Journal of Traffic and Transportation Engineering 9 (2021) 26-39
doi: 10.17265/2328-2142/2021.01.004

Estimation of Traffic Demand at Freeway Work Zones

Eil Kwon[1] and Chongmyung Park[2]

1. Department of Civil Engineering, University of Minnesota Duluth, 252 SCIV, 1405 University Dr., Duluth, MN 55812, USA

2. Department of Civil Engineering, University of Minnesota Duluth, 207 Eng, 1303 Ordean Ct., Duluth, MN 55812, USA

Abstract: An iterative process, combining a macroscopic simulator and a set of the traffic demand-change estimation models, is developed to estimate the traffic demand at work zones in urban freeway corridors. The process is designed to capture the interaction between work-zone conditions and traffic diversion in determining the traffic demand approaching the entrance and exit ramps at a given work zone. The proposed models and process were calibrated and tested with the field data from the work zones in the Minnesota metro-freeway network. The test results indicate promising possibilities of the proposed process in terms of the estimation accuracy and transferability of the demand-change estimation models developed in this study.

Key words: Work zone, traffic demand, diversion.

1. Introduction

One of the critical elements in developing effective strategies for work-zone traffic management is the capability to accurately estimate the effects of traffic delays and alternative route conditions on the traffic demand approaching given work zone sites. While there exist dynamic network models that could be applicable in determining the redistribution patterns of traffic flows responding to the capacity changes at work zones (Dynus-T 2013; Dynasmart-P 2007; Zhang 2009; Patil 2008), most network models developed to date adopt user-equilibrium approaches that tend to overestimate the amount of diversion to alternative routes (Tanvir 2016; Horowitz 2003). Further, they require time-consuming calibration efforts and the origin-destination demand data, which are not easily available to practicing engineers. The above issues have led the development of work-zone specific models, such as Quickzone (Mitretek 2001) and QUEWZ (Copeland 1999), which try to quantify the effects of work-zone delays on traffic flows without using origin-destination demand data. However, the simplified approaches in modeling flow diversion in these work-zone specific models, e.g., adopting fixed-queue thresholds for diversion, may not adequately reflect the 'queue stabilization' process, as observed by Ullman (Ullman 1996), which results from the natural interaction between diversion and traffic conditions at work zones. It can be also noted that there have been relatively few research efforts to develop work-zone traffic demand models on a corridor level. Ullman and Dudek proposed a theoretical-diversion model assuming a freeway corridor with lane-closure sections as a permeable pipe (Ullman et al., 2003). This approach requires substantial amount of data to calibrate the permeability factor, which represents the diversion potential of a given corridor. Liu and Horowitz also proposed a conceptual diversion model incorporating drivers' bias factor for their original routes, however, no specific functional forms have been developed (Liu et. al., 2011). A hybrid process developed by Chen et al. combined a microsimulation model with the logistic regression-based diversion models, which estimated the proportions of entrance/exit volumes to mainline flow during lane-closure periods (Chen et al., 2008). While the logit regression models in this approach were calibrated with the field data from the Milwaukee freeways, the predictors in those models only reflect freeway traffic conditions, e.g., queue

Correspongding author: Eil Kwon, Ph.D.

lengths and ramp/mainline volumes, and the alternative-route conditions of a given work-zone area were not explicitly incorporated into diversion estimation.

Estimating traffic demand for freeway work zones requires an explicit consideration of the interrelationship between traffic conditions and drivers' route-choice behavior. This paper presents an iterative process to determine the freeway work-zone traffic demand, resulting from such an interaction between drivers and work-zone conditions, by combining a freeway simulator and a set of the work-zone demand-reduction models newly developed with the data from the Minnesota work zones. The demand reduction models developed in this study estimate the traffic reduction rates as a function of both freeway and alternative route conditions at a given work-zone site. By integrating a traffic simulator with the demand-reduction models, the proposed process directly reflects the interaction between drivers and work-zone conditions in determining the traffic demand for a given site. The rest of the paper describes the work-zone data collected for this study, the work-zone demand-reduction models, the iterative process and its field application results in estimating the traffic demand for the sample work zones in the Minnesota metro freeway network.

2. Work-Zone Data Collection and Analysis

Fig. 1 shows the locations of 6-freeway work-zone sites selected for this study in cooperation with the

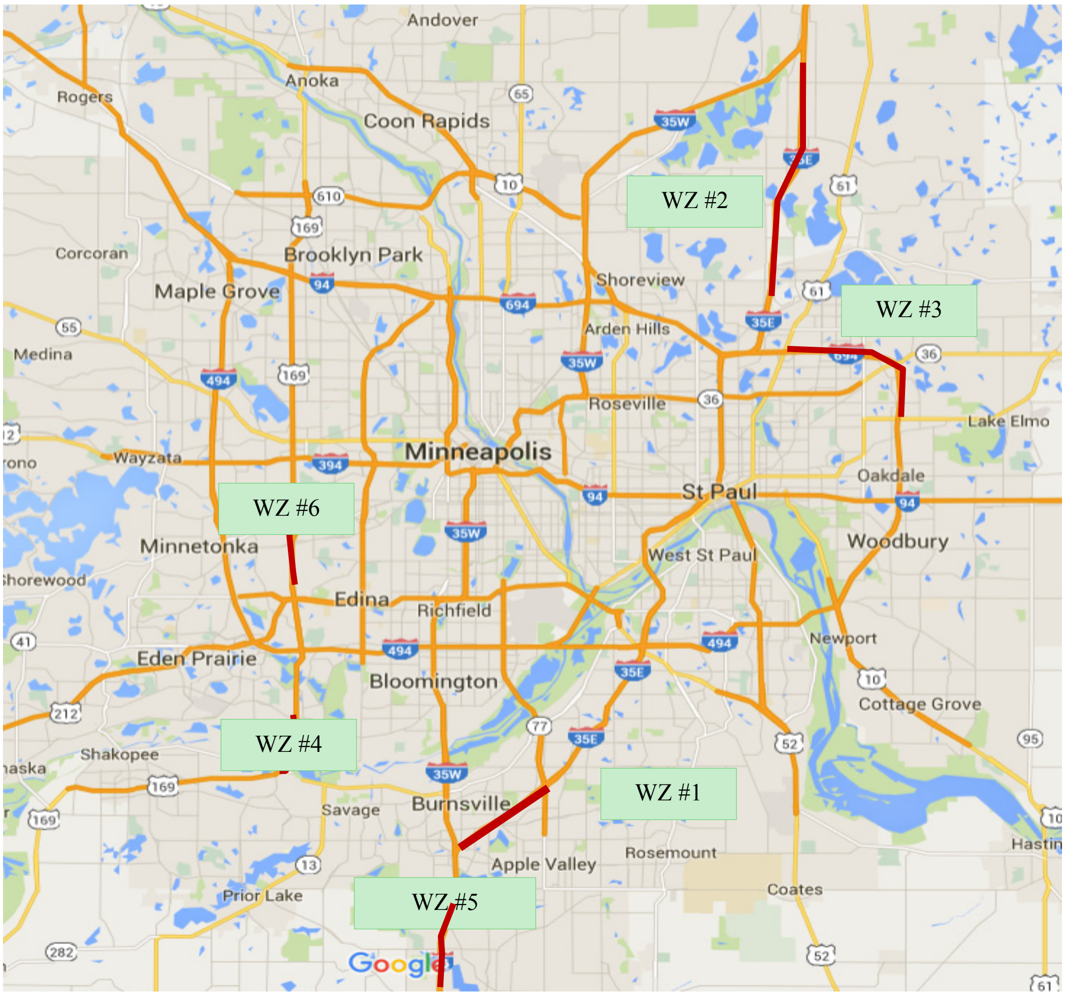


Fig. 1 Locations of Work-Zone Sites.

Table 1 Work Zone Sites Information.

#	Project Location	Boundary Station ID			Construction Period	Lane Closure Configuration
		Direction	From	To		
1	I-35 from Split to Cliff Road	NB	870	882	2013-06-15 ~ 2013-07-30	2 to 1
		SB	893	905		
2	I-35E - North I-694	NB	1449	1503	2011-08-02 ~ 2011-10-13	2 to 1
3	I-694 Improvement	WB	1414	1445	2012-06-19 ~ 2012-11-07	2 to 1
4	US-169 Ferry Bridge Improvement	SB	1611	1144	2013-06-26 ~ 2013-08-29	2 to 1
5	I-35 Improvements	SB	916	1584	2013-07-16 ~ 2013-10-24	2 to 1
6	US-169 Bridge	NB	428	437	2013-06-11 ~ 2013-06-27	2 to 1
		SB	453	461		

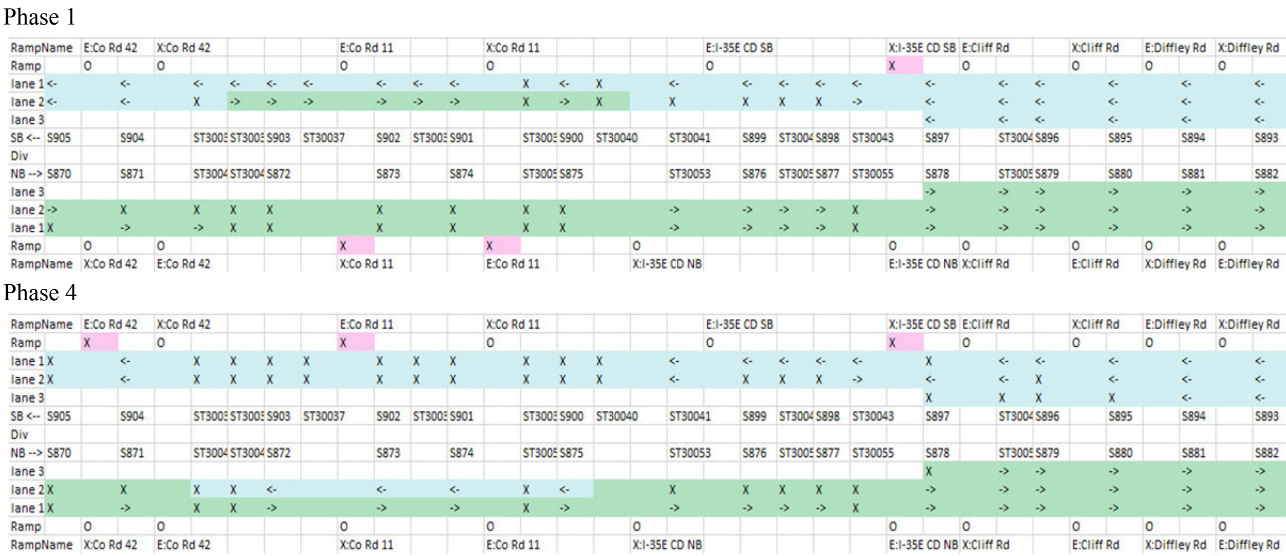


Fig. 2 Phase Identification Example (Work Zone #1: I-35E).

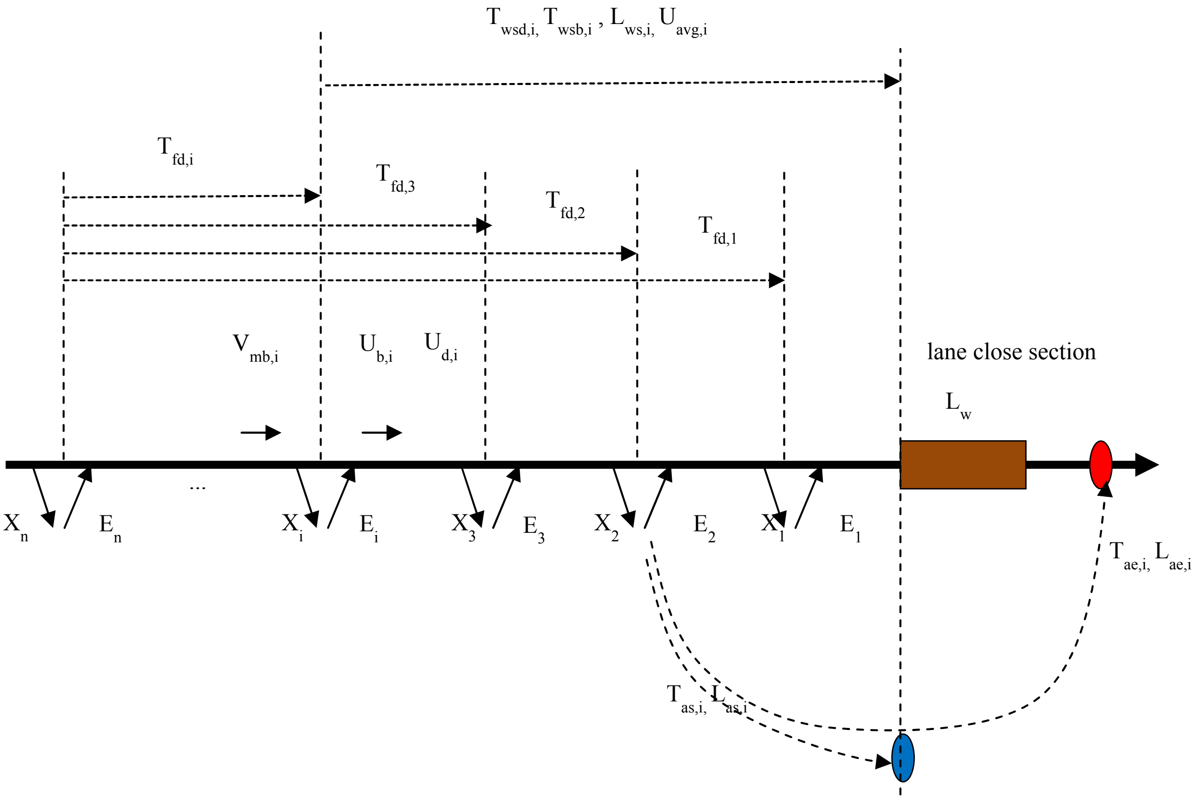
Minnesota Department of Transportation. Each site had lane-closures and the traffic data before/during construction periods from both mainline and ramp detectors upstream of its lane-closure section were collected. Table 1 includes the construction periods and lane-closure configurations at each site. In this study, the data collected from the Work Zones #1 through #5 were used to develop and test the iterative estimation process for work-zone traffic demand, while the data from Work Zone #6 were used to examine the transferability of the proposed process.

2.1 Identification of Time-variant Lane-closure Configuration Changes at Each Site

First, the time-variant lane-configuration changes at each site during construction periods were identified by examining the staging plans and the status of the traffic detectors during construction at each site. In this study, a period during which lane/ramp closure configuration remains same is defined as a 'phase'. Therefore, there could be multiple phases during a construction period at a given site depending on the number of changes in lane-closure configurations. Fig. 2 shows example schematic diagrams of two phases identified at the I-35E NB/SB work-zone, which had a total of 6 phases.

2.2 Traffic Data Collection for Before/During Construction Periods for Each Phase at Work-Zone Sites

After identifying the duration of each 'phase', i.e., the number of days with 'constant lane-configuration',



$V_{xb,i}$ = Exit flow rate at exit ramp i during construction;
$V_{xd,i}$ = Exit flow rate at exit ramp i before construction;
$V_{eb,i}$ = Entering flow rate from entrance ramp i before construction;
$V_{ed,i}$ = Entering flow rate from entrance ramp i during construction;
$V_{mb,i}$ = Mainline flow rate approaching exit ramp i before construction ;
$T_{wsb,i}$ = Freeway travel time to the upstream boundary of a work zone from ramp i before construction;
$T_{wsd,i}$ = Freeway travel time to the upstream boundary of a work zone from ramp i during construction;
$L_{ws,i}$ = Distance to the upstream boundary of a work zone from ramp i;
$U_{avg,i}$ = Average speed of the freeway section from the diversion point i to the upstream boundary of a lane closure section;
$U_{b,i}$ = Average speed of the freeway section from ramp i to the upstream boundary of lane-closure section before construction;
$U_{d,i}$ = Average speed of the freeway section from ramp i to the upstream boundary of lane-closure section during construction;
$T_{fd,i}$ =Freeway travel time from upstream reference point to diversion point i during construction;
$T_{as,i}$ = Alternative route travel time to the upstream boundary of a work zone from the diversion point i;
$L_{as,i}$ = Alternative route length to the upstream boundary of a work zone from the diversion point i;
$T_{ae,i}$ = Alternative route travel time to the end of work zone from the diversion point i;
$L_{ae,i}$ = Alternative route length to the end of work zone from the diversion point i.

Fig. 3 Types of Data Collected for Each Work Zone.

is identified for each work zone, a set of traffic flow and travel time data were collected for the morning or afternoon peak-hour period of every week day during a construction period. The daily peak-period data were further grouped for each construction phase at a given site. Figure 3 illustrates a simplified work zone and the types of data collected in this study. The detailed data collected from this study can be found elsewhere (Kwon, et. al., 2016). It can be noted that each entrance or exit ramp upstream of a given work zone is considered as a potential diversion point, whose traffic demand needs to be determined with the consideration of the traffic and alternative route conditions at a given site.

As shown in Figure 3, the collected data for each work-zone site can be grouped as follows (

- *Traffic-flow and travel-time data from all the detectors on the mainline and ramps at upstream of each work zone before and during construction periods*: For every week day of a construction period, 5-min speed and flow-rate measurements from each detector station during a peak-hour period were collected and aggregated into hourly values. Further, the freeway-travel times from each potential diversion point, i.e., either entrance or exit ramp, to the upstream/downstream boundaries of a given work-zone were estimated for a peak-hour period every weekday for each construction phase using the traffic speed data from the detector stations and the distances between stations at each site. These traffic data collected during active construction periods were used as the 'during-construction' data for a given site, while previous-year's data during same construction periods at same locations were considered to be the 'before-construction' data for a subjective work zone.
- *Length and travel-time of alternative arterial route for a given work zone*. The coordinates of the intersections connected to a given freeway work-zone were identified with the Google Map Engine and the travel time of each arterial link was estimated with its speed limit. Using the arteria-link travel-time data, a shortest-time-alternative route from each potential diversion point, i.e., an entrance or exit ramp upstream of a given work zone, to the downstream boundary of a lane-closure section was identified with the Dijkstra's algorithm.

3. Analysis and Modeling of Traffic Demand Change Rates at Work Zones

Using the data collected in the previous section, the effects of the traffic conditions during construction periods on the reduction of traffic demand at each potential diversion point, i.e., entrance and exit ramps upstream of a given work zone, were analyzed. In this study, the traffic-demand change rates for the peak-hour periods during construction at each diversion point are defined as follows:

Entrance Demand Change Rate at Ramp *i,*

$$R_{e,i} = \frac{V_{eb,i} - V_{ed,i}}{V_{eb,i}} \quad (1)$$

Exit Demand Change Rate at Exit *i,*

$$R_{x,i} = \frac{\Delta V_{x,i}}{V_{mb,i} - V_{xb,i} - \sum(Upstream\ \Delta Vx's)} \quad (2)$$

where, $\Delta V_{x,i}$= Increased Exit Volume at Exit i during construction: $V_{xd,i} - V_{xb,i}$, In the above definition, the Exit Demand Change Rate at an exit ramp *i*, $R_{x,i}$, denotes the proportion of the additional exit volume, i.e., diverted flow, within the total-mainline volume approaching an exit ramp i during a construction period.

In this study, an extensive data analysis was conducted to identify potential relationships between the above demand-change rates at the decision points of each work-zone and the various factors reflecting the traffic and route conditions for a given site. The major findings from the data analysis can be summarized as follows:

- The most important factors affecting the Exit Demand Change Rate of the freeway mainline flow at an exit ramp *i* are 1) the freeway-traffic conditions, e.g., speed levels, upstream of a given work zone during construction periods, and 2) the relative benefit of diverting at a given exit ramp i compared to exiting at further downstream ramps in terms of the total travel-time combining freeway and alternative-route times in a given corridor.
- For the Entering Demand Change Rate at an entrance ramp i, the most significant factors include the freeway traffic conditions during a construction period and the freeway travel time of the alternative-route from an entrance ramp i to the upstream boundary of a lane-closure section. Further, it was also noted that the entrance ramps with relatively short alternative-route travel times tend to have more diversion than others with long alternative routes.

• The sensitivity of both Entering and Exit Demand Change Rates with respect to the traffic/route conditions at given sites show clear differences between two groups of work-zones, i.e., the work zones with relatively short lane-closure sections are significantly more sensitive to the changes in work-zone configurations than those with long-closure sections.

Based on the above findings, the work zones are grouped into two categories depending on the lengths of lane closures: Group 1 consists of the work zones #1 (NB/SB) and #4 (SB), whose lengths are shorter than 9.66 km (6 miles), while Group 2 includes the work zones #2 (NB), #3 (WB) and #5 (SB). The work zones in Group 2 have 9.66 km (6 miles) or longer lane-closure sections, thus their alternative routes have substantially higher travel times than those in Group 1. Further, the demand-change rate at each entrance or exit ramp in a work-zone site is assumed to be a function of the variables reflecting the combined effects of freeway and alternative route conditions as follows:

Entrance Demand-Change Rate at entrance ramp i, $R_{e,i} = f[U_{avg,i} * (T_{as,i} / T_{as,min})]$ (3)

Exit Demand-Change Rate at an exit ramp i: $R_{x,i} = g[U_{avg,i} * (T_{fae,i} / T_{fae,min})]$ (4)

where,

$U_{avg,i}$ = *Average speed of the freeway section from entrance ramp i to the upstream boundary of a lane-closure section,*

$T_{as,i}$ = *Travel time of the alternative route from entrance ramp i to the starting point of a work-zone,*

$T_{as,min}$ = *Min* $[T_{as,i}]$ *for all entrance ramps upstream of a lane-closure section,*

$T_{fd,i}$ = *Freeway travel time from a reference point on a mainline to exit ramp i,*

$T_{ae,i}$ = *Alternative route travel time from exit ramp i to work-zone end point,*

$T_{fae,i}$ = *Total travel time with diversion at i, i.e., sum of freeway travel time and alternative route travel time if diverted at exit i:* $(T_{fd,i} + T_{ae,i})$,

$T_{fae,min}$ = *Min* $[T_{fd,i} + T_{ae,i}]$ *for all exit ramps upstream of a lane-closure section.*

In this study, the demand-change rates and the values of the above combined variables at each decision point of the sample work-zones were estimated with the traffic-flow data collected at each site for the peak-hour periods on weekdays during construction periods. Further, the daily measurements were aggregated into the phase values at each decision point. The relationships between the measured demand-change rates and the estimated values of the combined variables for each phase of a given work-zone group. are shown in Figure 4, which indicates, as expected, the demand-change at a decision point in a freeway work zone decreases as the average mainline speed to the work-zone boundary and alternative-route travel time increases.

Based on the above results, a set of the work-zone demand-change models were developed and calibrated with the data as shown in Figure 4. The general form of the work-zone demand-change models are as follows:

Entrance Demand-Change Rate at ramp i, $R_{e,i}$ =

$$\frac{\alpha}{\left(1+e^{\beta\left(U_{avg,i} * \frac{T_{as,i}}{T_{as,min}}\right)}\right)^{\gamma}} \quad (5)$$

Exit Demand-Change Rate at ramp i, $R_{x,i}$ =

$$\frac{\alpha'}{\left(1+e^{\beta'\left(U_{avg,i} * \frac{T_{fae,i}}{T_{fae,min}}\right)}\right)^{\gamma'}} \quad (6)$$

In the above formulation, α, α’, β, β’, γ, γ’ are the parameters that can be calibrated with the field data from given work zones. In this study, those parameters were determined with the phase data from each work zone by using the Generalized Reduced Gradient method in the Excel Solver. Table 2 includes the parameters for each model. It can be noted that the calibrated models have R^2 values ranging from 53% to 69%.

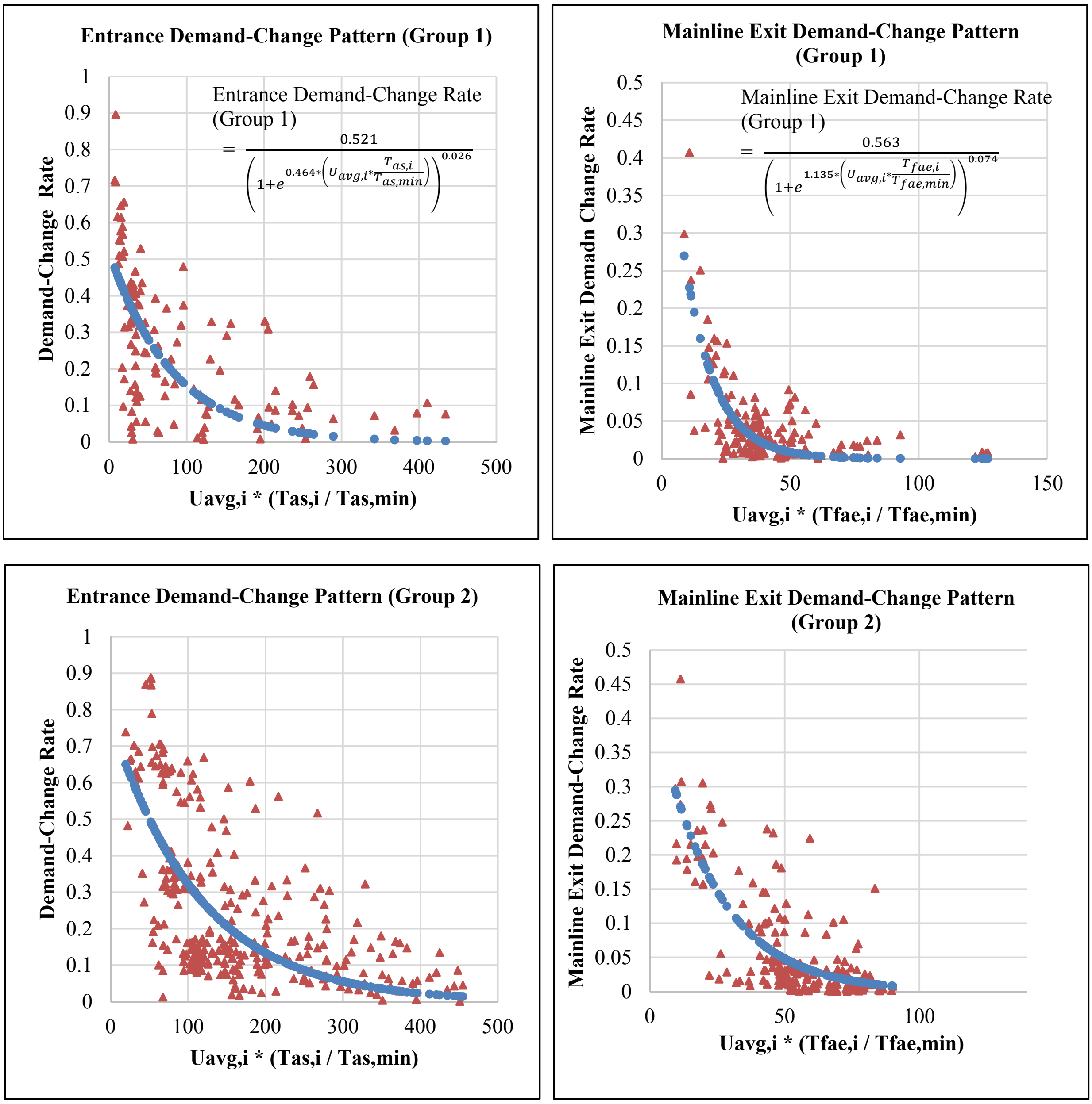


Fig. 4 Demand-Change Rate Patterns and Models for Work-Zone Groups.

Table 2 Parameters in Demand-Change Rate Models.

	α	β	γ	R^2
Group 1 Entrance Ramp Diversion	0.521	0.464	0.026	0.599
Group 1 Exit Ramp Diversion	0.563	1.135	0.074	0.681
Group 2 Entrance Ramp Diversion	0.777	0.118	0.075	0.526
Group 2 Exit Ramp Diversion	0.450	0.475	0.094	0.606

4. Iterative Process for Estimation of Traffic Demand-Change Rates at Work Zones

The findings from the work-zone demand-change data analysis and the models calibrated in the previous section indicate that the changes in the traffic demand approaching a freeway work-zone is a function of the mainline-traffic conditions during construction periods and the travel times of alternative routes from the potential decision points at a given work zone. Since the traffic diversion and the freeway traffic conditions during lane-closure periods at a given work zone are interrelated, an iterative process is proposed in this study to determine the demand-change rates whose resulting freeway traffic conditions can satisfy the functional relationships of the demand-change rate models developed in the previous section. Figure 5 shows the framework of the iterative process combining a freeway simulator with the demand-change rate models. In the current version, Freeval (Freeval, 2014), developed as the computation engine for the 2010 Highway Capacity Manual by the North Carolina State University, is adopted as the freeway simulator, while other simulation models, either macroscopic or microscopic, can be also used.

As indicated in Figure 5, the iterative process starts by modeling a given work zone with Freeval for the 'before' condition. After the Freeval model is calibrated with 'before construction' data, the 'during' condition is modeled with Freeval by adjusting the capacity of the lane-closure section at a given work zone. The first iteration of the simulation is conducted with the 'before construction' traffic-demand data, i.e., without considering the traffic demand changes because of work-zone delays. The resulting freeway-travel times and speed levels at each decision point are entered to the appropriate, i.e., either entrance or exit demand-change rate models, which estimate the first set of the demand-change rates at all the exit and entrance ramps upstream of a given work zone. Those estimated demand-change rates are then converted to the demand adjustment factors in Freeval, which proceeds with the second iteration of simulation with the adjusted demand data. The output from the second simulation, i.e., the updated freeway-travel times and speed values are entered to the demand-change rate

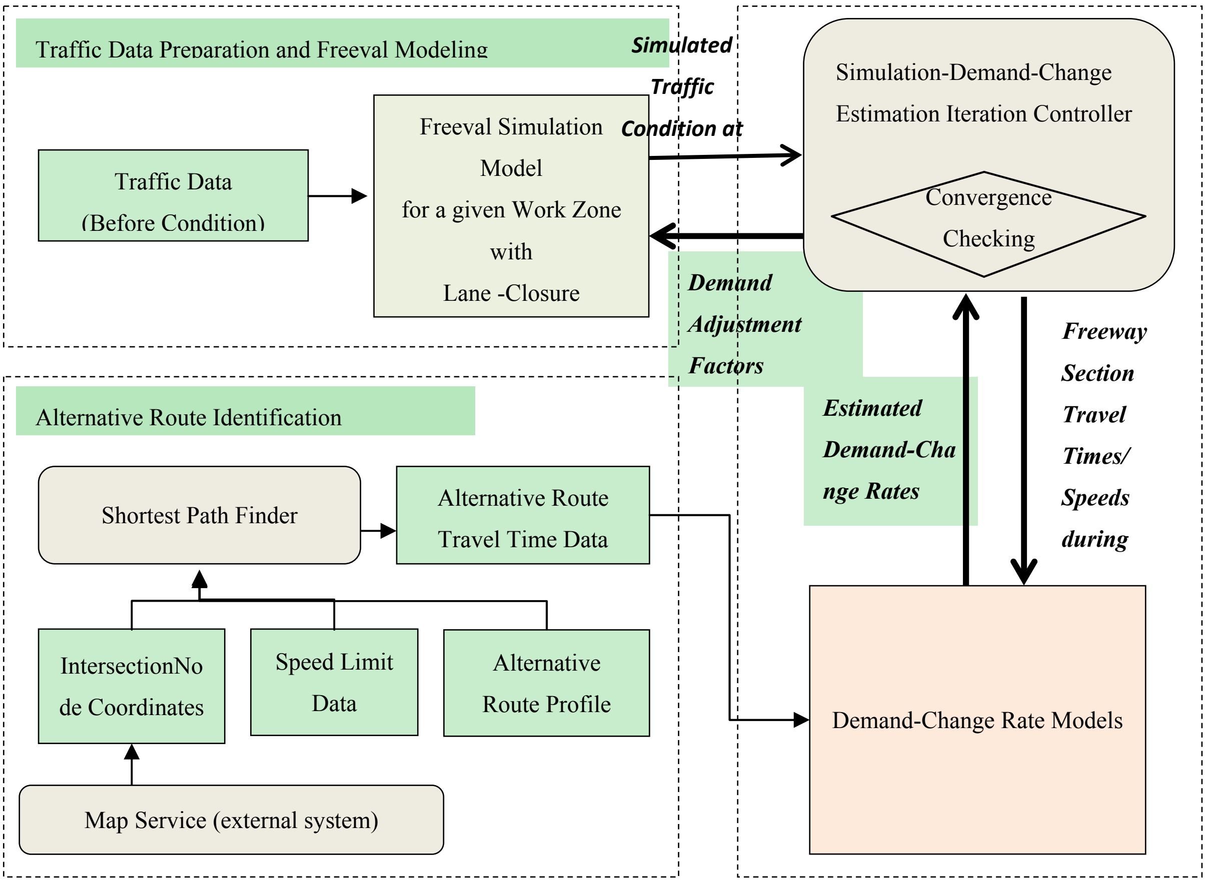


Fig. 5 Framework for Iterative Process for Demand-Change Rate Estimation.

models, which estimate a new set of the demand-change rates at each exit and entrance ramp. The updated demand-change rates are then converted to a new set of demand data for Freeval and the next iteration of the freeway simulation is performed. This demand-change estimation-simulation process keeps iterating until the changes in freeway-travel times and speed levels between successive iterations are within the pre-specified thresholds. The demand-change rates and the flow rates at each ramp at convergence are selected as the final estimates of the demand-change rates and the traffic demand at each ramp for a subjective work zone under given lane-closure and 'before' demand condition.

4.1 Testing Demand-Change Estimation Process for Sample Work Zones

The iterative process developed in this study for estimating the demand-change rates is first tested with those work zones whose data were used to develop the demand-change rate models. They include Work Zones #1 (35E-NB/SB), #2 (35E-NB), #3 (694-WB), #4 (169 SB) and #5 (35E-SB). For each of those sites, a Freeval simulation model was developed and calibrated with the geometry and traffic data for the 'before' lane-closure condition. Further, for each decision point in a given work zone, i.e., entrance or exit ramp, a shortest-time-alternative route was identified with the Dijkstra's algorithm and its travel time was estimated. For this testing, a peak-hour traffic data was used for each site, e.g., 7:00-8:00 a.m. or 4:00-5:00 p.m. depending on the peak direction at each work zone. Therefore, the demand-change rates resulting from the iterative process are those for peak-hour periods at given work zones. It needs to be noted that each Freeval case represents one set of lane-closure configuration at a given site, i.e., for the work zones with multiple phases, i.e., with the changes in lane-configurations, each phase requires a separate Freeval simulation model for the changed lane-closure configurations at a same site. Finally, the iterative simulation-demand-change estimation process was applied to each work zone until the freeway travel times and demand-change rates at each decision point converge to a predefined threshold value. Figure 6 shows one example convergence process for Phase 1 of the Work Zone #1 (35E-NB). In most cases, the convergence was achieved after 10-20 iterations.

Figures 7-8 show the estimation results from the iterative process for the demand-change rates and the resulting traffic flow rates at each decision point for two phases at Work Zone #1 (35E NB/SB). Tables 3 and 4 include the estimation results for a typical phase of those work zones, whose data were used in developing the demand-change rate models in this study. The test results indicate that the estimation error of the demand-change rate ranges 5-35% at typical entrance and exit ramps with well-defined alternative routes, while substantial differences were

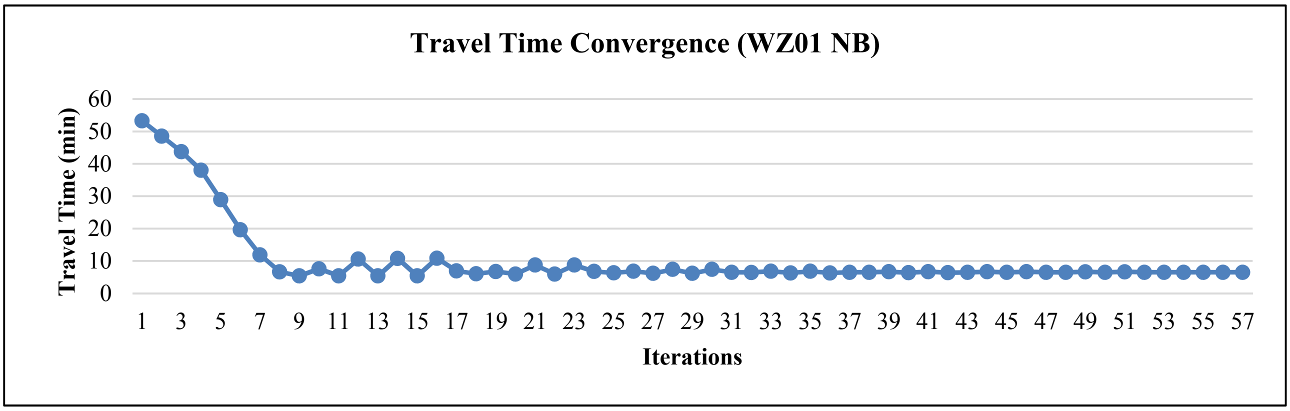


Fig. 6 An Example Convergence of Freeway Travel Time (I-35E NB Work Zone, Phase 1).

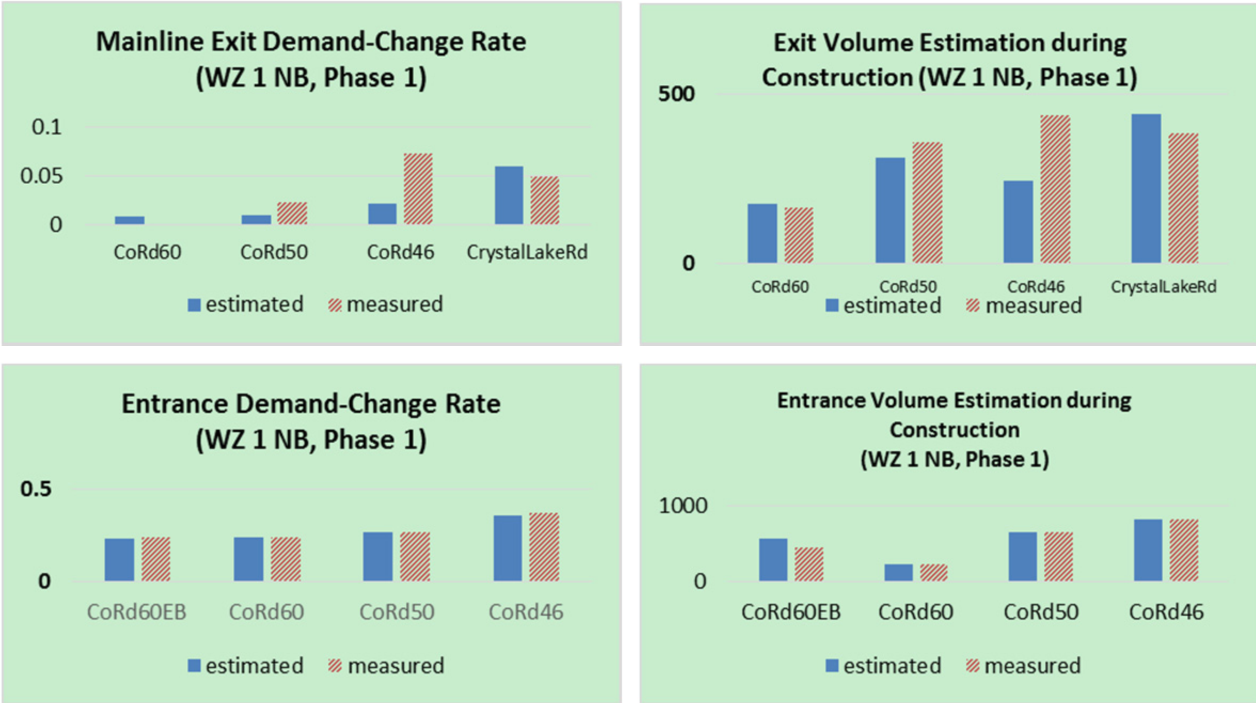


Fig. 7 Demand Estimation Results for WZ 1, Phase 1 (35E-NB, 7:00-8:00 a.m.)

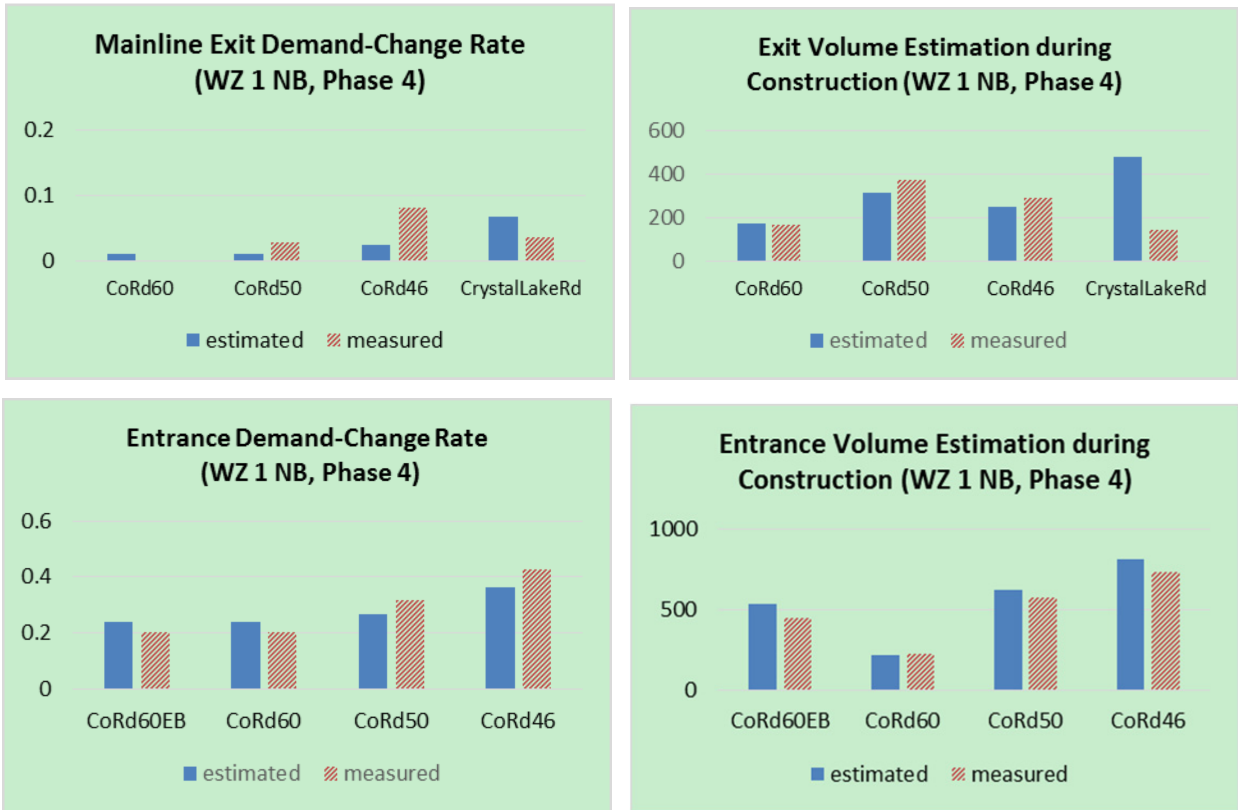


Fig. 8 Demand Estimation Results for WZ 1, Phase 4 (35E-NB, 7:00-8:00 a.m.).

Table 3 Exit Demand Estimation Results for Typical Phases at Each Work Zone.

WZ ID: Corridor	Time	Phase	Exit Ramp	Mainline Exit Demand-Change Rate		Exit Volume		
				estimated	measured	estimated	measured	difference (%)
#1:I-35E NB	7-8 AM	1	CoRd60	0.00913	0.00327	176	163	7.98
			CoRd50	0.00995	0.02359	313	355	11.83
			CoRd46	0.02249	0.07326	243	435	44.14
			CrystalLakeRd	0.06061	0.0502	439	384	14.32
#1:I-35E SB	4-5 PM	1	I-494 WB	0.01079	0.00358	438	412	6.31
			I-494 EB	0.00227	-0.00736	140	106	32.08
			Lone Oak Rd	0.01587	-0.00125	693	671	3.28
			Yankee Doodle Rd	0.0243	0.00026	966	930	3.87
			Pilot Knob Rd	0.02471	0.03408	805	887	9.24
			Diffley Rd	0.05667	0.02803	871	784	11.10
			Cliff Rd	0.08285	0.13002	1290	1329	2.93
			I-35E CD SB	0.12587	0.29867	1538	1667	7.74
#2:I-35E NB	4-5 PM	1	Maryland Ave	0.02813	0.02714	437	440	0.68
			Wheelock Pkwy	0.03337	0.0138	471	380	23.95
			Roselawn Ave	0.03583	0.00613	328	184	78.26
			T.H.36 EB	0.04505	0.02603	828	768	7.81
			T.H.36 WB	0.04604	0.02427	947	916	3.38
			Little Canada Rd	0.04605	0.0349	711	691	2.89
			I-694WB	0.07168	-0.06739	1666	1416	17.66
			Co Rd E	0.11836	0.04587	1229	1043	17.83
#3:I-694 WB	4-5 PM	3	T.H.61 NB	0.04132	0.00298	851	626	35.94
			Lake Rd	0.05	0.00581	792	628	26.11
			Valley Creek Rd	0.05207	-0.00012	833	670	24.33
			Tamarack Rd	0.04787	0.01497	494	404	22.28
			E Jct I-94 EB	0.05175	0.01027	1871	1816	3.03
			E Jct I-94 CD WB	0.06761	0.04618	566	590	4.07
			10th St	0.07443	0.08636	941	1064	11.56
			T.H.5	0.14445	0.27337	801	1110	27.84
#4:U.S.169 SB	4-5 PM	9	Anderson Lakes Pkwy	0.23178	0.13761	1162	772	50.52
			Pioneer Trail	0.12375	-0.03126	602	84	616.67
#12:I-35E SB	4-5 PM	1	Old Shakopee Rd	0.03078	-0.03021	375	174	115.52
			Lone Oak Rd	0.05027	-0.0018	953	682	39.74
			Yankee Doodle Rd	0.05579	0.01544	1171	975	20.10
			Pilot Knob Rd	0.05785	0.01271	1070	855	25.15
			Diffley Rd	0.06914	0.02844	932	780	19.49
			Cliff Rd	0.08052	0.05524	1146	1077	6.41
			I-35E CD SB	0.09353	0.21487	1340	1508	11.14

also observed at the ramps without clear alternative routes. Finally, the iterative process and the demand-change rate models were applied to Work Zone #6, whose data were not included in the development of the demand-change rate models. Tables 5 and 6 summarize the test results for Work Zone 6, whose estimation errors for both demand-change rates and traffic demand at each ramp are compatible with those from other sites. This indicates the promising possibilities for the transferability of the demand-change rate models and iterative process developed in this study.

Table 4 Entrance Demand Estimation Results for Typical Phases at Sample Work Zones.

WZ ID: Corridor	Time	Phase	Entrance	Entrance Demand Change Rate		Entrance Volume		
				estimated	measured	estimated	measured	difference (%)
#1: I-35E NB	7-8 AM	1	CoRd60EB	0.23519	0.24308	559	442	26.47
			CoRd60	0.23838	0.24308	222	221	0.45
			CoRd50	0.26508	0.26728	655	653	0.31
			CoRd46	0.35971	0.37468	826	807	2.35
#1:I-35E SB	4-5 PM	1	I-35E CD SB	0.01773	0.07	2100	2430	13.58
			Lone Oak Rd	0.13959	0.23	761	683	11.42
			Pilot Knob Rd	0.21901	0.23	789	781	1.02
			Diffley Rd	0.34816	0.42	191	171	11.70
			Cliff Rd	0.41741	0.58	168	122	37.70
#2: I-35E NB	4-5 PM	1	Pennsylvania Ave	0.02992	0.06317	643	621	3.54
			Maryland Ave	0.05389	-0.04808	486	538	9.67
			Larpenteur Ave	0.08751	-0.13103	303	375	19.20
			Roselawn Ave	0.09809	0.09489	149	149	0.00
			T.H.36 EB	0.15569	0.10127	755	802	5.86
			T.H.36 WB	0.15916	-0.06303	190	240	20.83
			Little Canada	0.14328	0.00937	264	305	13.44
			I-694WB	0.37725	0.32587	803	867	7.38
			Co Rd E	0.42944	0.40333	362	378	4.23
#3: I-694 WB	4-5 PM	3	T.H.61 NB	0.2031	0.12761	469	513	8.58
			Bailey Rd	0.2059	0.03683	123	150	18.00
			Lake Rd	0.2757	0.13181	239	287	16.72
			Valley Creek Rd	0.30407	0.08554	704	644	9.32
			Tamarack Rd	0.29344	0.0707	560	521	7.49
			E Jct I-94 EB	0.36045	0.31015	466	504	7.54
			E Jct I-94 CD WB	0.36429	0.3813	698	679	2.80
#4: U.S 169 SB	4-5 PM	9	10th St	0.39874	0.57538	340	240	41.67
			T.H.5	0.40499	0.62217	211	134	57.46
			Anderson Lakes Pkwy	0.41334	0.60485	301	203	48.28
			Pioneer Trail	0.44425	-0.11944	330	664	50.30
#12: I-35E SB	4-5 PM	1	I-35E CD SB	0.063	0.08725	2447	2383	2.69
			Lone Oak Rd	0.07832	0.29763	777	592	31.25
			Pilot Knob Rd	0.10722	0.31543	903	693	30.30
			Diffley Rd	0.15816	0.53282	252	140	80.00
			Cliff Rd	0.2047	0.54716	231	132	75.00
			Co Rd 42	0.13238	0.11538	463	472	1.91
			Crystal Lake Rd	0.1743	-0.04066	343	432	20.60
			Co Rd 46	0.22749	-0.6291	189	399	52.63
			Co Rd 60	0.33	0.08485	173	236	26.69

Table 5 Exit Demand Estimation Results for New Work Zone #6 (US-169 SB).

WZ ID: Corridor	Time	Phase	Exit	Mainline Exit Demand-Change Rate		Exit Volume		
				estimated	measured	estimated	measured	difference (%)
#6: U.S.169 SB (Exit Diversion)	4-5 PM	1	T.H.55 WB	0.0425	0.0264	298	272	9.56
			T.H.55 EB	0.03267	0.01829	347	329	5.47
			Betty Crocker Dr	0.04323	0.02913	481	437	10.07
			I-394 WB	0.06161	-0.01712	596	388	53.61
			I-394 EB	0.0425	0.07119	655	772	15.16
			Cedar Lake Rd	0.09411	0.04738	429	287	49.48
			Minnetonka Blvd	0.12931	0.05836	512	296	72.97
			36th St	0.08506	0.06033	327	271	20.66
			T.H.7	0.01025	0.14971	472	727	35.08
		3	T.H.55 WB	0.01923	0.02078	243	247	1.62
			T.H.55 EB	0.01346	0.03855	295	379	22.16
			Betty Crocker Dr	0.02486	0.03899	398	438	9.13
			I-394 WB	0.03526	-0.02539	516	349	47.85
			I-394 EB	0.01779	0.09802	627	837	25.09
			Cedar Lake Rd	0.05351	-0.00596	237	72	229.17
			Minnetonka Blvd	0.08683	0.10875	383	397	3.53
			36th St	0.11812	0.05915	532	255	108.63
			T.H.7	0.16375	0.382	1045	1082	3.42

Table 6 Entrance Demand Estimation Results for New Work Zone #6 (US-169 SB).

Corridor	Time	Phase	Entrance	Entrance Demand Change Rate		Entrance Volume		
				estimated	measured	estimated	measured	difference (%)
#6: U.S.169 SB (Entrance Diversion)	4-5 PM	1	Plymouth Ave	0.23117	0.11463	189	218	13.30
			T.H.55 WB	0.25001	0.23067	175	179	2.23
			T.H.55 EB	0.26375	0.16216	207	236	12.29
			Betty Crocker Dr	0.28336	0.13933	155	186	16.67
			I-394 WB	0.32578	0.48693	620	472	31.36
			I-394 EB	0.33281	0.47836	286	224	27.68
			Cedar Lake Rd	0.37494	0.4223	300	278	7.91
			Minnetonka Blvd	0.40365	0.35974	190	205	7.32
		3	Plymouth Ave	0.19833	0.12937	192	208	7.69
			T.H.55 WB	0.21552	0.1006	174	200	13.00
			T.H.55 EB	0.22845	0.10643	208	242	14.05
			Betty Crocker Dr	0.24775	0.02363	163	212	23.11
			I-394 WB	0.29205	0.52693	626	418	49.76
			I-394 EB	0.29753	0.55125	308	197	56.35
			Cedar Lake Rd	0.33197	0.38713	292	268	8.96
			Minnetonka	0.3984	0.40853	179	176	1.70

5. Conclusions

Accurate estimation of the changes in traffic demand for work zones, whose traffic conditions and drivers' diversion behavior continuously interact with each other, is of critical importance in developing effective strategies for traffic management in work-zones. The analysis of the traffic data collected from 5 work-zones in the metro-freeway network in Minnesota resulted in a set of the traffic demand-change estimation models, which are incorporated into an iterative process designed to capture the interrelationships between work-zone conditions and traffic diversion in determining the traffic demand for a work-zone site with given lane-closure configurations. In the proposed process, a given work zone is modeled with a freeway simulator, which interacts with the demand-change estimation models until a convergence is reached between the estimated demand-change rates and the traffic conditions resulting from the demand changes at a given site under given lane-closure configurations. The test results of the iterative process with both existing and new work-zone data showed promising results, indicating the potential transferability of the proposed methodology to other areas. It needs to be noted that, due to the types of the work zones used for this study, the mainline exit demand-change estimation model included in the current process can be applicable to those with 'two-to-one' lane reduction cases, while such restrictions do not apply to the entrance demand-change estimation models. Future study needs to include the expansion of the demand-change estimation process to the work-zones with different lane-closure configurations. The advantages of adopting a microscopic network-simulation tool instead of the current macroscopic model can also be studied.

Acknowledgements

This study was financially supported by the Minnesota Department of Transportation. The technical and administrative support from Tiffany Dagon and Nelson Cruz throughout this study is greatly appreciated.

References

[1] Chen, Y., Qin, X., Noyce, D. A., & Lee, C. (2008, January). "A hybrid process of micro-simulation and logistic regression for short-term work zone traffic diversion." In The 87th Annual Meeting of the Transportation Research Board. Washington DC.

[2] Copeland, L. (1998). "User's manual for quewz-98." Texas Transportation Institute, the Texas A & M University System.

[3] Dynasmart-P (2007), Internet, V. 1.3.0, User Manual, accessed on April 12th, 2015, http://mctrans.ce.ufl.edu /featured/dynasmart/

[4] Dynus-T (2013), Internet, V. 3.0.1 User Manual, accessed on May 1st, 2014, http://dynus.net

[5] Freeval User's Guide, Internet, accessed on February 12, 2018, htps://www.nap.edu/read/22487/chapter/12

[6] Horowitz, A., Weisser, I., & Notbohm, T. (2003). "Diversion from a rural work zone with traffic-responsive variable message signage system." Transportation Research Record: Journal of the Transportation Research Board, (1824), 23-28.

[7] Kwon, E., & Park, C. (2012). "Development of freeway operational strategies with iris-in-loop simulation." Final Report 2012-04, Minnesota Department of Transportation, January 2012, St. Paul, MN.

[8] Kwon, E., & Park, C. (2016). "Development of a guideline for work zone diversion rate and capacity reduction." Final Report 2016-12, Minnesota Department of Transportation, March 2016, St. Paul, MN.

[9] Liu, Y., & Horowitz, A. (2011). "Development of a traffic diversion estimation model for freeway construction work zones." Final Report for Smart Work Zone Initiative, University of Wisconsin, Milwaukee.

[10] Mitretek (2001). "Quickzone v0.99 user guide." Mitretek System, Washington, DC

[11] Patil, G. R., Sadek, A. W., Fowler, M., & Watts, R. (2008). "Regional microscopic simulation model for studying traffic control strategies at work zones." Final Report, Transportation Research Center, University of Vermont, Burlington, VT.

[12] Tanvir, S., Karmakar, N., Rouphail, N., and Schroeder, B. (2016). "Modeling freeway work zones with dynamic mesoscopic traffic simulator: validation, caps and guidance", Presented at 2016 TRB Conference, January 2016, Washington, DC.

[13] Ullman, G. (1996). "Queuing and natural diversion at short-term freeway work zone lane closures." Transportation Research Record: Journal of the Transportation Research Board, (1529), 19-26.

[14] Ullman, G., & Dudek, C. (2003). "Theoretical approach to predicting traffic queues at short-term work zones on high-volume roadways in urban areas". Transportation Research Record: Journal of the Transportation Research Board, (1824), 29-36.

[15] Zhang, M., Shen, W., Nie, Y., & Ma, J. (2009). "Integrated construction zone traffic management" California PATH Research Report, UCB-ITS-PRR-2008-9, Davis, CA.