Real-time Traveler Information Performance Measures for Work Zone Congestion Management

by Xiao Qin, Yali Chen, and David A. Noyce

To mitigate the work zone impacts on freeways, an advanced traveler information system (ATIS) was designed to promote the utilization of alternative routes and improve local road network performance. The system evaluation was performed during a bridge reconstruction project on the four-lane divided I-39/90 near the interchange with WIS59 at Edgerton, Wisconsin.

Field comparisons between ATIS presence and absence discovered different diversion patterns in northbound and southbound directions associated with traffic delay. Drivers remained on the freeway when the displayed delay was less than 15 minutes while more drivers chose to leave the freeway with displayed delay greater than or equal to 15 minutes. A linear regression analysis was further conducted to investigate the impact of several factors, such as displayed delay time, freeway volume, exiting volume during the normal days (without a work zone), and the number of days after system implementation, on driver's diversion behavior. The results showed that freeway volume, ramp exiting volume during normal days, and delay time were significant variables in causing a high diversion rate.

In addition, it was demonstrated that ATIS performed effectively in increasing the work zone operational capacity. Furthermore, the reduced operating speed associated with the advance speed warning (part of the system) suggested that drivers reacted to the warning messages responding to the real-time speed collected through detectors. This comprehensive evaluation enriched the knowledge of driver behavior and reaffirmed the effectiveness of ITS applications in congestion mitigation.

INTRODUCTION

Work zones are becoming more visible on all highway types because of the need to preserve and upgrade the transportation infrastructure. More construction is expected after the $787 billion stimulus package was signed into law. However, reduction in operating speed and the number of lanes is inevitable due to typical work zone activities. The likelihood of crashes may increase because performing construction activities on existing roads creates conflicts between work and traffic flow. In addition, work zones present an unusual traveling condition that often violates drivers' expectancy. Unaware of the real-time traffic conditions in or near work zones, drivers often experience unnecessary delay. Excessive delay causes anxiety and frustration, which becomes one of the major attributing factors to work zone crashes. The reduced roadway capacity, increased congestion, and related safety issues emphasize the importance of conveying prevailing travel conditions to drivers.

In response, an advanced traveler information system (ATIS) can be implemented in a work zone to communicate real-time traffic information to roadway users and facilitate drivers' decision making. The ATIS was implemented on I-39/90, a Wisconsin suburban freeway work zone, where the system's performance was assessed quantitatively. The system included two major components: real-time delay information and advance speed warning. The system was designed to advise and guide motorists to drive through the work zone safely and efficiently. It was assumed that drivers might take an alternative route to avoid congestion according to the delay information they received on the portable changeable message signs (PCMSs). As a result, the congestion on the reduced capacity road could be mitigated if reliable delay time was available. Besides the delay information, another PCMS provided a warning message of either slowed or stopped traffic ahead when travelers approached the work zone where the queue was present. The advance speed warning message was aimed at reducing the risk of rear-end crashes. The entire system was based on a series of detectors which continuously collected and relayed real-time traffic information through wireless communication to the PCMSs. The key objectives of the study are to estimate the driver's tolerance threshold for delay, to evaluate the system performance, as well as to identify the contributing factors in driver's detour decision making.

LITERATURE REVIEW

With the advancement of intelligent transportation systems (ITS) and the growing applications in transportation management, substantial studies have been conducted to evaluate the effectiveness of real-time traveler information. In the 1990s, several studies found that the process of individual decision making is complicated, depending on the alternative route availability, the route preference, the value of time, the traveler information reliability, driver's gender and age, and other socio-economic factors (Khattak et al. 1993a, Khattak et al. 1993b, Lotan 1997). The topic continues to draw a significant amount of research interest and attention. In Minnesota, researchers developed a route choice model to predict how drivers respond to the information provided by variable message signs (VMSs) and whether drivers will divert to avoid incidents (Levinson and Huo 2003). The study identified the percentage of drivers diverting to alternative routes, network-wide travel time benefits, and delay time savings as the main performance measures. Empirical traffic flow and vehicle density data were collected from pavement sensors on freeway and freeway ramps, as well as the messages on VMSs for one month, and a detailed incident log for 10 years. The study revealed that the diversion rate was significantly impacted by factors such as alternative exit availability, nature of incident (congestion or crash), time period, type of message, and the interaction between alternative exit availability and type of message. VMS was shown to be less effective under heavy traffic due to the difficulty in lane changing and merging.

Compared to the urban setting in Minnesota, several real-time information systems were applied and evaluated in work zones with no recurrent-congestion environments (Horowitz et al. 2003, Tudor et al. 2003, Chu et al. 2005a, and Lee and Kim 2006). The influence of VMS on alternative route selection for rural Wisconsin freeways was examined through the travel information prediction system (TIPS) implemented to warn drivers of estimated real-time delay (Horowitz et al. 2003). TIPS provided drivers with real-time travel time information through a collection of PCMSs, two signs on the freeway before two off-ramps and two signs on the local streets before the on-ramps. Each sign had two message frames indicating the distance to the end of the work zone and estimated travel time. The impact was measured mainly by traffic volume changes before and after the implementation of the travel time signage system. It was reported that alternative route selection did not occur prior to the work zone after the first freeway sign on both weekdays and Sunday. However, the PCMSs boosted the alternative route use from 7% to 10% after the second freeway sign.

Two smart work zone management systems, automated data acquisition and processing of traffic information in real-time (ADAPTIR™) and computerized highway information processing system (CHIPS™), were implemented and evaluated in five Arkansas work zones (Tudor et al. 2003). The comparison between work zones with and without the systems suggested that these systems improved safety by decreasing both fatal and rear-end crashes.

In addition, an automatic work zone information system (AWIS) was implemented in southern California and evaluated via the resulting traffic diversion and safety impacts (Chu et al. 2005a, Lee and Kim 2006). Chu et al. (2005a) observed the decrease in the maximum freeway delay and further suggested that AWIS improved safety by smoothing traffic flow. Another AWIS in Southern California was implemented in an effort to reduce peak hour delay in work zones by changing road user's travel patterns and diverting traffic to detour routes. The commuter survey indicated that approximately 90% of travelers thought the estimated travel time was accurate, and more than 70%

of drivers changed their travel pattern, such as travel schedules, trip routes, and modes (Lee and Kim 2006).

In addition to field evaluations, several studies applied simulation models to demonstrate the benefit of implementing a real-time traveler information system in terms of reducing queue length and maximum user delay (Bushman et al. 2004 and Chu et al. 2005b). Bushman et al. (2004) used QuickZone 1.0 software to evaluate the delay time system based on the scenarios of without and with the traveler information system. Chu et al. (2005b) studied the diversion under AWIS using PARAMICS simulation models. The simulation evaluation concluded that the system can effectively reduce traffic delay by comparing the delay reduction on the freeway between before and after periods.

STUDY DESIGN

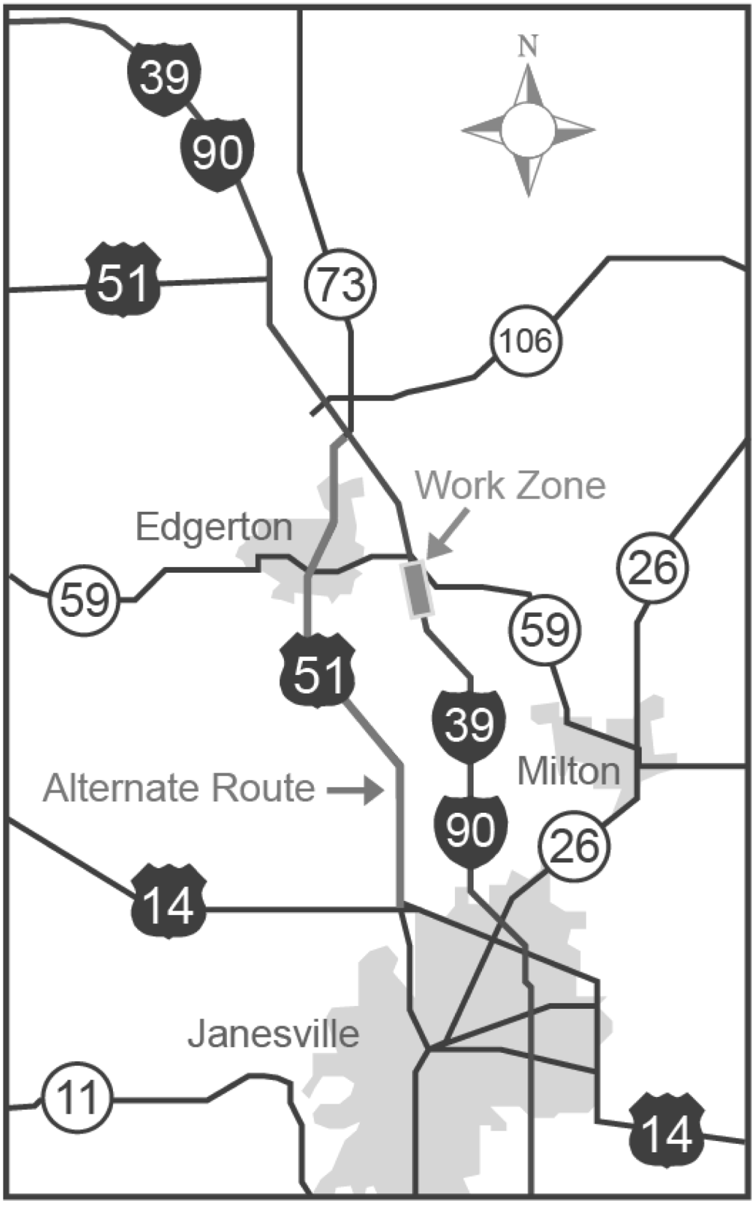
Project Background

The Wisconsin Department of Transportation (WisDOT) performed a bridge repair from September 29 to October 10, 2006, a total of 12 days of construction operations, near the interchange of I-39/90 and WIS59 at Edgerton, Wisconsin. The purposes of this work zone included replacement of the deteriorating back walls on the bridge abutments and resurfacing for a one-half mile segment on I-39/90 south of the Rock River. Therefore, during the rehabilitation, the northbound bridge was completely closed, and traffic was routed to the southbound by a median crossover, converting the southbound segment from one-way to two-way traffic. This segment of I-39/90 is a four-lane divided roadway (two-lane in each direction) carrying over 54,000 vehicles per day. The reduction from two-lane to one-lane in each direction will cause congestion. Hence, WisDOT provided an alternative route allowing drivers to divert from I-39/90 to avoid excessive delay. The designated alternative route in Figure 1 included US 14 and US 51, both two-lane undivided highways. Northbound drivers can take an exit ramp to US 14 and return to I-39/90 via an entrance ramp from US 51. Southbound drivers can divert to US 51 and return to I-39/90 from US 14. In addition, a real-time ATIS was implemented to facilitate drivers' detour decision making.

Advanced Traveler Information System (ATIS)

The system evaluated was designed and deployed by a Minnesota-based traffic consulting firm. It consisted of four key components: 1) microwave/Doppler radar traffic sensors, 2) master controller (the central controller that processes and transmits all the signals received), 3) portable changeable message signs (PCMSs), and 4) communications. Two types of communication links were used to transfer data among detectors, master controller, and PCMSs: a radio-based communication between the detectors and master controller and a modem-based communication channel between the master controller and PCMSs. The delay time was defined as the difference between the estimated travel time based on real-time traffic data and the travel time under free-flow condition. The sensors continuously collected speed data and relayed them to the master controller. The algorithm in the master controller calculated the instantaneous travel time based on the collected speed data from which the delay time was derived as the difference between the congestion and free-flow conditions.

Figure 1: Work Zone and Detour Route



The approaching area was divided into several segments by the sensors. For each segment, the travel time was calculated by dividing the distance between two sensor locations with the average speed of the sensors. Next, the total travel time before entering a work zone (the sum of all the travel times in individual segments) was compared against the travel time under free flow condition to calculate the delay time. The actual delay time posted was further calibrated through the travel time studies and observed queue length.

(1) $$DT = \sum_{i=1}^{n} \frac{l_i}{(v_i + v_{i-1})/2} - \sum_{i=1}^{n} l_i / v_f$$

Where:

DT – Delay time
l_i – Length of segment i
v_f – Free flow speed
v_i – Speed in ith segment
v_{i-1} – Speed in $(i-1)$th segment

Six remote traffic microwave sensors (RTMS) and eight Doppler radars were deployed in both northbound and southbound directions. The locations and types of sensors are listed in Table 1. The location of each PCMS was carefully designed in the effort to maximize system performance. Prior to the detour ramp, three PCMSs were placed successively along the approaching areas in each direction to provide real-time information, including one displaying only the delay time and two displaying the delay time along with the orange detour signs. After the detour ramp, two PCMSs were used to suggest drivers adjust their speed according to the work zone speed ahead, with the messages cycling between two phases: "Slow traffic ahead/Drive with caution" and "Stopped traffic ahead/Be prepared to stop." The displayed information was based on speed detected through the speed sensors.

Table 1: Sensor Locations and Types

Sensor	Location	Distance Between Sensors (mi)	Type
NB sensor 1	0.25 miles away from work zone	0.0	Doppler radar
NB sensor 2	0.75 miles away from work zone	0.5	Doppler radar
NB sensor 3	1.5 miles away from work zone	0.75	RTMS
NB sensor 4	2.5 miles away from work zone	1.0	Doppler radar
NB sensor 5	3.5 miles away from work zone	1.0	Doppler radar
NB sensor 6	4.5 miles away from work zone	1.0	RTMS
NB sensor 7	5.5 miles away from work zone	1.0	Doppler radar
NB sensor 8	8.7 miles from work zone	3.2	RTMS
SB sensor 1	0.25 miles away from work zone	0.0	Doppler radar
SB sensor 2	0.75 miles away from work zone	0.5	Doppler radar
SB sensor 3	1.5 miles away from work zone	0.75	RTMS
SB sensor 4	3.5 miles away from work zone	2.0	Doppler radar
SB sensor 5	4 miles away from work zone	0.5	RTMS

DATA COLLECTION

An extensive data collection was conducted to obtain freeway and freeway ramp traffic volume, speed, traffic density, queue length, message board information, and delay time. Each data point was time-stamped. The data collection was coordinated between the research team, WisDOT, and the vendor who provided the system. Data collection lasted for two weeks: one week before implementing ATIS from September 27, 2006, to October 4, 2006, and one week during the implementation from October 5, 2006, to October 12, 2006.

Analysis and Discussion

It is an effective approach to mitigating work zone congestion by moving traffic from congested roadway sections to alternative routes where the capacities are still underutilized. The diversion rate, defined as the percentage of traffic taking the alternative routes, is frequently referred to as a performance measure of the system effectiveness. The diversion rate was calculated as follows:

$$(2) \quad R_d = \left(\frac{V_{off\_ramp}}{V_{mainline}} \right)_a - \left(\frac{V_{off\_ramp}}{V_{mainline}} \right)_b$$

Where:

R_d – Diversion rate

$\left(\frac{V_{off\_ramp}}{V_{mainline}} \right)_a$ – Proportion of exiting traffic with ATIS

$\left(\frac{V_{off\_ramp}}{V_{mainline}} \right)_b$ – Proportion of exiting traffic without ATIS

Using the diversion rate in combination with the delay message and other variables, driver's tolerance for delay can be decided through statistical analysis. Driver's decision making is a stochastic and complex process, often mixed with other factors such as the preference of the routes, familiarity with the routes, trip purposes, driver's own perception of congestion, belief in the PCMS message, and random errors. Rather than taking the detour, some drivers would remain on the freeway to avoid getting lost in alternative routes. However, once the excessive congestion reflected through the delay time exceeds driver's tolerance level and becomes the dominant factor in the detour decision-making process, more traffic is expected to leave the freeway. Note that all the comparison and analysis, except for the speed analysis in this section, were based on 15-minute intervals.

Publishing real-time delay time information would encourage drivers to divert to alternative routes, thereby alleviating freeway congestion. Therefore, the diversion analyses were only conducted during congestion in both southbound and northbound directions. The discrepancy in the traffic taking exit ramps with and without the system presence was the measure of the effectiveness.

Southbound Direction

To ensure the comparability, only data available during the same period and on the same day of the week with and without ATIS were used. September 29 (Friday) and October 1 (Sunday) were two days with congestion without ATIS presence, and October 6 (Friday) and October 8 (Sunday) were two days with congestion with ATIS. Hence, one pair of weekday (Friday) and one pair of weekend (Sunday) days were compared in two different scenarios, with the results shown in Table 2 and Table 3, respectively.

Table 2: Southbound Diversion Rate With and Without ATIS (Friday)

Time	Without ATIS*			With ATIS			Detour Difference
	Detour	Estimated Delay(min)	Volume	Detour	Displayed Delay(min)	Volume	
12:00	33%	1	1758	36%	2	1629	3%
13:00	16%	5	1608	31%	3	1795	15%
14:00	24%	5	1781	24%	4	2065	0%
15:00	28%	5	2060	7%	5	1641	-21%
16:00	29%	6	2043	15%	4	1763	-14%
17:00	27%	6	2015	11%	4	1788	-16%
18:00	12%	5	1556	9%	4	1473	-3%
19:00	23%	1	1120	17%	2	1248	-6%
Average	24%	4	1742	19%	3	1675	-5%

*shaded values are estimated delay times which are not displayed to drivers

Table 3: Southbound Diversion Rate With and Without ATIS (Sunday)

Time	Without ATIS*			With ATIS			Detour Difference
	Detour	Estimated Delay(min)	Volume	Detour	Displayed Delay(min)	Volume	
11:00	12%	3	1748	16%	5	1778	4%
12:00	25%	7	2005	16%	7	1889	-9%
13:00	31%	8	2165	20%	7	1973	-11%
14:00	28%	10	2125	16%	7	1928	-12%
15:00	30%	10	2123	24%	7	2118	-6%
16:00	31%	11	2190	27%	6	2218	-4%
17:00	30%	7	2190	12%	5	1820	-18%
18:00	14%	5	1623	15%	5	1778	1%
19:00	26%	3	1385	5%	5	1585	-21%
20:00	33%	0	1153	16%	3	1353	-17%
Average	27%	8	1976	17%	6	1913	-10%

*shaded values are estimated delay times which are not displayed to drivers

The tables illustrate the interactive relations among delay (minutes), exiting traffic diversion, and arrival vehicle count (15-minute interval). It was unexpected to observe a higher exiting traffic percentage without ATIS than with ATIS on both Friday and Sunday. Further analysis revealed that the displayed delay time ranges from two to four minutes on Friday and five to seven minutes on Sunday, which were not intolerable to most road users. Both tables show that the exiting traffic decreased when ATIS was present, suggesting that acceptable short delay time encouraged drivers to stay on the freeway rather than taking alternative routes.

Northbound Direction

Northbound traffic presented a reversed scenario of ATIS performance because the displayed delay times in the northbound direction were much higher than southbound due to the higher traffic flow, ranging from 18 to 22 minutes. The proportions of exiting traffic with ATIS shown in Table 4 were approximately 2 to 8% higher than without ATIS. It indicates that delay time played an important role in drivers' diversion decision.

Table 4: Northbound Diversion Rate With and Without ATIS (Friday)

Time	Without DTIS*			With DTIS			Detour Difference
	Detour	Estimated Delay(min)	Volume	Detour	Displayed Delay(min)	Volume	
10:00	36%	1	1653	38%	18	1866	2%
11:00	38%	5	1913	42%	19	1934	4%
12:00	40%	13	1904	38%	21	1943	-1%
13:00	37%	17	2008	45%	21	2125	8%
14:00	41%	19	2099	43%	19	2318	2%
15:00	37%	19	2228	40%	20	2489	3%
16:00	39%	18	2364	45%	21	2596	6%
17:00	44%	22	2335	51%	22	2391	7%
18:00	22%	19	1745	30%	22	1863	8%
Average	37%	15	2028	42%	21	2246	5%

*shaded values are estimated delay times which are not displayed to drivers

ANOVA Test for Delay Tolerance Threshold

The preceding analysis indicates that displayed travel time may encourage drivers to stay on the freeway instead of taking the alternative routes if the delay time is tolerable. However, it was difficult to identify the driver tolerance threshold through the experimental data plots. More rigorous analysis was required to determine the delay time that can cause roadway users to make one of the two distinctive decisions, below which the majority of drivers will choose to stay on the freeway, and vice versa. A set of one-way ANOVA tests were designed to identify the value of the driver tolerance threshold. The general ANOVA model is shown as follows:

(3) $Y_{ij} = \mu_i + \varepsilon_{ij} \quad i = 1, 2;\ j = 1,2, \cdots, n$

Where:

Y_{ij} – Proportion of exiting traffic in the jth case for delay time i

μ_i – Mean proportion of exiting traffic associated with delay time i

ε_{ij} – random error

Essentially, the test was used to detect if there were any significant differences among the average proportions of exiting traffic associated with different levels of delay time. The null hypothesis was that the average proportions of exiting traffic were the same at different delay levels. Each ANOVA test was conducted for two levels: delay time either less than or more than or equal to the tolerance threshold. P-values in Table 5 suggest that no significant discrepancies are detected for the thresholds of five minutes and 10 minutes, respectively. The results for 15 and 20 minute thresholds, however, present a statistically significant difference at the 5% significance level. The smaller value, 15 minutes, is considered to be more practical for displaying the delay time. In other words, there is no need to display the delay time less than 15 minutes in the actual operations because drivers are inclined to remain on the freeway instead of taking alternative routes when a shorter delay time is displayed.

Table 5: One-Way ANOVA Analysis for Delay Tolerance Threshold

Delay Level (Minutes)	<5	≥ 5	<10	≥10	< 15	≥ 15	< 20	≥ 20
Mean	0.246	0.342	0.267	0.364	0.275	0.369	0.289	0.393
Variance	0.028	0.029	0.030	0.026	0.033	0.020	0.031	0.020
Observations	203	320	321	202	356	167	444	79
df	202	319	320	201	355	166	443	78
F	0.990		1.171		1.631		1.553	
P(F<=f)	0.472		0.111		0.000		0.009	

Contingency Table Analysis for Exiting Traffic Distribution

Contingency table analysis is one of the most commonly used techniques to identify whether the characteristics of two or more sets are independent (Washington et al. 2003). The contingency chi-square statistic in Equation 4 can be applied to examine the relationship between row variables and column variables in the contingency table for statistical significance. In the context of exiting traffic analysis, chi-square statistic χ^2 can be used to determine whether the ATIS presence makes a statistically significant impact on the distribution of the proportion of exiting traffic. The typical hypothesis of the test is:

H_0: The ATIS presence and proportion of exiting traffic are independent.
H_1: The ATIS presence and proportion of exiting traffic are not independent.

The chi-squared statistic χ^2 is calculated as follows:

(4) $$\chi^2 = \sum_1^i \sum_1^2 \left[\frac{(a_{ij} - e_{ij})^2}{e_{ij}} \right]$$

Where:

a_{ij}: Observed proportion of exiting traffic

e_{ij}: Expected value and $e_{ij} = \frac{R_i C_j}{T}$

$$R_i = \sum_{i=1}^{m} a_{ij}, \quad C_j = \sum_{j=1}^{n} a_{ij}, \quad \mathrm{T} = \sum_{j-1}^{n} \sum_{i=1}^{m} a_{ij}$$

Since drivers may make different decisions when delay time was less than 15 minutes compared with more than 15 minutes, the analysis was performed for both scenarios. The results are shown in Table 6. P-values for both congestion scenarios are less than 0.01, indicating that the ATIS presence always significantly affected the proportion of exiting traffic distribution regardless of the delay time threshold.

Table 6: Chi-Square Test for Exiting Traffic Distribution

Congestion Level	Cumulative Distribution of the Portion of Exiting Traffic	Number of Observation (Before)	Number of Observation (After)	Chi-square Value	DF	P Value
Delay Less than 15 Minutes	≤10%	31	61			
	≤20%	88	140			
	≤30%	159	206			
	≤40%	234	281			
	≤50%	319	310			
	≤60%	357	331			
	≤70%	393	337			
	≤80%	406	343			
	≤100%	413	352	65.7	8	0
Delay more than or Equal to 15 Minutes	≤10%	1	0			
	≤20%	5	8			
	≤30%	21	20			
	≤40%	36	49			
	≤50%	45	99			
	≤60%	66	137			
	≤70%	84	160			
	≤100%	86	167	20.3	7	0.005

Under the first scenario with delay time less than 15 minutes, only 71 out of 352 observations have a higher than 40% portion of the exiting traffic with the system presence, while there were 179 out of 413 with the system absence. In other words, the ATIS encouraged drivers to stay on the freeway when estimated delay time was less than 15 minutes. When the delay time was larger than or equal to 15 minutes, 118 out of 167 observations (almost three quarters of the proportions of exiting traffic) were above 40% when the system was activated, while there were only 50 out of 86 observations with system absence. These facts reinforce the preliminary conclusion from the simple comparisons between with and without the ATIS in previous sections.

Regression Analysis for Diversion

Preceding analyses uncovered that the exiting traffic after work zone presence was impacted by several factors, such as volume, congestion level indicated by displayed delay time, the number of days after the ATIS implementation, and exiting traffic before work zone presence. A linear regression analysis was conducted to investigate the relationship between the diversion and these factors. The linear regression model is expressed as follows:

(5) $Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_m X_m + \gamma_1 X_1 X_2 + \cdots + \gamma_n X_{m-1} X_m + \varepsilon$

Where:

Y – Proportion of exiting traffic with lane closures

X – Predictor variables

B – Coefficients for main factors

γ – Coefficients for interaction factors

The delay time factor was treated as a dummy variable in the regression model and was categorized into two levels: less than 15 minutes and more than or equal to 15 minutes. The number of days after the ATIS factor was also a dummy variable. Freeway volume in 15-minute intervals and exiting traffic without lane closures were continuous variables. The purpose of the regression analysis was to identify the main factors as well as the interactions affecting exiting traffic. Further, the statistical model was developed to estimate the possible exiting traffic under a given work zone traffic condition, including volume (vehicles per hour) and displayed delay time. Regression results are presented in Table 7.

Table 7: Linear Regression Model Result

Variable	Estimate	Std. Error	t value	Pr(>|t|)
Constant	-0.893	0.288	-3.102	0.002
Main Effect				
Volume (freeway)	0.002	0.0006	3.384	0.000
Delay level 2 (≥15 minutes)	0.392	0.18	2.172	0.031
PCT of exiting volume (without lane closures)	2.542	0.746	3.408	0.001
Interaction Effect				
Volume × PCT of exiting volume	-0.003	0.0015	-2.453	0.015

Fit: Multiple R-Squared = 0.6195, Adjusted R-squared = 0.6042
Model Test: F-statistic [6, 149] =40.43, p-value: < 2.2e-16

As indicated in Table 7, the predictors with p-value less than 0.05 include the traffic volume, delay level, exiting traffic under conditions without work zones, and interaction between volume and exiting traffic under conditions without work zones, which indicates that the four factors significantly affected the exiting traffic with the ATIS presence. Recall that the delay level was treated as a dummy variable and the positive coefficient of delay level 2 (≥ 15 minutes) implied that longer delay increased the traffic diversion compared with shorter delay (< 15 minutes). This result corresponded with the ANOVA analysis and chi-square test and is consistent with the previous studies (Levison and Huo 2003, Horowitz et al. 2003)

Work Zone Queue Analysis

It was envisioned that the length of the queue might be shorter if more drivers chose alternative routes. Recall that the sensors were installed along the approaching area and the space of two adjacent sensors was either one-half or one mile. The approximate queue length was determined solely by where the traffic sensors were located. For instance, when observing a sudden drop of speed at one specific sensor location, it was assumed that the queue extended to or beyond the location of the sensor. The comparison of maximum queue length in 15-minute intervals for the ATIS presence (October 6) and absence (September 29) in the southbound direction is presented in Table 8. The number of 15-minute intervals with maximum queue length equal to or longer than 3.5 miles before the implementation was 12, while none of 15-minute intervals reached 3.5 miles after the implementation.

Table 8: Maximum Queue Length in Southbound (Friday)*

	9/29/2006				10/6/2006			
Time	**Max Queue Length (miles)**	**Traffic Volume**	**Diversion Rate**	**Delay****	**Max Queue Length (miles)**	**Traffic Volume**	**Diversion Rate**	**Delay**
14:30	1.5-3.5	458	24%	5	1.5-3.5	458	11%	5
14:45	3.5	469	30%	5	1.5-3.5	425	18%	6
15:00	3.5	473	8%	5	1.5-3.5	433	5%	4
15:15	3.5	475	32%	6	1.5-3.5	373	2%	5
15:30	3.5	455	24%	5	1.5-3.5	433	6%	5
15:45	3.5	658	44%	5	1.5-3.5	448	18%	4
16:00	3.5	543	34%	6	1.5-3.5	488	25%	4
16:15	**>3.5**	**518**	**34%**	**7**	1.5-3.5	493	17%	4
16:30	**>3.5**	**520**	**34%**	**7**	1.5-3.5	335	16%	4
16:45	**>3.5**	**463**	**14%**	**5**	1.5-3.5	518	9%	4
17:00	3.5	533	33%	6	1.5-3.5	465	17%	5
17:15	**>3.5**	**543**	**32%**	**6**	1.5-3.5	405	1%	4
17:30	**>3.5**	**508**	**24%**	**5**	1.5-3.5	400	10%	4
17:45	1.5-3.5	433	16%	5	1.5-3.5	443	18%	4
18:00	1.5-3.5	413	12%	5	1.5-3.5	390	1%	4

* Bold fonts represent the maximum queue length exceeding the farthest detector
** Shaded values are estimated delay times which are not displayed to drivers

A similar process was applied to generate maximum queue length for northbound traffic shown in Table 9. With the ATIS presence on October 6, the queue never exceeded the farthest sensor location, which was 8.7 miles away from the work zone. The effectiveness of the ATIS was demonstrated once again by controlling maximum queue length within a given range.

Table 9: Maximum Queue Length in Northbound (Friday)*

	9/29/2006				10/6/2006			
Time	**Max Queue Length (miles)**	**Traffic Volume**	**Diversion Rate**	**Delay****	**Max Queue Length (miles)**	**Traffic Volume**	**Diversion Rate**	**Delay**
15:00	5.5-8.7	493	14%	21	5.5-8.7	541	42%	18
15:15	5.5-8.7	561	44%	18	5.5-8.7	582	45%	19
15:30	5.5-8.7	590	41%	17	5.5-8.7	555	39%	17
15:45	5.5-8.7	584	44%	18	5.5-8.7	640	47%	20
16:00	5.5-8.7	573	43%	21	5.5-8.7	644	59%	24
16:15	5.5-8.7	596	42%	18	5.5-8.7	589	42%	16
16:30	5.5-8.7	567	41%	13	5.5-8.7	622	30%	21
16:45	5.5-8.7	628	47%	18	5.5-8.7	634	42%	19
17:00	5.5-8.7	594	44%	20	5.5-8.7	678	51%	19
17:15	**>8.7**	**601**	**47%**	**22**	5.5-8.7	651	59%	20
17:30	**>8.7**	**588**	**49%**	**23**	5.5-8.7	601	40%	20
17:45	5.5-8.7	552	39%	24	5.5-8.7	666	30%	25
18:00	5.5-8.7	462	40%	23	5.5-8.7	616	50%	23

*Bold fonts represent the maximum queue length exceeding the farthest detector
**Shaded values are estimated delay times which are not displayed to drivers

Impact of Advance Speed Warning

Work zone crash facts show that the most common work zone crashes are rear-end caused by abruptly slow or stopped traffic (Hall and Lorenz 1996, Qin et al. 2007). As part of ATIS, the PCMSs and sensors collectively operated to inform drivers of the slow/stopped traffic in front of them so that they can be better prepared and adjust their speed accordingly. A two-phase message was displayed on the PCMSs according to the real-time traffic conditions (see study design section). A speed comparison was conducted to assess the effect of advance speed warning in controlling the speed in work zone approaching area. The impacts were measured by comparing the speed values between two sensors with the PCMS in the middle.

The southbound PCMS was 2.5 miles away from the work zone taper and placed between southbound sensor 3 (1.5 miles away from the work zone) and sensor 4 (3.5 miles away from the work zone). One hundred eight speed samples (5-minute average) and the displayed messages during the sign activation were collected. The speed samples were further split into two groups by different messages. Additionally, 50 speed samples without any displayed messages were used as the baseline. The results shown in Table 10 present the speed reduction in three scenarios, including the baseline condition. Although it was not sufficient to conclude that speed reduction was completely correlated to the message, the speed sensor data did indicate that drivers received the warning messages.

Table 10: Speed (miles per hour) Comparison for Advance Warning Messages

Display Message	Sensor 3	Sensor 4	Difference	STDV
Null (Baseline)	60.8	64.3	3.6	4.0
Slow Traffic Ahead	61.2	66.1	4.9	5.5
Stopped Traffic Ahead	62.4	65.1	2.8	4.4

CONCLUSIONS

An advanced traveler information system was implemented in a bridge reconstruction project on I-39/90 in Wisconsin to mitigate work zone congestion and improve safety. Through the suite of detectors, PCMSs, computers and communication technologies, ATIS effectively communicated real-time traffic information to drivers, assisted them with objective decision making, and promoted the utilization of alternative routes.

Field comparison between ATIS presence and absence uncovered different diversion patterns in the northbound and southbound directions. The proportion of exiting traffic was irrelevant to the actual delay when there was no delay information while the proportion of exiting traffic increased as displayed delay time increased. It was further discovered that travelers may choose to stay in or join the work zone queue if the delay time was tolerable. A 15-minute delay tolerance was found in the study, which implies that only displaying delay time larger than or equal to 15 minutes may improve the system effectiveness. The discrepancy of exiting traffic with and without ATIS fostered further examination of traffic condition related variables and driver behavior, which may affect the proportion of exiting traffic. More investigations were performed to derive the relationship between diversion and other factors, including estimated delay level, freeway volume, number of days after system implementation, and exiting traffic before work zone presence. The regression analysis suggested that traffic volume and proportion of exiting traffic without lane closure significantly impacted diversion.

Other performance measures, such as maximum queue length, were used to test how the work zone can accommodate the demand challenge with the assistance of the delay time system. It can be observed that ATIS performed relatively effectively in controlling the maximum queue length while accommodating similar traffic in work zones.

As part of ATIS, one of the PCMSs was designated to disseminate the real-time advance warning message of traffic ahead to drivers. The warning message aimed to reduce the risk of rear-end crashes by alerting drivers of the slow or stopped traffic in front of them. The surrogate safety performance was measured by the speed reduction measured from two sensors with the PCMS in the middle. The speed sensor data did indicate that drivers received the warning messages.

References

Bushman, R. and C. Berthelot. "Estimating the Benefits of Deploying Intelligent Transportation Systems in Work Zones." Transportation Research Board Annual Meeting, Washington, D.C., 2004.

Chu, L.Y., H.K. Kim, Y. Chung and W. Recker. "Evaluation of Effectiveness of Automated Workzone Information Systems." *Transportation Research Record: Journal of the Transportation Research Board* 1911, (2005a): 73-81.

Chu, L.Y., H.K. Kim, H.X. Liu, and W. Recker. "Evaluation of Traffic Delay Reduction from Automatic Workzone Information Systems Using Micro-simulation." Transportation Research Board Annual Meeting, Washington, D.C., 2005b.

Hall, J.W. and V.M. Lorenz. "Characteristics of Construction-Zone Accidents." *Transportation Research Record: Journal of the Transportation Research Board* 1230, (1996): 20–27.

Horowitz, A.J., I. Weisser, and T. Notbohm. "Diversion from a Rural Work Zone Owing to a Traffic-Responsive Variable Message Signage System." *Transportation Research Record: Journal of the Transportation Research Board* 1824, (2003): 23-28.

Khattak, A., F. Koppelman, and J. Schofer. "Stated Preference For Investigating Commuters' Diversion Propensity." *Transportation* 20 (2), (1993a): 107-127.

Khattak, A., J. Schofer, and F. Koppelman. "Commuters' Enroute Diversion And Return Decisions: Analysis and Implications for Advanced Traveler Information Systems." *Transportation Research Part A* 27, (1993 b): 101-111.

Lee, E.B and C. Kim. "Automated Work Zone Information System (AWIS) on Urban Freeway Rehabilitation: California Implementation." *Transportation Research Record: Journal of the Transportation Research Board* 1948, (2006): 77-85.

Levinson, D. and H. Huo. "Effectiveness of Variable Message Signs." Transportation Research Board Annual Meeting, Washington, D.C., 2003.

Lotan, T. "Effects of Familiarity on Route Choice Behavior in the Presence of Information." *Transportation Research Part C* 5, (1997): 225-243.

Qin, X., Y.L. Chen, and D. Noyce. "Examination of Wisconsin Work Zone Crashes." Proceeding of Institute of Transportation Engineers 2007 Annual Meeting And Exhibition. Pittsburg, PA, 2007.

Tudor, L.H., A. Meadors, and R. Plant, II. "Deployment of Smart Work Zone Technology in Arkansas." *Transportation Research Record: Journal of the Transportation Research Board* 1824, (2003): 3-14.

Washington, S.P., M.G. Karlaftis, and F. L. Mannering. *Statistical and Econometric Methods for Transportation Data Analysis*. Chapman & Hall/CRC, New York, 2003.

Acknowledgements

Funding for this project was provided by the WisDOT Bureau of Highway Operations. The authors thank Peter Amakobe, Tom Notbohm, Marie Treazise, and WisDOT Southwest Region staff for providing technical guidance and coordinating the work zone evaluation.

Xiao Qin*, Ph.D., P.E., is an assistant professor of Civil and Environmental Engineering at South Dakota State University in Brookings, SD. He also holds an Honorary Associate/Fellow appointment in the Department of Civil and Environmental Engineering at the University of Wisconsin – Madison (UW-Madison). He has both his B.S. and M.S. in Civil Engineering from Southeast University, Nanjing, China, and his Ph.D. degree in Civil Engineering (Transportation and Urban Engineering) at the University of Connecticut.*

Prior to joining the SDSU faculty, Dr. Qin was an assistant scientist at UW-Madison where he managed the traffic safety research program and advised graduate students at the Department of Civil and Environmental Engineering. Dr. Qin also spent two years working for Maricopa Associations of Governments (MAG) in Phoenix, Arizona. Dr. Qin's main research interests are traffic operations and safety, statistical modeling, GIS and GPS application, and sustainable transportation planning. Dr. Qin won the 2008 Transportation Research Board (TRB) Best Paper awarded by the Committee on Statistical Methods and Applications and has authored over 40 technical papers, including 20 refereed journal articles.

Yali Chen *is a research associate in the Geography Department at the University of California, Santa Barbara. She graduated from the University of Wisconsin Madison, and her Ph.D. study focused on safety and operation in construction zones. After graduation, she conducted a few traffic impact studies using micro-simulation to evaluate the performance of roadway segments for proposed construction design alternatives. Currently, she is involved in developing the travel demand forecasting system, the Simulator of Activities, Greenhouse Emissions, Networks, and Travel (SimAGENT), for the Southern California Association of Governments (SCAG).*

David A. Noyce*, Ph.D., P.E., is an associate professor and member of the transportation engineering faculty in the Department of Civil and Environmental Engineering at the University of Wisconsin – Madison (UW-Madison). He also holds a joint appointment in the Department of Industrial and Systems Engineering. Dr. Noyce received his B.S. and M.S. degrees in Civil and Environmental Engineering from UW-Madison in 1984 and 1995, respectively, and completed his Ph.D. in Civil (Transportation) Engineering at Texas A&M University in 1999.*

Dr. Noyce has over 26 years of experience in transportation engineering including state government, private consulting, and academia. He has held positions at the University of Massachusetts-Amherst, Texas A&M University, the Texas Transportation Institute, the Illinois Department of Transportation, and several U.S. consulting firms. Dr. Noyce is the Director of the Traffic Operations and Safety (TOPS) Laboratory at UW-Madison. He has authored more than 60 technical papers, research reports, and book chapters.

Dr. Noyce is a member of the Institute of Transportation Engineers (ITE) where he serves as past-chair of the Pedestrian and Bicycle Council. He is also the ITE student chapter advisor at UW-Madison. Dr. Noyce chaired several NCHRP project panels and has conducted NCHRP research. He is the current chair of TRB's AHB50 Traffic Control Devices Committee.