Statistical Analysis on the Mobility Impact of Urban Work Zones using Geo-coded Lane Closure and Archived Loop Detector Data

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ABSTRACT

Lane closures as a result of freeway work zone constitute 10% of urban congestion and relate to more than 87,000 annual crashes in the US. Researchers have been studying the mobility characteristics of work zones for many years, focusing on speed reduction, queue length, and capacity based on traffic flow data manually processed or collected for a limited number of work zones. With the increased availability of ITS data, especially geo-coded ITS data, new opportunities emerge for studying and evaluating the mobility impact of work zones. In this study, taking advantages of the comprehensive statewide ITS data archived at Traffic Operations and Safety (TOPS) lab, we correlate the detailed work zone data available through the WisLCS system to the 5-min loop detector data archives using the Wisconsin linear reference system STN(State Truck Network)-Link. Two statistical methods, one-sample percentile value test and two-sample Komogorov-Smirnov(K-S) test, are proposed and implemented to compare the speed and flow characteristics between work zone and non work zone conditions. Neither method requires fitting the traffic flow data to specific types of distribution. Using those tools, we further analyzed the mobility characteristics of freeway work zones within the urban area of Milwaukee, WI, USA in 2010. More than 50% of investigated work zones experienced speed drops and about 15-30% also have reduced volumes. Speed drops are more significant within and downstream of the work zones than the upstream of work zones. .

INTRODUCTION

Freeway work zone is "a segment of highway in which maintenance and construction operations impinge in the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the segment. (*1*). " According to Highway Statistic 2008 (*2*), among the 8 million miles of public roads, more than 4% on average has lane closures related to work zones each year due to the growing demand of vehicle miles traveled, aging infrastructure, and highway improvement projects. Work zone activities on freeway may cause both the mobility issues such as such as capacity drop, traffic breakdown, and safety issues e.g. rear-end and sideswiping crashes. Inappropriately managed work zones can become active bottlenecks resulting in severe congestion, significant delay and lower driver satisfaction. In the U.S., work zones constitute 10% of the urban congestion which translates into annual fuel loss of over $700 million (3). In Germany, nonrecurrent highway congestion as a result of work zone accounted for 30% of the nation's traffic congestion (*4*). Traffic congestion caused by work zone can be classified into the nonrecurrent highway congestion that can be attributed to traffic incidents, weather, work zones, and special events. Work zones account for nearly 24% of the nonrecurring delay in the US. The safety issues of work zones also pose serious concerns. The US had 87,606 crashes in work zones in 2010 approximately 1.6% of the total number of roadway crashes (*5*). Among those work zone related crashes, 0.6% were fatal crashes, 30% were injury crashes, and 69% were property damage only crashes. This equates to one work zone injury every 14 minutes and one work zone fatality every 15 hours.

This study focuses on exploring the mobility impact of work zones. Reader can refer to (*6*) for a similar study on the safety characteristic of work zone. Existing studies on the mobility of work zones have focused on three main characteristics: speed reduction, queue length, and capacity. The speed reduction is usually studied through regression methods. Rahim et.al (*7*) developed a model to determine speed reduction due to work intensity, narrow lanes and shoulders by using video data from 11 interstate highway work-zone sites in Illinois. Rouphail and Tiwari (*8*) established a similar model and found that the observed mean speed at lane closure was 3 mph lower than the predicted mean speed using non-work-zone data on average. The modeling of queue length at work zones includes two main methods, the deterministic queuing diagram method (*9, 10*) and artificial intelligence method (*11, 12*). The capacity is also a critical mobility characteristic studied for work zones. The HCM (Highway Capacity Manual) recommends the short-term work zone capacity model originally developed by Krammer and Lopez (*13*), which used data collected in 33 work zone sites at Texas between 1987 and 1991. The model uses *1,600 pc/h/ln* as a base value and adjusts the results with three adjustment factors that account for the intensity of work activity, heavy vehicles, and the presence of ramps respectively. After adjustment, work zone capacity can be found within a 10% range of base value. Maze et.al (*14*) showed the volume was stable before and after queuing, whereas the average speed dropped based on Iowa work zone data collected. They also suggested that the capacity for rural highway work zone in Iowa were from 1400 passenger car (PC) to 1600 PC. Al-Kaisy et al. (*15*) examined queue discharge flow as a measurement for long term work zone capacity with the data from Toronto, Canada. The observed capacity values were within *1,800 pc/h/ln* to *2,050 pc/h/ln* although with a large variation. Other work zone models using linear regression (Kim et al. 16) and decision tree models (Weng and Meng. 17) can also be found in the literature.

In the existing studies, the data source is a key limitation. Many traffic flow data were collected on-site by using video cameras and automatic counting system (*7, 14, 16*); while others went manual process to correlate the work zone data with the corresponding loop detector data (*10, 15, 17*). Meanwhile, many DOTs and statewide traffic data centers have improved or are in the process of improving the GIS functionality of their systems by geocoding the traffic detectors and operational data (*18, 19*). This creates new opportunities on analyzing work zone mobility characteristics on a large scale (e.g. the freeway system within an urban area) and conduct continuous monitoring and routine evaluation of the work zone operations. Traffic Operations and Safety (TOPS) lab (*20*) at University of Wisconsin-Madison currently hosts an ITS data hub for Wisconsin DOT. Using this rich data source, we correlated the detailed work zone data with the 5-min loop detector data through a statewide linear referencing system to provide a comprehensive analysis of the mobility characteristics of work zones within the urban area of Milwaukee,

WI, USA. Meanwhile, we developed two statistical methods to evaluate the work zone impact, the one-sample and two-sample method based on the empirical distribution of speed and volumes.

WISCONSIN WORK ZONE DATA

The work zone and traffic data used in this paper come from two sources: the Wisconsin Lane Closure System (WisLCS) (*21*) and V-SPOC (volume, speed and occupancy) (*22*) loop detector data system. Both data sources are accessible through the WisTransPortal system developed and maintained by the Traffic and Operation Safety (TOPS) Laboratory at University of Wisconsin-Madison.

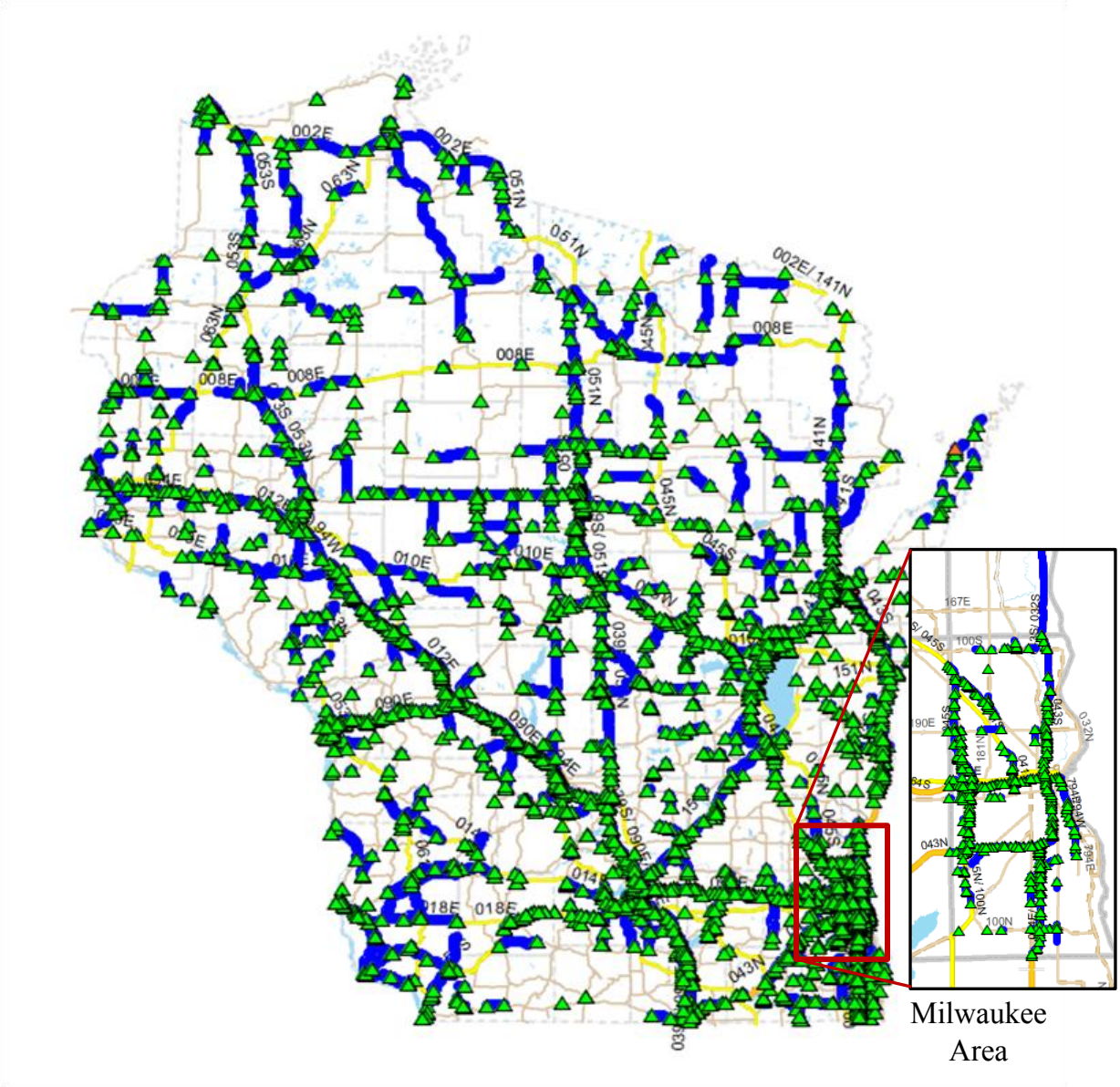

FIGURE 1 Wisconsin work zone locations 2010.

Wisconsin Lane Closure System

The Wisconsin Lane Closure System (WisLCS) provides a centralized management system for highway lane closures statewide since April 2008. The system includes a standard web-based interface and database system for local agencies in Wisconsin to report, approve, and track lane closures on state highways. It improves the completeness, reliability, and timeliness of lane closure data on state highways

in Wisconsin. The detailed information of each lane closure in Wisconsin includes work zone operation time, GIS information, work zone types, traffic impact etc. Meanwhile, its data archiving and retrieving system allows all the lane closure to be easily selected, classified and managed. In this study, we retrieve all work zones on state highway system in Milwaukee areas in the year 2010. The WisLCS returns 2297 work zones in Wisconsin during 2010 (See Figure 1). 40% percent of them were freeway work zones, and 307 of the freeway work zones located within the Milwaukee urban area. Within the 307 freeway work zones, 130 work zones are on the mainline which is the main focus of this study.

Wisconsin STN (State Trunk Network) Linear Referencing System

Wisconsin State Trunk Network (STN) is a GIS database of centerline files, shape files, and tables for state and federal highways in Wisconsin. STN also includes an STN-Link and STN-Chain linear referencing representation that enables corridor based analysis. STN-Link is a straight line bi-directional representation of state highways with the accurate link length; while STN-chain is a curvature representation that matches the geometry of state highways. TOPS lab receives annual updates of the STN database with the latest geometric changes. In STN-Link system, each link can be identified by its designated Route ID and Offset distance from the start of the route. Furthermore, the STN system also defines a statewide reference point (RP) system on STN-LINK system. Each point can be located with Route ID and offset. WisLCS uses this RP system to define the start and end of a work zone.

WisTransportal VSPOC (Volume, Speed, and Occupancy) Data System

TOPS lab also maintains a statewide, traffic detector data archiving and retrieving system for the Wisconsin Department of Transportation (WisDOT) Advanced Traffic Management System (ATMS) since 1997. The archived data contain five-minute volume, speed, and occupancy data obtained from WisDOT ATMS freeway detectors. The entire database is updated daily with data from the previous day. The V-SPOC (Volume, Speed, and Occupancy) is a web-based interface for data query, data visualization, data exporting, quality reporting, and corridor analysis. Traffic data archived in this system includes five main regions including North central, Northwest, Northeast, Southwest, and Southeast region. Milwaukee area is within the southeast region which includes 959 freeway count locations. It should be noted that in Milwaukee area loop detectors on the freeway are all "traps" (dual loop detectors) which can provide an accurate reading of spot speed at the detector location.

METHODOLOGY

Spatial-Temporal Correlation between WisLCS and VSPOC Data

TOPS lab is in the process of geocoding all loop detectors onto the STN-Link system and currently, all loop detectors in the Milwaukee area have been geocoded with several GIS coordinate systems including longitude and latitude, state plane, and the linear referencing coordinates in STN-Link and STN-Chain. Using the route and route offset information in the STN-Link system, each work zone can be spatially matched with detector locations that are within, upstream, and downstream of the work zone and all traffic data within the work zone duration and the corresponding non-work-zone data at the same time of the day can be obtained. More specifically, given a work zone located between two RPs, RP1 (r_1, o_1) and RP2 (r_2, o_2), where r_1 and r_2 are route IDs, o_1 and o_2 are the corresponding offset on their routes, respectively. Assume the work zone duration is specified by a date range (d_1, d_2), and a time of day range (t_1, t_2), where d_1 and d_2 are the starting and ending date, t_1 and t_2 are the starting and ending time of day. Then database views can be created to obtain the corresponding traffic data at time t and day d at location (r, o) where r and o are the route ID and offset of the detector respectively. The spatial matching scenarios are as the following.

Within

$$r_1 = r_2 = r \text{ and } o_1 \le o \le o_2$$

Upstream

$$r_1 = r_2 = r \text{ and } o_1 - d \le o \le o_1$$

Downstream

$$r_1 = r_2 = r \text{ and } o_2 \le o \le o_2 + d$$

where d is the predefine buffer distance towards the upstream and downstream of a work zone. In this study, d = 0.5 mile (0.805 km). Since the duration of a work zone is specified by a date range and a time range within a day, there are two temporal matching scenarios depending on the time order of t1 and t2 as follows.

Within midday:

$$d_1 \le d \le d_2 \text{ and } \boldsymbol{t}_1 \le \boldsymbol{t} \le \boldsymbol{t}_2$$

Passing midnight:

$$d_1 \le d \le d_2 \text{ and } t_2 \le t \text{ and } t \le t_1$$

Statistical Evaluation Methods

In this study, we propose two statistical methods to identify the difference between the work zone and non-work-zone traffic speed and volume. Field speed and volume readings may not always follow a specific type of distribution, and sometimes can even have irregular shapes. Therefore, in this study, we select statistical comparison methods that 1) do not assume specific underlying distributions, e.g. Normal or student-T distribution; 2) do not require the calibration of specific types of distribution. In this way, the reliability and generality of the proposed methods can be ensured when used against field data. Furthermore, two types of statistical tests, one-sample test and two sample test comprehensively evaluate the traffic impact of work zones for both the time-of-day differences and the collective traffic flow impact during work zone duration.

One-Sample Test based on Percentile Values

Denoting the random variables of speed (or volume) at a five-minute time interval i of the day as $X^{(i)}$ within samples (x_n, n =1, …, N, where N is the total number of five-minute readings during the investigation time periods). In the one sample test, evaluate if any measurement $x_n^{(i)}$ during the period of a work zone is significantly different from the mean using one-tailed or two-tailed tests. One-tailed tests evaluate whether significant impact on speed (or volume) occurs. Two-tailed tests identify significant speed (or volume) drop or increase. Let $\{\bar{x}_n, n = 1,...,N\}$ be a reordering of $\{x_n\}$, s.t. $\bar{x}_1 \le \bar{x}_2 \le ... \le \bar{x}_n$. Then the significant values for the one-tailed and two-tailed tests can be calculated using the p^{th} percentile value in the reordering. The index of freeway detector location is denoted as d, $\forall d = 1, 2, ..., D$ and D is the total number of work zone related detectors. Given these notations, the p^{th} percentile speed (or volume) of detector location d at the i^{th} five-minute time interval of the day can be calculated as

$$x_p(d,i) = \bar{x}_{(m)}(d,i)$$

such that

$$m = [Np] + 1$$

where N is the total number of days, and $[Np]$ is the greatest integer smaller or equal to Np. Then we apply the following hypothesis test using the empirical percentile values as the following.

H_0: There is no significant difference between the selected work zone data and the rest of data within the same distribution.

One-sample test method compares the work zone traffic measures at each time interval of the day during work zone period with the historical traffic state pattern. More specifically, for greater than, the 85^{th} percentile value is used; while for less than the 15^{th} percentile value is used.

Two-Sample Komogorov-Smirnov (K-S) Test

The two sample Komogorov-Smirnov (K-S) (*23*) test is based on the maximum difference between two cumulative functions. The method can effectively test whether these two underlying one-dimensional probability distributions are significantly different without knowing fitting the data into a specific distribution. Meng et al. (*24*) applied this test for evaluation headway distribution by using work zone data. However, the nonparametric nature of this test allows it to be used for other traffic variables. The traffic data from the same month of work zones are divided into two sets, work-zone and non-work-zone data. Denote the two work zone data sets as follows.

$X_w = \{x_{wd}(d, i) \mid d \in$ non work zone operation days, $i \in$ work zone operation time$\}$

$X_n = \{x_d(d, i) \mid d \in$ non work zone operation days, $i \in$ work zone operation time$\}$

In order to test whether the work zone data sample has the same cumulative distribution as that of non-work-zone data, $F_{n'}(x)$, K-S test uses the following statistics

$$D_n = \max\{S_n(x) - F_{n'}(x)\}$$

where $S_n(x)$ is the cumulative distribution function of work zone data. When D_n exceeds the critical values for confidence level α, the K-S test rejects the null hypothesis and reports greater than (or less than) for one-tailed test. Moreover, this study uses the two-sample K-S test function implemented in Matlab® .

DATA PROCESSING AND EVALUATION SCENARIOS

The data processing procedure starts with 130 candidate mainline work zones in the Milwaukee urban area. All work zones are first inspected for their traffic data availability. Work zones may cause issues to the electrical and communication system for detectors and field crew may sometimes shut down the detectors to protect those systems. Meanwhile, the work zone operations can also cause false alarms and calibration errors with the loop detectors. A series of detector quality screening criteria are executed using database view (*25*). The screening test eliminates about 56 work zones whose detector data are invalid 40% of the time. None of the long term work zones passes the availability test since the detectors usually get shut down during long-term road work in Milwaukee. Table 1 shows the detector data validity statistics within, upstream and downstream of different types of short-term work zones.

TABLE 1 The Data Validity Rate of Filtered Work Zones

	Work Zone Types	Count	Within	Upstream	Downstream	Total
Lanes Affected	Single Lane	49	53.3%	71.8%	70.3%	61.2%
	Two Lane	22	52.7%	94.5%	73.5%	58.6%
	Shoulder	3	83.5%	N/A	32.1%	71.7%
Peak/ Off Peak	AM Peak Closure	16	68.1%	67.7%	64.3%	67.6%
	PM Peak Closure	14	75.1%	59.9%	68.5%	71.8%
	Day Off Peak	10	68.3%	68.3%	68.3%	68.3%
	Night Off Peak	59	55.0%	72.8%	72.0%	59.8%
Total		74	55.3%	74.4%	69.8%	61.0%

As shown in Table 1, the average valid rate of detector data among the selected work zones is around 61%. Detector data valid rate within a work zone is lower than that of the upstream and downstream which can be expected. When breaking down the availability rate by lanes affected and peak or nonpeak hours, the valid rates of different categories are quite similar. The shoulder lane closures do not have detectors within the 0.5 mile (0.805 km) upstream of the work zones. The valid rate is lower at night which may be caused by the lower traffic volume. The volume and speed measurements are used to analyze the work zone mobility impact. Meanwhile, since the VSPOC data are lane-specific, at each count location, traffic data from all lanes are aggregated to form the approach volume and speed for

further analysis. Assume the detector reading for time t across lane l = 1, …, L, can be denoted by $q_l(t)$ and $v_l(t)$, then the approach volume *q(t)* and speed *v(t)* can be calculated as follows:

$$q(t) = \sum_l q_l(t)$$

$$v(t) = \sum_l [q_l(t) v_l(t)] / q(t)$$

Evaluation Scenarios

In this study, the mobility characteristics within, upstream, and downstream of work zones will all be investigated. From the work zone performance monitoring point of view, we use one-tailed instead of two-tailed tests for both one-sample and two-sample methods. Furthermore, for traffic flow upstream of a work zone, speed drop, volume drop, and volume increase are evaluated. Volume increase is included to evaluate the potential travel demand increase upstream of work zone. For detector data within work zone, the key focus is to evaluate the performance reduction; hence only the speed drop and volume drop tests are conducted. Traffic data downstream can provide insights regarding the traffic flow discharged from work zone. The speed increase, speed drop, and volume drop are all evaluated at this location. The speed increase is included to capture the possible acceleration of traffic flow passing through the work zone location. Meanwhile, the drop of traffic state is compared with 15th percentile values; while the increase is compared with 85th percentile values.

RESULT ANALYSIS

One sample test result analysis

One sample test examines whether the work-zone detector data fall into the significant tails of the historical distribution of non-work-zone detector data for the same time interval of day. A total of 74 work zones, 181 detector locations, and 16,531 observations are examined to identify the mobility impact on speed and volume due to work zone.

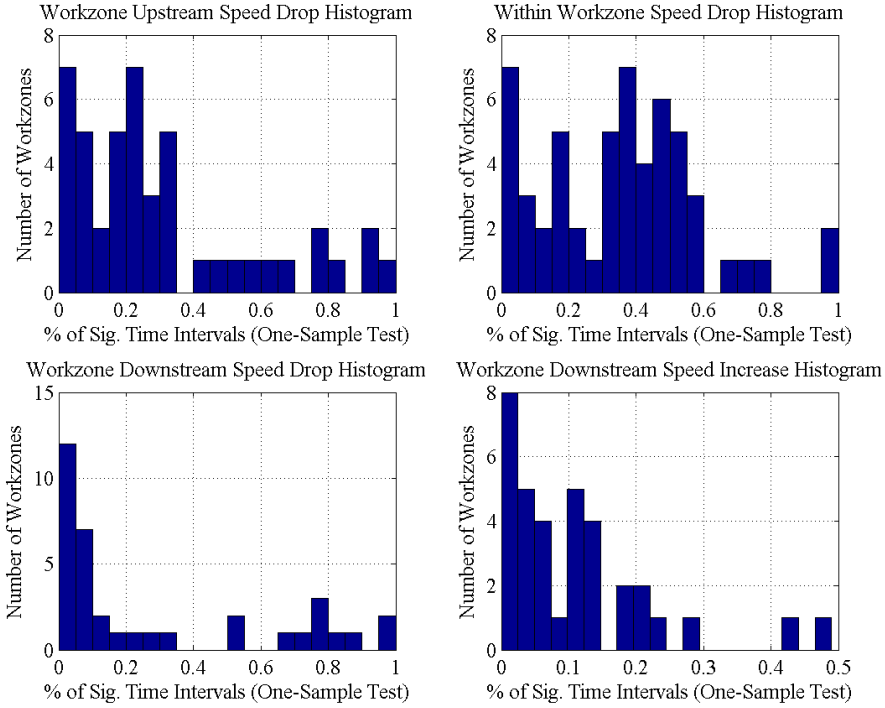

FIGURE 2 Histogram of one sample speed test.

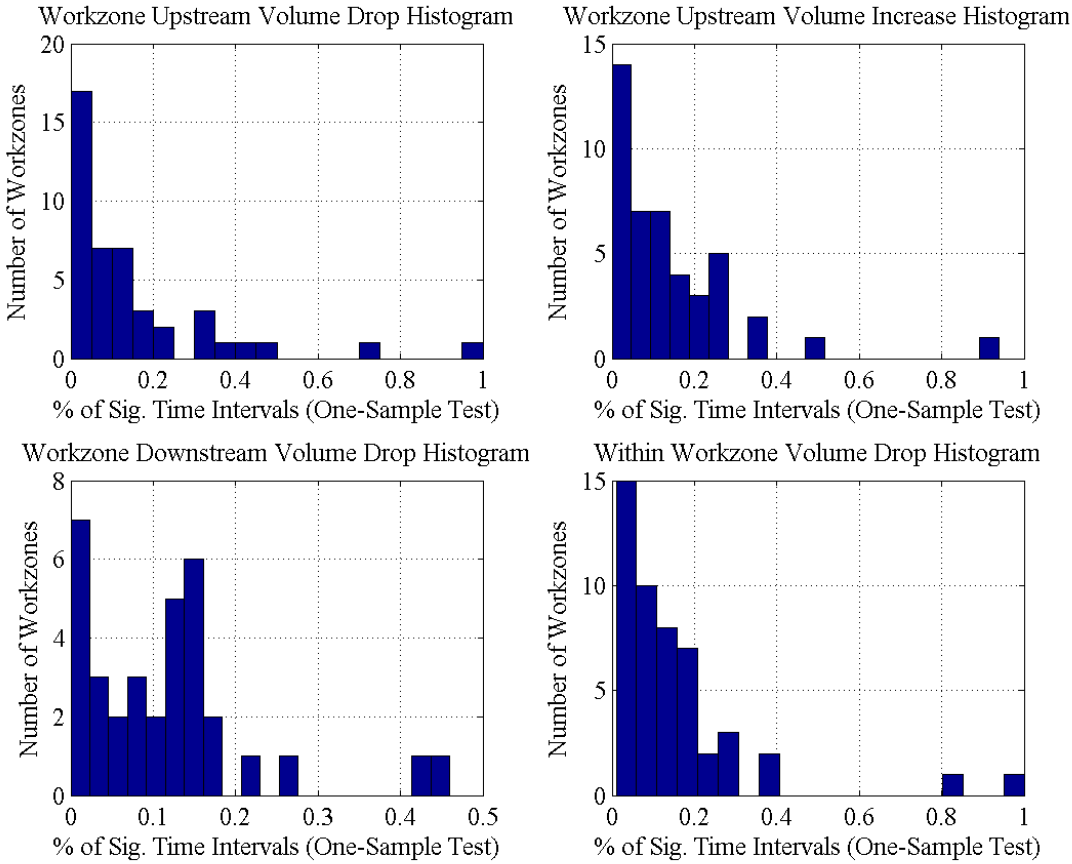

FIGURE 3 Histogram of one sample volume test.

Figure 2 illustrates the histogram of the percentages of the total number of time intervals rejected by the null hypothesis for each testing scenario. Based on the histogram, significant speed drop can be observed both within and upstream of many work zones with more than 80% of the work zones 20-100% of the time during work zone period. Speed drop is also observed at downstream although the number of detectors available is not as many as those within and upstream of work zones. The speed increase at the downstream can be observed at half of the work zones 10-50% of the time intervals during work zones. Figure 3 displays the percentage histogram for all volume testing scenarios. It can be observed that at many work zones. The percentages of time intervals with significant volume drop are less than 20%. Meanwhile, about half the studied work zones experienced volume increase 10-40% of the time during work zone. This may indicate the demand increase upstream induced by work zones.

Two sample K-S test result

Among the 74 work zones, 18 work zones with the valid detector data at all three locations, upstream, within, and downstream are selected. The speed and volume at the three relative locations of 18 selected work zones are examined by K-S test at 0.05 confidence level respectively. Table 2 listed the testing results for the speed at all 18 work zones. At the upstream location, four work zones experience speed increase; while half of the work zones experienced speed decrease, indicating the effectiveness of temporal speed limit or the backward-propagated traffic congestion from the work zone location. Within the work zones, 16 out of 18 work zones experienced significant speed drop when the work zones were active. At the downstream location, travel speed at half of the work zones dropped significantly, indicating that vehicles getting out of the work zones did not recover their normal speed within 0.5 miles (0.805 km).

TABLE 2 Speed Tests of Two Sample Test

WORK ZONE	UPSTREAM		WITHIN		DOWNSTREAM	
	Impact	P-value	Impact	P-value	Impact	P-value
1	+	1.76E-03	-	1.07E-23	=	5.87E-02
2	-	3.02E-07	-	1.35E-14	-	5.34E-04
3	=	1.59E-01	-	1.62E-22	=	2.87E-01
4	=	2.73E-01	-	3.86E-22	-	4.01E-04
5	-	3.64E-12	-	7.76E-05	-	9.94E-19
6	-	2.09E-10	-	2.13E-05	-	3.58E-04
7	+	9.70E-14	+	2.93E-22	+	2.05E-08
8	-	2.09E-08	-	3.67E-06	=	6.37E-02
9	-	5.48E-04	-	1.06E-02	-	1.62E-02
10	=	1.31E-02	-	1.13E-09	=	1.60E-01
11	=	1.54E-01	-	1.29E-04	-	4.29E-05
12	+	2.63E-16	-	4.03E-27	=	1.07E-01
13	-	3.36E-02	-	1.43E-05	-	2.17E-02
14	-	3.07E-10	+	2.30E-02	-	1.06E-02
15	+	1.75E-02	-	1.99E-11	NA	NA
16	=	1.71E-01	-	3.99E-23	NA	NA
17	-	1.00E-04	-	8.91E-20	-	2.13E-48
18	-	7.08E-22	-	1.38E-20	=	1.79E-01

Note: + increase, - drop, = unchanged

To further check the details of two-sample test results, the speed CDF (cumulative distribution function) plots of the K-S tests are evaluated. It can be observed that K-S tests are quite sensitive to the dominating relationship between the tested two CDF curves. As illustrated in Figure 6(a, b, f), even though the decrease is only around 3-5 km/h, K-S tests still report significant test results. At the meantime, Figure 6(c, d, e) all exhibit significant differences in speed CDF plot.

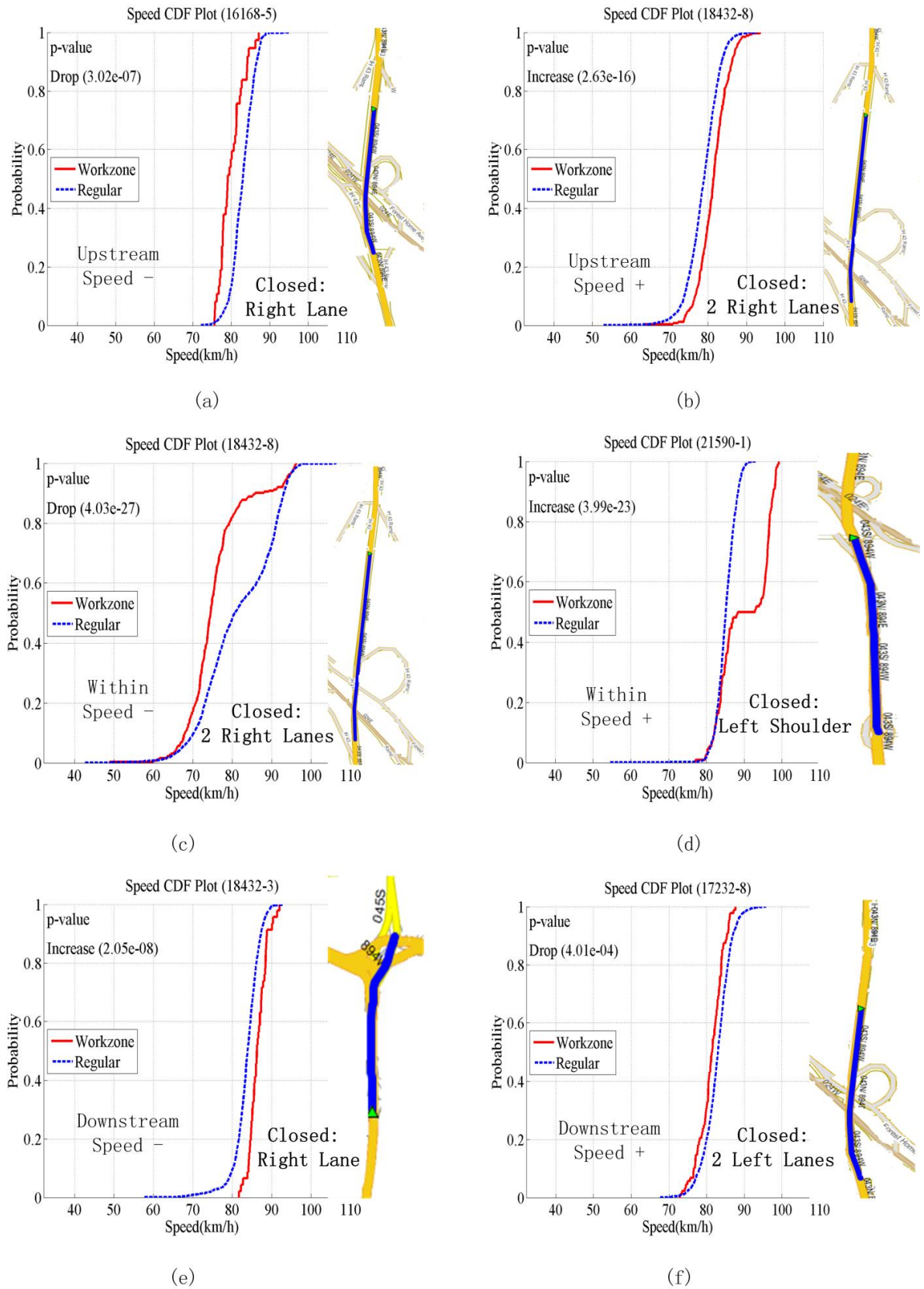

FIGURE 4 Example of K-S speed test with work zone layout.

Table 3 evaluates the volume test results at the three relative locations of a work zone. At the upstream location, traffic volume at 7 locations experienced decrease, remain unchanged for 8 work zone locations. Traffic volumes within 9 work zones are found to be unchanged most of the time during work zone, indicating insignificant traffic breakdown during those work zone periods. At the downstream location, five work zones experienced volume drop; while the volume of the other work zones remain unchanged.

TABLE 3 Volume Result of Two Sample Test

WORK ZONE	UPSTREAM		WITHIN		DOWNSTREAM	
	Impact	P-value	Impact	P-value	Impact	P-value
1	+	1.74E-02	+	1.70E-02	=	9.41E-04
2	=	2.70E-01	=	9.86E-03	=	1.86E-04
3	+	2.22E-02	=	1.18E-01	=	2.10E-04
4	=	4.18E-01	=	6.42E-02	-	1.88E-02
5	-	2.20E-05	-	2.53E-05	-	1.28E-03
6	-	2.10E-59	=	1.20E-01	=	8.16E-02
7	=	2.30E-01	=	1.41E-01	=	2.57E-01
8	-	1.00E-03	-	1.28E-02	-	5.66E-03
9	-	2.10E-04	=	5.92E-02	-	1.51E-02
10	-	3.14E-03	-	8.10E-03	-	1.21E-02
11	=	1.62E-01	+	9.61E-03	=	4.68E-04
12	=	9.34E-01	=	9.56E-01	=	1.66E-01
13	=	1.50E-01	+	7.92E-03	+	3.75E-54
14	-	4.32E-09	-	1.37E-07	=	3.43E-10
15	=	4.83E-01	=	5.86E-01	NA	NA
16	=	5.73E-01	=	3.64E-01	NA	NA
17	+	1.33E-06	+	5.23E-05	=	7.94E-05
18	-	3.58E-07	-	5.98E-10	=	4.54E-04

Figure 5 illustrates the CDF comparison results. Except for Figure 5(d), significant difference between the distributions can be observed. In Figure 5(d), even though the changes in volume are small, the dominance of the regular traffic volume over the work zone traffic volume can still be observed.

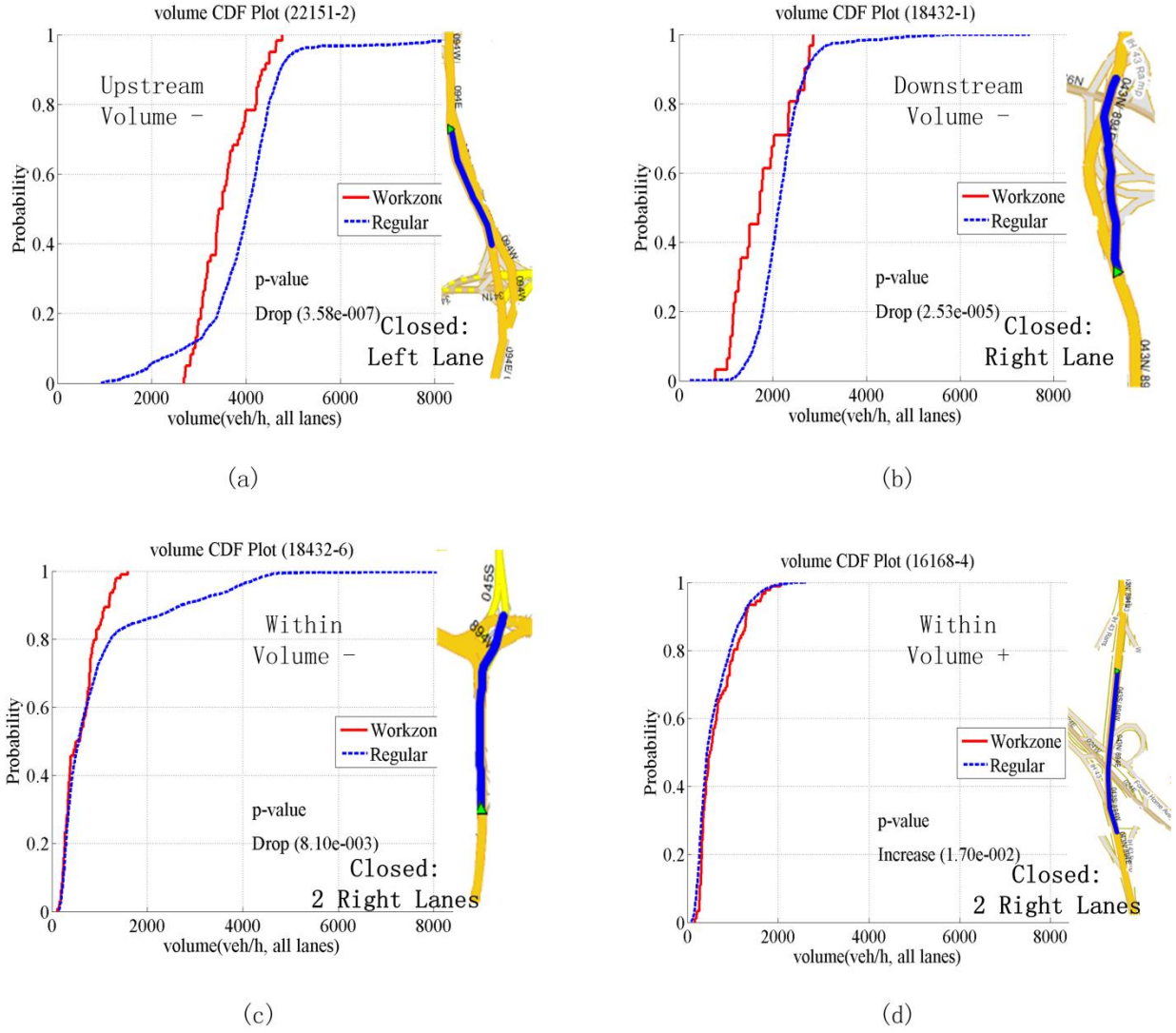

FIGURE 5 Example of K-S volume test with work zone layout.

TABLE 4 The Percentage of Work Zones Experiencing Significant Changes in Speed or Volume

	One-Sample Test				Two-Sample Test			
Location	Spd+	Spd-	Vol. +	Vol.-	Spd+	Spd-	Vol. +	Vol.-
Upstream	--	44.74%	10.50%	21.05%	--	44.4%	16.7%	38.9%
Within	--	58.33%	--	8.33%	--	88.9%	--	27.8%
Downstream	4.00%	24.00%	--	8.00%	13%	56.3%	--	31.25%

Note: -- = not applicable

Table 4 compares the overall test results between one-sample and two-sample tests. The percentage within each cell is calculated by the number of work zones that are significant in a testing scenario over the total number of work zones. A work zone is only considered significant for the corresponding test scenarios if more than 30% of the time the null hypothesis is rejected. The results from both tests are consistent in general with discrepancy in describing the severity of the speed drop and volume drop among the investigated work zones. The two-sample test may overestimate the speed or

volume drops since it is quite sensitive to the dominance relationship on CDF even with minor difference overall.

CONCLUSION

This study proposes two evaluation tools, one-sample percentile value test and the two-sample K-S test, for work zone mobility monitoring and evaluation. Both tests can identify the work zone mobility impact by comparing work zone data and normal data without assuming specific types of statistical distribution. The spatial-temporal correlated WisLCS and VSPOC data available from the WisTransPortal website are used as input the evaluation tests. The mobility characteristics of freeway mainline work zones at the Milwaukee area in 2010 are analyzed using the proposed tools. More than 50% of work zones experience speed drop within and upstream of the work zones. Such phenomenon may be caused by drivers' compliance with the temporal work zone speed limit and possible congestion built up and its propagation towards upstream of the traffic flow. Meanwhile, speed increase can be observed in half the work zones for 10-50% of the time. The two-sample tests generate similar results, although higher estimates on the number of work zones with volume drop, which may be caused by its high sensitivity to the domination of one CDF curve to another even with small overall differences.

Future work of this study may include the following directions. First, due to the strict screening criteria, many work zones with only partial valid data are eliminated. Since the proposed methods are distribution based, exploring the work zone characteristics may still be possible for work zones with only partial detector data. Second, parameters in the proposed tool such as the *p*th percentile, significant percentage threshold for one-sample test and the confidence level for two-sample test need to be calibrated and validated. Third, further improvement may be needed to improve the K-S test methods to accommodate the situation when the CDF of one speed distribution is the same as the original one..

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