Development of Traffic Delay Assessment Tool for Short-Term Closures on Urban Freeways

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A certain amount of delay in work zones is typically assumed to be unavoidable and often considered a cost of doing business when roadway improvements are in progress. Therefore, developing a method to predict delay, such that appropriate countermeasures to minimize delay can be implemented, is critical to successful work zone management. Predicting work zone delay in an effective and efficient manner should not require extensive data collection or long, complex coding efforts. The procedure should be customizable for local data availability, easy to use, and, for practitioners, easy to interpret. To this end, the Work Zone Capacity Analysis Tool (WZCAT) analytical software program was developed to predict delays and queues for short-term (daily) work zone closures. WZCAT queue-length predictions are based on a simple input–output model, with capacity of the work zone controlling the throughput. The purpose of this study was to evaluate and enhance WZCAT with field data as well as summarize various aspects of traffic flow and queuing patterns during work zone operations on selected urban freeways. Findings from field observations were significant traffic volume changes on exit and entrance terminals upstream of work zones and the stabilization of vehicle queue after initial queue development. A demand–adjust factor was developed and applied to WZCAT-R for effectiveness and efficiency. WZCAT-R produces effective results for queue prediction. It can be an effective and reliable tool in predicting work zone delay and queue development. The tool can also help engineers proactively plan work phasing, lane restrictions, and potential detour routes to move traffic more efficiently.

Most states spend millions of dollars each year resurfacing, rehabilitating, and reconstructing their roadways. Roadway construction work zones are established to safely perform the needed work while maintaining a sufficient amount of daily traffic flow through the construction area. Inevitably, delays occur in and around the work zone due to associated restrictions in traffic flow. Such delays cost the economy millions of dollars each year in lost productivity, potential decreases in safety, and increased emissions from slowing or idling vehicles, or both. Considering that some level of delay in roadway work zones is typically unavoidable, developing a method to predict the delay, such that appropriate countermeasures can be established, is critical to successful work zone management. Reliable prediction of work zone delay and queue development may help engineers proactively plan work phasing, lane restrictions, and potential detour routes in an effort to move traffic more efficiently.

The FHWA Final Rule on Work Zone Safety and Mobility, published on September 9, 2004, requires all state and local governments that receive federal-aid funding for roadway improvements to develop and implement procedures to assess and manage work zone impacts on individual roadway construction projects. Each state was to comply with the provisions no later than October 12, 2007. To measure the traffic impacts of work zone operations in an effective and efficient manner, an evaluation methodology is needed to provide accurate prediction results without the need for extensive data collection or long and complex modeling efforts. In other words, procedures for evaluating the impacts of work zones should be both customizable for local data and user-friendly.

To this end, the Work Zone Capacity Analysis Tool (WZCAT) software program was developed to predict delays and queues for short-term (daily) work zone closures. WZCAT is a relatively simple input–output model that predicts the delay associated with proposed roadway lane closures and computes a predicted queue development as a function of delay. Based on a precoded average vehicle length, WZCAT provides a graphic output of the predicted queue development and queue dissipation throughout the duration of the construction work zone.

The purpose of this study was to validate and calibrate the WZCAT with field data collected from work zone operations on southeastern (SE) Wisconsin freeways. A total of eight work zones were observed on SE Wisconsin freeways between July 2005 and November 2005. Work zones were randomly selected based on the type of closures and geographic locations throughout the SE Wisconsin freeway system. Because of the extensive network of permanent volume and speed detectors, existing detector locations upstream, downstream, and within the selected work zone locations were used as traffic operations data sources for before, during, and after analysis of work zone activity.

LITERATURE REVIEW

Most previous construction work zone traffic flow studies have focused on calculating reduced capacity due to lane closures. For example, Benekohal et al. showed a methodology to determine work zone capacity based on several factors, such as work intensity, lane width, and lateral clearance (*1*). It was concluded that each characteristic affected vehicle operating speed. Sarasua et al. evaluated Interstate highway capacities for short-term work zone lane closures and found 1,460 passenger cars per hour per lane (pcphpl) as a base

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threshold value for work zone capacity (*2*). Karim and Adeli used a radial basis function neural network to improve the accuracy of estimation for work zone capacity and modified traffic demand (*3*). They used 40 work zone samples to train the model and tested with 27 sets of field data. As for work zone capacity, the difference was normally less than 10% for 17 samples, but 10 samples showed 20% to 71% error, which is relatively high. Further investigation revealed that this was largely due to significant impact from the percentage of heavy vehicles.

Because most deterministic traffic flow models calculate delay and queue length based on estimated work zone capacity under the assumption that traffic flow in a work zone is a function of the queue discharge rate, accuracy of the model's results depend on good estimates of work zone capacities. Schnell et al. evaluated the accuracy of commercially available macroscopic and microscopic traffic simulation tools, such as CORSIM and SimTraffic for work zone traffic analysis using four work zones in Ohio (*4*). The study showed that it is very difficult to calibrate microscopic models for work zone traffic estimations, and the models significantly underestimated the length of queues and delay time. It also showed work zone capacity estimation was found to be much more accurate than the maximum queue estimation. The study failed to find an acceptable reason for this discrepancy, although it did mention a relaxed car-following driver behavior and instabilities of the vehicle queue.

Several commercially available software packages have been specifically developed for work zone delay estimation. QuickZone, a work zone delay estimation tool developed by Mitretek Systems and sponsored by FHWA, allows analysis of the impact of work zone delays on a roadway. QuickZone requires input data such as work zone location, projected detour routes, anticipated volumes of traffic, and construction dates and times. QUEWZ98, a microcomputer analysis tool for planning and scheduling freeway work zone lane closures, analyzes traffic conditions on a freeway segment with and without a lane closure in place. It provides estimates of additional road user costs and queuing resulting from a work zone lane closure.

Generally, most studies reported in the literature attempted to capture the precise impact of various work zone characteristics on freeway capacity using various techniques; however, there is little research on determining anticipated demand changes due to work zone operations on urban freeways and the associated impacts. Ullman addressed queue stabilization due to natural diversion effect at a short-term freeway work zone lane with filed data observation (*5*); later, he developed a theoretical approach to explain the phenomena (*6*).

Furthermore, it was noticeable that a wide array of methodologies exists for evaluating work zone impacts, ranging from simple customized worksheets to commercially available packages requiring extensive input data. The WZCAT program developed by the Wisconsin Department of Transportation was designed to provide sufficient analysis detail while minimizing the depth of required input data by packing into a simple input–output user interface. An easy-to-use tool like WZCAT would help transportation professionals better manage the impacts of work zones if the tool were effective and accurate in its prediction capabilities. Therefore, validation of WZCAT's work zone queue length prediction capabilities was needed.

DATA COLLECTION

Traffic and queue length field data were collected from eight different freeway work zone locations. All work zones were temporary closures with lane closures placed between 8 a.m. and 3 p.m. As presented in Figure 1, operating speed and volume data were collected

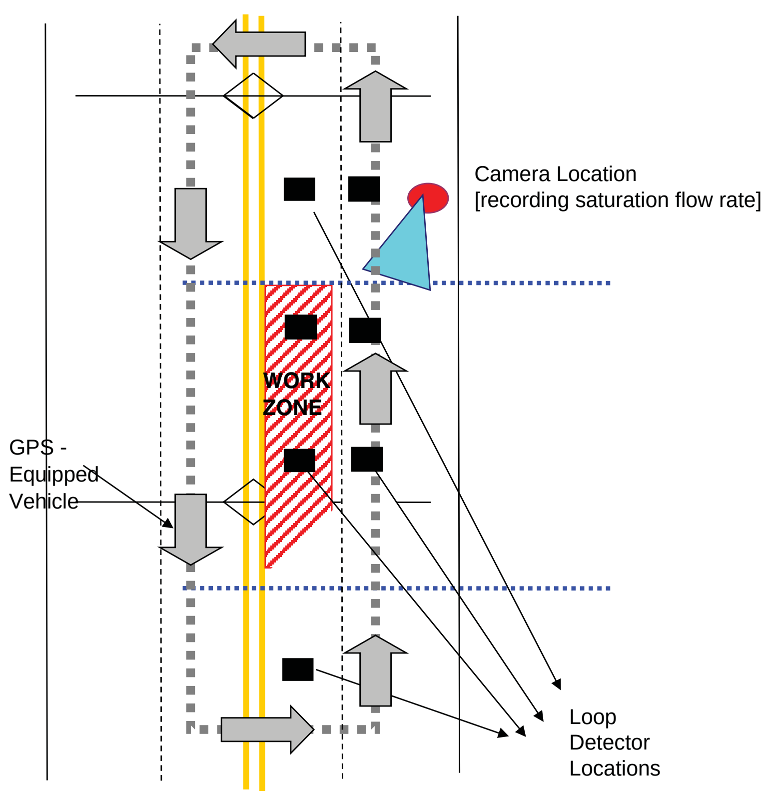


FIGURE 1 Traffic data collection in work zone.

TABLE 1 Summary of Information Obtained at 8 Work Zones

	WZ1	WZ2	WZ3	WZ4	WZ5	WZ6	WZ7	WZ8
Location (on highway)	I-94 WB	I-43 SB	I-94 WB	I-94 EB	I-43/I-94 SB	I-894/US-45 NB	I-94 NB	I-94 WB
AADT	75,600	43,000	75,600	81,600	61,800	74,600	39,100	84,000
Lane closure 1[a]	2 right lanes closed	Left lane closed	Right lane closed	Left lane closed	Left lane closed	2 left lanes closed	Left lane closed	2 left lanes closed
Lane closure 2[a] (no. of lanes/ open lanes)	3 > 1	2 > 1	3 > 2	3 > 2	3 > 2	3 > 1	3 > 2	3 > 1 and 4 > 2
WZ length	1.88 mi	0.8 mi	1.2 mi	0.62 mi	0.25 mi	0.5 mi	1.5 mi	1.17 mi
WZ time	8:30 a.m. to 2:30 p.m.	9:40 a.m. to 2 p.m.	9 a.m. to 2 p.m.	9 a.m. to 2 p.m.	9 a.m. to 2 p.m.	9 a.m. to 2 p.m.	9 a.m. to 2 p.m.	9 a.m. to 2 p.m.
WZ duration (h)	6	4.2	5	5	5	5	5	5
WZ activity	Maintenance	Inlet repair	Guardrail repair	Lighting	Barrier wall repair	Maintenance	Maintenance	Bridge maintenance
WZ intensity[a] (3 = high, 1 = low)	3	3	2	1	1	3	3	2

NOTE: WZ = work zone, AADT = annual average daily traffic, WB = westbound, SB = southbound, EB = eastbound, NB = northbound.
[a]Subjective measurement based on visual observation (1 = no worker presence; 2 = workers in active work area; 3 = workers in active work area and close to open lane) (*1*).

using existing freeway loop detectors. Traffic flow at the end of the work zone was videotaped with use of a portable video camcorder. The video records were analyzed by using Car Count version 0.9, a software program that provides automated methods for calculating headway, volume, and heavy vehicle ratios. Video data also provided another source of traffic volume and operating speed data.

Vehicle queue length was measured and recorded every 10 to 30 min throughout the duration of the work zone closure. Initially, the measurement was obtained by a trained spotter in a vehicle that followed the end of queue on the opposite side of the freeway. This method was later replaced by a slightly more precise method using a Global Positioning System (GPS)-equipped vehicle. A GPS-equipped vehicle was continuously driven upstream of work zone (free-flow area) to the end of work zone. Location (latitude, longitude) and speed (mph) data determined from GPS data were downloaded and transferred to a laptop computer every 1 to 4 s. Typically, the GPS vehicle passed through the entire work zone area and vehicle queue at least twice per h. Table 1 summarizes information obtained at eight work zones observed during the project.

WORK ZONE CAPACITY ANALYSIS TOOL

WZCAT was developed using the principles of the Delay Enhanced (DelayE) software program developed in the late 1990s (*7*). The DelayE concept is based on a deterministic queuing analysis, the foundation of the basic input–output analysis. WZCAT was developed as an add-on program that operates within Microsoft Excel. As shown in Figure 2, WZCAT in its current version executes an input–output analysis to estimate traffic queue development and associated delay due to work zone activities as follows:

Step 1. WZCAT compares the expected travel demand at the work zone location to the work zone capacity. If demand exceeds capacity, the excess is assumed to be stored in a queue upstream of the work zone.

Step 2. Input–output analysis is used to keep track of the amount of excess vehicles stored over time.

Step 3. Vehicular delays and queue lengths are computed by using the estimates of stored number of vehicles and approximate average vehicle lengths in the queue.

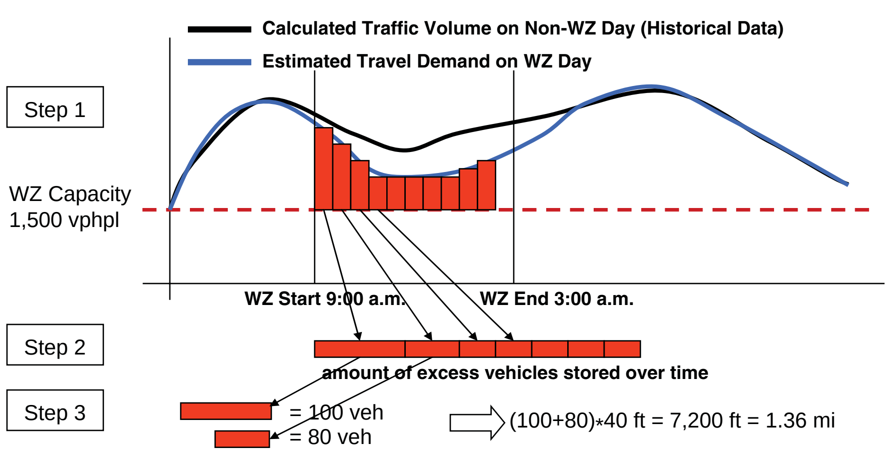


FIGURE 2 WZCAT queue estimation.

Since WZCAT relies on a simple input–output analysis, a good estimation of work zone capacity and travel demand is critical to calculating traffic delay. WZCAT calculates work zone capacity by *Highway Capacity Manual* (HCM) (*8*) methods and provides an option to use an empirical value for work zone capacity, which was acquired from reviewing other states work and field observations in Wisconsin. Also, WZCAT allows users to input a customized value for work zone capacity as needed; however, only single fixed value can be used for the entire duration of work zone. Currently, WZCAT does not include suggested parameters for travel demand reductions; however, anticipated travel demand could be captured through a robust manipulation of historical data.

WZCAT accumulates vehicle input and output from a given work zone to determine queue length. The end vehicle balance on a given time interval is multiplied by an average queue headway to determine the estimated queue length. The HCM suggests a default value of 40 ft per queued vehicle (*8*). Therefore, this 40-ft per vehicle default value is used to calculate queue length. The number represents the average space occupied by a vehicle in a queue, not the average vehicle length.

INITIAL CASE STUDY

A work zone on eastbound Interstate Highway 94 near Milwaukee, Wisconsin, was selected for the initial evaluation of WZCAT. Figure 3 shows the location of the work zone and existing detector locations upstream and within the work zone. Figure 3 also illustrates the distance between detectors and the distance from the starting point of the work zone to each detector location upstream of the work zone. Two right lanes of the approximately 1.8-mi work zone were closed (three lanes total) from 8:30 a.m. to 2:30 p.m. Field observations showed that a vehicle queue started to develop around 8:00 a.m., immediately after a maintenance vehicle appeared on the side of roadway, and the queue quickly extended to the Moorland Road interchange, nearly 3 mi upstream from the work zone starting location.

The default capacity values of 2,200 vphpl for normal conditions and 1,500 vphpl for work zones were used in WZCAT. Additionally, the work zone hour was coded as obtained from field observations. As described, WZCAT calculates the number of queued vehicles by subtracting capacity (1,500 vph) from given demand. This calculation is conducted in 6-s intervals. The number of queued vehicles were then multiplied by a 40-ft vehicle headway and divided by the number of available lanes. WZCAT assumed the vehicles would use all open lanes up to the taper area.

Since it was assumed that the saturation flow rate would remain rather constant during work zone operation hours, the study aimed to find a single detector location that was highly associated with the expected arrival rate, and which could generate the observed queue from the field, given the observed work zone capacity.

For WZCAT to estimate delay, two different types of traffic volume data were collected in 15-min intervals. One type of data was historical traffic volume, acquired by averaging traffic volumes from the same day of the week and time period for the 12 previous weeks. The second type consisted of actual traffic volumes in the work zone on the day of construction (in this case July 14, 2005), obtained from the detector locations. Ten different detector locations upstream of the work zone were used to generate separate input files to WZCAT for both the historical data and the observed traffic flow on the work zone day. That is, 20 different sets of input data were considered to identify the best location for traffic volume input to WZCAT that best matched the observed length of the queue.

Figures 4 and 5 illustrate the results from WZCAT for all detector locations using historical and actual data, respectively. As can be seen, there were significant differences between the queue length observed

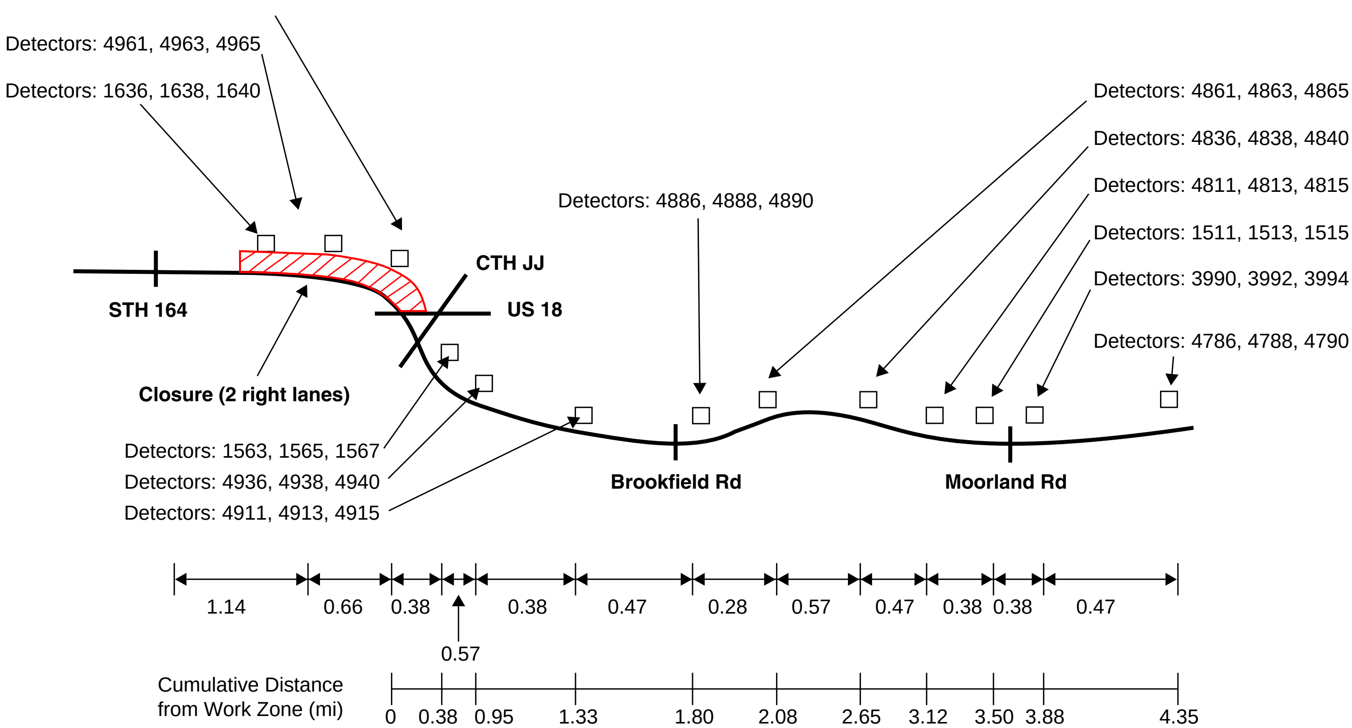


FIGURE 3 Work Zone 1 (I-94 eastbound).

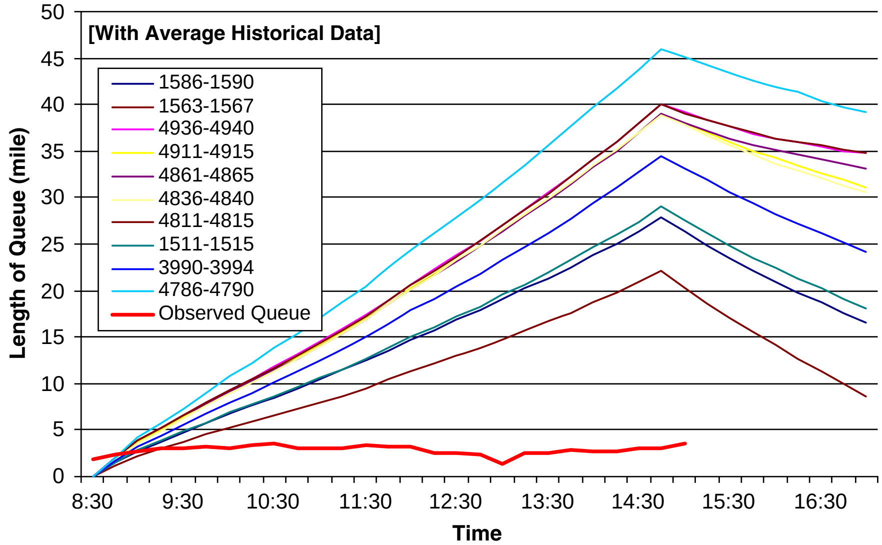


FIGURE 4 Estimated length of queue by WZCAT with historical data (WZ1).

in the field and queue length predicted by WZCAT for both the historical and actual data. The observed queue length remained consistent at approximately 3.5 mi, while WZCAT significantly overestimated the length of the queue. Regardless of the input volume data used, large differences in the length of queue results were found, which raised more questions pertaining to travel demand.

It was expected that the use of actual traffic volume from the work zone day as an input to WZCAT would produce a queue length somewhat identical to the observed length. However, as presented in Figure 5, WZCAT did not generate a queuing pattern similar to field observations with any of the detector locations. Figure 6 shows the observed maximum back of queue as a comparison. A queue developed very quickly after the lane closure and stayed near the 3-mi maximum for all work zone hours except for a slight drop in queue length between noon and 1 p.m. WZCAT estimated that queue length was almost five times longer than the observed value. This overestimation was initially found in all other work zone simulations.

Table 2 shows that the capacity of work zone varies as a function of several factors, such as work zone length, work zone setup, and others. These variations would not significantly influence the inflated queue length outputs. Observed traffic flow through work zone remained +/– 300 vphpl of the default value in WZCAT, which further showed the relative stability of the value.

According to multiple field observation throughout this study, vehicle queues at work zone locations started to build immediately on arrival of maintenance vehicles on the freeway shoulder. When traffic control devices were actually placed to establish a work zone on the freeway, vehicle queues were already established and approaching maximum values, which were typically maintained in a relatively steady-state condition for the duration of the work zone. This was a very common pattern observed from all work

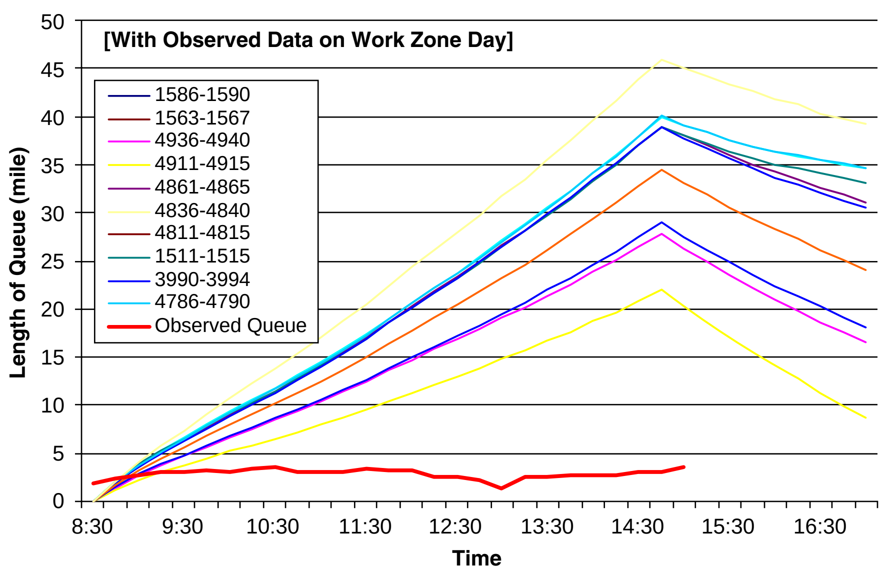


FIGURE 5 Estimated length of queue by WZCAT with observed data (WZ1).

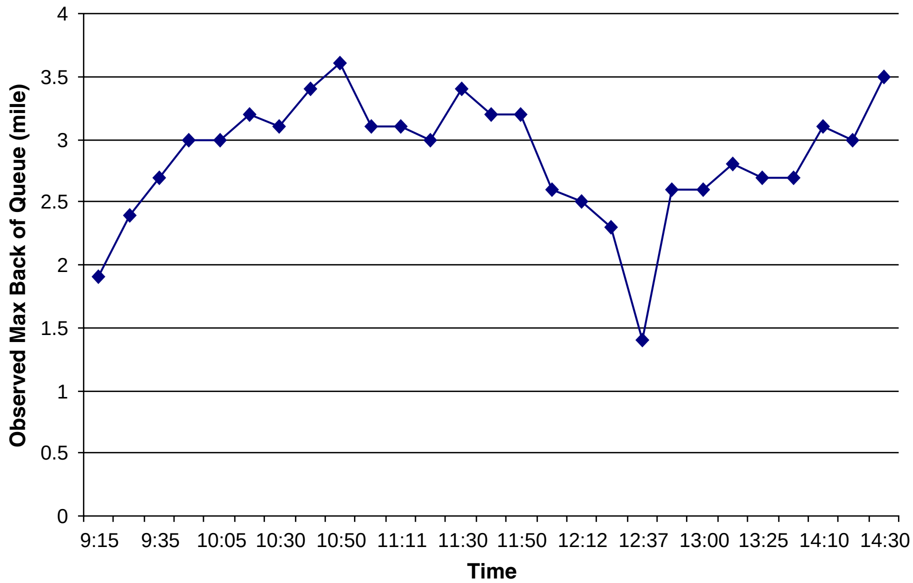


FIGURE 6 Observed maximum back of queue (WZ1).

zones and a noticeable distinction from the result of the WZCAT simulation. To reproduce the observed queue in WZCAT or similar simulation software, travel demand would need to be equivalent with the work zone capacity after the initial queue development. Because this is generally not the case, most software models show a growing queue, while field observations show a rather stable queue length.

DELAY ESTIMATION WITH RAMP TRAFFIC

On the basis of the observed work zone capacity and the length of queue variation, it is reasonable to believe that traffic movements at ramp terminals are strongly associated with traffic delay due to work zone operations as traffic delay grows. Figure 7 illustrates vehicle queue growth due to work zone operation on the urban freeway over time (t_0–t_2). The initial version of WZCAT calculates delay due to work zone operations based on two inputs. One input is work zone capacity, which is simply the capacity measured within a work zone (c_1). The second input is demand, which is traffic volume usually obtained from single detector location upstream of a work zone (d_1–d_6). Deterministic input (d_x) and output (c_1) calculation is applied to keep track of balance of queued vehicles (d_x–c_1) over time.

Initially, the study was focused in finding a single best upstream location (d_x) that can be used as a demand estimate that produced identical queuing patterns in the field. However, it was found that this input–output calculation with two attributes (c_1, d_x) generated the incessant growing queue that was quite different from field observations. Further reasoning found that this is because c_1 is reduced capacity due to work zone operation. So if c_1 is significantly smaller than any given d_x at time t, the balance of queued vehicles (d_x–c_1) at time t will always be much greater than 0, and the summation of the balance over time will produce a continuous growth of queue. Figure 8 shows a simplified queuing pattern with work zone on urban freeways.

To replicate this observation by using WZCAT, upstream traffic flow (d_x), which is an input demand, should become very close to work zone capacity (c_1) after the first 1 to 2 h from initial work zone setup, or the balance of input (d_x) and output (c_1) should be the same as summation of ramp traffic (R_1–R_4) upstream of work zone.

Table 3 shows traffic flow data obtained from loop detector locations upstream of work zone. The work zone was started at detector USH18 (221), and two lanes were closed among three

TABLE 2 Traffic Flow in Work Zones

	WZ1, 1 Open Lane	WZ2, 1 Open Lane	WZ3, 2 Open Lanes	WZ4, 2 Open Lanes	WZ5 and WZ6, 1 and 2 Open Lanes	WZ7, 2 Open Lanes	WZ8, 2 Open Lanes
WZ capacity—max. (vph)[a]	1,223	1,579	2,782	2,905	No data	2,852	2,659
WZ capacity—min. (vph)	985	1,060	2,564	1,900		2,636	2,143
WZ capacity—mean (vph)	1,134	1,279	2,710	2,705		2,774	2,643
Saturation flow rate (vph)[b]	1,100	1,269	2,613	3,770[c]		2,750	2,800
Heavy vehicles (%)	16	15	10	9	11	9	10

[a]Capacity was measured at the first detector location upstream of work zone (within 1,500 ft).
[b]Saturation flow rate was measured at the end of work zone.
[c]1 on-ramp exists very close to end of work zone and on-ramp traffic added to saturation flow.

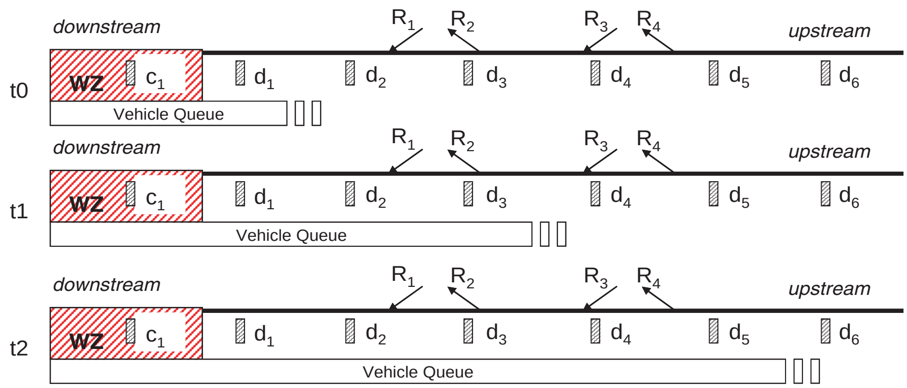


FIGURE 7 Queuing due to work zone operation at southeastern Wisconsin freeways.

existing lanes. A detailed analysis of the work zone revealed three major findings:

- As shown in Table 3, traffic flow at all main-line detector locations (207–219) are at least 1,000 vph higher than traffic flow at work zone (221). Therefore, deterministic queue calculation using a fixed work zone capacity and any given upstream detector location creates a continuous growth of queue, as seen in WZCAT.
- WZCAT uses only a single detector location for delay calculation, limited in its capacity to represent proper demand in queuing calculation as the end of queue moves, because if the selected location is too close to the work zone, it will become a part of the queue soon after work zone start. Also, if the selected location is too far from the work zone area, incorrect demand will be used for the queue calculation until the end of the queue becomes close to the location in WZCAT. Therefore, an appropriate demand for queue calculation should be obtained from the first detector location upstream of the queue at the beginning of the work zone, and it should be changed during work zone operation as the end of queue changed.
- There are many entrance/exit ramps on urban freeways, so the development of vehicle queue by any given work zone is likely to be extended beyond several entrance/exit ramps. Table 3 clearly shows that the proper consideration of entrance/exit ramp traffic significantly improves the performance of delay estimation. This shows that it will not be feasible to estimate the delay due to work zone activity without considering ramp traffic, even if the work zone capacity is known. Therefore, to improve WZCAT, traffic movement at each ramp terminal upstream of work zone should be included as a part of delay calculation routine, as well as a good estimation on ramp traffic changes due to work zone operation.

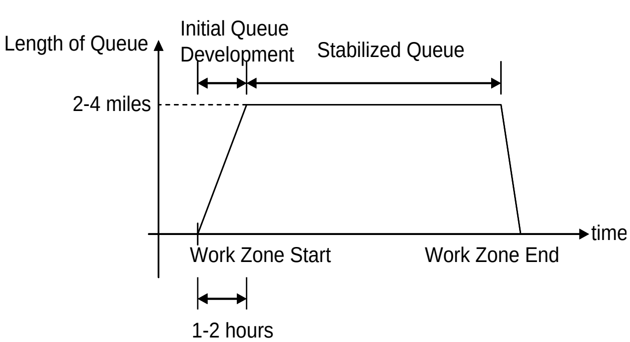


FIGURE 8 Vehicle queue development with work zone in urban freeways.

VERSION WZCAT-R

Two major enhancements were made to improve the delay estimation by WZCAT, leading to a version labeled WZCAT-R. First, all in and out ramps upstream of work zone within reasonable range were included in delay calculation. Second, a demand adjustment factor (DAF) was introduced to reflect travel demand increase or decrease due to work zone activities. Figure 9 shows the enhanced delay calculation with ramp traffic and the DAF. As vehicle queues grow and reach a ramp location upstream of the work zone, the DAF was applied to a historical hourly average traffic at that particular ramp location. The aggregated traffic flow including the entrance/exit ramp upstream of work zone was used as an input for deterministic input–output analysis.

The DAF aims to incorporate the significant amount of traffic volume changes on entrance/exit ramps upstream of work zones. For example, most entrance ramps located upstream of work zones showed 20% to 40% reductions in hourly volume due to work zone activities, compared with those of historical traffic volume, which is obtained from averaging traffic volumes from the same day of the week and time period for the 12 previous weeks. To reflect this in WZCAT-R simulation, DAF 0.6 to 0.8 was multiplied to historical traffic volume at the historical ramp traffic volume. Three different DAFs are applied to main-line, entrance ramp, and exit ramp separately. Each DAF is further refined to apply two different stages—initial queue development and stabilized queue—of queue developments due to work zone operation. According to field observations in this study, the first 1 to 2 h after work zone setup can be considered an initial queue development stage.

As for the main line, a 10% reduction of traffic flow due to work zone operations was considered; 0.6 to 0.8 DAF was applied to the entrance ramp, and 1.5 to 1.6 DAF was applied to the exit ramp. These parameters are empirical numbers obtained from the field observation in this study. Interestingly, these numbers showed minimal variation between work zones.

WZCAT-R produces much improved results for all four work zones that were evaluated. As can be seen in Table 4, the queue estimations by WZCAT-R are very close to field observations. Mostly, WZCAT-R generated rather wider variation of queue throughout the work zone hours. Mean absolute percentage error (MAPE), which

TABLE 3 Delay Calculation With and Without Ramp Traffic Consideration (WZ1)

	Work Zone Hours							
	8	9	10	11	12	13	14	15
Detector Location								
Underwood Creek Pkwy. (207) (mainline)	4,947	3,505	3,570	3,519	3,252	3,602	4,025	5,203
Elm Grove Rd. (208) (mainline)—*dx*	4,961	3,510	3,560	3,493	3,255	3,630	4,001	5,157
Sunnyslope Rd. (209) (mainline)	4,991	3,542	3,554	3,505	3,212	3,631	4,009	5,359
Woodridge Ct. (210) (mainline)—*dx*	4,780	3,541	3,580	3,489	3,199	3,626	4,009	5,253
Moorland Rd. NB (211) (exit)	923	*770*	*1,053*	1,033	1,236	1,173	1,110	860
E. of Moorland Rd. (1,322) (mainline)	3,872	2,809	2,509	2,452	1,964	2,724	2,855	4,352
Moorland Rd. SB (843) (exit)	437	390	*707*	824	805.5	787	898	563
W. of Moorland Rd. (212) (mainline)	3,604	2,381	1,760	1,586	1,786	2,166	1,935	3,871
Moorland Rd. (213) (entrance)	471	*418*	*347*	315	428	422	356	627
E. of Calhoun Rd. (214) (mainline)	4,304	2,740	2,145	1,981	2,266	2,441	2,344	4,873
Calhoun Rd. (215) (mainline)	4,222	2,663	2,160	2,081	2,241	2,465	2,396	4,851
Brookfield Lakes (216) (mainline)	4,277	2,569	2,146	2,149	2,171	2,526	2,388	4,881
Brookfield Rd. (217) (mainline)—*dx*	4,103	2,513	2,186	2,114	2,192	2,483	2,432	4,895
W of Brookfield Rd. (218) (mainline)—*dx*	4,073	2,519	2,188	2,087	2,252	2,437	2,471	4,907
Poplar Creek (219) (mainline)	4,118	2,611	2,199	2,116	2,327	2,459	2,546	4,996
Barker Rd. (220) (exit)	829	843	573	607	682	789	608	723
USH-18 (221) (WZ)	2,778	1,184	1,186	1,110	1,178	1,149	1,527	3,729
Moorland Rd. NB (211) (exit)—*R*4			−1,053	−1,033	−1,236	−1,173	−1,110	−860
Moorland Rd. SB (843) (exit)—*R*3			−707	−824	−805.5	−787	−898	−563
Moorland Rd. (213) (entrance)—*R*2			347	315	428	422	356	627
Barker Rd. (220) (exit)—*R*1	−829	−843	−573	−607	−682	−789	−608	−723
(1) Ramp InOut total (*R*1+*R*2+*R*3+*R*4)	−829	−843	−1,986	−2,149	−2,295.5	−2,327	−2,260	−1,519
(2) *dx*: WZ upstream (veh/h)	4,073	2,513	3,580	3,489	3,199	3,630	4,001	5,157
(3) *c*1: observed WZ cap(veh/h)	2,778	1,184	1,186	1,110	1,178	1,149	1,527	3,729
Delay Calculation								
WZCAT								
Queued vehicle at time t = (2) − 1,500 vph	1,295	1,013	2,080	1,989	1,699	2,130	2,501	1,428
(4) ? Queued vehicle at time t	1,295	2,308	4,388	6,377	8,076	10,206	12,707	14,135
(5) Estimated queue length (mi)	3.92	6.99	13.30	19.32	24.47	30.93	38.51	42.83
WZCAT with corrected WZ capacity								
Queued vehicle at time t = (2) − (3)	1,295	1,329	2,394	2,379	2,021	2,481	2,474	1,428
(4) ? Queued vehicle at time t	1,295	2,624	5,018	7,397	9,418	11,899	14,373	15,801
(5) Estimated queue length (mi)	3.92	7.95	15.21	22.42	28.54	36.06	43.55	47.88
Delay calculation including In/Out ramp traffic								
Queued vehicle at time t = (2) + (1) − (3)	466	486	408	230	−274.5	154	214	−91
(4) ? Queued vehicle at time t	466	952	1,360	1,590	1,315.5	1,469.5	1683.5	1,592.5
(5) Estimated queue length (mi)	1.41	2.88	4.12	4.82	3.99	4.45	5.10	4.83
(6) Observed queue length (mi)	1.9	2.7	3.3	3.6	2.7	2.6	3.1	3.5

NOTE: Traffic flow at first detector location upstream of the end of queue: [light shading]; work zone capacity: [dark shading].

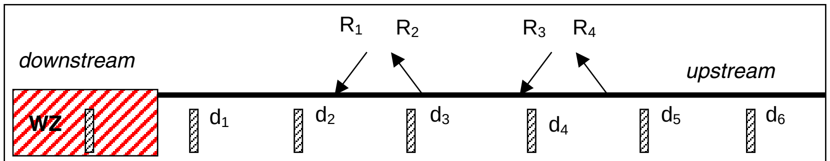
measures the accuracy of predicted value, was calculated along with the mean absolute deviation (MAD) to show the accuracy of predicted values produced by WZCAT-R. All MAD values for each of the four work zones were smaller than 1 mi.

CONCLUSIONS AND RECOMMENDATIONS

A traffic delay assessment software package was developed to predict the queuing impacts of short-term work zones in urban area where many entrance/exit ramps exist. Comprehensive field data were obtained from multiple work zones. Data collected included the queue length due to work zone activity, lane usage at the upstream of work zones, and traffic flow characteristics.

Traffic volumes from both the average of historical data and observed work zone day data were prepared and applied to WZCAT. Initially, WZCAT was not able to produce a pattern identical to what was observed during field data collection. WZCAT significantly overestimated the length of queue. Moreover, the pattern of queuing in WZCAT was very different in that queues continued to grow and never reached the steady-state condition that was observed in the field a short time after the work zone traffic control was deployed. Observed vehicle queue typically grew to its maximum length within the first 1 to 2 h after work zone setup and showed modest changes throughout the duration of the work zone, remaining in a relatively steady-state condition. This pattern was observed at most work zones on urban freeways where upstream interchanges were located.

Considering the structure of WZCAT, the inflated result was not directly related to any deficiencies within the software itself. Therefore, the study focused on validating work zone capacity and travel demand, which are the two major components of the input–output analysis in WZCAT. The observed capacities of the work zones remained rather constant and were close to the default value used in



d_x : Existing detector locations on freeway
R_x : Existing detector locations on ramp locations
$T_{d_x}^{H(t)}$: Historical traffic volume of detector location d_x at time t of day (vph)
$T_{R_x}^{H(t)}$: Historical traffic volume of detector location R_x at time t of day (vph)
$\theta_{main,enter,exit}$: Demand adjustment factor (DAF)
Dist_{d_x} : Distance between detector location d_x and the taper of work zone (mile)
Q_t : Length of traffic queue at time t (mile)
Del_t : Delayed traffic at time t (veh)

$$Del_t = Del_t + Del_{t-1}$$

$$\begin{cases} Del_t = [\theta_{main} \times T_D^{H(t)} + \sum^{X}[(-\theta_{exit}, \theta_{enter}) \times T_{R_t}^{H(t)}] - WZCAP & Q_t > Dist_R \\ Del_t = [\theta_{main} \times T_D^{H(t)}] - WZCAP & [\theta_{main} \times T_D^{H(t)}] - WZCAP > 0 \ \& \ Q_t < Dist_R \\ Del_t = 0 & O.W \end{cases}$$

$$\text{if } Del_t > 0 \text{ then } Del_t * \text{Fixed Vehicle Spacing } (40\ ft : HCM) = Q_t$$

FIGURE 9 WZCAT-R delay estimation.

WZCAT while travel demand requires a more careful analysis of upstream activities.

The study found that traffic changes on entrance–exit ramp terminals upstream of the work zone contribute to the stabilization of vehicle queue. Additionally, an appropriate main-line demand for queue calculation is required from the first available detector location upstream of the end of the vehicle queue.

WZCAT-R was developed to incorporate those findings, and it produces much improved results. In particular, consideration of all entrance/exit ramps upstream of work significantly improved the estimation of delay due to work zone activities on urban freeways. These traffic volume changes at ramps upstream are a very complex phenomenon. They also depend on drivers' perception of the downstream traffic conditions in addition to knowledge about the availability of alternate routes. However, even simplified demand adjustment parameters that can be cumulated and calibrated easily through continuous data collection efforts are very helpful in effectively and efficiently improving the accuracy of delay assessment. WZCAT-R produces effective results for queue prediction. It can be an effective and reliable tool in predicting work zone delay and queue development. Also, the tool can help engineers proactively plan work phasing, lane restrictions, and potential detour routes in an effort to move traffic more efficiently.

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TABLE 4 Result of WZCAT-R Simulation

	WZ1		WZ2		WZ4		WZ8	
Time	WZCAT-R	Obs.	WZCAT-R	Obs.	WZCAT-R	Obs.	WZCAT-R	Obs.
8	1.21	1.9	*	*	1.64061	1.9	0.1	0.3
9	1.85455	2.7	0.71232	0.7	3.33545	2.7	1.5303	0.75
10	2.24758	3.3	1.51217	1.62	3.43333	3.3	1.09121	0.8
11	2.86636	3.6	2.81211	2.52	4.07455	3.6	1.20636	0.9
12	2.93061	2.7	3.22121	2.56	4.89727	2.7	1.82667	1.28
13	3.42788	2.6	3.15	3.15	5.35242	2.6	1.32	1.35
14	3.712	3.1	3.1	2.9	2.82636	3.1	0	0.5
15	3.877	3.5						
MAPE (%)	23.84		8.8		35.79		55.14	
MAD (mi)	0.67		0.21		0.96		0.38	

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