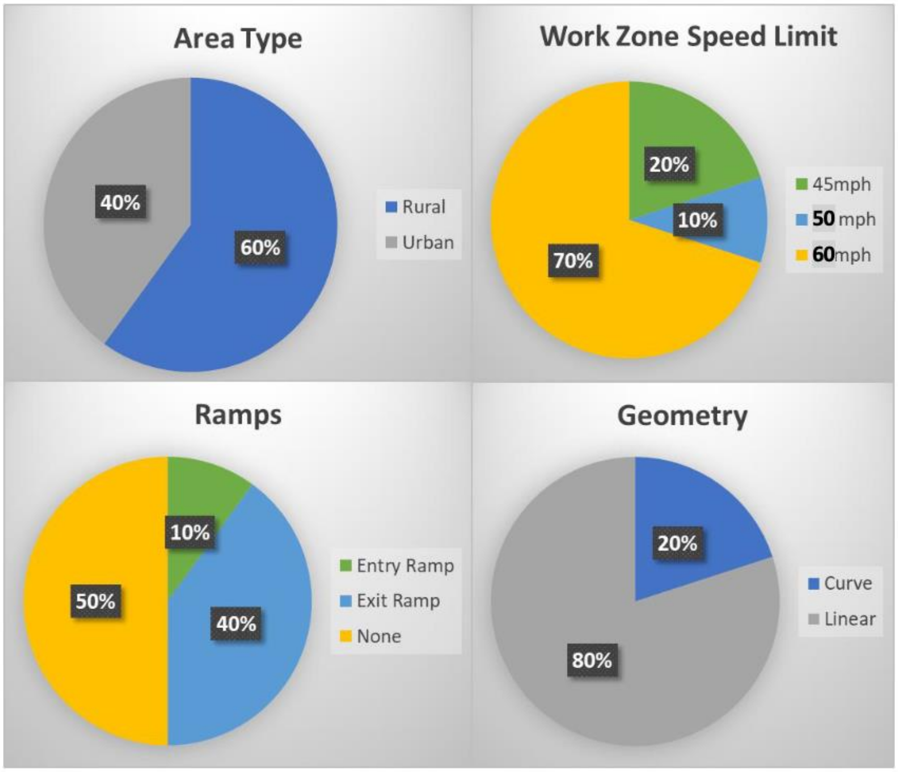


Table 1 shows the timeframe for the data collection at each site. The entire data collection period lasted from March to August 2019. The start time of the data collection at each active work zone was done in coordination with associated DTOEs or relevant personnel responsible for the work zones in question. Each of the sites are described separately in terms of the geometric and traffic flow features of the work zone. Apart from site 7, where data was collected for only two days because of the duration of the closure, traffic data was collected for at least four days for the remaining sites.

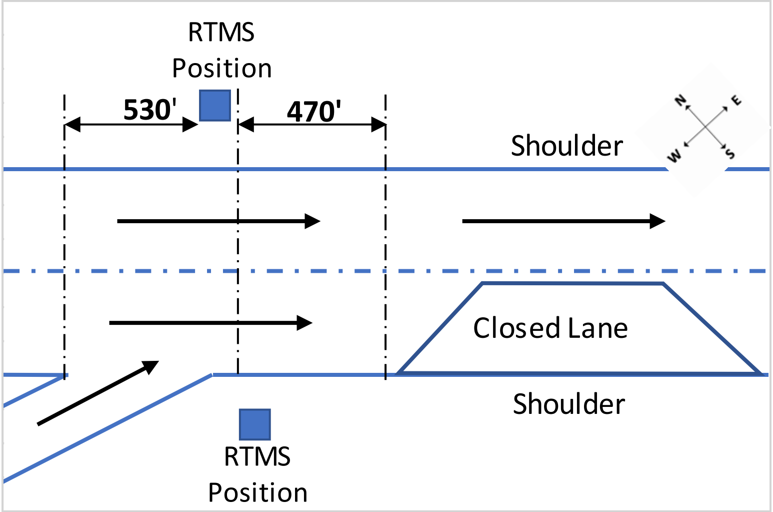
**Table 1. Time frame for data collection**

| Site Number | Latitude | Longitude | Route | Direction | Number of days of data collection | Dates of Data Collection |
|---|---|---|---|---|---|---|
| 1 | 30°13'17.81"N | 93°17'49.67"W | I-210 | Eastbound | 11 | 05/28/2019-06/07/2019 |
| 2 | 30°11'45.89"N | 93°15'43.52"W | I-210 | Westbound | 9 | 05/28/2019-06/05/2019 |
| 3 | 30°21'6.92"N | 91° 2'2.65"W | I-10 | Eastbound | 6 | 03/12/2019-03/17/2019 |
| 4 | 32°27'34.90"N | 94° 2'25.77"W | I-20 | Eastbound | 5 | 05/10/2019-05/14/2019 |
| 5 | 32°27'5.35"N | 94° 0'22.77"W | I-20 | Westbound | 15 | 04/30/2019-05/14/2019 |
| 6 | 32°19'17.84"N | 90°56'5.00"W | I-20 | Eastbound | 15 | 04/30/2019-05/14/2019 |
| 7 | 30°28'44.30"N | 90°29'37.04"W | I-12 | Eastbound | 2 | 05/07/2019-05/08/2019 |
| 8 | 30°14'48.57"N | 92°58'8.56"W | I-10 | Westbound | 9 | 05/13/2019-05/21/2019 |
| 9 | 30°15'25.17"N | 92° 1'16.98"W | I-10 | Eastbound | 4 | 07/26/2019-07/29/2019 |
| 10 | 30°28'24.71"N | 90°49'37.02"W | I-12 | Westbound | 10 | 08/20/2019-08/29/2019 |

## Site Description

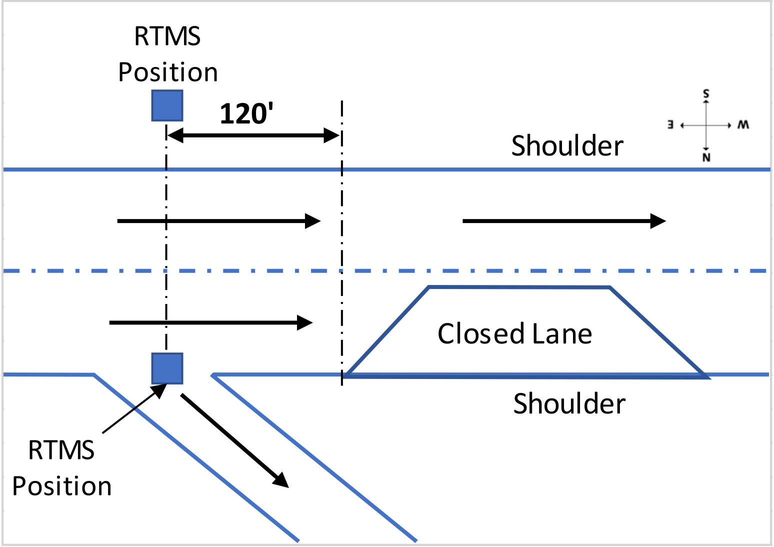
**Site 1:** The site was located west of Lake Charles on I-210 around 0.5 miles south of I-10. The direction of work zone at this site was facing eastbound direction with traffic flow away from I-10. The latitude and longitude of the site is 30°13'17.81"N, 93°17'49.67"W. The site was located in an urban area with a normal posted speed limit of 60 mph. In terms of the lane closure configuration, out of two lanes, the right lane was closed during the day and at night. The work zone had a length of around 3 miles with the work zone speed limit of 45 mph. A lateral clearance of one foot was maintained from the edge of the travelling lane to the adjacent work zone barrier. The work zone was separated from the moving lane by drums and super cones. There was an entry ramp around 1,000 feet upstream of the start of the work zone. Figure 3 provides detail on the location of the RTMS device, location of entry ramp and the closed lane, and the direction of traffic flow. Details like lateral clearance, alignment of the roadway, and lane widths were not incorporated in the figure. Figures 4 – 12 show similar site configuration for their respective sites.

**Figure 3. Site 1 west of Lake Charles on I-210**



**Site 2:** Site 2 was also located on I-210 around 3 miles east of site 1. The site was located in the westbound direction with traffic flowing towards I-10. The latitude and longitude of the site is 30°11'45.89"N, 93°15'43.52"W. The site was located in an urban area with a normal posted speed limit of 60 mph. In terms of the work zone characteristics, out of two lanes, the right lane was closed during the day as well as the night. The work zone length was approximately 3 miles with a work zone speed limit of 45 mph. No lateral clearance was maintained from the edge of the travelling lane to the adjacent work zone barrier. The work zone was separated from the moving lane by drums and super cones. There was an exit ramp just upstream of the start of the work zone. Figure 4 shows the site configuration in detail.

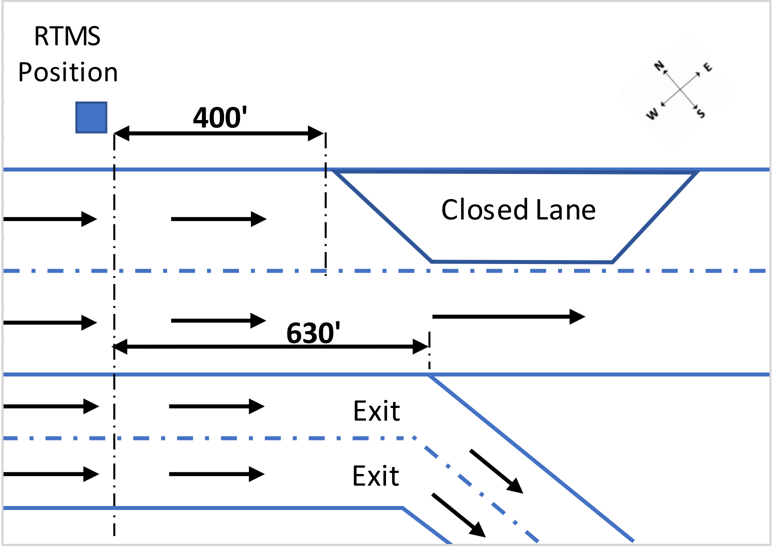
Figure 4. Site 2 west of Lake Charles on I-210



**Site 3:** Site 3 was located on I-10 in Baton Rouge. The site was located in the eastbound direction with traffic flowing towards Highland Road. The latitude and longitude of the site is 30°21'6.92"N, 91° 2'2.65"W. The site was located in an urban area with a normal posted speed limit of 70 mph. Unlike the two previous sites, out of two lanes, the left lane was closed only at night. The work zone was approximately 6.3 miles long with a work zone speed limit of 60 mph. A foot of lateral clearance was maintained from the edge of the travelling lane to the adjacent work zone barrier. The work zone was separated from the open lane by super cones. There was an exit ramp to Highland Road, right at the start of the work zone. Figure 5 shows the site configuration in detail.

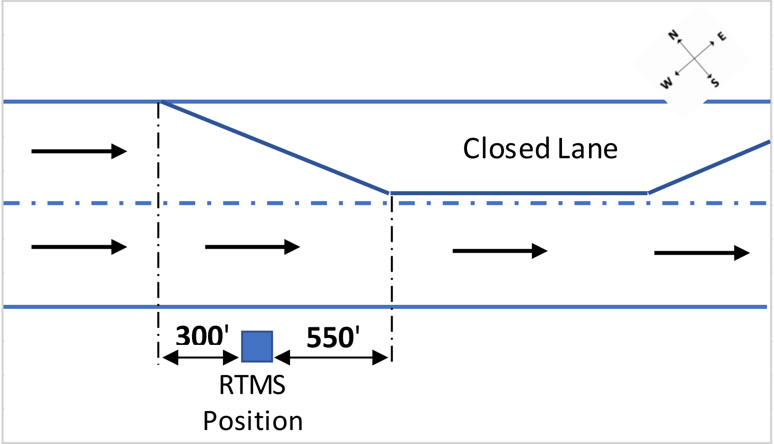
**Site 4:** Site 4 was located on I-20 west of Shreveport. The site was located in the eastbound direction with traffic flowing towards Shreveport from Texas state border. The latitude and longitude of the site is 32°27'34.90"N, 94° 2'25.77"W. The site was in a rural area with a normal posted speed limit of 70 mph. Similar to site 3, out of two lanes, the left lane was closed during both day and night times.

Figure 5. Site 3 in Baton Rouge on I-10



The work zone was approximately 2.1 miles long with a work zone speed limit of 60 mph. The work zone has no lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. Similar to the other sites, the work zone was separated from the open lane by super cones. Figure 6 shows the site configuration in detail.

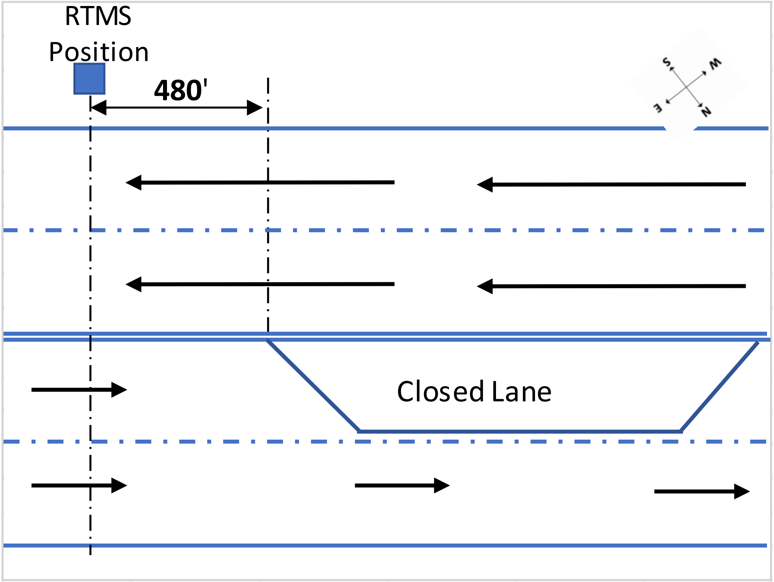
Figure 6. Site 4 west of Shreveport on I-20



**Site 5:** Site 5 was located on I-20 around 2 miles east of the site 4. The site was located in the westbound direction with traffic flow heading to Texas. The latitude and longitude of the site is 32°27'5.35"N, 94° 0'22.77"W. Roadway characteristics were the same as of site 4. Similarly, out of two lanes, the left lane was closed for both day and night-time. The site was located in a rural area with a normal posted speed limit of 70 mph. The work zone was roughly 2.1 miles long with a work zone speed limit of 60 mph. The work zone

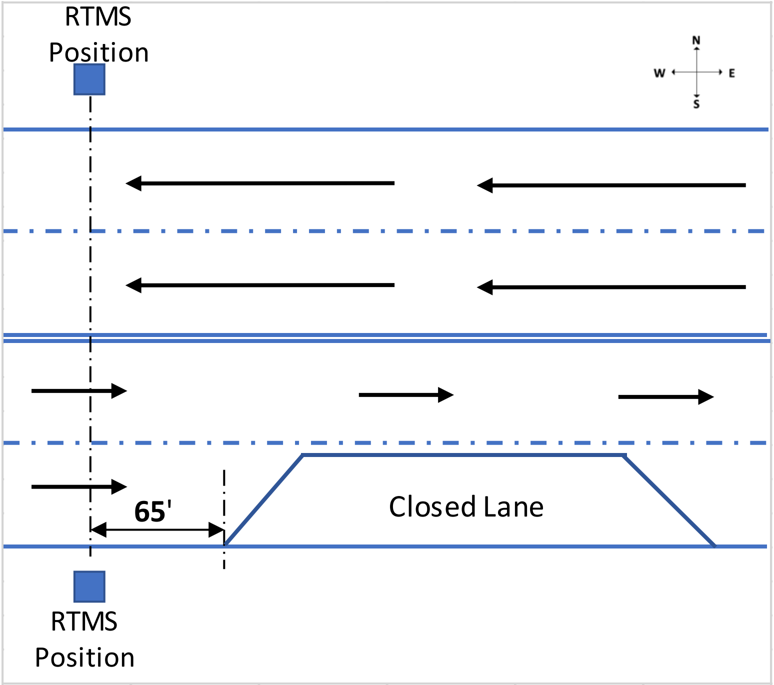
had no lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. Similarly, the work zone was separated from the open lane by super cones. Figure 7 shows the site configuration in detail.

**Figure 7. Site 5 west of Shreveport on I-20**



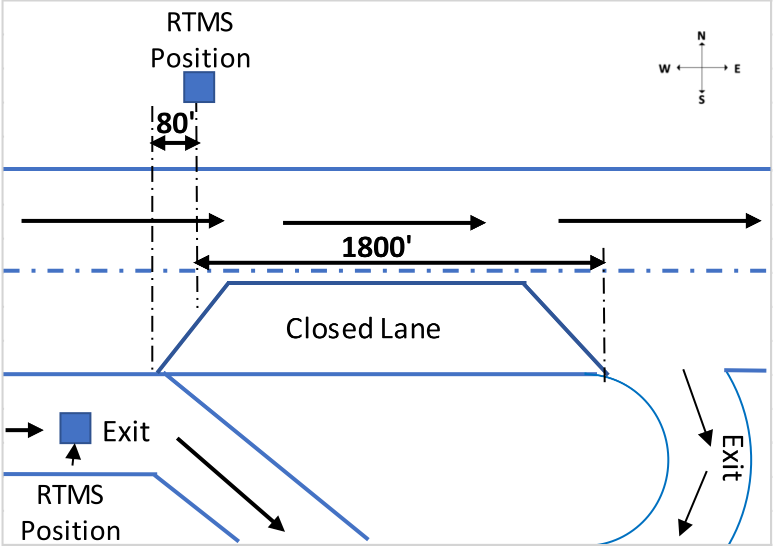
**Site 6:** Site 6 was on I-20 near the border of Mississippi. The site was 2.5 miles long with the right lane closed and traffic flowing in the eastbound direction towards Mississippi. The latitude and longitude of the site is 32°19'17.84"N, 90°56'5.00"W. Roadway characteristics were the same as of site 5. The site was located in a rural area with a normal posted speed limit of 70 mph and a work zone speed limit of 50 mph. The work zone was separated from the open lane by barrels and super cones. Figure 8 shows the site configuration in detail.

**Figure 8. Site 6 on I-20 near Mississippi border**



**Site 7:** Site 7 was located on I-12 east of Baton Rouge near Hammond. The direction of traffic was in the eastbound direction. The latitude and longitude of the site is 30°28'44.30"N, 90°29'37.04"W. The site was located in a rural area with a normal posted speed limit of 70 mph. Out of two lanes, the right lane was closed during night-time only. The work zone was roughly half a mile long with a work zone speed limit of 60 mph. Both exit and entry ramps were present in the vicinity of the work zone. The work zone had no lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. Similarly, the work zone was separated from the open lane by super cones. Figure 9 shows the site configuration in detail.

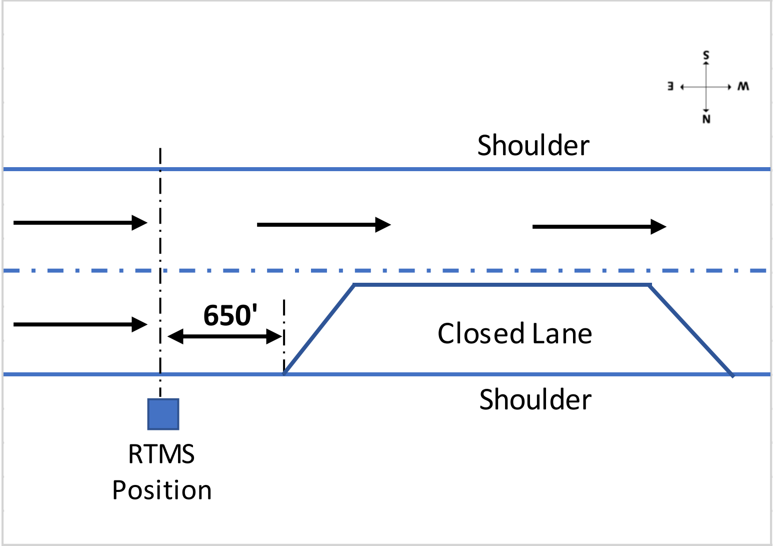
Figure 9. Site 7 I-12 east of Baton Rouge near Hammond



**Site 8:** Site 8 was located on I-10 east of Lake Charles. The direction of traffic was westbound towards Lake Charles. The latitude and longitude of the site is 30°14'48.57"N, 92°58'8.56"W. The site was located in a rural area with a roadway speed limit and a work zone speed limit of 70 mph and 60 mph, respectively. Out of two lanes, the right lane was closed during both day and night times. The work zone was approximately 0.8 miles long with no lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. The work zone was separated from the open lane by the barrels. Figure 10 shows the site configuration in detail.

**Site 9:** Site 9 was located on I-10 near Lafayette. The direction of traffic was eastbound towards Baton Rouge. The latitude and longitude of the site is 30°15'25.17"N, 92° 1'16.98"W.

Figure 10. Site 8 I-10 east of Lake Charles



The site had the normal and work zone speed limits of 70 mph and 60 mph, respectively, and was located in an urban area. Out of two lanes, the right lane was closed during the night-time only. The work zone was roughly a mile long with no lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. There was an exit ramp located just before the start of the work zone. Figure 11 shows the site configuration in detail.

**Site 10:** Site 10 was located on I-12 east of Baton Rouge. Traffic was flowing in the westbound direction towards Baton Rouge. The latitude and longitude of the site is 30°28'24.71"N, 90°49'37.02"W. The site had both a normal speed limit and work zone speed limit of 70 mph and 60 mph, respectively, and was located in a rural area. Out of two lanes, the left lane was during the night-time only. The work zone was roughly two miles long with a foot of lateral clearance maintained from the edge of the travelling lane to the adjacent work zone barrier. Figure 12 shows the site configuration in detail.

Figure 11. Site 9 near Lafayette on I-10

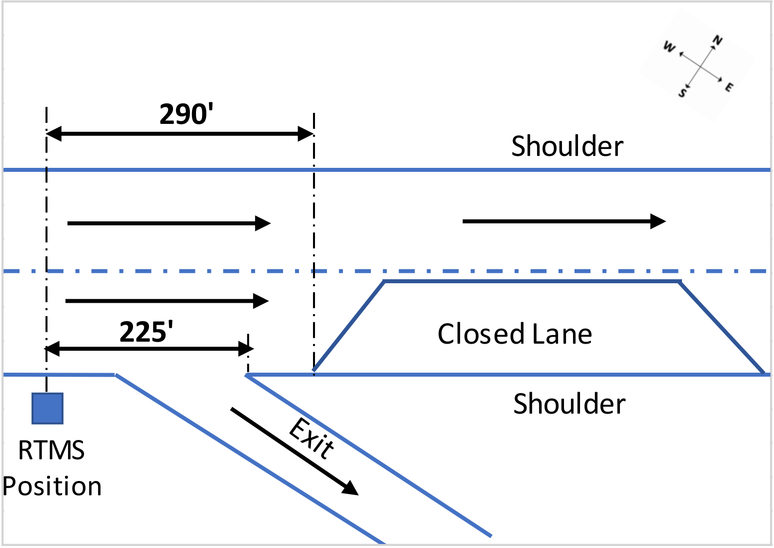
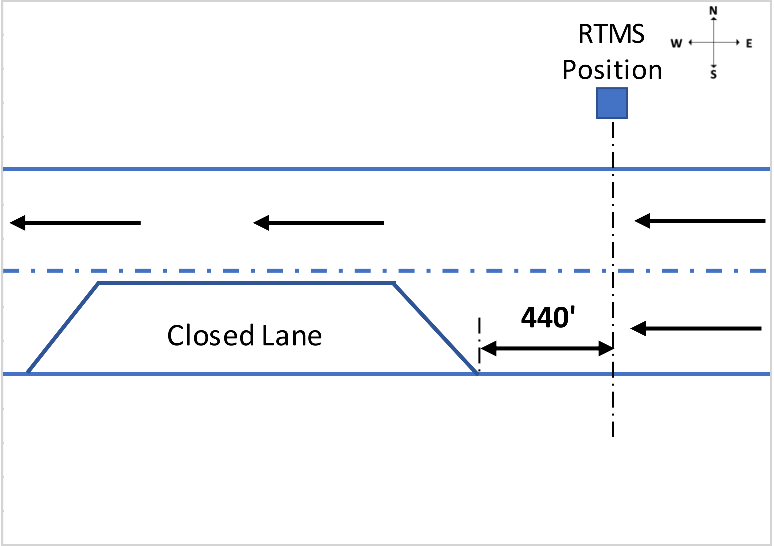


Figure 12. Site 10 located east of Baton Rouge on I-12



# Determining Work Zone Capacity

There has been much discussion on which definition of capacity is the most appropriate for work zone studies. As presented in the literature review, some past studies defined work zone capacity as the traffic flow just before a sharp drop in speed, followed by low traffic flow speed or congestion [11], [44], [45]; the HCM 2016 edition recommended using pre-breakdown flow rates as freeway capacity; and, Kim et al. (2001) also defined pre-breakdown flow rate as 5-minute flow rate immediately before the traffic breakdown [46].

## Definition of Pre-Breakdown Capacity

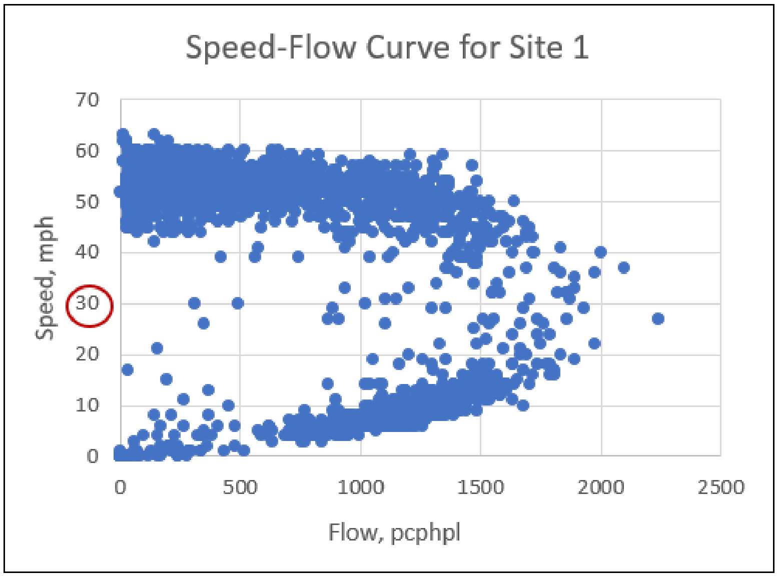
For this study, the work zone capacity was defined as the pre-breakdown capacity (PBC) corresponding to the 5-minute flow rates observed immediately before a breakdown. This was based on a definition given in literature which states that, "pre-breakdown capacity is the 5-minute flow rate observed immediately before breakdown" [11], [46]. A Microsoft Excel spreadsheet was developed to detect the pre-breakdown capacity for each site and is explained below.

## Determining Pre-Breakdown Capacity

To determine the pre-breakdown capacity, the following parameters were used; flow rate, passenger car equivalent of flow rate, speed at capacity, queue duration, queue length, average queue discharge rate, and pre-breakdown capacity. Flow rates (vph) were obtained by a simple multiplication of the 5-minute flow rates by a factor of 12. Flows were then converted to passenger car units by using the heavy vehicle adjustment equation in Equation 4. The speed-flow curve was plotted for each site and used to determine the speed at capacity. The speed at maximum flow was defined as the speed at capacity. It differentiates flow from uncongested to the congested state. In Figure 13, a plot of the speed-flow curve for site 1 is provided. The speed at capacity in this case is 30 mph.

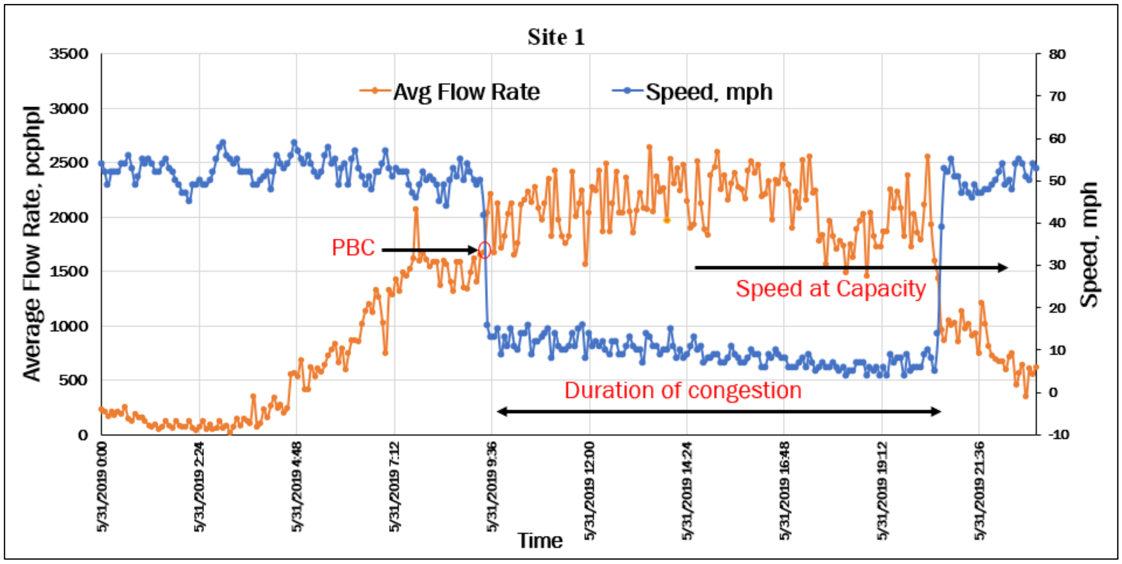
The state of the traffic flow, congested or uncongested state, was determined using the speed at capacity. In Figure 13, the flow above 30 mph at site 1 shows the uncongested flow, while flow below that threshold was in the congested state. A 5-min flow immediately before the breakdown was used to determine pre-breakdown capacity at that specific breakdown.

**Figure 13. Speed curve for site 1**



Duration of queue shows the duration of the flow of the traffic when speed was below the speed at capacity. Figure 14 shows how the pre-breakdown capacity and the duration of congestion for a particular time frame at site 1 were determined.

**Figure 14. Determining pre-breakdown capacity**



# Determining Queue Lengths Using Probe Data

## Traffic Message Channel Selection

A Traffic Message Channel (TMC) is a predefined roadway segment accompanying the NPMRDS data and may not be amended by the platform user. These segments are those for which travel time and speed data are generated for within the NPMRDS platform.

All ten work zone sites were plotted in ArcGIS, and a shape file of the roadway segments from the NPMRDS data set was downloaded and projected in ArcGIS, along with the site locations. The location of the sites was defined as the location of the RTMS device because the device was installed near the taper of the work zone. Depending on the flow of the traffic and location of the work zone, four to six (4 – 6) TMC segments were selected upstream of each site to estimate queue or congestion upstream. This covered an upstream distance of no less than 2.79 miles (as in the case of site 2) and no more than 14.34 miles (as in the case of site 8).

Table 2 shows the detail of the TMC segments at each site. The first TMC segment length at each site was the segment where the site was located. For instance, site 1 was located on the TMC segment of length 0.23 miles followed by upstream TMC segments of 1.00, 0.51, 1.50, 0.49, and 0.47 miles long. All the speed and travel time data at 5-minute intervals were summarized by each TMC segment. Shorter TMC segments provide more precise queue lengths as the congested attribute (speed below speed at capacity) applies to the segment in its entirety. Longer TMC segments may not have uniform congestion attribute throughout the segment and may be sensitive to extreme conditions at selected locations in the segment.

**Table 2. Length of TMC segments at each site**

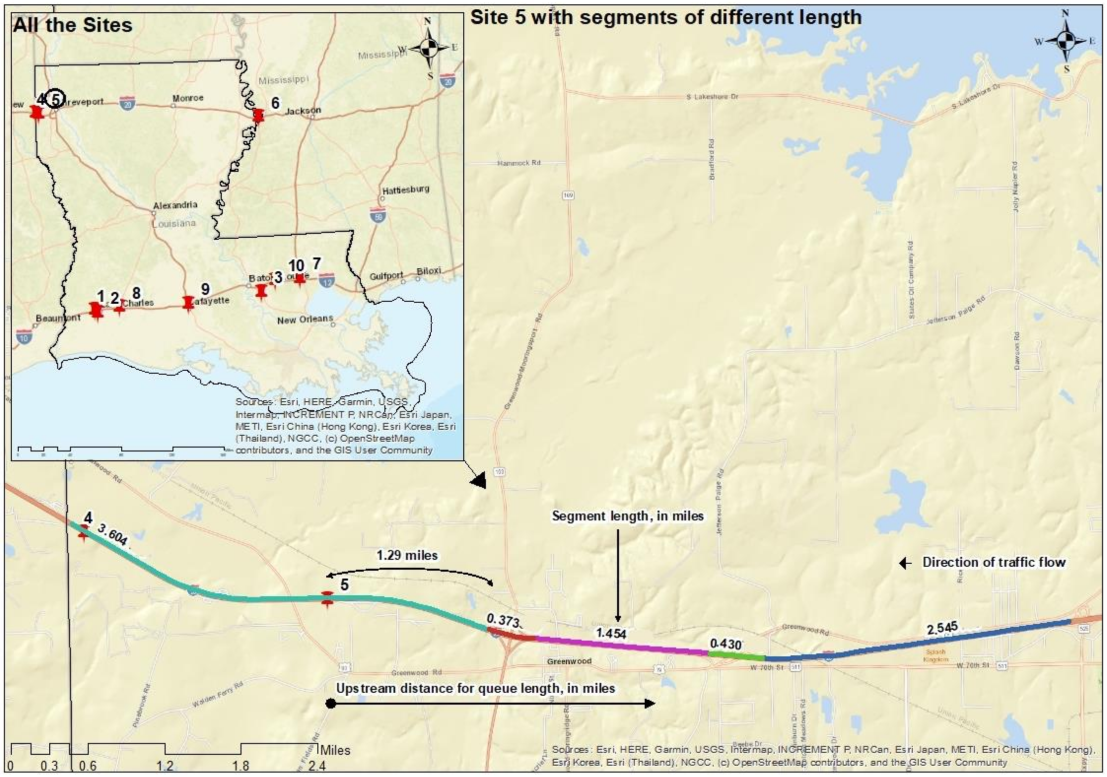
| Sites | Length of TMC segments (starting from the site to upstream), in miles |
|---|---|
| **Site 1** | 0.23, 1.00, 0.51, 1.50, 0.49, 0.47 |
| **Site 2** | 0.51, 0.69, 0.41, 0.35, 0.45, 0.38 |
| **Site 3** | 2.63, 0.47, 1.15, 0.56 |
| **Site 4** | 0.54, 0.78, 1.24, 0.58, 1.17, 3.78 |
| **Site 5** | 3.60, 0.37, 1.45, 0.43, 2.55 |
| **Site 6** | 3.08, 0.53, 1.23, 0.62, 1.32 |
| **Site 7** | 2.57, 0.55, 1.47, 0.83, 3.15 |
| **Site 8** | 3.17, 0.35, 6.09, 0.36, 4.37 |
| **Site 9** | 0.81, 0.52, 1.39, 0.41, 2.04 |

| Sites | Length of TMC segments (starting from the site to upstream), in miles |
|---|---|
| **Site 10** | 3.43, 0.49, 2.33, 0.60, 5.73 |

As an example, Figure 15 shows the layout of the TMC segments at site 5 and also shows procedure for the queue length estimation for each site using site 5. It shows that site 5 is located in a TMC segment with length of 3.60 miles (segment with green color and red pin). As traffic was flowing in the westbound direction at this specific site, the distance between the location of the site (within the segment) up to the beginning of the next TMC segment was measured using ArcGIS tools to be 1.29 miles.

Queue length for this study was defined as the length of a roadway section upstream of the site location with an average traffic flow speed of below the speed at capacity. Again, using site 5 and Figure 15 as an example, if the speeds reported for the first three TMC segments were found to be below the speed at capacity, then the queue length was determined to be 1.29 + 0.37 + 1.45 = 3.11 miles. Similar plots were developed for all the remaining sites to estimate the queue lengths. Data from each day starting from the beginning to the end of the data collection period were queried separately and checked for the queue lengths.

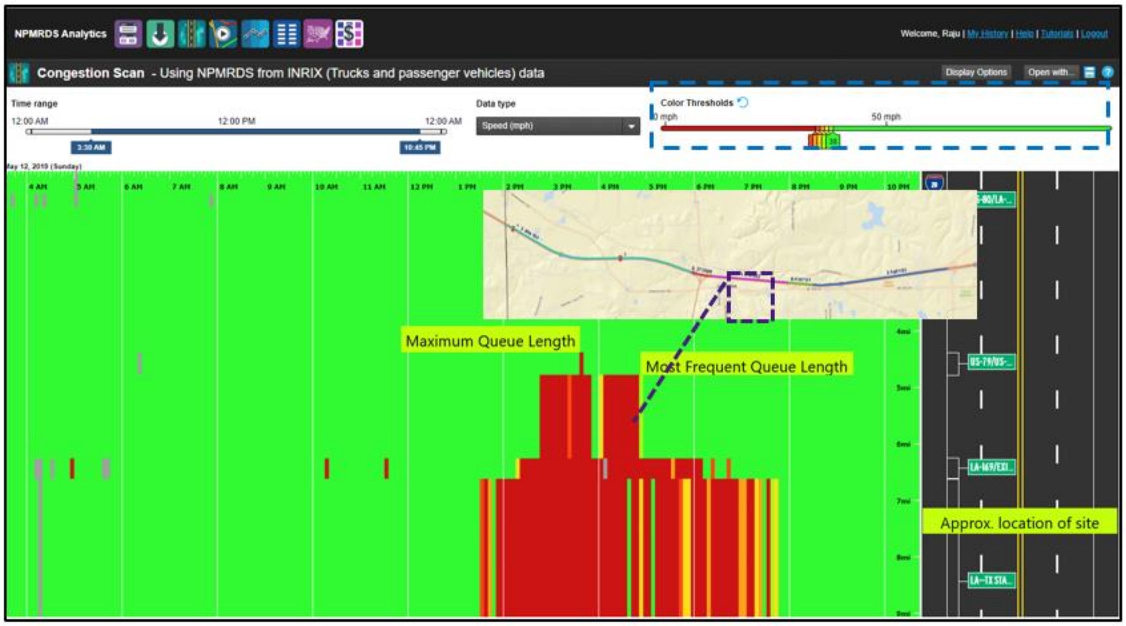
**Figure 15. Site 5 showing different TMC segments**



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

To determine whether a TMC segment was below the speed at capacity, first the speed at capacity of a site was determined as explained earlier and depicted in Figure 13. The “Congestion Scan” tool in the NPMRDS data analytics platform was then used to identify TMC segments, for each site, that had lower speeds than the speed at capacity, using separate full day’s data. Figure 16 is an example of a Congestion Scan for site 5. Two measures are extracted from the Figure: maximum queue length, and the most frequent queue length. Maximum queue length was the maximum length of queue upstream during a time frame the roadway was congested (average speed below speed at capacity). The most frequent queue length (queue length that reoccurred the most) was the queue lengths that were observed to occur more at the particular site, during congested moments where the operating speed was below the speed at capacity.

**Figure 16. Snapshot of NPMRDS analytics speed data at site 5**



For each time frame the roadway was congested, the two measures, as discussed above were extracted. For site 5, the speed at capacity was determined to be 34 mph.  The congestion scan (Figure 16) was set up such that speeds below 34 mph will show as dark red. The figure also shows the time periods the TMC segments upstream of site 5 were congested.

## Performance Indicators

Root Mean Square Error (RMSE) and the Mean Absolute Percentage Error (MAPE) were used as key performance indicators to check theoretical values estimated from field to actual values estimated from the field. The RMSE is the square root of the average of the squared differences between the prediction and actual observation. It is calculated as shown in equation 8 below:

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{N=10}(\text{Field Collected Pre-breakdown Capacity}_i - \text{HCM estimated QDR}_i)^2}{\text{N } (=10)}\right]^{\frac{1}{2}} \qquad [8]$$

The MAPE is the sum of the individual absolute errors divided by the number of observations. Equation 9 shows how it is computed

$$\text{MAPE} = \frac{100\%}{\text{N } (=10)}\sum_{i=1}^{N=10}\left|\frac{\text{Field Collected Pre-breakdown Capacity}_i - \text{HCM estimated QDR}_i}{\text{Field Collected Pre-breakdown Capacity}_i}\right| \qquad [9]$$

Smaller values of both RMSE and MAPE indicate lesser disparity between predicted and observed values. While RMSE gives an indication of the magnitude of very large disparities between sets of data points, the MAPE gives a normalized indication of the average disparity when considering all data points. Both indicators are used to present a better picture of the disparities seen between the HCM2010/HCM2016 work zone capacities and the field observed pre-breakdown capacities.

## Study Limitations

This study has two main limitations that are acknowledged below:

- Although the data collected was from a larger number of sites than most work zone studies from the literature review, it is worth mentioning that only 10 sites were used for this study. The results would be more representative of all Louisiana work zone sites if data had been collected from a larger number of sites across all DOTD districts. However, this was not possible due to the challenge in mounting equipment and collecting data at scheduled periods to coincide with freeway lane closures.

- The queue lengths extracted from the NPMRDS data set was largely dependent on the length of the traffic message channel (TMC) segments associated to the particular site. Some of these TMC segments were very long. Shorter segments would yield more accurate queue lengths. The queue lengths determined from this study are therefore approximate.

# Discussion of Results

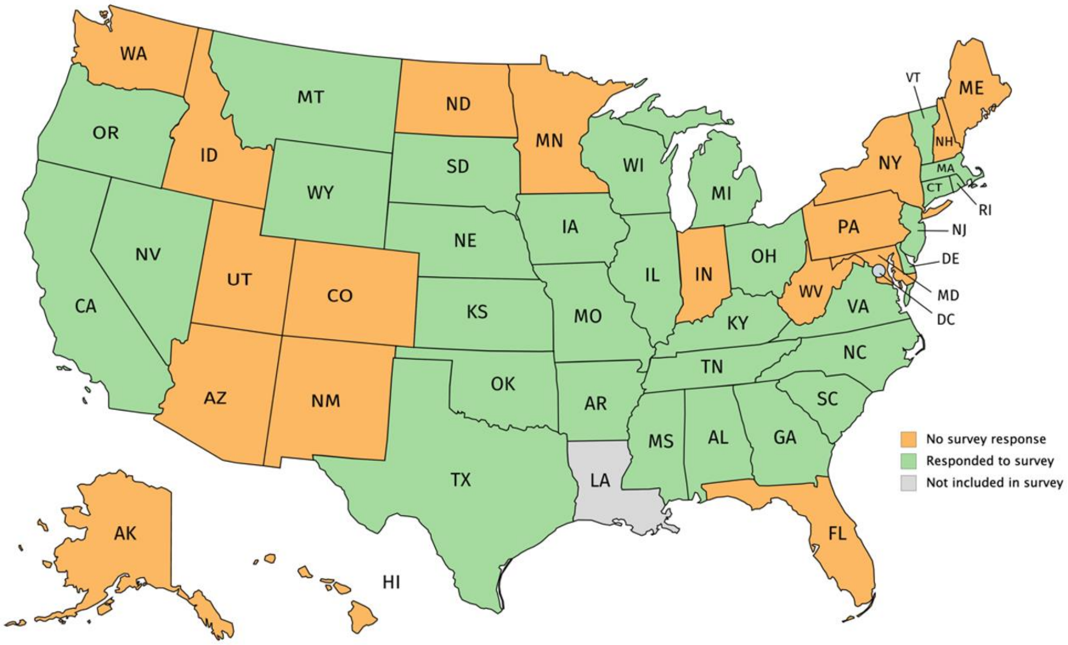
Responses from the survey conducted amongst state departments of transportation and districts within DOTD are reported in this section. Work zone capacity values, pre-breakdown flow rates and length of queues are also presented. Finally, validation of the results obtained from the field are conducted by comparing results to that from the models in the Highway Capacity Manual.

## Survey Results

### Lane Closure Policies and Requirements: State of Practice Nationwide

The survey conducted amongst the state departments of transportation consisted of five questions that were sent to appropriate state officials via email for a response. Louisiana Department of Transportation and Development was excluded from this survey, as the objective was to assess what other state DOTs were practicing. Thirty-one out of the remaining 49 state DOTs responded to the survey. Responses received for each question are further analyzed in subsequent texts. Percentages, reported under each question, are based on the 31 states that responded to the questionnaire. Figure 17 shows the states that responded and those that did not respond to the survey. Louisiana is shown as not included in the survey.

**Figure 17. State responses to survey**



The questions and analysis of responses are documented below:

*Question 1. Do you require a minimum capacity (vehicles per hour open lane) to be maintained when determining if short-term work zone lane closures can be allowed? If so, please state the value.*

Approximately, 39% of state DOTs (12 out of 31) responded that they require a minimum capacity to be maintained before closing lanes for short term work zones, and stated thresholds ranging from 1,100 – 1,900 pcphpl. An additional 10% (3 out of 31) responded that, while they do not enforce a minimum threshold, they do sometimes use minimum capacity criteria to help decide when to effect work zone lane closures. These stated a minimum capacity ranging from 1,100 – 2,000 pcphpl. The remaining 51% (16 out of 31 states) noted they did not require minimum capacity thresholds to be met. Figure 18 shows the states and their responses.

**Figure 18. Minimum work zone capacity requirement by State**

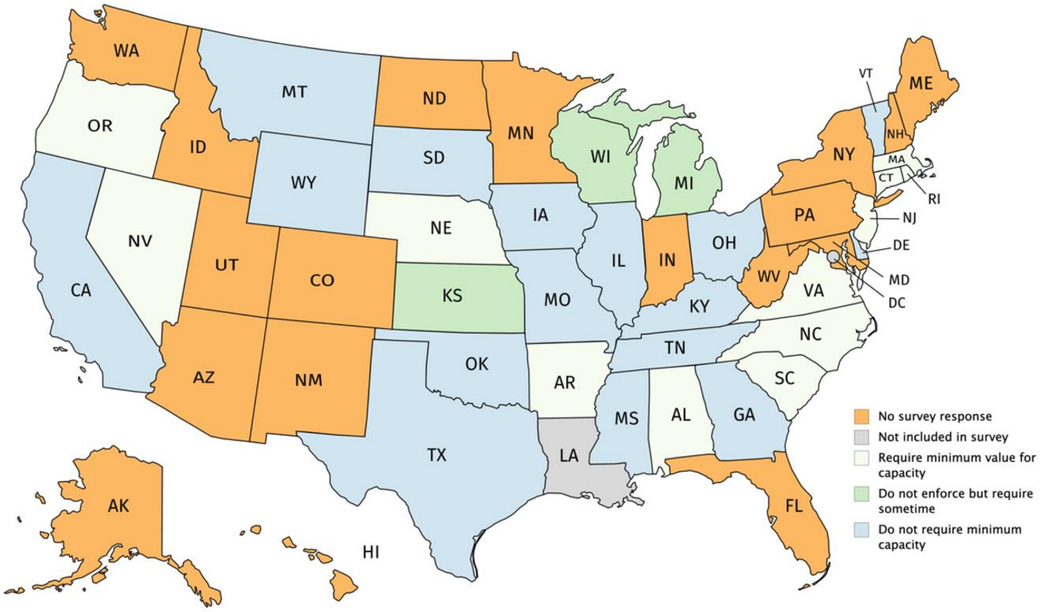


Table 3 reports the actual minimum capacity thresholds reported in response to the first survey question. States with an asterisk (*) are those who do not require a minimum capacity threshold to be maintained, but sometimes refer to the accompanying capacity values to provide guidance on when to effect lane closures. When compared to Louisiana’s threshold of 1,309 pcphpl, it can be seen that 7 out of the total 15 states that provided a value, require a higher minimum capacity value to be maintained before effecting lane closures.

*Question 2. Do you undertake queue analysis for applicable interstate short-term lane closures? YES/NO*

The responses were recorded in Yes/No format. Responses showed that 45% of the states (14 out of 31 states) undertake some form of queue analysis before closing a lane on the interstate. 52% of the respondents (16 out of 31 states) do not undertake queue analysis

**Table 3. Minimum capacity reported by state Department of Transportations**

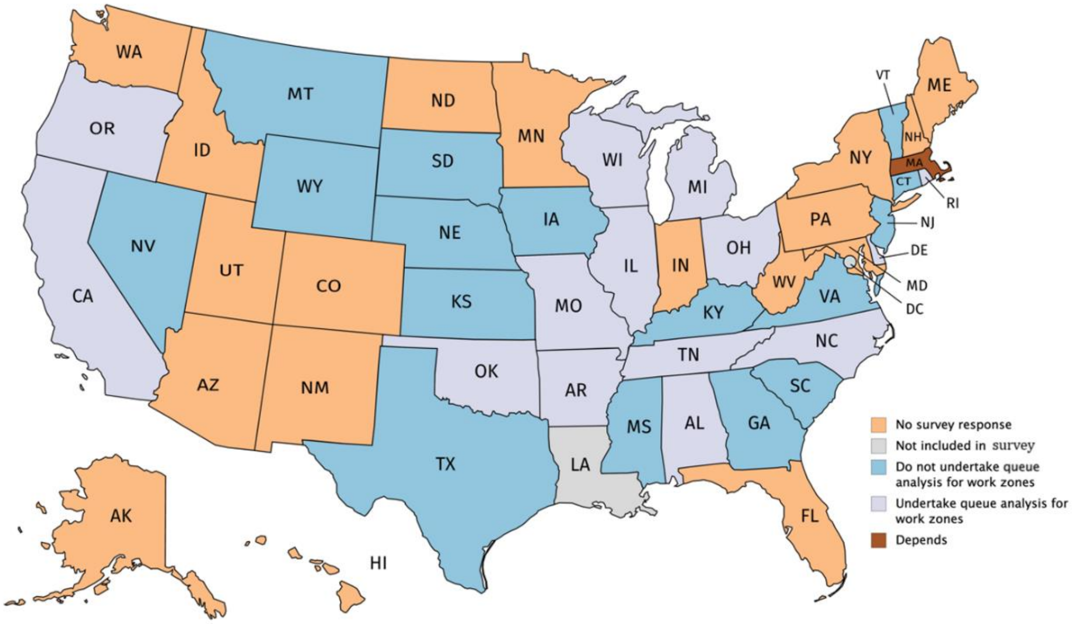
| State | Capacity Value (pcphpl) |
|---|---|
| Alabama | 1,400 |
| Arkansas | 1,200-1,400 |
| Connecticut | 1,500-1,600 |
| Kansas* | 1,500 |
| Massachusetts | 1,900 |
| Michigan* | 1,100-2,000 |
| Nebraska | 1,300 |
| Nevada | 1,600 |
| New Jersey | 1,300 |
| North Carolina | 1,200-1,600 |
| Oregon | 1,600 |
| Rhode Island | 1,240 |
| South Carolina | 1,200 |
| Virginia | 1,100-1,300 |
| Wisconsin* | 1,600 |

before work zone lane closure on an interstate. The remaining 3% of respondents (1 out of 31 states) responded that lane closure analysis is dependent on the nature of the work zone. Some reasons that warranted queue analysis were:

- Cases where delay may not exceed 15 minutes
- Scenarios where the recommended work zone closure hours are not feasible (i.e. 5-hour shift) and the work requires a minimum of 8 hours
- When peak periods are to be avoided

Figure 19 shows the survey responses for Q2 in detail.

**Figure 19. Queue analysis for interstate lane closure**



The findings revealed a slight majority for the number of states not requiring queue analysis. However, Louisiana requires queue analysis to be undertaken for interstate lane closures.

*Question 3. If you answered YES to Q2, what tools or software programs do you use in estimating queues and delays?*

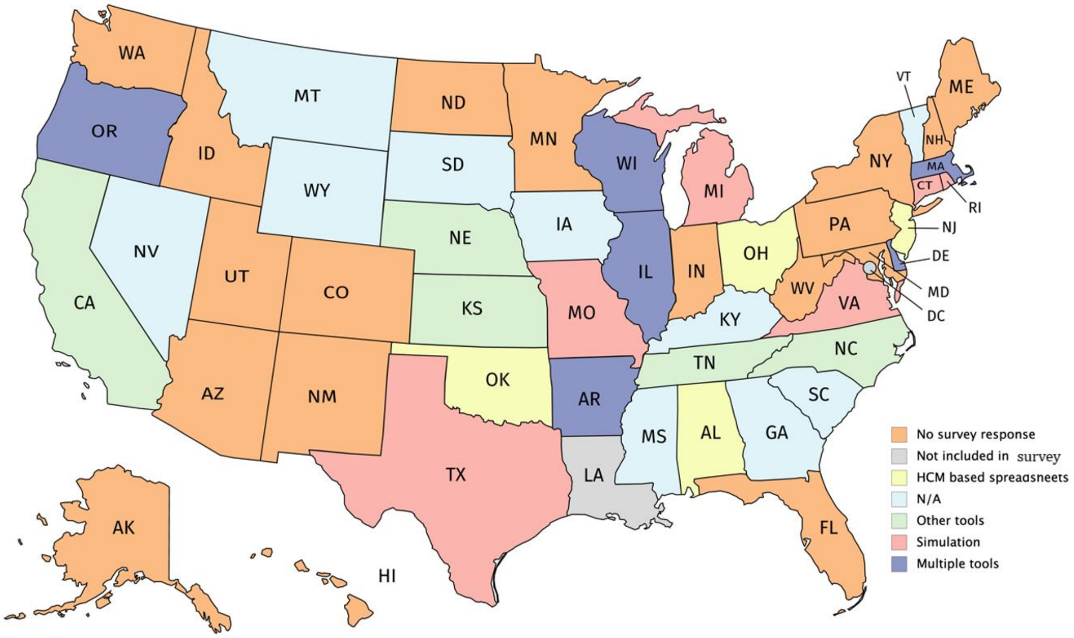
Out of the 14 states that answered YES to Q2, 13 states provided a list of tools or software programs they use to estimate queues and delays. However, 8 states that responded NO to Q2 went on to list tools or software programs that they sometimes use to estimate queues and delays for their work zones, making 21 states altogether. The difference between the two is that while the former requires a formal queue analysis to be undertaken, this is not a requirement for the latter. However, when the latter needs to estimate queues or delays with their associated work zones, the tools/software programs listed are what they use. For this reason, percentages used here refer to the numbers using a particular tool/software when compared to the thirty-one states that responded to the survey.

From the responses, while multiple states use more than one type of tool, simulation is usually used for intersections, roundabouts, and complex projects in general, and 19% (6 out of 31 states) reported using simulation tools to estimate queues and delays. States such as Arkansas, Wisconsin, Oregon, Massachusetts, Delaware, and Illinois use multiple tools, also accounting for 19% (6 out of 31 states). 13% (4 out of 31 states) use HCM-based spreadsheets, and 16% (5 out of 31 states) uses other tools that were not listed. Figure 20 summarizes the survey response. It is worth noting that Louisiana utilizes HCM-based spreadsheet analysis, along with 24 hour-, 7 day- traffic volumes in 15-minute intervals to estimate queues and delays at its work zones.

*Question 4: If you answered NO to Q2, how do you determine lane closure times?*

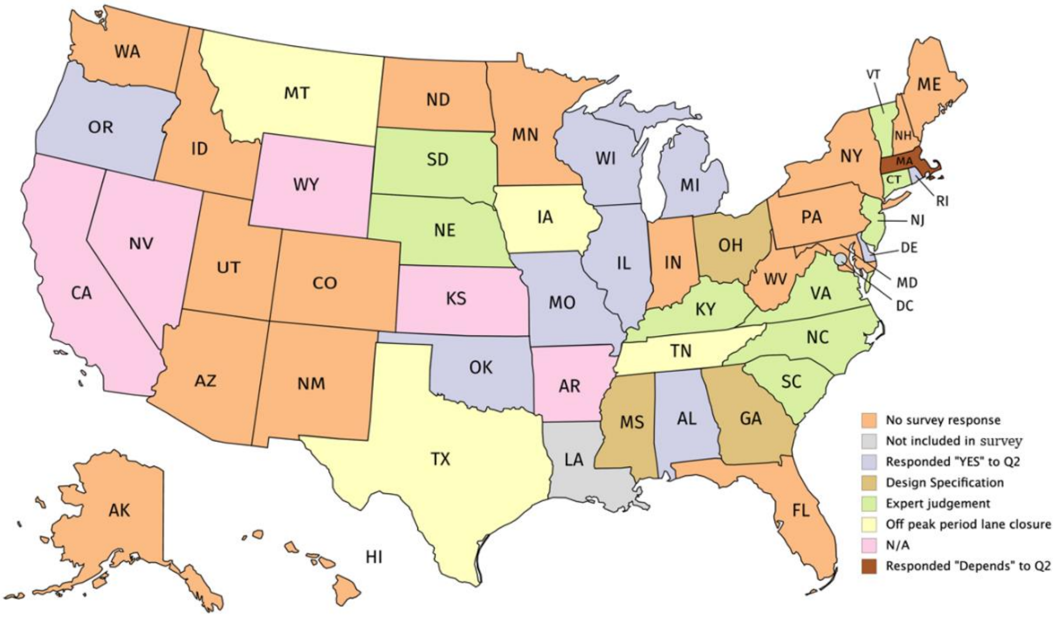
Out of the 16 states that responded NO to Q2, responses were received from 13 states on alternate ways that they use to determine lane closure times. Additionally, even though those who responded YES to Q2 were not required to answer this, 5 states responded with additional ways they use to determine lane closure times, making 18 states altogether. Therefore, percentages shown here refer to the number of responses as a proportion of the thirty-one states that responded to the survey.

**Figure 20. Tools used for queue analysis**



16% of the respondents (5 out of 31 states) indicated this question was not applicable to them, in that they did not use alternate means to determine lane closure times other than the tools listed in Q3. These have been labeled as N/A in Figure 21. 29% of the respondents (9 out of 31 states) used expert judgement on when to anticipate low traffic flows as a way of determining when to implement lane closures; 10% (3 out of 31 states) used design specifications; and 13% (4 out of 31 states) only effected lane closures during off peak periods such as night time only. Figure 21 summarizes the responses by different states.

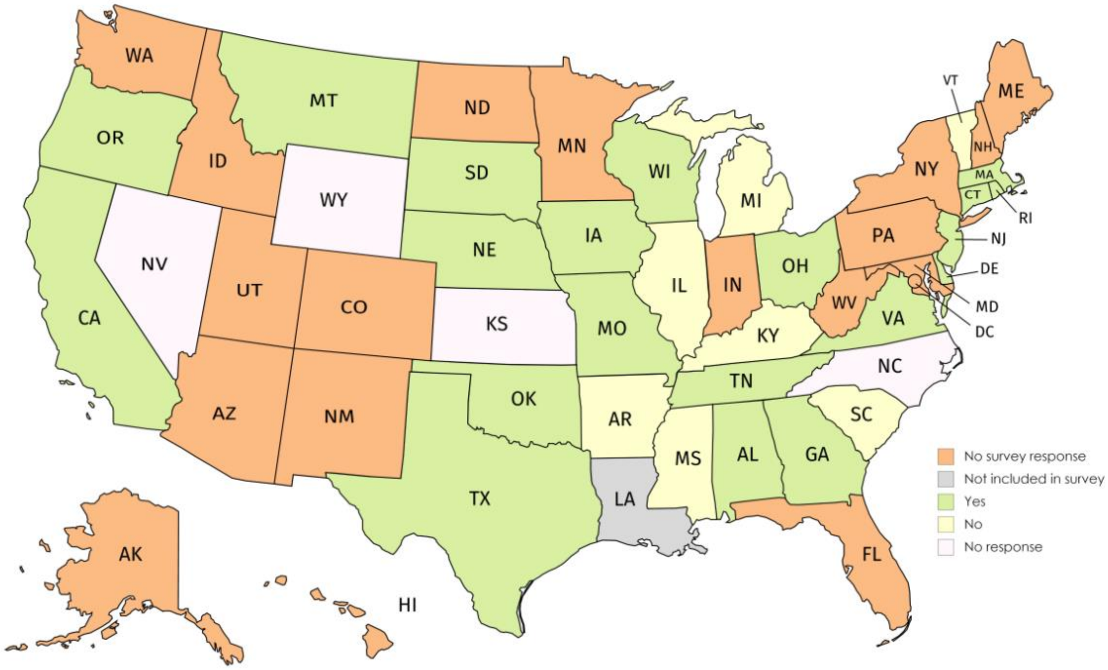
**Figure 21. Determination of lane closures**



*Question 5: Do all the districts in your state use the same tools/software programs? If no, please list all the other tools/software programs used by the different districts if possible.*

This question was included to assess whether the survey response being received from a state DOT was applicable to all districts or offices statewide. Approximately 65% of the respondents (20 out of 31 states) stated that they use the same tools/methods across their statewide district offices. From this subset, some have centralized offices that determine the lane closure information for their districts, and others use contractors for the analysis and therefore use the same method for all districts. 13% (4 out of 31 states) did not respond to the survey. The remaining 23% of the states (7 out of 31 states) that responded in the negative usually allow their district engineers to decide what tools are most appropriate for their respective regions. Figure 22 shows the responses from the survey.

**Figure 22. Uniformity within districts**



## Lane Closure Policies and Requirements: State of Practice in Louisiana

A survey was conducted within DOTD districts to determine whether consistent lane closure practices were upheld among the various district offices. Particularly, the survey was to determine the methodology and tools that the nine districts within DOTD use for traffic analysis before implementing interstate lane closures. District 58 could not participate in the survey because it does not have an interstate within its jurisdiction, so responses are based on the remaining eight (8) DOTD districts (i.e., Districts 02, 03, 04, 05, 07, 08, 61, and 62).

The survey, consisting of three questions, was emailed to the appropriate DTOE. The questions and a summary of the responses are documented below:

*Question 1: Do you undertake queue analysis, as per attached, for applicable Interstate lane closures? YES/NO*

The "per attached" referred to DOTD's directive on queue analysis for lane closures on interstates. A copy of this directive has been included as Appendix C. Out of the eight districts, five districts mentioned that they regularly undertake queue analysis for interstate lane closures while three districts responded negatively to this question. For those that did, some districts undertook queue analysis for every project and maintenance work affecting the interstates. For those that didn't, they had gained insights of volume fluctuations on their network such that they only allow lane closures on interstates at night times whenever possible. Other districts do not undertake queue analysis typically if work is scheduled in rural areas where traffic volumes usually are not problematic.

*Question 2: If you don't, do you determine lane closure times by referencing traffic counts from the Interstate Speed Study GIS Map developed by Arcadis (sample spreadsheet attached)?*

The "Interstate Speed Study GIS Map developed by Arcadis" is a GIS based map that provides speed and volume data for segmented sections of the I-10 and I-12 interstate roadways within the extents of Louisiana boundaries. DTOEs that perform queue analysis are expected to use its volume data in their analysis, in the absence of current 24-hour, 7-day traffic volumes in 15-minute intervals. This question was supposed to ensure that all those districts that were not undertaking queue analysis were not using this GIS based map either. Responses showed that out of the three districts that answered NO to Q1, one of them did not use the GIS based map.

*Question 3: If you do, what tools or software programs do you use in estimating queues and delays?*

Respondents to this question had the option to choose HCM-based spreadsheets, Quickzone, QUEWZ, simulation software like Synchro, SimTraffic, Corsim, etc., or specify any other tools they used. The question was to determine whether all DOTD districts performing queue analysis used HCM-based spreadsheets (along with current traffic volumes or those generated from the GIS based map) or some other tools. Responses showed that all of the five districts that performed queue analysis (and answered YES to Q1) used the HCM-based spreadsheets or some form of worksheet.

## Results of Work Zone Capacity Analysis

### Determining Speed at Capacity

Lane by lane traffic flows (vph), recorded by the RTMS device, were converted to passenger car units (pcphpl). Recorded speeds were then plotted against corresponding traffic flows for each site. Using the universally accepted speed-flow-density relationship, a parabola curve is expected, with the lower half corresponding to congested conditions and the upper half corresponding to free-flow conditions. The congestion speed, also referred to as the speed at capacity, was defined as the speed corresponding to the optimum flow which divides the free-flow and congested halves of the speed-flow curve. Figure 23 shows speed-flow curves for all ten different sites. For example, at site 1, a speed at capacity of 30 mph was identified. Any flow less than 30 mph through site 1 was defined as congested flow or flow under congestion. Similarly, different speed thresholds were defined for each site to differentiate congested and uncongested traffic flows. In certain instances, such as for site 5, the speed-flow curve was not symmetric to be able to easily identify the speed at capacity. In such instances, an Excel file was generated, and several interpolations performed to identify the speed at capacity. Figure 23 presents the speed flow curves and resulting values for all 10 sites.

**Figure 23. Speed-flow curve for sites 1 to 10**

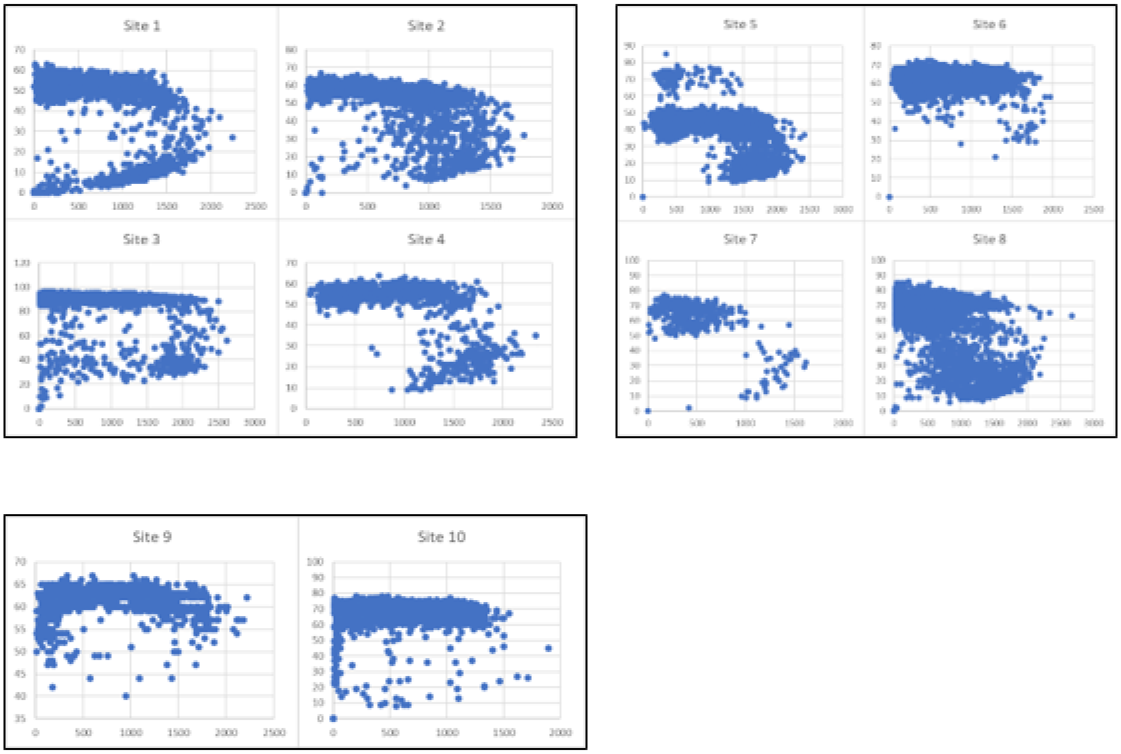


Table 4 shows the resulting values of speed at capacity at all ten sites, which happens to be a function of the work zone characteristics, roadway characteristics, vehicle composition, and flow rates of the site. The values ranged from 30 to 60 mph, with the most frequently observed speeds at capacity occurring below 45 mph.

**Table 4. Speed at capacity at ten different sites**

| Site | Speed at Capacity |
|---|---|
| Site 1 | 30 |
| Site 2 | 34 |
| Site 3 | 60 |
| Site 4 | 41 |
| Site 5 | 34 |
| Site 6 | 47 |
| Site 7 | 34 |
| Site 8 | 44 |
| Site 9 | 57 |
| Site 10 | 44 |

## Observed Pre-Breakdown Capacity and Queue Duration

A total of 136 breakdowns occurred at all ten sites. Pre-breakdown capacity and duration of the congested flows at each breakdown was then estimated using the methodology previously outlined. A heavy vehicle equivalent factor ($E_T$) is needed to convert flows to passenger car equivalent. HCM 2000 uses $E_T$ of 1.5 while HCM 2016 uses $E_T$ of 2.0. Reference is made to HCM 2000 because that is what the current DOTD flat capacity rate of 1,309 pcphpl is based on, and also HCM 2016 because that is the most up-to-date model available. For this reason, average pre-breakdown capacities were computed for each site, using $E_T = 1.5$ and $E_T = 2.0$.

Table 5 shows the results of the observed pre-breakdown capacities using $E_T = 1.5$ and $E_T = 2.0$, along with their corresponding queue durations. Duration of queues ranged from 36 minutes to 285 minutes, with an average of 120 minutes across all ten work zone sites. The corresponding pre-breakdown capacities represent field-observed work zone capacities for each work zone site.

**Table 5. Field-Observed capacities ($E_T = 1.5$ and $2.0$) and queue duration at work zones**

| **Site Number** | **Queue Duration (minutes)** | **Average Field PBC, $E_T = 1.5$ (pcphpl)** | **Average Field PBC $E_T = 2.0$ (pcphpl)** |
|---|---|---|---|
| **1** | 199 | 1,676 | 1,983 |
| **2** | 63 | 1,142 | 1,353 |
| **3** | 104 | 1,298 | 1,483 |
| **4** | 124 | 1,323 | 1,531 |
| **5** | 145 | 1,512 | 1,839 |
| **6** | 36 | 1,080 | 1,322 |
| **7** | 70 | 1,122 | 1,392 |
| **8** | 285 | 1,713 | 2,147 |
| **9** | 74 | 1,436 | 1,675 |
| **10** | 103 | 801 | 1,020 |
| **Average** | 120 | 1,310 | 1,575 |

Using $E_T = 1.5$, values ranged from 801 pcphpl to 1,713 pcphpl, with a mean pre-breakdown capacity of 1,310 pcphpl across all sites. However, as expected, using $E_T = 2.0$ yielded higher field-observed capacities ranging from 1,020 pcphpl to 2,147 pcphpl, and a mean pre-breakdown capacity of 1,575 pcphpl across all ten sites.

Since DOTD is interested in determining which value of work zone capacity associated with queue durations of 30 minutes, a trend line was developed by plotting average pre-breakdown capacities against duration of queues. Figures 24 and 25 represent capacities based on $E_T = 1.5$ and $E_T = 2.0$, respectively.

**Figure 24. Trend line for capacity versus queue duration, $E_T = 1.5$**

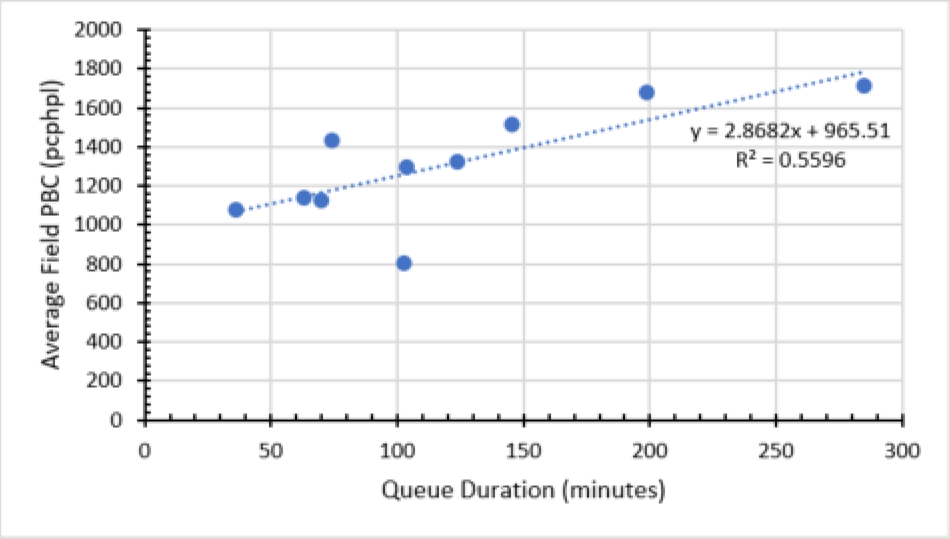
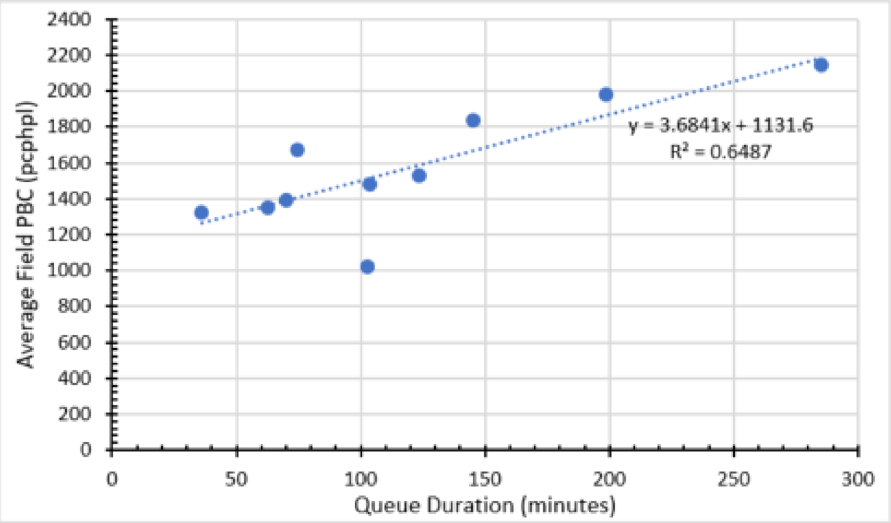


**Figure 25. Trend line for capacity versus queue duration, $E_T = 2.0$**



Both trend lines showed positive correlation between pre-breakdown capacity and duration of queues. In effect, higher pre-breakdown capacities were associated with longer queue durations, and lower pre-breakdown capacities were associated with shorter queue durations. From Figure 24, the trend line equation generated from the plot shows an R-square of 0.56 with an estimated capacity of 1,052 pcphpl corresponding to a 30-minute queue duration. Likewise, Figure 25 shows an even stronger R-square of 0.65

with an estimated capacity of 1,242 pcphpl corresponding to a 30-minute queue duration. Since DOTD currently uses $E_T = 1.5$ for its work zone analysis, the appropriate capacity corresponding to 30 minutes of queueing will be 1,052 pcphpl.

## HCM 2016 Analysis of Queue Discharge Rate and Work Zone Capacity

As discussed earlier, Equation [1] provides the HCM 2016 equation to calculate queue discharge rate (QDR) for a work zone, given the barrier type, area type, lateral distance from edge of travel lane to the barrier, day time or night time working, and lane closure severity index which is a function of the number of lanes before and during the work zone closure. Data on these parameters were compiled for each of the work zone and used to compute the QDR for each site. Equation [3] provides the equation to convert QDRs to work zone capacities, using the default speed drop of 13.4% recommended for work zones by the HCM 2016. Table 6 provides details populated for each work zone site along with the respective computed QDR and work zone capacity. For sites that operated closures during day and night, two values were computed and the average of the two used to represent the site.

It was observed that sites with similar work zone configurations produced similar queue discharge rates and capacities. Queue discharge rates ranged from 1,353 pcphpl to 1,571 pcphpl with an average QDR of 1,446 pcphpl across all sites. Work zone capacity, computed based on HCM 2016 methodology, ranged from 1,562 pcphpl to 1,814 pcphpl with an average of 1,670 pcphpl across all sites. It is worth noting that the HCM 2000 suggests a base capacity of 1,600 pcphpl for short-term freeway work zones regardless of the lane closure configurations.

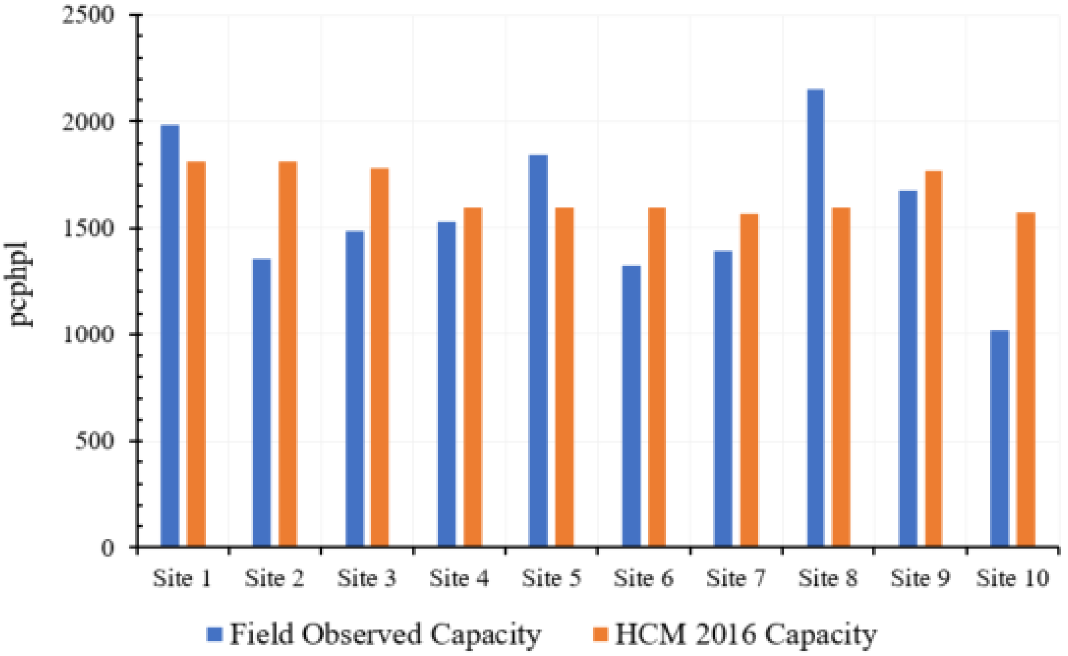
**Table 6. HCM 2016 queue discharge rates and work zone capacities**

| Site No | No of open Lanes | Total No of lanes | Open ratio | Lane closure severity index | Barrier type | Area type | Lateral distance from edge, feet | Day or night | HCM 2016 QDR per lane (pcphpl) | Average QDR for each site (pcphpl) | HCM 2016 Work Zone Capacity (pcphpl) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 2 | 0.5 | 2 | Cones | Urban | 1 | Daylight | 1,600 | 1,571 | 1,814 |
| **1** | 1 | 2 | 0.5 | 2 | Cones | Urban | 1 | Night | 1,541 | | |
| **2** | 1 | 2 | 0.5 | 2 | Cones | Urban | 1 | Daylight | 1,600 | 1,571 | 1,814 |
| **2** | 1 | 2 | 0.5 | 2 | Cones | Urban | 1 | Night | 1,541 | | |
| **3** | 1 | 2 | 0.5 | 2 | Cones | Urban | 1 | Night | 1,541 | 1,541 | 1,779 |
| **4** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Daylight | 1,412 | 1,383 | 1,596 |
| **4** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Night | 1,353 | | |
| **5** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Daylight | 1,412 | 1,383 | 1,596 |
| **5** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Night | 1,353 | | |
| **6** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Daylight | 1,412 | 1,383 | 1,596 |
| **6** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Night | 1,353 | | |
| **7** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Night | 1,353 | 1,353 | 1,562 |
| **8** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Daylight | 1,412 | 1,383 | 1,596 |
| **8** | 1 | 2 | 0.5 | 2 | Cones | Rural | 0 | Night | 1,353 | | |
| **9** | 1 | 2 | 0.5 | 2 | Cones | Urban | 0 | Night | 1,532 | 1,532 | 1,769 |
| **10** | 1 | 2 | 0.5 | 2 | Cones | Rural | 1 | Night | 1,362 | 1,362 | 1,573 |
| Average | | | | | | | | | | 1,446 | 1,670 |

## Comparison of HCM 2016 Capacities and Field Observed Capacities

While Table 6 provides a summary of work zone capacities based on the HCM 2016 methodology, Table 5 provides the field observed work zone capacities in the form of pre-breakdown capacities. This section compares the field observed capacities with the HCM 2016 generated capacities. It is to be noted that field observed capacities are dependent on the choice of heavy vehicle equivalent factor ($E_T$) used. The HCM 2016 uses $E_T = 2.0$ rather than the $E_T = 1.5$ used by the HCM 2000 and from which the DOTD flat capacity rate of 1,309 pcphpl was derived. Since the field observed capacities will be compared to the HCM 2016, it is appropriate to maintain 2.0 as the heavy vehicle equivalent factor to convert flow rates to pcphpl for the field observed capacities. Table 5 shows the field observed values respectively for $E_T = 1.5$ and $E_T = 2.0$. For this comparison, the capacities corresponding to $E_T = 2.0$ will be used. Likewise, Table 6 shows the HCM 2016 work zone capacities generated for Louisiana work zones using the HCM 2016 model and site specifics. Figure 26 illustrates a visual comparison of the two sets of data.

Figure 26. HCM 2016 capacity vs field-observed capacity



It can be observed that for seven sites (Sites 2, 3, 4, 6, 7, 9, and 10) out of 10 sites, the HCM 2016 estimated capacities were higher than the field observed values. For the remaining three sites (Sites 1, 5, and 8), the HCM 2016 estimated capacities were lower. When all sites are considered, the HCM 2016 estimated an average capacity of 1,670 pcphpl as compared to the field observed average capacity of 1,575 pcphpl. Table 7 provides the descriptive statistics of the two data sets.

Table 7. Descriptive statistics for HCM 2016 and field-observed capacities

| **Statistic** | **Average Field Capacity (pcphpl)** | **HCM 2016 Work Zone Capacity (pcphpl)** |
|---|---|---|
| Mean | 1,575 | 1,670 |
| Median | 1,507 | 1,596 |
| Standard Deviation | 340 | 109 |
| Minimum | 1,020 | 1,562 |
| Maximum | 2,147 | 1,814 |

Furthermore, when the difference is quantified, the two data sets resulted in RMSE of 334 and the MAPE of 19.83%. Lower values of these performance indicators suggests the data sets are more closely matched. The results obtained for this comparison shows there are not wide disparities between the two data sets even though the HCM 2016 model generally overestimates the actual field observed capacities. This agrees with numerous other validation studies, discussed in prior sections, which finds the HCM generated capacities to be always different from local conditions. This also supports the recommendation from the HCM for agencies to always validate the HCM models with localized data for local use.

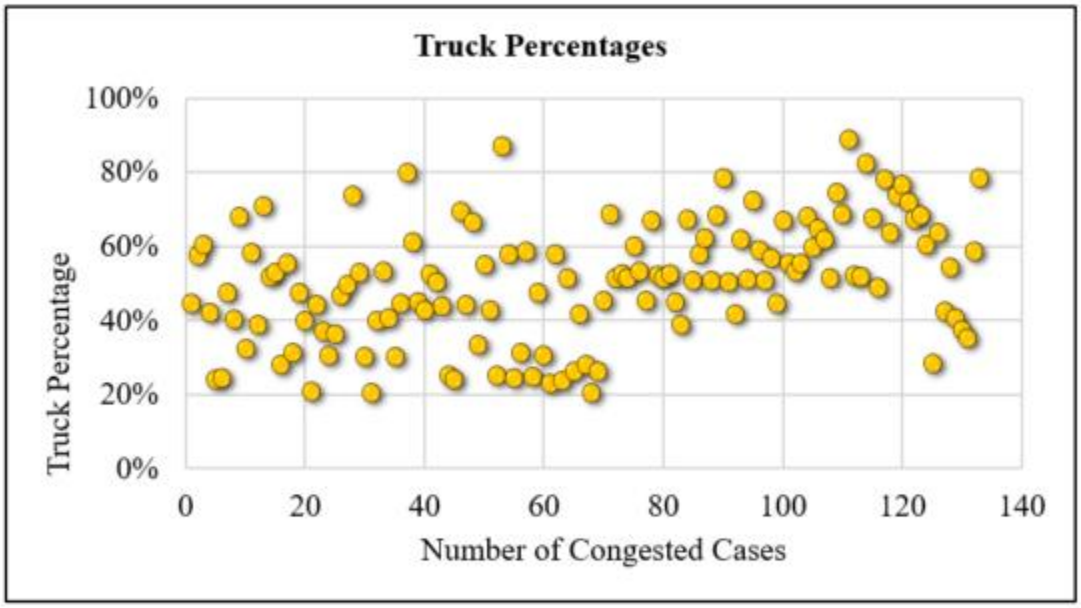
### Validating Work Zone Capacity Threshold Value of 1,309 pcphpl

DOTD's current flat capacity rate of 1,309 pcphpl is the minimum capacity to be maintained to effect work zone lane closures. This was computed based on a theoretical base capacity of 1,600 pcphpl, 20% heavy vehicle traffic composition, and a 10% work zone intensity adjustment. This also assumes $E_T = 1.5$, which is currently used by DOTD. Since field observed data have been collected for this study, it is now possible to validate this threshold value using field collected data.

Table 5 shows that when using $E_T = 1.5$, generally, traffic breakdowns, lasting an average of 120 minutes, occur at traffic flow volumes over 1,310 pcphpl. This could also explain why some DTOEs reported observing traffic queues when they used the flat capacity rate of 1,309 pcphpl, which is very identical to the field-observed rate of 1,310 pcphpl. For the validation, the field-observed capacity average of 1,310 pcphpl can replace the theoretical base capacity of 1,600 pcphpl and the 10% work zone intensity adjustment.

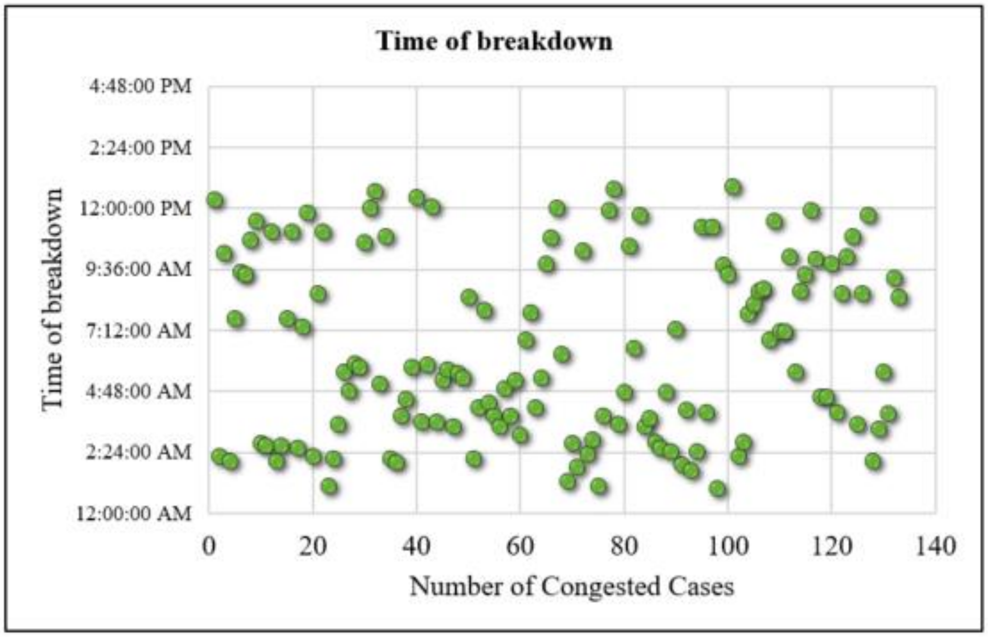
For the heavy vehicle adjustment, it is important to use an appropriate field observed percentage rather than a theoretical value as trump composition has an effect on when breakdowns occur. Figures 27 and 28 show the truck percentages and times of each of the 136 breakdowns that was observed across all 10 work zone sites. Figure 27 shows each case of breakdown and the truck percentage of the traffic make up. It shows a varying truck percentage across Louisiana work zones, but more importantly, that all the breakdowns occurred at truck percentages over 20%.

Figure 27. Truck percentages in traffic stream at pre-breakdown capacity



Likewise, Figure 28 shows the temporal distribution of the breakdowns. It shows that most frequent breakdowns occurred between 2 am to 4 am and 9 am to 12 pm.

Figure 28. Time of breakdown for all recorded congested cases



Based on these, the average truck percentage at which roadways experienced congestion from all the 136 cases used in this study was determined to be 51%. Hence, for the validation, 51% (rather than the 20% previously used) was used to determine a heavy vehicle factor as in Equation [10], and used to adjust the field observed capacity of 1,310 pcphpl as in Equation [11]

Using an $E_T$ of 1.5 and $P_T = 51\%$,

$$fHV = \frac{1}{1+P_T(E_T-1)} = 0.79 \qquad [10]$$

$$Adjusted\ Capacity = 1{,}310 \times 0.79 = 1{,}034.90 \approx 1{,}035 \text{ pcphpl} \qquad [11]$$

Therefore, using field observed data, DOTD’s current flat capacity rate of 1,309 pcphpl can be replaced with a flat rate of 1,035 pcphpl. However, from the trend line developed in Figure 24, this new threshold corresponds to an average of 24 minutes queueing delays.

Since DOTD is more interested in thresholds that will result in 30 minutes or less of queueing, as determined previously and by using the trend line from Figure 24, a field value of 1,052 pcphpl is recommended. In effect, it is recommended that lanes should not be closed during the hours when the lane capacity will exceed 1,052 vehicles per hour per lane if delays are to be kept under 30 minutes.

### Queue Lengths from NPMRDS

It was not possible to observe queue lengths corresponding to the delays observed at each work zone but the NPMRDS was used, as previously described, to determine the maximum and frequent queue lengths for each work zone, and then averaged to obtain an average for Louisiana work zones. Each site experienced a number of traffic breakdowns, totaling 136 breakdowns across all ten sites. For each case, the minimum and maximum lengths of both the maximum queue lengths and the most frequent queue lengths were recorded and summarized as in Table 8.

**Table 8. Summary of maximum and frequent queue length, in miles**

| Maximum Queue length, miles | Minimum | Maximum | Std. | Average |
|---|---|---|---|---|
| **Site 1** | 0.31 | 0.31 | 0.00 | 0.31 |
| **Site 2** | 0.40 | 1.60 | 0.32 | 0.65 |
| **Site 3** | 0.00 | 4.80 | 1.42 | 2.71 |
| **Site 4** | 0.001 | 2.74 | 1.21 | 1.95 |
| **Site 5** | 0.00 | 3.54 | 1.25 | 1.71 |
| **Site 6** | 0.00 | 3.01 | 1.35 | 0.60 |
| **Site 7** | 2.56 | 3.11 | 0.39 | 2.84 |
| **Site 8** | 2.10 | 8.53 | 2.74 | 3.75 |
| **Site 9** | 0.81 | 3.13 | 0.94 | 2.10 |
| **Site 10** | 4.24 | 4.84 | 0.42 | 4.54 |
| **All Sites** | 0.00 | 8.53 | 1.73 | 1.66 |
| **Most frequent queue length, miles** | **Minimum** | **Maximum** | **Std.** | **Average** |
| **Site 1** | 0.31 | 0.31 | 0.00 | 0.31 |
| **Site 2** | 0.40 | 0.91 | 0.26 | 0.63 |
| **Site 3** | 0.00 | 3.09 | 1.01 | 2.26 |
| **Site 4** | 0.00 | 1.50 | 0.63 | 0.89 |
| **Site 5** | 0.00 | 3.11 | 1.02 | 1.46 |
| **Site 6** | 0.00 | 3.01 | 1.35 | 0.60 |
| **Site 7** | 2.56 | 2.56 | 0.00 | 2.56 |
| **Site 8** | 2.10 | 2.44 | 0.16 | 2.20 |
| **Site 9** | 0.81 | 3.13 | 1.04 | 1.95 |
| **Site 10** | 4.24 | 4.24 | 0.00 | 4.24 |
| **All Sites** | 0.00 | 4.24 | 1.07 | **1.30** |

Of particular interest are the average queue lengths recorded for all sites since these will correspond to the delays observed overall. It must be noted that the standard deviations (Std.) and averages computed for "All Sites" were based on the total data points for all sites, and not the averages determined for each site. This results in an average of 1.66 miles (with standard deviation or Std. of 1.73) of maximum queue length, and an average of 1.30 miles (with standard deviation or Std. of 1.07) of the most frequent queue lengths. With reference to previously observed field data, it can be summarized that the ten work zones recorded on average, a work zone capacity of 1,310 pcphpl, with breakdowns averaging 120 minutes duration that resulted in average queue lengths of 1.30 miles with a maximum queue length of 1.66 miles.

To verify whether the queue lengths observed were a result of the work zones, and not specific to the locations, the same congestion analysis was undertaken for all ten work zone locations, during the same days and months and times, but for the previous year. The results showed no queue lengths at each of the sites. It was therefore assumed that the presence of queues was a result of the delays encountered because of the work zones.

# Conclusions

This study reviewed the state of practice of work zone lane closure methods, both nationwide and statewide across DOTD districts, estimated the capacity of Louisiana's work zones, attempted to validate the HCM 2016 work zone capacity model, and validated the 1,309 pcphpl threshold currently used by DOTD to determine work zone lane closures.

From the nationwide study, it was determined that approximately half of the states (15 out of 31 states) that responded to the survey require a minimum capacity (threshold), ranging from 1,100 – 2,000 pcphpl, and with an average of 1,480 pcphpl, to be maintained when determining when to allow work zone closures. However, approximately half of those that reported a minimum capacity (7 out of 15 states) reported a higher threshold than Louisiana's current threshold of 1,309 pcphpl. The survey also revealed that approximately 65% of respondents (20 out of 31 states) implement consistent statewide policies across their various district offices and use similar tools to determine when to effect lane closures.

The statewide survey revealed that majority of DOTD districts regularly performed queue analysis using HCM-based or similar spreadsheets and only used the Arcadis GIS-based traffic counts in the absence of available up-to-date traffic counts. There was a general perception that the current DOTD threshold of 1,309 vphpl was too high, based on local knowledge of site conditions.

The study determined the capacity of Louisiana work zones based on observations of 136 traffic breakdowns across ten work zone sites spread around the state. The values of the field observed capacities were sensitive to the value of heavy vehicle equivalent factor ($E_T$) used, with HCM 2000 using $E_T = 1.5$ and HCM 2016 using $E_T = 2.0$. It is to be noted that Louisiana's threshold of 1,309 pcphpl is based on $E_T = 1.5$. Accordingly, average field observed work zone capacities of 1,310 pcphpl and 1,575 pcphpl corresponding to $E_T = 1.5$ and $E_T = 2.0$, respectively, were obtained. These also corresponded to an average queue duration of 120 minutes and average queue length of 1.30 miles. This observation may justify the perceived notion that the current 1,309 pcphpl threshold was too high (similar to the observed 1,310 pcphpl capacity with 120 minutes of queueing).

The study also determined that the HCM 2016 work zone capacity model only slightly overestimated the average field observed capacity by 6%, with the HCM 2016 estimating a theoretical average of 1,670 pcphpl compared to the average field observed capacity of 1,575 pcphpl. It was, however, not possible to replicate the HCM work zone capacity model using the Louisiana data to develop a similar Equation [1] localized model for Louisiana work zones. This was because there was not enough variability in the work zone configuration and site characteristics of the data collected for the sites.

Lastly, the study determined a new threshold for lane closures that will result in queues of less than 30 minutes. Again, this is sensitive to value of $E_T$ used, with a $E_T = 1.5$ resulting in a new threshold of 1,052 pcphpl and $E_T = 2.0$ resulting in a new threshold of 1,242 pcphpl. Since the current threshold is based on $E_T = 1.5$, the corresponding revised threshold determined by this study is 1,052 pcphpl, an approximate 20% reduction of the current threshold.

# Recommendations

Currently, Section 6A.1 of the DOTD Traffic Engineering Manual (attached as Appendix C) demands that queue analysis be undertaken on interstates before lanes can be closed for roadworks. It demands lanes shall not be closed when capacity of a lane exceeds 1,309 pcphpl, which is also approximated to 30 minutes of queuing. The results of this study show that traffic flow breakdown occurs at lower capacities than is currently being used, resulting in approximately 120 minutes of queuing. The study recommends a new threshold of 1,052 pcphpl, which will result in approximately 30 minutes of queueing.

The study recognized that although there is a recommended standard to be used in determining when to implement lane closures, several DOTD districts implemented lane closures using their own proven methods and experience of local conditions. This could be as a result of observing that the 1,309 pcphpl threshold resulted in longer queues than expected, as evidenced from the study findings and also reported by some DTOEs. The suggested new threshold may offer an opportunity to implement a consistent practice statewide within all districts. However, it was outside the scope of this study to evaluate how enforcing this reduced threshold will impact on stakeholder travel times and economic competitiveness of the region.

The study compared the field observed capacities with the HCM 2016 work zone capacity model (Equations [1] and [2]) and found out that the HCM 2016 model slightly overestimated the capacity at seven out of 10 sites, and underestimated at the remaining three sites. However, overall, HCM 2016 only overestimated slightly by an average 6%. It is recommended that in the absence of field data, the HCM 2016 model (Equations [1] and [2]) be used to estimate capacities at Louisiana work zones.

# Acronyms, Abbreviations, and Symbols

| Term | Description |
|---|---|
| AADT | Annual Average Daily Traffic |
| EDSM | Engineering Directives and Standard Manual |
| FHWA | Federal Highway Authority |
| GIS | Geographic Information System |
| HCM | Highway Capacity Manual |
| DOTD | Louisiana Department of Transportation and Development |
| DTOE | District Traffic Operations Engineers |
| LCSI | Lane Closure Severity Index |
| MAPE | Mean Absolute Percentage Error |
| NPMRDS | National Performance Management Research Data Set |
| PBC | Pre-Breakdown Capacity |
| PCPHPL | Passenger Car Per Hour Per Lane |
| QDR | Queue Discharge Rate |
| RMSE | Root Mean Square Error |
| RTMS | Remote Traffic Microwave Sensors |
| TRD | Total Ramp Density |
| VPHPL | Vehicle Per Hour Per Lane |

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# Appendix

## Appendix A: Pictures from Data Collection and Work Zone Site

Figure 29. Installation of RTMS device (circled)

Figure 30. Solar panel serves as source of power for RTMS device

Figure 31. Right lane closure on I-210

Figure 32. Lane closure on I-210

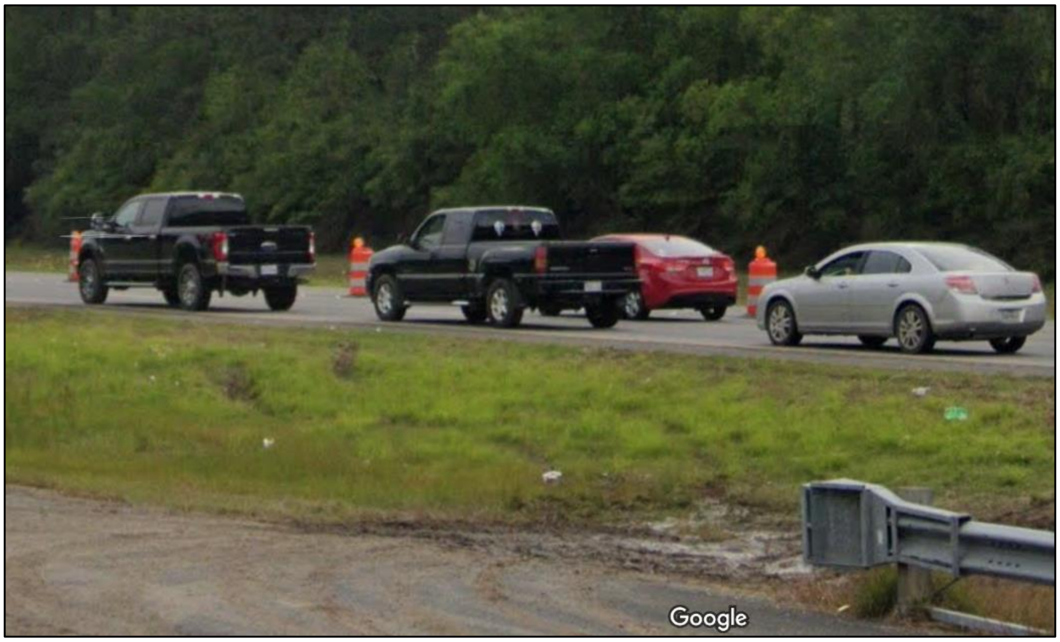


Figure 33. Queue back up due to work zone

# Appendix B: Instructions on Replicating Research Efforts

Part 1 details how to determine the work zone capacity from field data. It contains information on how to collect and analyze traffic data for this purpose in steps. Part 2 details how to validate the 1,309 pcphpl currently being used as a limiting value for work zones.

## Part 1

1. Collect the following traffic flow parameters in 5-minute intervals using appropriate measuring devices; speed, volume, and number of trucks. This study utilized Remote Traffic Microwave Sensors (RTMS) because they could provide all the necessary variables for analysis.
2. If the RTMS is used for data collection, the output will be in the "asc" format which is difficult to read. Therefore, it is necessary to convert the data into a format ready for use. This conversion can be done using the ASC Converter application archived in the project files at LTRC. The application is easy to use. Open the application, navigate to the file of interest. Open the file and click convert to csv.
3. Once the file has been converted, clean the data set and set up the variables as shown in the table below:

**Table 9. Sample formatted data from RTMS**

| Date/Time | Volume_1 | Speed_1 | Truck_1 |
|---|---|---|---|
| 5/7/2019 14:20 | 4 | 70 | 2 |
| 5/7/2019 14:25 | 16 | 68 | 6 |
| 5/7/2019 14:30 | 10 | 68 | 4 |
| 5/7/2019 14:35 | 8 | 67 | 5 |
| 5/7/2019 14:40 | 15 | 68 | 4 |
| 5/7/2019 14:45 | 15 | 68 | 7 |
| 5/7/2019 14:50 | 9 | 67 | 4 |
| 5/7/2019 14:55 | 20 | 67 | 8 |

4. Calculate the truck percentage by dividing the number of trucks recorded by the total volume for each time interval.

5. Calculate the flow rate (hourly flow rate) by multiplying the volume in the 5-minute interval by a factor of 12 to give a 60-minute equivalent.

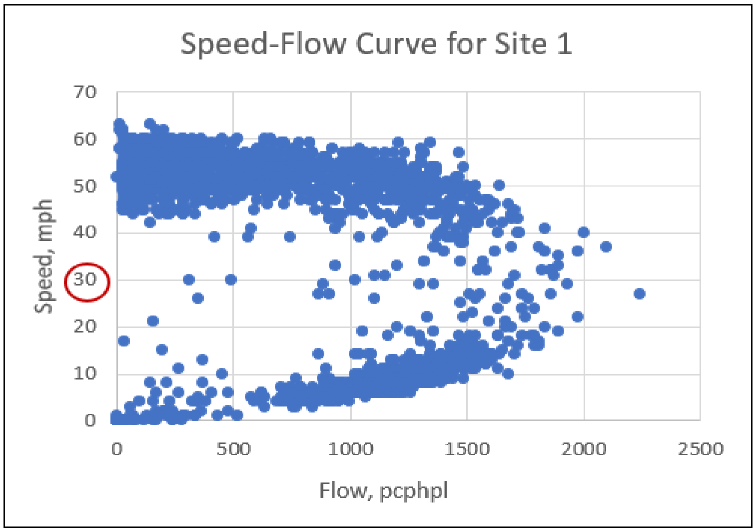
6. Compute the heavy vehicle adjustment factor for each interval by using the following formula, where $P_T$ is the truck percentage calculated in step 4 and $E_T$ is the truck equivalent to a passenger car (1.5 from HCM 2000 and 2.0 from HCM 2016).

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)}$$

7. Convert the flow rate into passenger car equivalent by dividing the flow rate in step 5 by the heavy vehicle adjustment factor in step 6 for each interval.

8. Plot speeds against the adjusted flow rate in step 7 to obtain the speed flow curve and speed at capacity for each site. Figure 34 shows an example that shows the speed flow curve for a specific site. The speed at capacity was estimated manually to be 30 mph, which is the speed corresponding to the apex of the curve.

**Figure 34. Sample speed flow curve**



9. To determine congested periods from the data set, a code was written in Microsoft Excel to note when there was a speed drop below the speed at capacity for 15 minutes or more and also when speeds rose above the speed at capacity for 15 minutes or more.
10. Pre-breakdown capacity can be determined as the traffic flow rate (in pcphpl) just before the speed drop in step 9.
11. The duration of congestion is the time period between the start and end of the speed drop.
12. The average pre-breakdown capacity can be calculated by finding the means of all the pre-breakdown capacities recorded for each site.
13. This average pre-breakdown capacity is what is used as the base value for work zone capacity.
14. Repeat steps 5 – 13 to determine the work zone capacity.

## Part 2

1. To determine the threshold value for work zone capacity, the base value of 1600 has to be adjusted for work zone intensity and truck percentage in a work zone (based on the HCM 2000 methodology).
2. A 10 percent reduction in the base value is recommended. Therefore, compute:

Modified PBC = Base Value PBC (from field) * 0.9

3. It is recommended that the truck percentage be computed on a 24-hour volume for each site, and then averaged for all sites to get a single truck percentage, $P_T$.

4. Next, determine the truck equivalent value, $E_T$, to use. HCM 2000 recommends a $E_T$ of 1.5 for flat terrains while HCM 2016 recommends a value of 2.0.

5. Compute the heavy vehicle factor using the formula:
   $f_{HV} = \frac{1}{1+P_T(E_T-1)}$

6. Further adjust the modified PBC from step 2 by multiplying with the $f_{HV}$ determined from step 5

   Adjusted Capacity (in pcphpl) = Modified PBC * $f_{HV}$

# Appendix C: Queue Analysis for Lane Closure on Interstate

Traffic Engineering Manual
Temporary Traffic Control

## Section 6A.1

## QUEUE ANALYSIS FOR LANE CLOSURES ON INTERSTATE

### 6A.1.1 LEGAL

Revised Statute 48:279

### 6A.1.2 DEFINITION

This policy is regarding queue analyses for scheduled Interstate lane closures for construction, maintenance and permit projects.

### 6A.1.3 POLICY

The queue analysis shall determine delay caused by lane closures. A queue analysis shall be performed for all lane closures on Interstates with ADT's equal to and greater than 25,000. Lanes shall not be closed during the hours where the lane capacity exceeds 1,309 vehicles per hour lane. The restrictions may be more restrictive if the District Traffic Operations Engineer (DTOE) or Project Engineer (PE) deems necessary.

i. Queue analysis shall be requested by:
   1. Construction projects - during Stage 0 and reevaluated by the Project Manager at Stage 3 and Stage 4 to validate traffic volumes
   2. Maintenance projects - during the planning stage by Maintenance Project Managers
   3. Permitted projects - prior to issuance of the permit by the District

ii. The DTOE, Metropolitan Planning Organizations, Office of Planning and Programming, or consultants may collect traffic volumes. Traffic volumes shall consist of 24 hour, 7 day counts in 15 minute intervals.

iii. Adjust raw volumes with adjustment factors obtained from the DOTD Planning Division. These factors are:
   1. % Trucks
   2. Axle Adjustments
   3. Adjustment for month of count
   4. Adjustment for month of construction

iv. The DTOE shall perform or review and approve all queue analyses based on the following method:
   1. Using the 7 day 24 hour adjusted volumes, the minimum work restrictions shall occur where there are more than 1,309 vehicles per hour per open lane (*Highway Capacity Manual*, 2010, Ch.10)

v. The PE shall report back to the DTOE on actual queues experienced during construction. This will allow the DTOE to refine the queue analysis.

**Alternatives to Prevent, Reduce, and Mitigate Queues Due to Lane Closures:**

i. Projects with expected delay due to lane closures shall include:
   1. Standard Temporary Traffic Control Details (TTC) in plans
   2. Standard specification for Temporary Traffic Control pay item

ii. The designer should consider the following to mitigate delays when lane closures are necessary:
   1. Alternate route plan
   2. Limit lane closures to off peak week nights and weekends
   3. Limit maximum physical length of lane closure
   4. Maintain existing number of lanes with lane narrowing and lane shifts
   5. Merge left before a lane closure
   6. Public information program identifying alternate routes through press releases

## 6A.1.4 APPROVAL

The District Traffic Operations Engineer shall perform or review all queue analyses based on using 7 day 24 hour adjusted volumes and the minimum work restrictions where 1,309 vehicles per hour per open lane.

The Project Engineer shall report back to the DTOE during construction to allow for the refinement of the queue analysis.

## 6A.1.5 WAIVERS

The minimum work restrictions may be less restrictive with a written justification based on the history of a previous project recommended for approval by the DTOE and the District Administrator and approved by the Chief Engineer.

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