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16. ABSTRACT

In the next decade many of the busy urban freeways will be undergoing major repairs. In the past, routine repairs were often carried out over night hours, or weekends, but this may no longer be feasible because the pavement of many of these urban arteries has exceed their design life and needs major reconstruction. Construction work during commuting hours could be quite common in the years to come. Both Caltrans and the traveling public want to know how different types of closures affect traffic and the environment, and how to cope with such closures. Three construction plans for Fix I-5, a 36-day directional closure plan, a 110-day A+B plan, and a 195-day lane closure plan[1] were evaluated for their traffic and environmental impact using a state-of-the-art dynamic work zone traffic analysis tool, NetZone, and extensive traffic data collected in a related previous project. It was found that the directional closure plan did not significantly increase the daily peak delay than the other two lane-closure plans in the Fix I-5 case, because drivers made good use of ample alternative routes in the area. Furthermore, all three plans produced slightly higher/lower emissions (<2%) for most pollutant types and consumed slightly more/less fuel (<2%) on a daily basis as compared with the base scenario (i.e., no construction). Considered for the whole project duration, the 36-day directional closure plan is more preferable because the total delay cost was 80% less than the traditional 195-day plan, $21M compared to $109M. The A+B plan is still preferable to the 195-day plan with more than 50% less total delay cost than the 195-day plan, $47.5M compared to $109M. However, it should be cautioned that directional closure should be used only when there is reasonable number of alternative routes to divert traffic to.

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Evaluation of Alternative Construction Plans for the I-5 Closure in Downtown Sacramento

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Executive Summary

In this project, we evaluate three work zone plans for the Fix I-5 project in the Sacramento Metropolitan Area using dynamic network analysis. The three plans are: 1) the actual directional closure plan implemented from May 20 to July 28 with directional NB and SB closures; 2) the 195-day lane closure alternative plan which would last 10 months with 12 lane closure stages; and 3) the A+B lane closure alternative plan which would last six months with the same staging as the 195-day plan.

The modeling process involves several steps. First of all, the network of Sacramento Metropolitan Area is encoded in NetZone, a dynamic work zone analysis tool. Using the 5-min PeMS traffic counts on selected 28 freeway segments and 15-min traffic counts on major arterials on the periphery of Downtown Sacramento, we estimate the time-dependent O-D demands by a Logit Path Flow Estimator for the morning peak and the afternoon peak, respectively. We then load the time-dependent Origin-Destination (O-D) demands to the network where no work zone is deployed. By trial-and-error, the network properties, O-D connectors and route choice models are appropriately calibrated so as to produce the actual traffic count observation. This serves as the baseline scenario. For the cases with the presence of work zone plans, the same method is also applied but the time-dependent demands are adjusted accordingly using a demand diversion model and engineering judgment. By network calibration and simulation, we obtain the network performance measures, link specific measures of effectiveness and emissions for all the three plans.

From our analysis of the modeling results, we draw the following lessons/conclusions:

- Considered for the whole project duration, the 36-day directional closure plan is more preferable because the total delay cost was 80% less than the traditional 195 day plan, \$21 M compared to \$109 M. The A+B plan is still preferable to the 195 day plan with more

than 50% less total delay cost than the 195 day plan, \$47.5M compared to \$109 M.

- Use directional over lane closures whenever possible, because the former can considerably reduce overall user delay costs (and possibly construction costs), while producing comparable levels of fuel consumption and emissions.

- Adequate number of alternative routes and amount of reserve capacity are prerequisites for using directional closures, because traffic diversion plays an important role in softening the traffic impact of directional closures.

- Demand reduction is likely to be minor in work zone projects with predominantly commuting trips. The specific levels of reduction largely depend on the availability of alternative modes and the extent of public awareness. Before enough data are assembled to reliably estimate demand reductions, the level of demand reduction is the biggest unknown in any large work zone project.

- A well executed transportation management plan (TMP) for work zone projects can increase disaster preparedness because it makes the traveling public become more aware of travel alternatives and reveal the vulnerable elements of the transportation system.

- Good data coverage and quality, as well as adequate modeling tools, are essential to the development of effective TMPs.

Chapter 1

Introduction

1.1 Project background

Non-recurrent traffic congestion caused by construction work constitutes a large proportion of traffic congestion on urban roadway networks. As more and more highway rehabilitation/reconstruction work is conducted on heavily traveled urban corridors which are already “capacity-hungry”, how to minimize its disruption to commuting traffic presents a big challenge to transportation agencies.

There are usually two work zone closure strategies that can be chosen from, full road closure where one of the two directions or both directions are fully closed, or lane closure where one or more lanes of one direction are closed while the freeway is still accessible. A full closure has the potential to accelerate the project completion and reduce the total construction cost, but is likely to cause more disruption to the traffic (sometimes more severe congestion) than a lane closure during the rush hours of a typical weekday. It is usually a challenging issue to plan and evaluate alternative work zone plans implementing these two strategies in large highway reconstruction/repair projects, and the associated traffic management plans, guidelines as well as data needed to develop and evaluate alternative construction plans are often lacking. Consequently, there is a real need to study, as much as one can, the few completed large highway reconstruction projects to learn valuable lessons from them, so as to prepare the transportation agencies to deal more effectively with large routine highway maintenance or emergency repair projects in the presence of natural or man-made disasters. The directional full closure of the I-5 in downtown Sacramento in the summer of 2008 offers an excellent opportunity to do such a case study.

A section of I-5 from I Street to the U.S. Highway 50/Capitol City Freeway Interchange in the Downtown Sacramento area was shut off from May 30 to July 28 in the summer of 2008 to replace pavement and improve drainage using a directional closure plan. A team of researchers, led by Professor Michael Zhang, conducted a study to assess the traffic impact of, motorists' response to, and lessons learned from the I-5 closure. In that CalEPA funded study (Zhang et al. 2010), the research team collected various kinds of traffic, transit and travel behavior data, and seek answers to the following questions:

1. What levels of demand reduction/redistribution are needed to control traffic delay to a tolerable level (say, for example, the longest delay is below twice the level before construction)? The demand reduction comes from several sources, including cancelation of trips and telecommuting, and redistribution from changing departure times, travel routes and travel modes (e.g., transit, carpool or vanpool).
2. What are the actual travel behavioral changes during construction? These would include the usage of telecommuting and potentially e-shopping (conducting activities remotely), eliminating activities altogether (forgone trips), the adoption of flexible working hours (departure time changes) and alternative routes (route changes), and the usage of bus, light rail, and HOV (mode shifts).
3. Does truck traffic respond to the construction event substantially differently from passenger traffic?
4. Does a major construction event like this one induce long term mode or other behavioral shifts (for example, some of the travelers who switch from driving to light rail during the construction period may decide to continue using light rail after the construction is over), and if yes, to what magnitude?

While this CalEPA funded study focuses on the collection of traffic and transit data and travel behavior surveys that can reveal travel behavior changes in the event of major traffic disruptions like the I-5 closure, as well as their implications to air pollution and energy usage, this project supplements the current Fix I-5 study through investigating how different alternative construction plans for the I-5 closure could affect traffic on both the highway and major arterial roads, emissions and fuel consumption in the affected areas. Unlike the CalEPA funded component, this project requires extensive modeling work that takes into account travel demand changes and re-routing. By quantifying the user costs (delays and fuel costs) and environmental impact (emissions and energy usage) of different construction plans for the I-5 closure, we can pinpoint what plan works and what does not for what reasons, and help the development of more effective construction plans for large construction projects in major urban corridors.

1.2 Objective and tasks

This project has three objectives,

1. to assess the potential traffic and environmental impact of the alternative construction plans for the full closure of I-5.
2. to help develop a set of guidelines for the development of construction/traffic management plans for future large-scale highway reconstruction projects based on a full range of performance measures: network performance, travel delay, fuel consumption, and emissions,
3. and to extract lessons for improving disaster preparedness.

The specific tasks of this project include,

- **Identify alternative construction plans**.

  We contact the Caltrans District Fix I-5 project team (e.g., Ken Solak and Marlo Tinney) to gather detailed information about the alternative construction plans for the I-5 closure, including geographical scope of the closure, lane closure configurations and construction schedule.

- **Selection of modeling tools**

  Three types of tools are often used for modeling construction projects: planning level tools (coarse), microscopic simulation tools (fine) and mesoscopic simulation tools (middle of the pack). While being powerful and high fidelity, microscopic simulation tools are known to be labor intensive to apply and difficult to calibrate, and have rarely been attempted to model large urban networks. It could easily take an entire year to code and calibrate the Sacramento network in a microscopic simulation, which is not feasible for this project. We therefore plan to choose a planning tool and a mesoscopic simulation tool.

The reason for choosing two instead of one tool is to compare their efficacy for modeling large-scale construction projects, where significant amount of queuing can occur. As we all know that planning models, while simple to apply, do not explicitly model queuing and peak spreading. By comparing them with models that can do both, we can quantify the magnitude of the error we get from applying planning models in situations where congestion can be heavy, and determine their suitability for such applications.

- **Network Coding and Testing**

  The Sacramento network, together with the construction plans, will be coded into NetZone and the selected planning software. NetZone is a dynamic network analysis tool capable of estimating network-wide traffic impact for any general networks consisting of freeway, arterials and local streets. It implements the mesoscopic traffic flow model and emission/energy models. We will code the network in NetZone, along with the actual construction plans and the alternative construction plans, and also code the network into the planning software.

- **Preparation of travel demand data**

  Base (before construction) travel demand was obtained by an Origin-Destination (O-D) demand estimator that reproduces freeway traffic counts from PeMS and arterial traffic counts collected in the Fix I-5 project. Under each alternative construction plan, however, travel demand during construction will change in response to the level of congestion that it produces. We will estimate the demand reductions (due to cancelation of trips, telecommuting, and mode shifts) based on the congestion levels under the do-nothing scenario. This will be done by first loading the network with base demand in both NetZone and the planning model, then extracting the path delays for each O-D pair, and finally estimating the demand reductions based on these perceived delays.

- **Modeling Emissions**

  We will review the state of art transportation green house gas emission models, select one of them and implement it into the NetZone. We will then apply the model for each of those construction plans and estimate their respective emission footprint.

- **Modeling fuel consumption**

  We will select an appropriate fuel consumption model and implement it into NetZone. Once this is done, we will then apply this model for each construction plan to obtain the overall fuel consumption under each plan.

- **Modeling congestion**

  We will estimate the user cost (mainly travel times) and the network performance under each construction plan using both NetZone and the planning software.

- **Report findings**

  Prepare final report. This report will synthesize the findings and help develop a guideline for making construction plans that produce the smallest congestion, emission, and energy footprints.

1.3 Relations to other Caltrans projects

This project complements the CalEPA funded Fix I-5 study in the sense that that study looks into the actual travel patterns during the I-5 closure, how the traveling public coped with the closure of the I-5 in Downtown Sacramento, and what were the environmental impacts of the I-5 closure, while this project focuses on what would happen if one of the alternative construction plans was used, how it compares with the actual plan, and how to evaluate these alternative plans. It also complements Caltrans funded projects: TO 5300 Integrated Construction Zone Traffic Management and its continuation, which developed a software tool, NetZone, for network-wide work zone traffic analysis. NetZone will be used, with some modifications, in the current project to model the work zone effects.

Chapter 2

The Fix I-5 project

In this chapter, we present the background of the Fix I-5 project. The actual work zone plan used for the Fix I-5 project is first described. Besides the actual plan, there are also two alternative work zone plans available for Caltrans to choose from in the summer of 2008. The actual plan and the alternative plans involve the same freeway segment on the I-5, while their closure time frames for each part of the segment are different. In addition, each plan has different ramp restrictions. All these details of the three plans will be coded into the network for dynamic traffic analysis later on.

2.1 Background

Interstate 5 (I-5) is a major interstate that runs south-north, connecting Mexico to Canada through California, with construction beginning in 1947 by the Federal Highway Administration. The Downtown Sacramento portion of I-5 was completed in the 1960's and is nicknamed the "Boat Section" because it was constructed below the water level of the Sacramento River, which runs adjacent to the freeway. In order to construct the Boat Section of the freeway, Caltrans had to initially drain this section, and engineer a drainage system of pipes and pumps. The Boat Section was manually monitored during each winter season to ensure pumps were working properly.

After over 40 years and without major renovation, pavement cracking and sediment accumulation required the Boat Section to undergo repair, and an opportunity was provided for drainage system upgrades. The California Department of Transportation (Caltrans) engineers' estimate projected that the rehabilitation of drainage and pavement of Interstate 5 in downtown

Sacramento, dubbed "Fix I-5", would take 305 working days at a cost of more than $44 million (Myers 2009). On February 2, 2008, the Rancho Cordova-based engineering firm, C.C. Myers, Inc., won the Fix I-5 project bid with a proposed 85 working days and 29 night and weekend schedule at a substantially lower cost of $36.5 million, with financial incentives for earlier completion. Although not emergency work this time around, the Fix I-5 project specifically included a reconstructed six-inch pavement slab, an upgraded drainage system, new de-watering wells, and installation of electronic monitoring equipment. The renovated segment on the I-5, "Boat Section", starts from the interchanges to/from US-50 and ends at I St. ramps in both directions. The project was completed in a shorter period than predicted, from May 30, 2008 to July 28, 2008 in 35 days and 3 weekends using four full unidirectional closures.

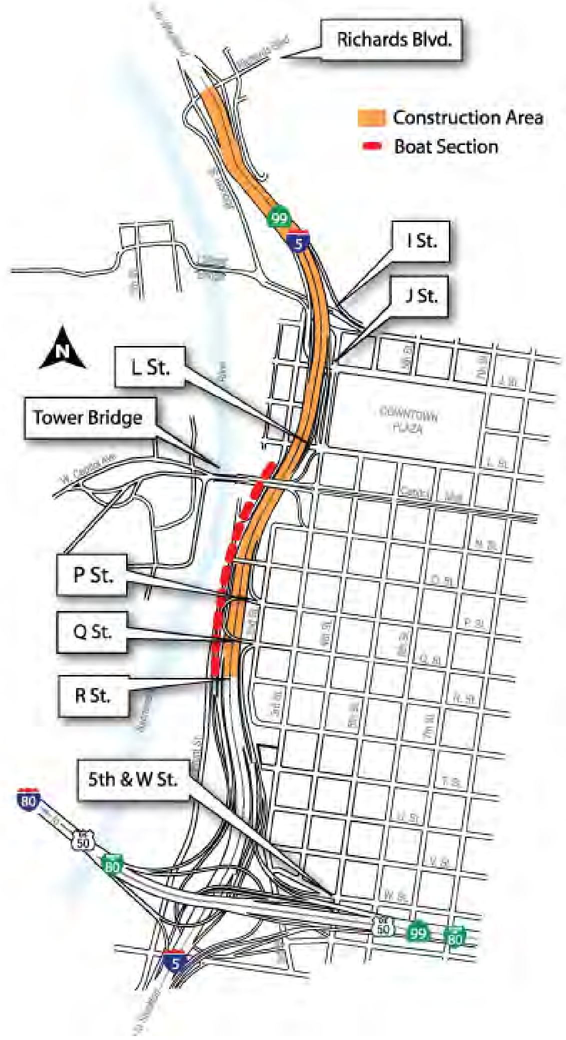


Figure 2.1: The Fix I-5 Construction Area (source: www.FixI-5.com)

The construction area of the Fix I-5 project is shown in Figure 2.1. This freeway segment, particularly the “Boat Section”, is on a major commuting route and connects major arterial roads in Downtown Sacramento. It is estimated that it carries approximately 200,000 vehicles on Interstate 5 in Sacramento each day (Schwarzenegger 2009). Reports projected that during closure periods, traffic congestion could increase nineteen times. During closure periods, traffic was detoured to arterial streets and other freeways. In order to alleviate congestion, media outreach alerted commuters about projected traffic conditions as well as advised alternative modes of travel. Employers, including the State of California which is one of the largest employers in the area with 75,000 commuters, encouraged employees to use alternative modes of travel.

2.2 Actual work zone plan: directional closure

The actual construction schedule periodically closed entire northbound (NB) or southbound (SB) portions of Interstate 5 through Sacramento, a relatively new technique for non-emergency construction. It consisted of a plan that closed all lanes (either NB or SB) for a specific period of time over the course of two months. Scheduled construction began on May 20, 2008 at 8:00pm and was completed on July 28, 2008 at 5:00am. Within those two dates were several periods of non-closures, where all lanes in each direction were open. The actual plan adopted directional closures, i.e. when one direction of the freeway was fully closed, the other direction remained open. Overall, freeway lane closures of any direction lasted for a total duration of 60 days, including approximately 18 days for NB closures and 18 days for SB closures. Table 2.1 shows the time line of the actual work zone plan.

Table 2.1: The timeline of the actual work zone plan

Stage	Start	Finish	Closure Duration	Closure Lanes
1	5/31/08	6/8/08	9 days	NB
2	6/14/08	6/23/08	10 days	SB
3	7/9/08	7/16/08	8 days	SB
4	7/19/08	7/27/08	9 days	NB

During each directional closure, various on-ramps and off-ramps in the area were closed. In addition, outside the construction area, the adjacent segments of the I-5 are restricted by lane closures which served as the transition area to the work zone and warned motorists to detour. Table 2.2 lists the status of ramp and lane restrictions associated with the work zone for NB closures. In total, 6 ramps were subject to closures, 1 to intermittent closures, and 6 ramps remained open. While the entire I-5 NB section from U.S. 50 to L St. was closed, the freeway opened two lanes from L St. to Richards Blvd. on weekdays. During weekends, only one NB lane was open from L St. to Richards Blvd.

Table 2.2: Northbound Closure Restrictions in the actual directional closure plan

Northbound Closure Restrictions			
On-ramp Location	status	Off-ramp Location	Status
5th St. to NB I-5	Closed	East U.S. 50 to Q St.	Closed
East U.S. 50 ramp to SB I-5	Open	NB I-5 to J St.	Closed
I St. to NB I-5	Open	NB I-5 to Richards Blvd.	Intermittent Closure
L St. to NB I-5	Open	Q St. from NB I-5	Open
P St. to NB I-5	Closed	West U.S. 50 ramp to Q St.	Closed
P St. to SB I-5	Open		
Richards Blvd. to NB I-5	Open		
West U.S. 50 ramp to NB I-5	Closed		
The entire I-5 NB section from U.S. 50 to L St. was closed Two lane open from L St. to Richards Blvd. on weekdays			

SB I-5 restrictions included four ramp closures. In addition, only two lanes between the freeway portion of Richards Blvd. and the J St. exit were open on weekdays. For all other times, only one lane was open. Refer to Table 2.3 for the SB closure restrictions.

Table 2.3: Southbound Closure Restrictions for the actual plan

Southbound Closure Restrictions			
On-ramp Location	status	Off-ramp Location	Status
I St. to SB I-5	Closed	SB I-5 to J St.	Open
P St. to U.S. 50 and SB I-5	Open	SB I-5 to Q St.	Closed
Richards Blvd. to SB I-5	Closed		
SB I-5 ramp to EB & WB U.S. 50	Closed		
The entire I-5 SB section from J St. to U.S. 50 was closed Two lane open from Richards Blvd. to J St. exit on weekdays			

2.3 Alternative work zone plan: lane closure

Caltrans presented two alternative work zone plans to the actual directional closures that was used. The first plan would close specific lanes, but not all, for periods of time and last nearly a year. There are in all 195 days with active work zone construction. The second plan, referred to as "A+B", would follow the lane closure staging of the first plan but utilize more efficient yet more expensive construction materials and methods to halve the closure days for certain stages. Overall, this plan has a total duration of nearly half a year, and there are in all 110 days with active work zone construction.

Table 2.4 lists the closure schedule for the 195-day closure plan. The majority of the closures occur between stages 1 through 8. Like the actual directional closure plan, when one or two lanes in one direction of the highway is closed, the other direction remains fully opened. In this plan, one lane of the highway is closed for stages 1 and 2 while 2 lanes are closed for stages 3 through 8. Construction would commence at an earlier date, 5/16/08, but would end the following March.

Table 2.4: 195-Day Closure Plan

		♯			Lane			
Direction	Description	Closure Days	Early Start	Early Finish	1	2	3	4
SB	Stage 1	17	5/16/08	6/4/08	×			
NB	Stage 2	17	6/5/08	6/21/08	×			
SB	Stage 3	13	6/22/08	7/4/08	×	×		
SB	Stage 4	28	7/5/08	8/1/08			×	×
SB	Stage 5	24	8/2/08	8/25/08			×	×
NB	Stage 6	13	8/26/08	9/11/08	×	×		
NB	Stage 7	34	9/12/08	10/15/08			×	×
NB	Stage 8	13	10/16/08	10/28/08			×	×
	Stage 9	2	11/1/08	11/2/08	J St. Ramp Closure			
	Stage 10	2	11/8/08	11/9/08	WB US 50 Ramp Closure			
	Stage 11	6	11/15/08	11/30/08	EB US 50 Ramp Closure			
	Stage 12	2	11/15/08	11/16/08	P St. Ramp			
	Stage 12	2	11/22/08	11/23/08	P St. Ramp			
	Stage 12	2	11/29/08	11/30/08	P St. Ramp			
SB	PC Overlay - Stage 1	2	12/6/08	12/7/08	×			
NB	PC Overlay - Stage 2	2	12/13/08	12/14/08	×			
SB	PC Overlay - Stage 3	2	12/20/08	12/21/08	×	×		
SB	PC Overlay - Stage 4	2	12/27/08	12/28/08			×	×
SB	PC Overlay - Stage 5	2	1/3/09	1/4/09			×	×
NB	PC Overlay - Stage 6	4	1/10/09	1/18/09	×	×		
NB	PC Overlay - Stage 7	4	1/24/09	2/1/09			×	×
NB	PC Overlay - Stage 8	2	2/7/09	2/8/09			×	×
	PC Overlay - Stage 9	2	2/14/09	2/15/09	J St. Ramp Closure			
	PC Overlay - Stage 10	2	2/21/09	2/22/09	WB US 50 Ramp Closure			
	PC Overlay - Stage 11	2	2/28/09	3/1/09	EB US 50 Ramp Closure			
	PC Overlay - Stage 12	2	3/7/09	3/8/09	P St. Ramp			

Note: × represents lane closure

From the perspective of the work zone traffic analysis, a regular stage and its counterpart under PC Overlay, if the same lanes are closed, can be combined. In addition, we assume the closure on each of those lanes has the same effects to the traffic. Therefore, according to the closure restrictions in different stages, the alternative plan can be divided into eight scenarios for this project, as shown in Table 2.5.

Table 2.5: The scenarios for the 195-Day Closure Plan

Direction	Scenario	♯ Closure Lanes on I-5	♯ Closure Days
SB	Stage 1	1	19
NB	Stage 2	1	19
SB	Stage 3∼5	2	67
NB	Stage 6∼8	2	66
NB	Stage 9	N/A	4
NB	Stage 10	N/A	4
NB	Stage 11	N/A	8
NB	Stage 12	N/A	8
Total		195	

From beginning to end, the A+B plan would last 85 fewer days with work zone construction being active, and its schedule is listed in Table 2.6. However, this would have a greater effect on travel demand due to more intensive construction and media campaign. The use of different and more efficient materials would halve the construction time for stages 1 to 8.

Table 2.6: The scenarios for the A+B Closure Plan

Direction	Scenario	♯ Closure Lanes on I-5	♯ Closure Days
SB	Stage 1	1	10
NB	Stage 2	1	10
SB	Stage 3∼5	2	33
NB	Stage 6∼8	2	33
NB	Stage 9	N/A	4
NB	Stage 10	N/A	4
NB	Stage 11	N/A	8
NB	Stage 12	N/A	8
Total		110	

Chapter 3

Methodology

Before we analyze the work zone's traffic impact, the first step is to collect all the necessary data, including real time traffic data for the work zone area before/during/after the construction and network properties. Using the network properties and traffic data, we can estimate the travel demand, which is then, together with the work zone plan, serve as the basic input for the dynamic traffic simulation. Furthermore, this chapter discusses the key traffic models and emission models adopted to perform the dynamic traffic simulation in this project. The work flow of the assessment process is finally presented.

3.1 Data collected

The real time traffic data collected in this project are mainly the traffic count data which include vehicles counts of individual roadway detectors and freeway vehicle counts. Those data were collected directly through vehicles detectors placed on downtown streets and freeways.

Roadway detectors were generally placed on heavily traveled streets located on the boundaries (East, North, South, and West) of Downtown Sacramento, measuring vehicle flow into and out of the area. The locations of those detectors are marked in Figure 3.1.

The East boundary consisted of detectors that measured westbound flow on (1) W Street, between 25th and 26th Streets (2) P Street, between 27th and 28th Streets and (3) L Street, between 27th and 28th Streets. These westbound detectors were used to measure the inflow of vehicles into Downtown Sacramento. Eastbound detectors that measured the outflow of the central area were located on (1) Q Street, between 27th and 28th Streets and (2) J Street, between 27th and 28th Streets.

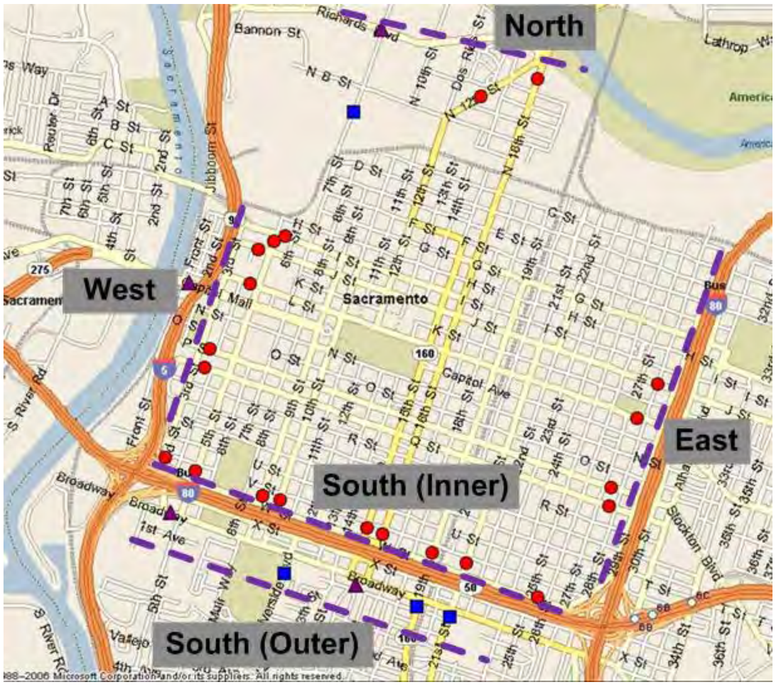


Figure 3.1: Local Street Detectors

The Southern Boundary is composed of two portions that are divided by the US-50 freeway, an inner boundary and an outer boundary. The inner boundary is more likely to count vehicles utilizing the freeway on/off-ramps into and out of the downtown area while the outer boundary used to analyze the local counts coming from the Southern areas of Sacramento. The inner portion of the Southern boundary consisted of 4 detectors measuring inbound flow and 4 detectors measuring outbound flow. The inbound detectors measuring NB flow were located on the following streets between W and V, (1) 5th Street (2) 10th Street (3) 16th Street and (4) 21st Street. The outbound detectors measuring SB flow were locating on the following streets between W and V as well on (1) 3rd Street (2) 9th Street (3) 15th Street and (4) 19th Street.

The South (Outer) boundary is composed of 5 detectors measuring the Eastbound flow on (1) Broadway, between 3rd and 5th Streets and the Northbound flows on (2) Riverside Boulevard, South of Broadway (3) Land Park Drive, South of Broadway (4) Freeport Blvd, South of Broadway and (5) 21st Street, South of Broadway. Outbound flow, which measures flow going south, consisted of 5 detectors but 2 were discarded due to detector inconsistencies. The remaining 3 detectors were on streets south of Broadway as well, consisting of (1) Freeport Blvd (2) Land Park Drive and (3) Riverside Boulevard.

The West boundary had four detectors that measured the inbound flow while 6 detectors measured the outbound flow. The inbound detectors were composed of (1) J Street, West of 5th Street (2) Capital Mall, West of 2nd Street (3) Q Street, East of 3rd Street and (4) Jibboom Street, South of Richards Boulevard. As for the outbound detectors, their locations were on (11) I Street, between 5th and 6th Streets (2) 5th Street, South of I Street (3) L Street, West of 5th Street (4) Capital Mall, West of 2nd Street (5) P Street at 3rd Street and (6) Jibboom Street, South of Richards Blvd.

For the North Boundary, three detectors measured vehicle counts on both of the direction flows. Inbound detector locations were on (1) Richards Boulevard, West of 7th Street (2) 7th Street, South of North B Street and (3) 16th Street, North of Sproule Avenue. Outbound detectors were on the same street locations as the inbound flows, except in opposite directions.

The major freeways in the Metropolitan Sacramento Area are I-5, I-80, SR-51(Business 80), SR-99, SR-113, SR-160, Tower Bridge Gateway (Old SR-275), and US-50. The freeway traffic counts were taken from the Freeway Performance Measurement System (PeMS) which is a consolidation database of information collected via Caltrans loop detectors. The collected period is from May to the end of August in 2008. As of 8/27/2008, 626 VDSs (Vehicle Detector Stations) are covered with 284 VDSs along mainlines, 89 VDSs on carpool lanes, 18 VDSs on intersections between freeways, 85 VDSs on freeway off-ramps and, 150 VDSs on freeway on-ramps. However, only a fraction of those detectors are under healthy conditions within this time period of the Fix I-5 project. Finally, 28 freeway detectors, covering all major freeway routes, were chosen as the data input of this project.

3.2 Traffic model

In this section, we briefly discuss the key traffic models adopted in this project including travel demand prediction model, work zone model and network assignment model.

3.2.1 Travel demand prediction

Unlike most transportation planning applications which focus on the long-term equilibrium traffic patterns in the network, work zone traffic impact assessment is usually interested in the short-term, dynamic queuing process produced by the work zone construction activity. Therefore, time-dependent travel demands, rather than static travel demands, are required in this project.

For simple networks where most travelers enter the network from the same entry point and leave from the same exit point, one can obtain the time-dependent demand by counting the time-dependent arrival flow rate at the entry point. However, reality is usually much more complicated than this ideal case. Travelers may enter and exit the network at various traffic zones. A time-dependent travel demand estimator to infer the demand from traffic data is necessary.

We use the *logit path flow estimator* (LPFE), a method originally proposed by Bell et al. (1997). LPFE seeks to find the path flow pattern that satisfies the stochastic user equilibrium condition and closely reproduce the observed traffic counts. Originally designed to estimate steady-state travel demand, it was extended to handle the the time-dependent case through the introduction of *residual queues*. These queues are used to capture the carryover of congestion from one time period to the next. Zhang et al. (2006) made several extensions to the original LPFE. They represented link travel times in terms of flow through a link performance function (rather than a constant link travel time and plus queueing delay), counted for measurement errors, and made use of historical travel demand information. Though LPFE can only partially capture the temporal traffic evolution, it is a quite stable, efficient, and theoretically sound method. For more details of the algorithm and its computer implementations, readers are referred to Zhang et al. (2006).

3.2.2 State-of-the-art mesoscopic traffic simulation

This research adopts mesoscopic traffic simulation to estimate traffic flow evolution and estimate the network performance. Mesoscopic traffic models fill the gap between the aggregate travel behavior over the traveler population and interactions among individual traffic entities. It provides adequate accuracy for the work zone traffic impact analysis while it is computationally plausible for a large-scale network. The mesoscopic traffic models consists of two components, the travelers' route choices and the dynamic network loading (DNL).

Route choice model

The route choice model, is central to the mesoscopic traffic simulation. It determines the routing patterns for each of the travelers depending on their generalized travel costs. The conventional routing pattern is usually referred to as a user-equilibrium (UE) flow pattern. In the dynamic context, there are generally two types of UE in the literature. One is the so-called Boston User Equilibrium (BUE) (Friesz et al. 1993), which is an adaption of the static Wardroppian UE. It assumes a traveler chooses the shortest route only based on the prevailing traffic condition at the time of his choice decision (Kuwahara & Akamatsu 2001). The other UE type is the so-called Predictive User Equilibrium (PUE). Under this behavioral assumption, travelers choose the shortest route based on "anticipated" travel times, or travel times that they actually experienced from previous days. The result is a UE in which the actual travel times/costs for travelers from any O-D pair are minimal and identical (Friesz et al. 1993), regardless of the routes they take.

In real life, travelers' route choice behavior is likely to be more complex than what was assumed in both BUE and PUE. For example, travelers may not consider all the possible routes but have several pre-trip routes in mind prior to their departure, which are selected from their day-to-day traveling experiences. Moreover, these pre-selected routes may not be user-optimal ones. Although travel time and schedule delay costs are dominant factors in travelers' route choice decisions, several other factors, such as road accessibility, pavement conditions, and so on, may influence their decisions as well. Besides these factors, a traveler's personality should also play an important role in his or her route choice. Thus real traffic is more likely to be the product of various types of choice decisions rather than cost-minimizing BUE or PUE applied uniformly across the entire traveling population. In addition, PUE requires an iterative procedure where traffic simulation is implemented in each iteration, which is apparently highly time consuming for large-scale networks. Both PUE and BUE can easily fall into the network gridlock where no traffic can move due to the unrealistic assumption on route choices in large-scale networks. Therefore, in this project, we adopt a new route choice model that can produce realistic traffic performance and is easy to calibrate with less computational complexity.

Suppose the network is represented by a directed graph that includes a set of nodes, N, and a set of links, A. Let a denote the link index, $a \in A$. Let R and S denote the set of origin nodes and destination nodes, respectively. $r - s$ represents an O-D pair, where $r \in R$ and $s \in S$. K_t^{rs} and q_t^{rs} is the set of paths and O-D demand for an O-D pair $r - s$ departing at time t, respectively. The generalized travel cost of commuters departing at time t on path p of O-D pair rs, $c_p^{rs}(t)$, consists of I number of terms $(w_{1,pt}^{rs}, w_{2,pt}^{rs} ..., w_{I,pt}^{rs})$ which represent those factors that travelers perceive on path p of O-D pair rs departing at time t (including travel time, schedule delay cost and toll) and are weighted by scalers λ_i,

$$c_p^{rs}(t) = \sum_{i=1}^{I} \lambda_i w_{i,pt}^{rs} \tag{3.1}$$

Let $[0, T]$ be an assignment horizon (i.e., the analysis period). The network is assumed to be empty at $t = 0$. Corresponding to the assignment period, we define a loading horizon $[0, T']$, where T' marks the time when the network is cleared up. Furthermore, let ϕ_a denote an assignment interval, a discrete duration during which the departure flow rate for any O-D pair is assumed to be constant (m_a is the number of assignment intervals, i.e., $T = m_a\phi_a$). ϕ_l is the loading interval, a discrete duration during which network conditions are assumed to be stationary (a loading horizon consists of m_l loading intervals of uniform length, i.e., $T' = m_l\phi_l$). ϕ_a must be a multiple of ϕ_l.

We introduce two groups of travelers: travelers who are willing to deviate from their predetermined routes and those who are not. The reason is simple. Some conservative travelers, once they determine which routes to take and get familiar with those particular routes, would rather stick to them than risking on finding new (or unknown) routes that may actually turn out to be worse than their previous routes, unless congestion they experience in their current routes becomes unacceptable to them. Those travelers are normally reluctant to deviate from their prescribed routes. We call this group of travelers **habitual travelers** ($1 - \theta$ percentage of travelers). On the other hand, some adventurous travelers are more willing to explore new routes in response to their travel experience and/or up-to-date traffic information. They may be equipped with devices that offer real-time navigation, or they may be familiar with the entire network and are able to change their routes to avoid the congestion. We call this group of travelers **adaptive travelers** (θ percentage of travelers). In a real network, the proportion θ, also referred to as the **Diversion Ratio**, may not be a constant and may change with respect to network conditions. For example, the diversion ratio can increase in the event of a major accident or a highway reconstruction project. Nevertheless, we expect the diversion ratio to be relatively stable for a network at least in the short run barring the occurrences of various major incidents.

For the habitual travelers, their routes are determined based on a number of factors, such as travel distance, historical travel times, and personal preference for major streets and freeways. These routes, however, may not be the same as the dynamic User Equilibrium routes when everyone is a habitual traveler, since now mixed with adaptive travelers, User Equilibrium is no longer achievable. In NetZone, we assume those prescribed routes are K shortest paths for each pair of O-D with respect to the free-flow travel times. Let P_t^{rs} denote the set of those routes that habitual travelers departing at time t between O-D pair rs strictly comply. The proportion of travelers who use a path $p \in P_t^{rs}$ in the group of habitual travelers, also known as the prescribed route rate, is,

$$\pi_p(t) = \frac{\exp(-c_p(t))}{\sum_{p' \in P_t^{rs}} \exp(-c_{p'}(t))} \tag{3.2}$$

Therefore, the number of travelers who depart at time t between O-D pair rs and use path $p \in P_t^{rs}$ is,

$$q_p(t) = (1-\theta) q_s^{rs} \pi_p(t) \tag{3.3}$$

For adaptive travelers, we assume that they always take their respective shortest path with respect to the instantaneous travel cost at each time interval. Adaptive travelers behave in a similar way as in the en-route route choice model embedded in BUE (Friesz et al. 1993, Kuwahara & Akamatsu 2001), but the time period at which travelers update their shortest paths using the instantaneous travel cost can be relaxed from the assignment interval, ϕ_a in the BUE, to an arbitrary time interval in multiples of the loading time interval, i.e. $\gamma\phi_l$ (where γ is an integer). $\gamma\phi_l$ indicates how frequent the adaptive travelers are able to obtain up-to-date traffic information and choose an alternative route if necessary.

It is crucial to define the instantaneous travel time of link a at entry time t, $\tau_a(t)$, which equals $l_a/s_a(t)$ where $s_a(t)$ is the instantaneous travel speed of link a at entry time t and l_a the length of link a. Given the density of link a at time t, $k_a(t)$, $s_a(t)$ is estimated by,

$$s_a(t) = \begin{cases} u_a & \text{if } k_a(t) \le k_{a,m} \\ \dfrac{k_{a,j} - k_a(t)}{k_{a,j} - k_{a,m}} \dfrac{C_m}{k_a(t)} & \text{if } k_a(t) > k_{a,m} \end{cases} \tag{3.4}$$

Where $k_{a,j}$ is the jam density of link a, $k_{a,m}$ the critical density and C_m the maximum flux of link a (also known as the capacity). If the density of link a at time t is smaller than $k_{a,m}$, then the instantaneous travel speed is the free-flow speed of link a, i.e. u_a; otherwise, it equals the division of the flux of link a at time t by its density at time t where the flux can be solved using the triangular fundamental diagram of link a given $k_a(t)$.

This new route choice model no longer requires an iterative solution procedure as PUE does. Instead, a one-shot traffic simulation can produce all the simulation results. Before the simulation is implemented, a shortest path calculation is first implemented to fix the prescribed routes for all the habitual travelers. During the simulation process, the shortest path calculation is needed in every certain time intervals to obtain the new routes for those adaptive travelers, and it is finished when every traveler reaches her destination.

Dynamic network loading

We adopted a revised cell-transmission model (CTM) to describe flow propagations through the entire network including the work zone segment. Refer to Daganzo (1994, 1995) for details of the CTM model.

Each link, regardless of the presence of a work zone, is divided into three components, an entry boundary (ENB), an exit boundary (EXB) consisting of multiple movements and a traffic propagation section, as shown in Figure 3.2 (Nie 2006). ENB is a fictitious element that temporarily receives the traffic flow ready to enter the link at the current time. Conversely EXB holds all vehicles that are about to leave the link in the next time step provided the associated node model would allow them to do so. Note that EXB consists of a list of sub elements called movements, each corresponding to a downstream link. Vehicles will be classified upon their arrival at an EXB and sent to the movement corresponding to the next link in their journey. The ENB and EXB are connected by a section where CTM is used to capture realistic flow propagation.

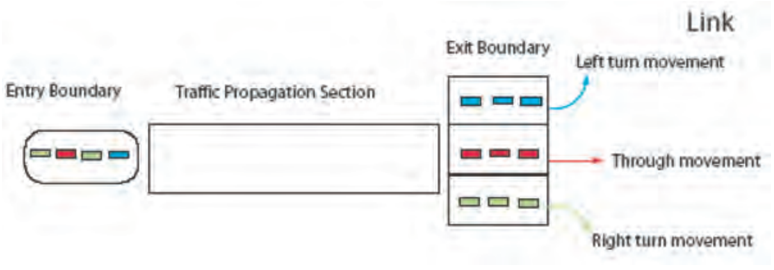


Figure 3.2: Link model in traffic simulation (Nie 2006)

Let ϕ_l denote the length of each time step (i.e. loading time interval) in the mesoscopic simulation. Traffic flow is measured in the unit of *vehicular quantum*. A vehicular quantum is similar to an individual vehicle except that a quantum may carry an arbitrary amount of traffic flow (Nie 2006). Usually we assume that each vehicular quantum should carry the identical amount of traffic, denoted by δ_f. Each link is divided into $L-1$ cells, with an identical length

$$\delta x = u_f \phi_l \tag{3.5}$$

where u_f is the free-flow speed or the speed limit of that link. The number of cells L is calculated by

$$L = [dist/\delta x]_- \tag{3.6}$$

where $dist$ is the link length and $[a]_- \equiv \text{argmax}\{i < x, i \in Z\}$. The EXB element is also a cell with a length $\delta x_l = dist - (L-1)\delta x \geq \delta x$.

Consider a link with a capacity C_0 and free-flow speed u_0. Its jam density is $k_{jam,0}$, while its density at maximum flow rate is $k_{c,0}$. The maximum backward wave speed is w_0. Recall that each link is homogeneous in terms of road properties where no work zone is present. In that case, the fundamental diagram (FD) is identical for all the cells. Let l_i denote the number of vehicular quanta in cell i and the density at cell i is given by

$$k_i = \frac{l_i \delta_f}{\delta x} \tag{3.7}$$

Let $F_0(k)$ represent the original FD, i.e. the function of flow rate with respect to the density. For every loading time interval, we update the flux $v_{i,i+1}$ across the boundary between cells i and $i+1$ using the following supply-demand approach where no work zone exists,

$$v_{i,i+1} = \min\{D_i, S_{i+1}\} \tag{3.8}$$

where D_i and S_{i+1} are demand of cell i and supply of cell $i+1$ respectively, and

$$D_i = \begin{cases} F(k_i) & \text{if } k_i < k_{c,0} \\ C_0 & \text{if } k_i \geq k_{c,0} \end{cases} \quad S_i = \begin{cases} C_0 & \text{if } k_i < k_{c,0} \\ F(k_i) & \text{if } k_i \geq k_{c,0} \end{cases} \tag{3.9}$$

3.2.3 Work Zone model

The capacity reduction and speed limit reduction in work zone are incorporated in the revised CTM-based traffic flow model.

Let us still consider a link with a capacity C_0 and free-flow speed u_0. Its jam density is $k_{jam,0}$, while its density at maximum flow rate is $k_{c,0}$. The maximum backward wave speed is w_0. With the presence of a work zone, suppose the capacity of the link reduces to C_1 measured by the downstream vehicle discharging rate and the reduced speed limit is u_1. We assume the maximum backward wave speed does not change, i.e., $w_1 = w_0$. Therefore, the changes in the fundamental diagram (FD) for the link are shown in Figure 3.3.

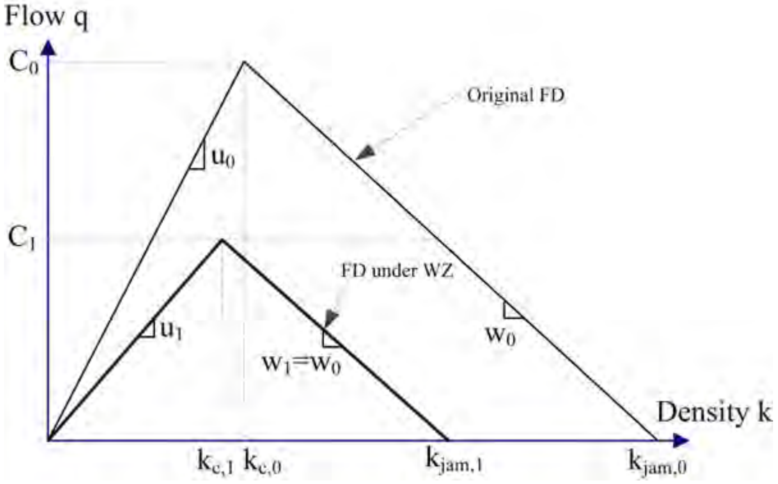


Figure 3.3: Changes in fundamental diagram (FD) with the presence of a work zone

When a work zone is activated in a certain segment of the link, the cells within the work zone segment follow a different FD with reduced capacity and/or reduced free-flow speed, while other cells outside of the work zone segment resembles the same FD as the original one. Therefore, the roadway link becomes inhomogeneous with the presence of the work zone. In fact, following Equation 3.5 to determine the cell size (Lebacque 1996), we should re-generate the cells for the work zone segment with a smaller cell size $\delta x = u_1\phi_l < u_0\phi_l$. However, changing the cell size and thus the number of cells in the middle of the dynamic network simulation can bring in some computational issues. For instance, the length of the work zone segment is usually not divisible by the new cell size. Whenever some cells are re-generated during the simulation, the vehicular quanta in old cells will be assigned to the new cells; both of which can produce significant computational errors. In addition, it is necessary to store the dynamic changes in the density of each cell, which are used later to retrieve traffic propagation information after the simulation. Changing the cell size could increase the computational complexity substantially. After all, in the case of the presence of work zone, we assume the same cell size as the case without the work zone. Rather, we revise the formula of boundary flux to capture the work zone effect brought by the FD change.

For every loading time interval, with the presence of work zone, we update the flux $v_{i,i+1}$ across the boundary between cells i and $i+1$ using the following supply-demand approach,

$$v_{i,i+1} = \min\{D_i, S_{i+1}\} \tag{3.10}$$

where D_i and S_{i+1} are demand of cell i and supply of cell $i+1$ respectively. If cell i falls outside of the work zone segment, then use Equation 3.9 to determine the cell demand and supply. However, if cell i falls in the work zone segment, then

$$k_i = \frac{\delta f}{\delta x}\left(l_i \frac{u_1}{u_0}\right) \tag{3.11}$$

$$D_i = \begin{cases} F_1(k_i) & \text{if } k_i < k_{c,1} \\ C_1 & \text{if } k_i \geq k_{c,1} \end{cases} \quad S_i = \begin{cases} C_1 & \text{if } k_i < k_{c,1} \\ F_1(k_i) & \text{if } k_i \geq k_{c,1} \end{cases} \tag{3.12}$$

k_i in Equation 3.11 indicates the equivalent density of cell i with the length of $u_0\phi_1$ under the new FD (i.e. F_1 function).

This work zone model is fully capable of modeling the case where a roadway section is fully closed in certain time periods. Recall that travelers are categorized into two groups, habitual travelers and adaptive travelers. When links with the presence of work zone are fully closed, e.g. directional NB/SB closures in the actual work zone plan, those links are temporarily removed from the network. Adaptive travelers choose their routes from the temporary network at every loading time interval. As for habitual travelers, they strictly follow prescribed paths and do not change during the trip. We generate prescribed path sets for habitual travelers using K-shortest paths based on the temporary network, i.e. the network with all the work zone links removed.

3.3 Fuel consumption and emission models

In this project, we calculate the fuel consumption and the emissions of the network during the analysis time horizon. The emission includes carbon dioxide (CO2), carbon monoxide (CO), hydrocarbon (HC) and nitric oxide and nitrogen dioxide (NOX).

The transportation Energy Data Book (FHWA 2009) shows a recent study on the relationship between fuel economy and average vehicle speed. The data points in that study were fit by a polynomial regression model. Let v denote the average speed in miles per hour. The fuel economy is calculated as follows and its fitting curve is shown in Figure 3.4,

$$\begin{aligned}\text{fuel economy} &= -1.47718733159777 * 10^{-13}v^{10} + 6.8247176456893 * 10^{-11}v^{9} \\ &-1.38867659079602 * 10^{-8}v^{8} + 1.63502795565324 * 10^{-6}v^{7} \\ &-0.000123021415999858v^{6} + 0.00616148672549657v^{5} \\ &-0.207343000174098v^{4} + 4.61456181374348v^{3} \\ &-64.856033832593v^{2} + 519.768517199759v - 1780.82307640254\end{aligned} \tag{3.13}$$

where $15mph \leq v \leq 75mph$. For the case where the average speed is less than 15mph (or higher than 75mph), the fuel economy at 15mph (or 75mph) is used.

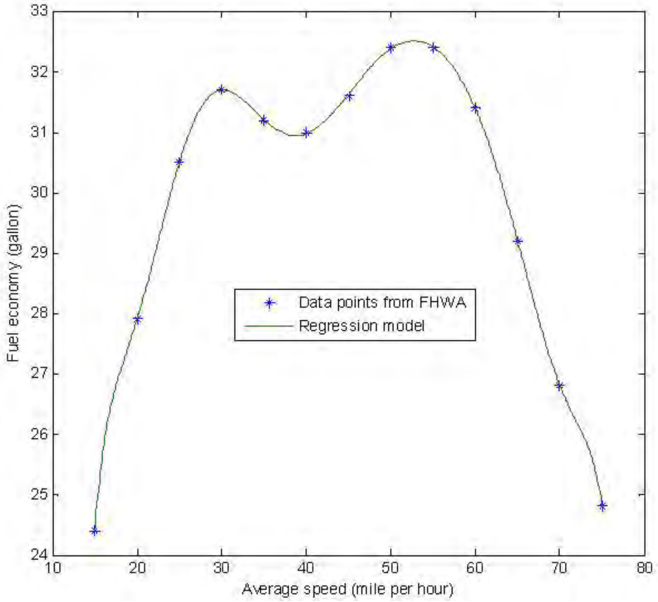


Figure 3.4: Fitting curves and data points of fuel economy with respect to the average speed

Then the fuel consumption rate is computed as follows,

$$\text{Fuel consumption rate (gallon/mile)} = \frac{1}{\text{fuel economy}} \tag{3.14}$$

We assumed that all carbon in the fuel contributes to CO2 emissions after flaming. Hence, the CO2 emission rate is calculated by,

$$\text{CO2 emission rate (gram/mile)} = 8875 * \text{fuel consumption rate (gallon/mile)} \tag{3.15}$$

The microscopic emission models of HC, CO and NOX are based on the speed correlation factor provided by EPA (2001). As all the vehicles are standardized to be light-duty gasoline vehicles (LDGV) in the network simulation, we use "speed correlation factor and baseline predicted freeway emissions" of Tier 0 (normal emitters) in Mobile 6 to represent the relationship between average vehicle speed and emissions. The data points were also fit by polynomial regression models.

The emission rate of HC is calculated as follows and its fitting curve is shown in Figure 3.5,

$$\begin{aligned}\text{HC Emission Rate} &= 1.61479076909784 * 10^{-13}v^8 - 1.27884474982285 * 10^{-10}v^7 \\ &+2.92924270300974 * 10^{-8}v^6 - 3.23670086149171 * 10^{-6}v^5 \\ &+0.000201135990745703v^4 - 0.00737871178398462v^3 \\ &+0.15792241257931v^2 - 1.82687242201925v + 9.84559996919605\end{aligned} \tag{3.16}$$

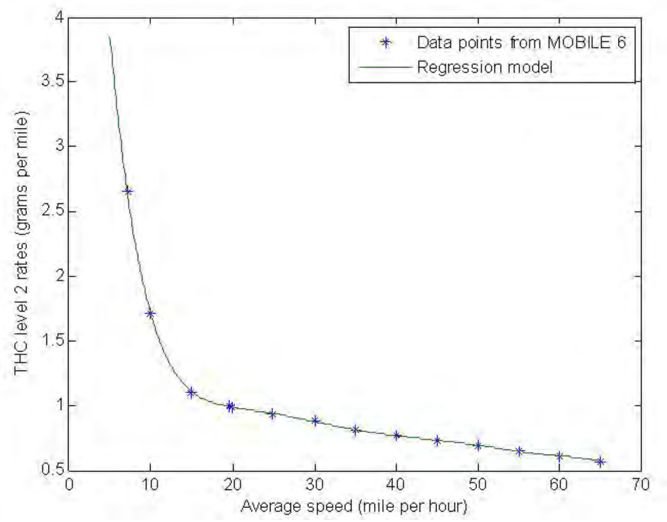


Figure 3.5: Fitting curves and data points of hydrocarbon with respect to the average speed

The emission rate of CO is calculated as follows and its fitting curve is shown in Figure 3.6,

$$\begin{aligned}\text{CO Emission Rate} &= -1.08317411174986 * 10^{-12}v^8 + 2.53340626614398 * 10^{-10}v^7 \\ &-2.12944112670644 * 10^{-8}v^6 + 5.97070024385679 * 10^{-7}v^5 \\ &+1.79281854904105 * 10^{-5}v^4 - 0.00170366500109581v^3 \\ &+0.047711166912908v^2 - 0.615061016205463v + 4.12900319568868\end{aligned} \tag{3.17}$$

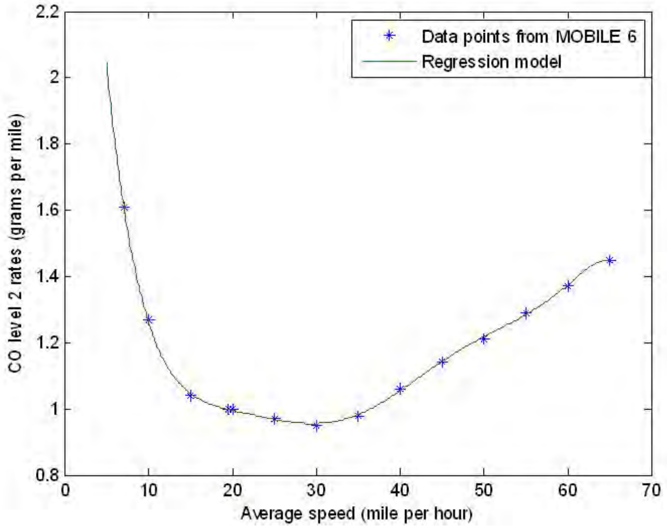


Figure 3.6: Fitting curves and data points of CO with respect to the average speed

The emission rate of NOX is calculated as follows and its fitting curve is shown in Figure 3.7,

$$\begin{aligned}\text{NOX Emission Rate} \quad &= -6.52009367269462 * 10^{-13}v^8 + 1.25335312366681 * 10^{-10}v^7 \\ &-4.67202313364846 * 10^{-9}v^6 - 6.63892272105462 * 10^{-7}v^5 \\ &+8.01942113220463 * 10^{-5}v^4 - 0.00374632777368871v^3 \\ &+0.0895029037098895v^2 - 1.07265851515536v + 6.06514023873933\end{aligned} \tag{3.18}$$

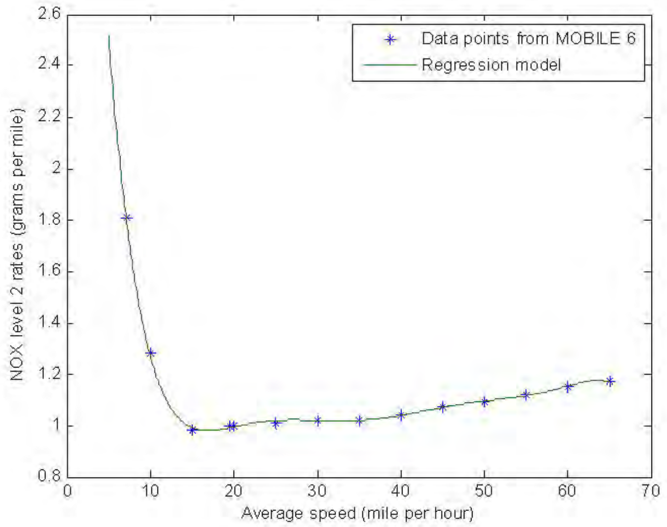


Figure 3.7: Fitting curves and data points of NOX with respect to the average speed

In all the three regression models regarding HC, CO and NOX, $5mph \leq v \leq 65mph$. For the case where the average speed is less than 5mph (or higher than 65mph), the fuel economy at 5mph (or 65mph) is used.

Those regression models provide the relationships between the average speed (over a certain time period, e.g. 5 min or 10 min) and fuel consumption/emission rates. To compute the total fuel consumption and emissions, we first calculate the average speed and the hour-based Vehicle Miles Traveled (VMT) of each link, for every hour of the simulation horizon. The fuel consumption/emission rates are then obtained by applying those regression models. Multiplying the fuel consumption/emission rates by hourly based Vehicle Miles Traveled (VMT) for each link and then adding up the fuel consumption/emissions over the entire simulation horizon and the entire network yields the total network fuel consumption/emissions.

3.4 Work flow

All the above models and functionalities have been implemented in NetZone, a work zone dynamic traffic analysis tool developed by the research group led by Prof H. Michael Zhang at UC Davis. NetZone is expected to help traffic professionals estimate traffic congestion, system performance and emissions caused by construction work zones in large-scale networks, evaluate the effectiveness of a variety of traffic management measures, and design efficient construction and traffic management plans. Unlike previous work zone traffic impact assessment tools such as the Highway Capacity Software or QuickZone which only estimate the queue on the freeway, NetZone is a dynamic network analysis tool capable of estimating network-wide traffic impact for any general networks consisting of freeway, arterials and local streets.

In this project, we use NetZone to perform the work zone dynamic traffic analysis. Figure 3.8 illustrates the work flow adopted in this project.

The network of Sacramento Metropolitan Area was imported to NetZone from GIS shape files. We further edited the roadway properties in NetZone, such as length, capacity, number of lanes, maximum density, etc. All interchanges of freeways and major arterials are manually drawn in NetZone for realistic display. We created 27 traffic analysis zones for this project, each of which contains an origin node and a destination node. The origin-destination connectors are created in a trial-and-error way that the results of the dynamic traffic assignment based on those

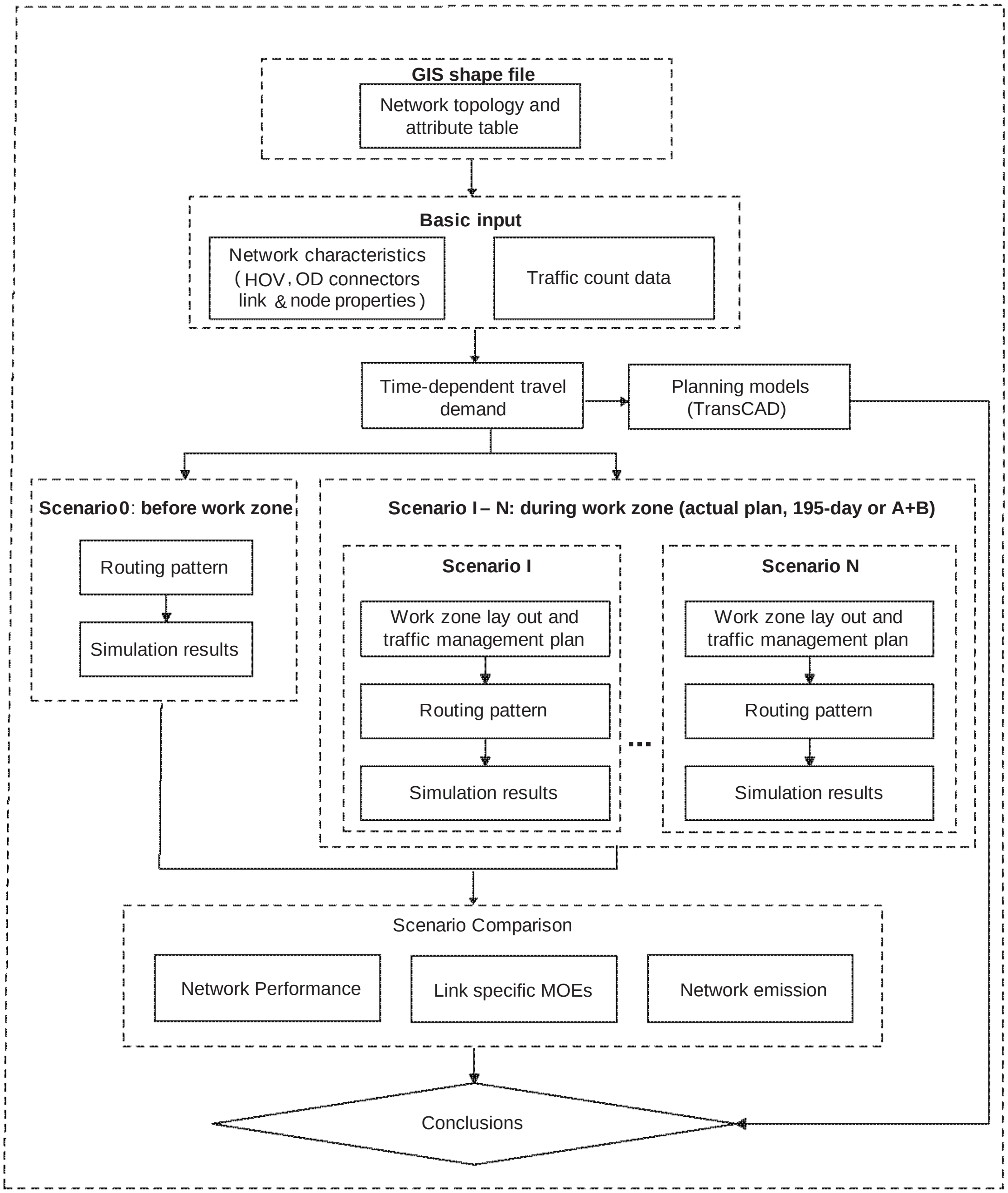


Figure 3.8: The work flow for this research

connectors are stable and best match the actual traffic data.

We selected three Wednesdays before the Fix I-5 project started, during directional NB closure and during directional SB closure, as the representative weekdays for the baseline, NB closure and SB closure of the actual plan, respectively. We then processed the real-time traffic count data on both the arterials and freeways for the three Wednesdays. NetZone was provided 12-hour PeMS traffic counts on 28 freeway segments and 12-hour traffic counts on 28 major arterials on the periphery of Downtown Sacramento. The 12-hour period consists of the 6-hour morning peak (6:00am-12:00pm) and the 6-hour afternoon peak (2:00pm-8:00pm). Those traffic data are input into a Logit Path Flow Estimator (LPFE) to estimate dynamic Origin-destination demands with 15-min intervals for the morning peak and the afternoon peak in all three Wednesdays.

We import the network of Sacramento Metropolitan Area into TransCAD from NetZone, and then aggregated the time-dependent O-D demands for the 6-hour morning peak with 15-min interval into six hourly-based O-D trip matrix. In TransCAD, we loaded each of those six O-D trip matrices to the network respectively, and sum up all the statistics of the network performance for each case to obtain the overall assessment for the baseline and construction days. The results will be later compared to the results obtained from NetZone. This is to find how accurate (close or far) the static planning model can access the work zone effect as compared to the dynamic models.

We next assessed the work zone effect for both the directional closure plan and the two lane closure plans using NetZone, which is the focus of this research.

The three Wednesdays' demands were first loaded to a network where no work zone is deployed, a network with directional NB closure in the actual plan and a network with directional SB closure in the actual plan, respectively. The simulation models are thereafter calibrated appropriately in the way to reproduce the actual traffic count observation. Meanwhile, appropriate no-show rates (i.e. demand reduction) for the cases with NB/SB closures can be estimated. The new time-varying demand were then loaded to the network to obtain network performance measures, link specific measures of effectiveness (MOE) and emissions for the actual directional closure plan.

We created eight scenarios, each of which corresponds to one of the 12 stages in the alternative work zone schedules. In each scenario, assuming a 20% $\sim$ 50% increase of diversion ratio and 1% $\sim$ 2% total demand reduction compared to the baseline scenario, we loaded the dynamic Origin-destination demands on to the network with the corresponding work zone layout. The indices of network performance, link specific MOEs and emissions were obtained and compared to those of actual directional closure plan.

Finally, we report the findings from the simulation results, and develop a guideline for accessing work zone effects and developing construction plans.

Chapter 4

Network Calibration and Simulation

This chapter describes in detail the process of network encoding, dynamic O-D estimation, dynamic network model calibration and how dynamic traffic simulation is performed for each scenario. Some assumptions in regards to the model calibration and simulation are also presented.

4.1 Network coding

The original Sacramento Metropolitan Area network was obtained from the Sacramento Area Council of Government (SACOG) in Dynasmart format. The file contains 1197 traffic analysis zones (TAZ), 14399 links and 7497 nodes. The boundaries of the network were defined as follows: the north boundary defined by Rio Linda, the west boundary by Davis and Woodland, the east boundary by Rancho Cordova, and the south boundary by Galt. The Dynasmart file was exported to the standard GIS shape files and further imported into NetZone, and the entire network is shown in Figure 4.1.

The following steps were carried out to pre-process the network before the network analysis was conducted.

1. First, we consolidate the small TAZs to 27 large TAZs. Each TAZ was constructed using census block information for specific cities in the SACOG region, such as the City of Davis, the City of Woodland, and the City of Elk Grove. This consolidation of TAZs provided a more accurate estimation of the Origin-Destination (O-D) demands at the network level.
2. The original network was trimmed such that no "isolated" nodes and links exist. "Isolated" nodes are those who have only one forward link and one backward link, and the head node

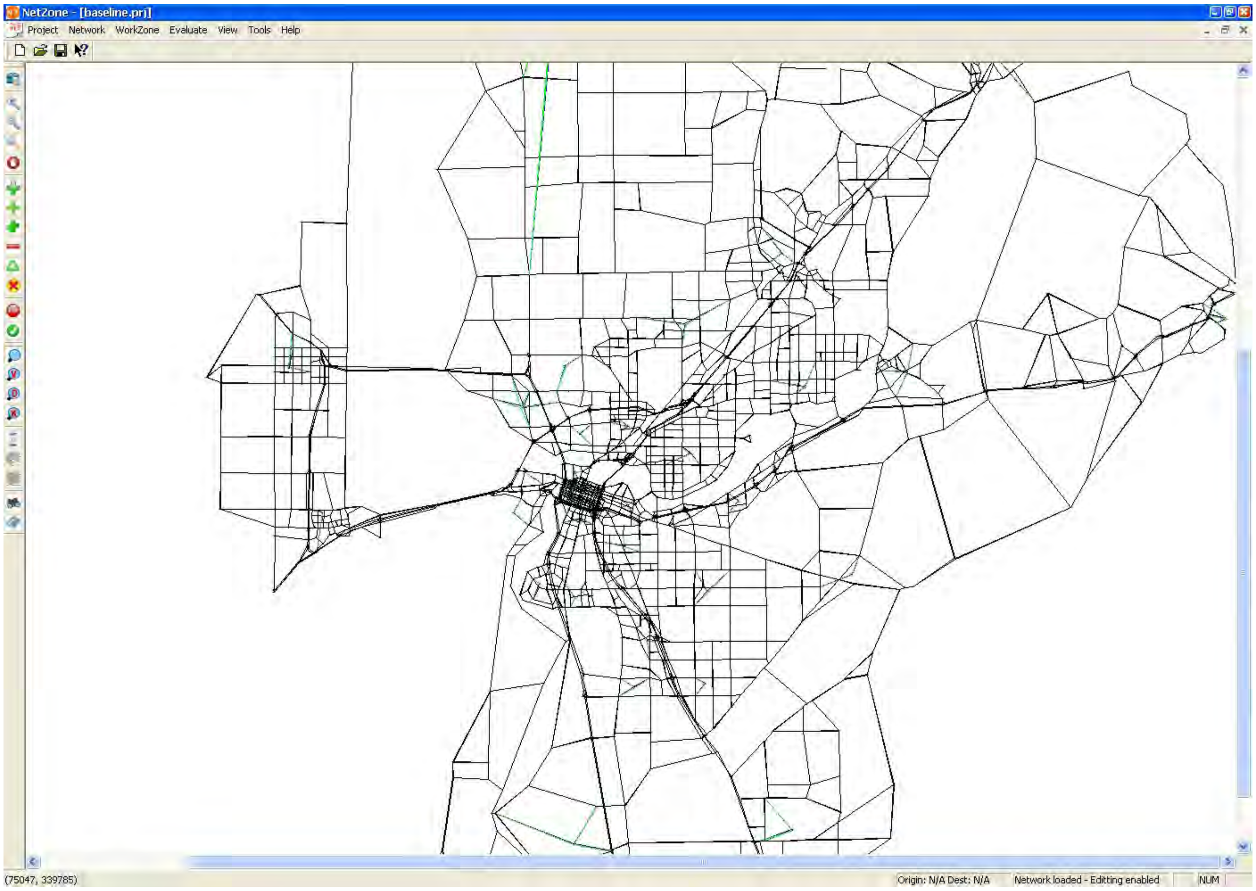


Figure 4.1: The Sacramento Metropolitan Network in NetZone

of the forward link is exactly the tail node of the backward link. Further, "isolated" links are the forward links and backward links of "isolated" nodes. The absence of such nodes and links does not affect the dynamic network analysis, but allows for a more precise estimation of network performance indicators.

3. An origin dummy node and a destination dummy node were attached to each centroid. Therefore, the entire network contained 27 origin/destination nodes with 729 O-D pairs. For each traffic zone, a selection set of connector nodes from the original networks within the zone was constructed. A connector node is a real network node that is neither on the freeway (or equivalently, the speed limits of both its forward links and backward links are more than 55 miles per hour) nor on the freeway ramp. Connector nodes were constructed in a different way from the regular method, because trips are most likely to start and end on local streets. In addition, we made three or four connections between real network

nodes (in the selection set) and those dummy nodes, rather than those centroids directly. This method ensures through traffic will never use connectors to reduce travel time. In addition, for those TAZs on the edge of the network (such as City of Davis), corresponding dummy nodes are additionally connected to the freeway, so that through traffic was able to be released directly on to the freeway. Note that those O-D connectors may be adjusted by trial-and-error during the process of network calibration in order to avoid the gridlock, as well as to produce realistic flow patterns.

4. Consolidated neighboring links with small lengths and the same speed limit. This process substantially reduced the network scale. More importantly, this was desirable to achieve more accuracy for the mesoscopic traffic flow models.

5. The speed limits of all the arterial roads in Downtown Sacramento were set to 25mph∼35mph.

6. The work zone plans (the directional closures, 195-day lane closure plan and 110-day A+B lane closure plan) are coded using NetZone Graphical User Interface (GUI).

This project adopted a six hour morning peak, from 6:00am to 12:00pm, and a six hour afternoon peak, from 2:00pm to 8:00pm, as the analysis time horizon for the O-D estimation and network simulation.

4.2 Dynamic O-D estimation

Reliable dynamic origin/destination data are critical to the dynamic network analysis. However, "true" O-D data cannot be obtained directly in most cases. Therefore, we estimate time-dependent O-D demands from link flows (traffic counts collected by vehicle detectors) using a Dynamic Origin-Destination Estimator (DODE). The objective of the DODE in this project is to obtain a time-dependent O-D table (expressed in the form of time-dependent path flows) for the baseline scenario that, once loaded onto the network without the presence of the work zone, will reproduce observed link traffic counts on May 28 as closely as possible. In this project, the complete set of 28 arterial road detectors and 28 freeway detectors were available (under healthy conditions) on May 28, i.e. the Wednesday in the baseline scenario. We extracted 15-min traffic count data for those 56 detectors which were then input to NetZone. NetZone estimates time-dependent O-D demands in 15-min intervals based on traffic count data for both morning peak and afternoon peak on May 28. We checked the estimated O-D demands by comparing the estimated link flow (based on estimated O-D demands) to the observed link flow. The results of the verification show that the estimated link flow (e.g., as shown in Figure 4.2 for the ninth time interval of the baseline Wednesday) effectively approximated the observed link flow. The resultant O-D demands for the baseline scenario were then used for deriving O-D demand of other scenarios and for network simulations.

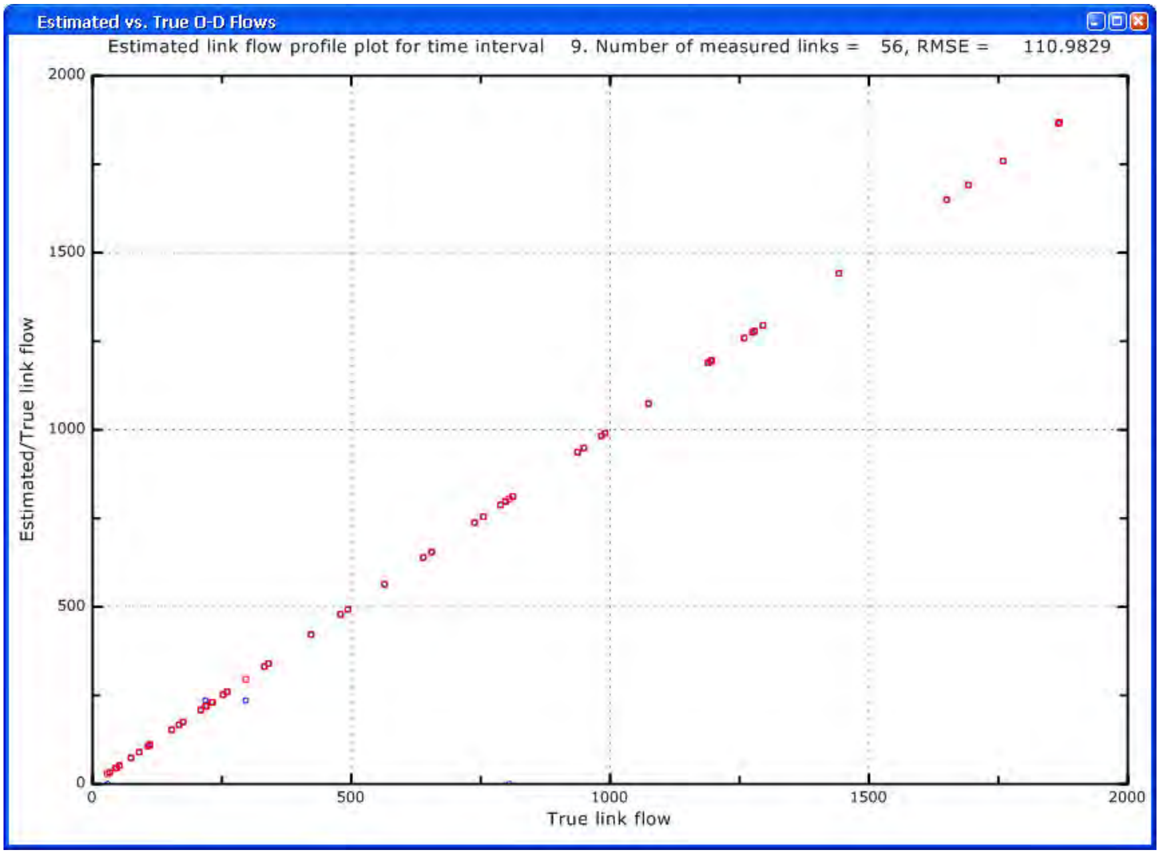


Figure 4.2: Estimated O-D demands reproduce approximately the same link flows as the observation for the ninth 15-min time interval of the baseline Wednesday

The time-dependent O-D table for the actual plan (directional NB closure or directional SB closure) is determined by the demand diversion model, a build-in demand estimator specially for work zones in NetZone. The demand diversion model is proposed by Zhang et al. (2007). It estimates the reduction in travel demand and the diversion to other routes due to the construction work, and it is developed based on the data from multiple work zone projects in California. The diversion model takes into account the effects of induced delay, work zone characteristics and potential traffic management measures. In this project, the diversion model is applied and further calibrated. The overall demand reduction for the directional closure plan is estimated to be around 1% compared to the baseline scenario. In other words, we estimate that nearly 1% of the travelers cancel their trips or switch to the transit under the directional closure plan. The reduction is applied uniformly to all the O-D pairs. In reality, however, the reduction of demand is not even, and the O-D pairs that are more affected by the closure are likely to see greater demand reductions. Indeed we did observe significant reductions in traffic volume on portions of I-5 and some other routes during the directional closures, but the majority of detectors on the freeways show little or no change in daily traffic volumes. The estimated overall 1% demand reduction is consistent with changes in observed traffic counts.

Since the 195-day and A+B plans close less lanes than the directional closures, their traffic impact are less likely to be worse than the directional closure, hence their demand reductions would not be higher than 1%. After consulting with Caltrans engineers, we took a 1% overall demand reduction for the 195-day plan and a 2% reduction for the A+B plan. The main reason for taking a 2% instead of a 1% reduction for the A+B plan is to find out how sensitive the network performance indices are to demand reduction, since these two alternative plans have exactly the same staging, so their differences in network performance is purely determined by the amount of demand reduction. Moreover, the A+B plan is likely to have more extensive media coverage and therefore could have slightly higher reduction in demand.

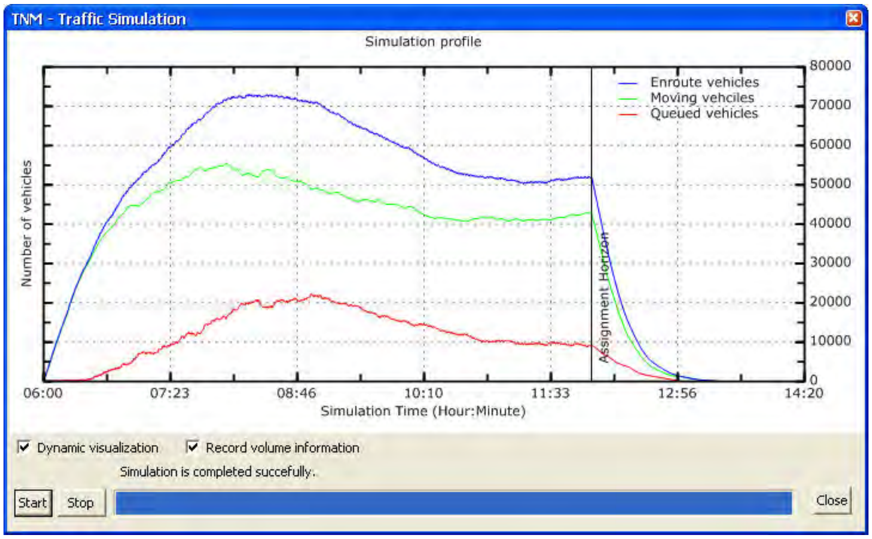
4.3 Calibration and simulation

Using the full Sacramento Metropolitan Network and time-dependent O-D demands, we performed the dynamic network simulation for the baseline scenario and all the stages in the directional closure plan and alternative lane closure plans. It is possible that the simulation terminates unsuccessfully because sometimes the network loading produces “gridlock”, a condition defined as the inability of vehicles to move. This is a common issue in mesoscopic network simulation. By trial-and-error, we calibrated the parameters of link properties and routing criteria, and adjusted the O-D connectors such that the simulations succeed without gridlock and meanwhile produce the traffic conditions as close as to the observed data (counts, travel time and queues) and/or the engineer judgement.

We first perform the model calibration and network simulation for the baseline scenario. The network parameters are set as the following: loading time interval 10 seconds; $K = 3$ in the K shortest path route generation for habitual travelers; and the traffic information will be updated every 5 minutes for adaptive travelers.

The diversion ratio, if set too high or too low, may cause serious queuing. In this case, the simulation terminates without gridlock only when the diversion ratio is within a certain range, i.e., from $0.3 \sim 0.55$. Overall, a 0.55 diversion ratio looks reasonable in the sense that the resultant average travel time, average travel delay and time-varying link flow on designated links (28 segments of freeways and 28 major arterials) approximately match the actual observation. When the diversion ratio is smaller than 0.55, less travelers are willing to switch routes and travelers are subject to more queuing delay on average. In contrast, when the diversion ratio is larger than 0.55, more travelers respond to real-time information and switch routes, but this may cause excessive queuing on certain routes or links due to herding, which may even produce a gridlock. The same trial-and-error methods are also applied to other "during-construction" scenarios for the actual plan and alternative plans. Finally, a diversion ratio of 0.80 and 0.75 is used for directional NB closure and SB closure in the actual plan, respectively. It is set to 0.75 for NB lane closure and SB lane closure in the two alternative plans.

For any network simulation that is successfully terminated, NetZone produces a simulation profile to provide users general information regarding network-wide traffic conditions over the simulation horizon. The simulation profile for the baseline scenario in the morning peak is shown in Figure 4.3, where blue, green and red lines represent the changes in the number of en-route vehicles (i.e. those vehicles which depart their origins and have not reached their destinations), moving vehicles and queued vehicles, respectively, during the simulation horizon. The queue in the network started approximately at 6:30am, and gradually increased. The total number of trips loaded on the network achieved its peak between the periods of 7:30am to 9:00am, which is approximately the period with greatest traffic flow. The worst network condition is during the period of 7:45am to 9:30am, as indicated by the greatest number of queued vehicles. The network congestion is slightly alleviated after 8:45am. Since the input of O-D demands ends at 12:00pm and it takes some time for those vehicles to move to their destinations, and thus there is a 86 minutes duration tail of the simulation profile (i.e., 86 minutes to clear up the network loading). The entire simulation terminates at around 1:26pm.

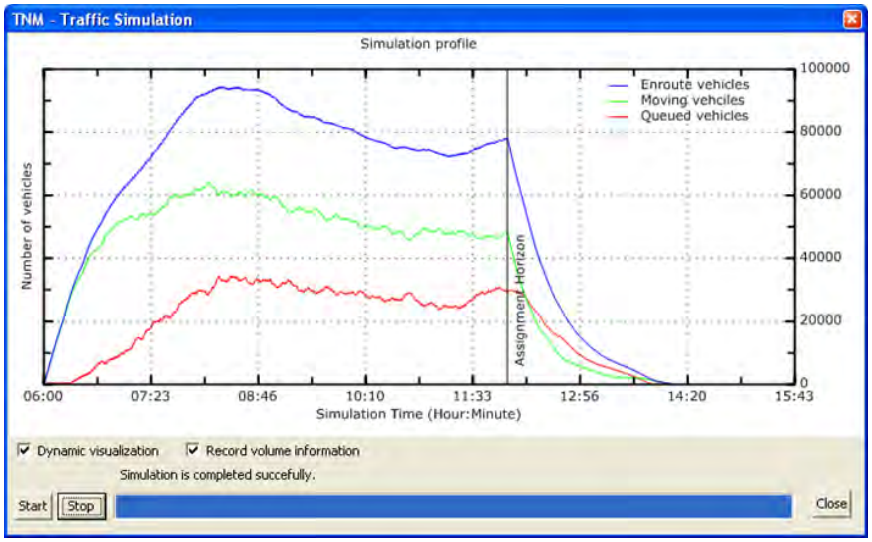


☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.3: The simulation profile of the baseline scenario (morning peak)

The simulation profiles of the directional NB closure and directional SB closure in the morning peak for the actual plan are shown in Figure 4.4 and 4.5. It is easy to see that, compared to the baseline scenario, the morning peak during the work zone tends to spread out and more travelers are queued up over the entire simulation period.

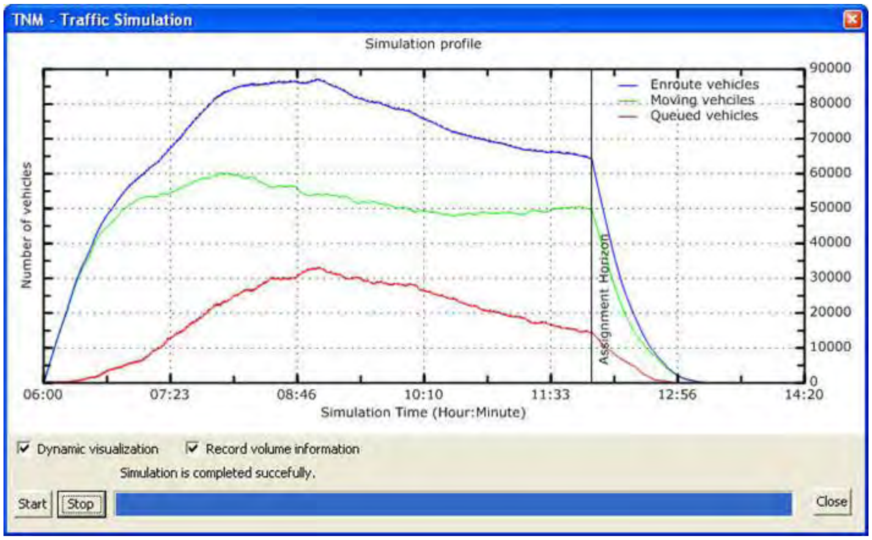


☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.4: The simulation profile of the directional NB closure in the actual plan (morning peak)

We also verified our simulation results by checking the observed traffic counts, queuing



☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.5: The simulation profile of the directional SB closure in the actual plan (morning peak)

pattern and sample travel times. Under appropriate settings of simulation parameters, the simulation reproduces approximately the same link traffic counts as the observation. Figure 4.6 and 4.7 plot the simulated (estimated) traffic counts and observed traffic counts on those 56 locations where detectors are deployed between 6:45am and 7:00am and between 8:15am and 8:30am, respectively. The statistical analysis indicates that if the points are fit by a straight line where the estimated counts equals the observed counts, then the coefficient of determination, i.e., R^2, is 0.91 between 6:45am and 7:00am and it is 0.85 between 8:15am and 8:30am. In other words, our simulation model explains 91% and 85% of the variation in the traffic counts in those two time intervals, respectively. In fact, of all the 24 time intervals, R^2 is no less than 0.82.

In addition, the time-varying density and queues on those critical links approximately match the real observation. For instance, Figure 4.8, 4.9 and 4.10 show a snapshot of the queues on critical links at 8:00am for the baseline and the directional NB closure and during the directional SB closure, respectively. As can be seen from the figures, there is significant increase in queues on the I-5 NB before the construction area, as well as the US-50 WB and Business 80 NB under the directional NB closure. For the directional SB closure, more severe congestion occurs on the I-5 SB before the construction area, Richards blvd. EB, as well as the Business 80 NB ramps. The congestion distribution in the network is consistent with the reality on both the freeway and the arterials. In addition, the travel times between several critical O-D

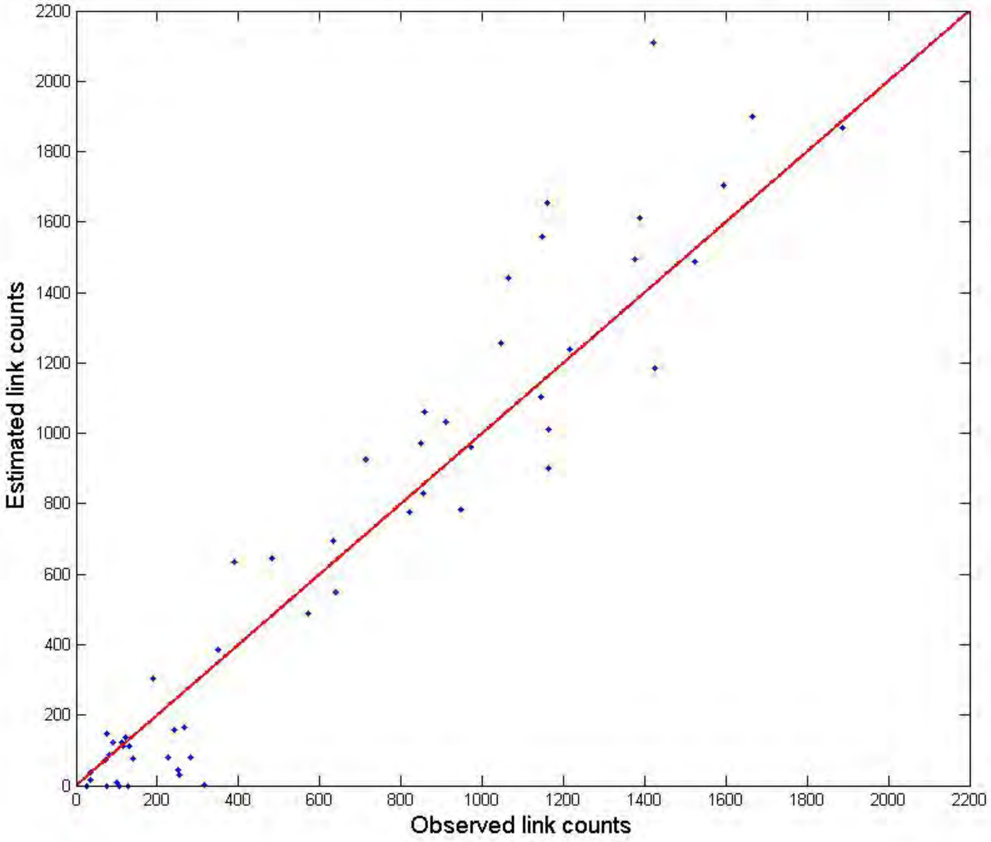


Figure 4.6: Estimated traffic counts versus observed traffic counts between 6:45am and 7:00am ($R^2 = 0.91$)

pairs also match the real travel times measured by floating vehicles. For instance, the travel time from the City of Elk Grove to Downtown Sacramento is estimated to be 27 minutes and 23 minutes for the NB and SB closures, respectively. The travel time from the City of Davis to Downtown Sacramento is estimated to be 37 minutes and 39 minutes for the NB and SB closures, respectively.

Similarly, we show the simulation profiles of the baseline scenario, the directional NB closure and the directional SB closure in the afternoon peak in Figure 4.11, 4.12 and 4.13, respectively. We see that in the baseline scenario, the afternoon peak for travel demands approximately starts from 3:00pm and ends at 7:00pm, and the network is the most congested from 4:45pm to 6:15pm. The work zone can cause a longer queuing time during the afternoon

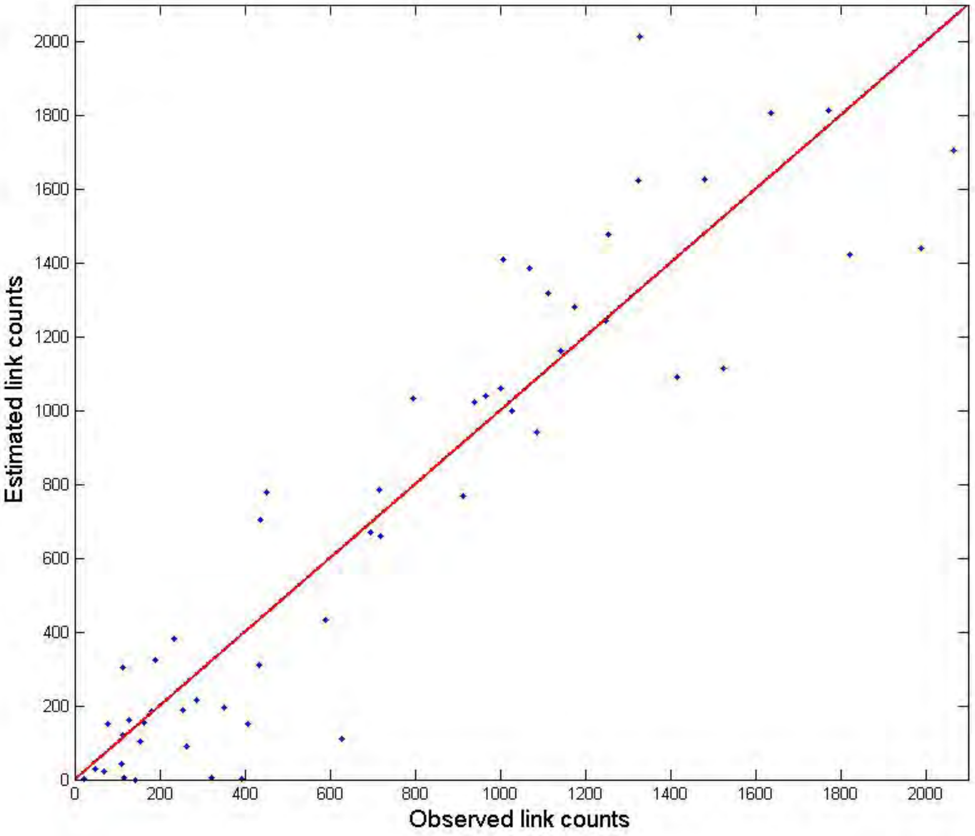


Figure 4.7: Estimated traffic counts versus observed traffic counts between 8:15am and 8:30am ($R^2 = 0.85$)

peak, as well as to extend the demand peak ending time as late as 7:30pm.

The simulation for stages in the alternative lane closure plans also imply similar profiles as the directional NB/SB closure, and therefore those profiles are not repeated here.

4.4 Statistics

NetZone provides a detailed report summarizing the aggregated statistics for the network as well as for each O-D pair, such as Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), total trips, total travel delay, average travel speed, average travel time, average travel delay, average travel distance, link with the longest travel delay, link with the maximum queue length, etc. Aggregated statistics of fuel consumption and emissions are also provided in the report.

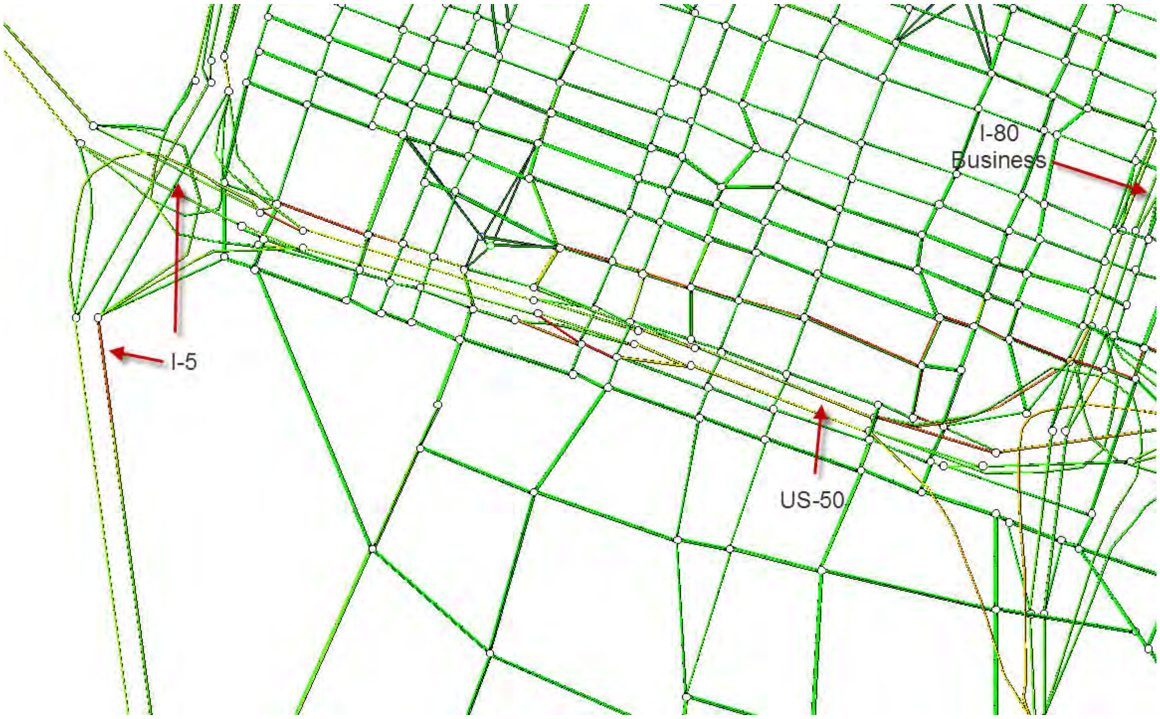
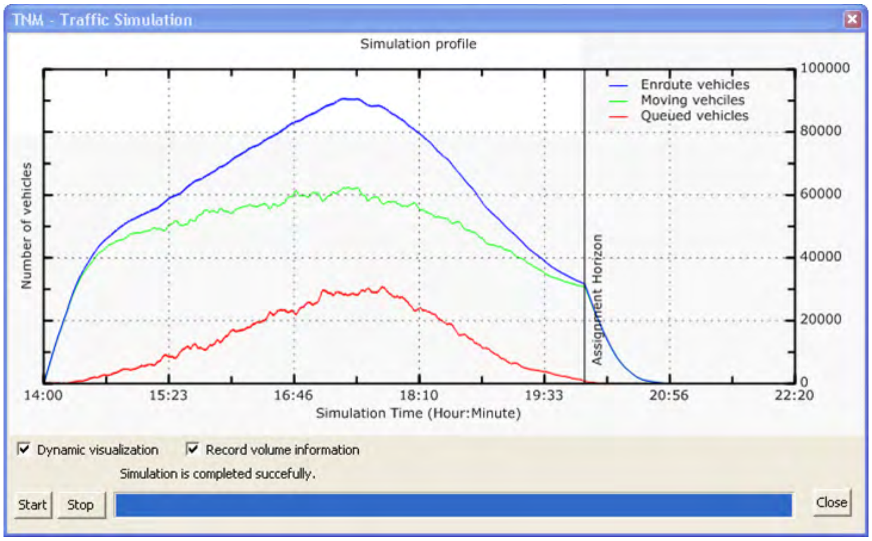


Figure 4.8: A snapshot of the queues on I-80 and US-50 at 8:00am for the baseline (morning peak)

Figure 4.9: A snapshot of the queues on I-80 and US-50 at 8:00am during the directional NB closure in the actual plan (morning peak)

Figure 4.10: A snapshot of the queues on I-80 and Business 80 at 8:00am during the directional SB closure in the actual plan (morning peak)

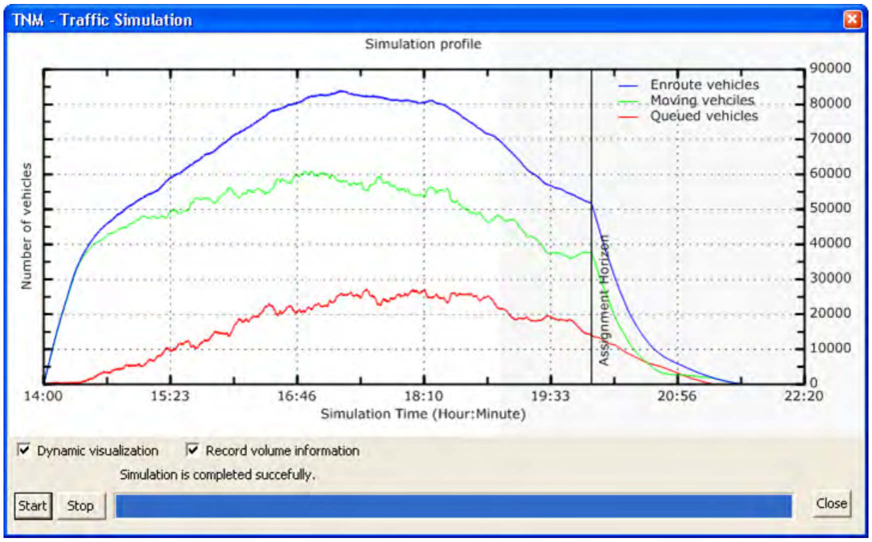


☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.11: The simulation profile of the baseline scenario (afternoon peak)

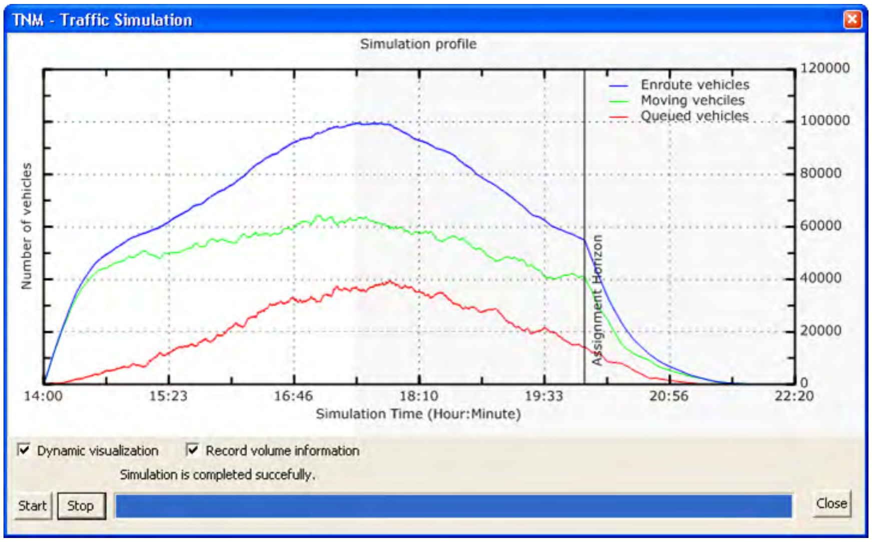
The emissions include hydrocarbon (HC), carbon dioxide (CO2), carbon monoxide (CO), and nitric oxide and nitrogen dioxide (NOX) for the entire network. The detailed statistics for all the scenarios are summerized in the following chapter.



☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.12: The simulation profile of the NB closure in the actual plan (afternoon peak)



☑ Dynamic visualization ☑ Record volume information

Simulation is completed succefully.

Figure 4.13: The simulation profile of the SB closure in the actual plan (afternoon peak)

Chapter 5

Simulation results

This chapter shows the simulation results for the baseline scenario and the scenarios for the actual plan and alternative plans. The network performance and emissions for the morning peak and afternoon peak of a single day in each scenario are compared among those scenarios, and finally are summed up to assess the overall effects caused by each of the three work zone plans. As discussed in Section 4.2, the demand reduction in vehicle trips for the 36-day (directional closure) and 195-day (lane closure) plan is taken to be 1% and that for the 110-day A+B (lane closure) plan is 2%. We assume no demand reduction for those minor stages, i.e. Stage 9 $\sim$ 12, in the two alternative plans where only one on-ramp or off-ramp is closed. Therefore, the simulation results of Stage 9 $\sim$ 12 in the two alternative plans are identical.

5.1 Morning peak

5.1.1 Daily network performance

The simulation results for the morning peak of a single weekday based on each of those plans are presented in tables 5.1, 5.2 and 5.3, respectively.

Table 5.1: Simulation results for the directional closure plan (morning peak 6:00am-12:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Open	361,120	42,553	25.15	32.61	7.07	46.28	9,083,748	196,285
NB	357,509	82,398	25.15	40.09	13.69	37.64	9,081,179	241,279
SB	357,509	62,656	25.30	36.78	10.41	41.27	9,134,550	221,362

Table 5.2: Simulation results for the 195-day lane closure plan (morning peak 6:00am-12:00pm)

Stage	Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
1	SB/1L	356,871	55,026	25.47	35.36	9.25	43.22	9,089,850	210,295
2	NB/1L	356,871	67,182	25.43	37.41	11.30	40.79	9,075,210	222,501
$3 \sim 5$	SB/2L	356,871	64,440	25.47	36.87	10.83	41.45	9,090,734	219,297
$6 \sim 8$	NB/2L	356,870	90,414	25.46	42.32	15.20	36.09	9,085,379	251,739
9	J St. off	360,426	50,109	25.27	34.04	8.34	44.54	9,107,954	204,491
10	W50 on	360,479	53,480	25.26	34.70	8.90	43.68	9,105,703	208,482
11	E50 on	360,888	49,398	25.20	33.91	8.22	44.64	9,094,382	203,745
12	P St. on/off	360,500	55,769	25.27	35.10	9.28	43.20	9,109,834	210,889

Table 5.3: Simulation results for the A+B lane closure plan (morning peak 6:00am-12:00pm)

Stage	Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
1	SB/1L	353,270	58,621	25.45	35.89	9.96	42.56	8,991,547	211,286
2	NB/1L	353,270	58,765	25.43	36.09	9.98	42.28	8,982,487	212,470
$3 \sim 5$	SB/2L	353,270	60,432	25.48	36.19	10.26	42.24	8,999,792	213,053
$6 \sim 8$	NB/2L	353,270	80,160	25.55	40.92	13.61	37.46	9,024,552	240,907
9	J St. off	360,426	50,109	25.27	34.04	8.34	44.54	9,107,954	204,491
10	W50 on	360,479	53,480	25.26	34.70	8.90	43.68	9,105,703	208,482
11	E50 on	360,888	49,398	25.20	33.91	8.22	44.64	9,094,382	203,745
12	P St. on/off	360,500	55,769	25.27	35.10	9.28	43.20	9,109,834	210,889

The simulation results for the directional closure plan show that the average travel delay in the six-hour morning peak during each closure increases, compared to the open week, as expected. The average travel delay is the greatest during the directional NB closures at 13.69 minutes while directional SB closures result in an average travel delay of 10.41 minutes. As a result, the total network traffic delay increases by nearly 100% during the NB closure and almost 50% during the SB closure. However, the average travel distance for vehicles during NB closures is less than for SB closures, and the former remains the same as the open day. This is because the major alternative routes to I-5 SB, if going through the American River, are limited to Richards Blvd., 9 St. or 15 St., and US 50 EB. Those in town detours increase travelers' travel distance. However, for NB closures, the major alternative routes for travelers to avoid the work zone are Riverside Blvd. or Freeport Blvd to the north and furthermore they take WB arterials to return to the I-5 NB. Both Riverside and Freeport Blvd. are parallel arterials to the I-5 and they are, as a matter of fact, have a slightly shorter distance than the I-5. Those routes does not increase the distance as the detour routes do in the SB closures.

Due to a less travel distance and a demand reduction, the VMT for the directional NB closure is slightly less than that without a work zone, while the VMT is higher for the directional SB closure as a result of longer detour routes which the demand reduction cannot pay off. The VHT is greater for NB closures than SB closures, and both are significantly greater than the open day.

For the 195-day lane closure plan, simulation results of each stage are presented. The average travel delay is the highest for stages 6-8 where 2 lanes on NB I-5 are closed. The higher travel delay translates into a greater value for VHT, by about 55,000 vehicle-hours and 28%. SB lane closures result in a further average travel distance, albeit minimal, compared to the NB closures. Closures of on/off-ramps do not reduce the amount of trips in the area so there are additional travel delays, but not to the level of the freeway lane closures. Ramp closures, each at a time, do indeed lead to longer detour routes than the baseline scenario, and result in greater VMT as compared to other stages.

Overall, the 110-day A+B plan yields a similar change in all those measures as the 195-day plan. Keep in mind that it only halves the duration of each stage while the daily work zone closure schedule remains the same. However, since it has a greater demand reduction, there is overall less congestion for each stage of this plan than the counterpart of the 195-day plan. Aside from stage 1, stages 2, 3-5, and 5-8 each have lower average delays for this plan when compared to the 195-Day plan. With similar travel distances, the decrease in vehicle trips also decreases the VMT compared to the 195-day plan.

A comparison of the simulation results in the morning peak for all three plans during NB closures is presented in Table 5.4, and the SB closures in Table 5.5. The simulation results for the 110-day A+B and 195-Day plan are represented by the stage with two-lane closures. The average travel distance for the lane closure plans is significantly greater than the directional closure plan and the baseline scenario, implying that travelers are actually taking longer detour routes during the lane closure plans than the directional closure plan. This is because travelers are likely to intend to use I-5, while the congestion on I-5 leads them to detour after they observe the queuing on the freeway or may have been stuck on the freeway. Therefore, the routes they actually take could be even longer than the route in the actual plan where they avoid the freeway in the first place. This is also the main reason the average travel delay and VHT resulted from the 195-day plan is even greater than the directional closure plan. Although both of them are subject to the same degree of demand reduction, travelers, if the majority still take the route through the work zone area, could be subject to greater delay than the case where they all use the alternative routes to avoid the work zone. For instance, the 195-Day plan has a travel delay of 15.2 min during the NB closure, almost 1.5 min greater than the actual plan NB closure. The A+B plan yields approximately the same average travel delay as the actual plan, but note that its demand reduction is twice as much as the actual plan. This implies that **a lane closure of the freeway can sometimes result in even more congestion than a directional closure because travelers have less incentive to seek alternative routes and concentrate on the freeway when it is not fully closed, which produces a long queue on the freeway.** A comparison of the average travel delay and VMT in the morning peak among those plans is shown in Figure 5.1 and 5.2. Since there are least vehicle trips for the A+B plan, its VMT, both during the NB closure or the SB closure, is the lowest among all.

Table 5.4: Simulation results for all three plans during the NB closure (morning peak 6:00am-12:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Baseline	361,120	42,553	25.15	32.61	7.07	46.28	9,083,748	196,285
Actual	357,509	82,398	25.15	40.09	13.69	37.64	9,081,179	241,279
A+B	353,270	80,160	25.55	40.92	13.61	37.46	9,024,552	240,907
195-DAY	356,870	90,414	25.46	42.32	15.20	36.09	9,085,379	251,739

5.1.2 Daily Emission

The simulation results on the emissions for the directional closure plan, the 195-day lane closure plan and 110-day A+B plan are displayed in Table 5.6, 5.7 and 5.8, respectively.

For the directional closure plan, while fuel consumption is slightly higher during the SB closures than the other two cases, and thus CO2 emissions, HC are greater during the NB

Table 5.5: Simulation results for all three plans during the SB closure (morning peak 6:00am-12:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Baseline	361,120	42,553	25.15	32.61	7.07	46.28	9,083,748	196,285
Actual	357,509	62,656	25.30	36.78	10.41	41.27	9,134,550	221,362
A+B	353,270	60,432	25.48	36.19	10.26	42.24	8,999,792	213,053
195-DAY	356,871	64,440	25.47	36.87	10.83	41.45	9,090,734	219,297

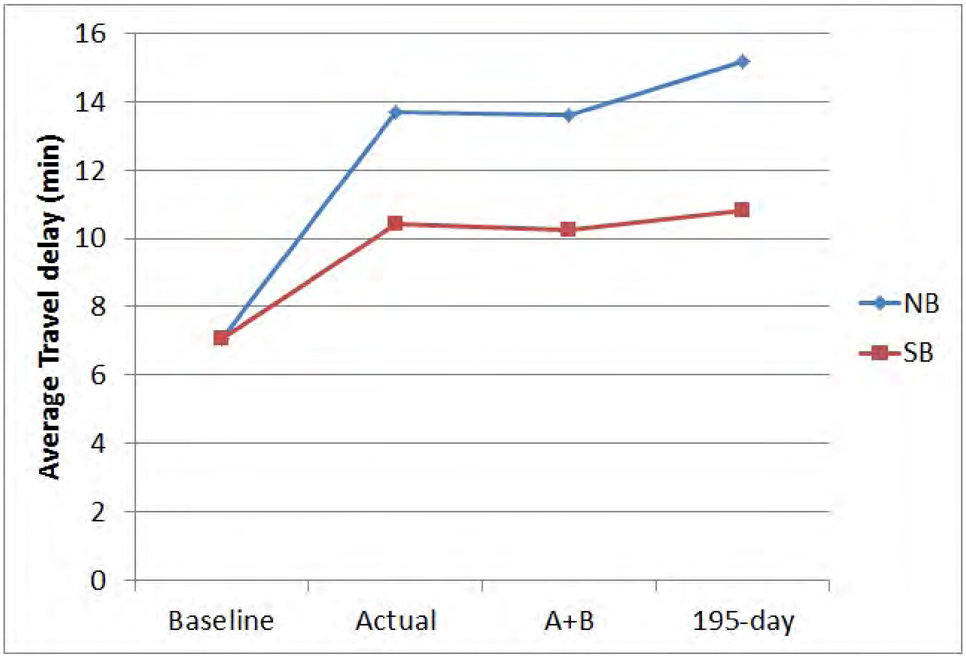


Figure 5.1: Average Travel Delay of the directional closure plan and lane closure plans in the morning peak

closures. Both NB closures and SB closures yield a less CO emissions than the baseline scenario. For the lane closure plans, the simulations imply that the fuel consumption is greater during two-lane closures than one-lane closures due to the additional congestion as a result of capacity restriction. The stage with two-lane NB closures results in the highest HC emissions, but, on the other hand, the lowest CO emissions. Except for the HC emissions, stages during on/off-ramp closures generally produce more emissions than the stages with freeway lane closures, as well as more fuel consumption. This is mainly because there is no demand reduction during those ramp closure stages, while either 1% or 2% reduction applies in other stages. Compared to the

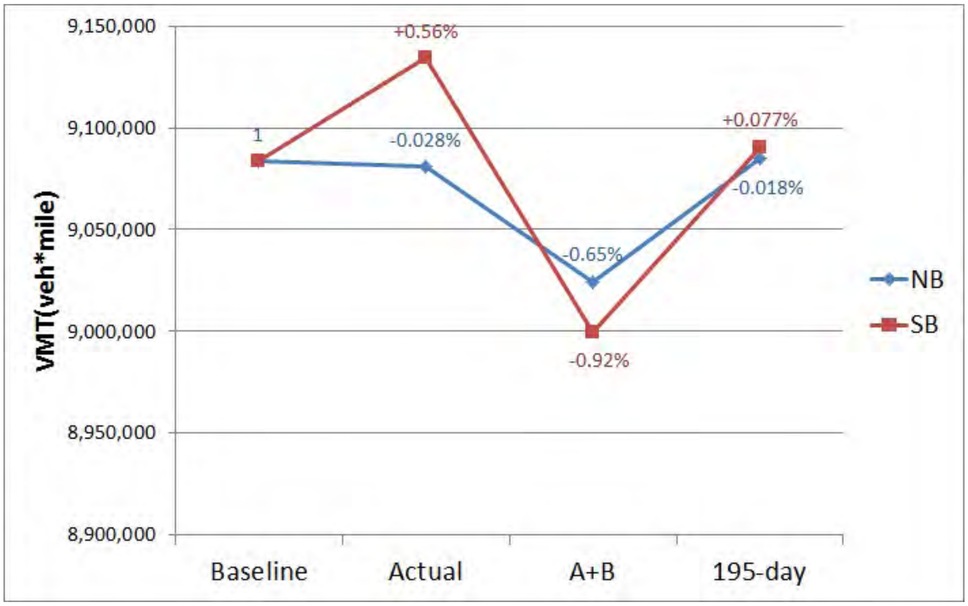


Figure 5.2: Vehicle Miles Traveled (VMT) of the directional closure plan and lane closure plans in the morning peak

195-Day lane closure plan and the directional closure plan, emissions during the A+B plan are less, which is expected because of the higher demand reduction.

Keep in mind that emission levels are dependent on factors such as distance traveled and speeds traveled, which in itself are dependent on the level of traffic. Therefore, the travel demand is one of the main factors for deciding the level of emissions on the network. Overall, all three work zone planes do not affect the fuel consumption and emissions as much in terms of percentage changes. The emissions for CO2, HC, CO, and NOX, are roughly the same among those stages with a change of less than 1%. Besides other factors, this is also attributable to the models used to estimate these quantities: they have a flat portion in the middle range of travel speed, which makes them insensitive to speed changes in the network when the average speed falls in this range.

Table 5.6: Simulation results on the six-hour emissions for the directional closure plan (morning peak 6:00am-12:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	293,937	2,608	6.22	11.80	10.27
NB	294,876	2,617	6.72	11.55	10.28
SB	297,479	2,640	6.64	11.59	10.28

Table 5.7: Simulation results on the six-hour emissions for the 195-day lane closure plan (morning peak 6:00am-12:00pm)

Stage	Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
1	SB/1L	294,970	2,618	6.43	11.53	10.18
2	NB/1L	294,621	2,615	6.54	11.56	10.22
3 ∼ 5	SB/2L	294,865	2,617	6.44	11.60	10.22
6 ∼ 8	NB/2L	293,885	2,608	6.76	11.31	10.17
9	J St. off	295,836	2,625	6.28	11.82	10.29
10	W50 on	296,309	2,629	6.36	11.78	10.28
11	E50 on	295,099	2,619	6.28	11.80	10.27
12	P St. on/off	296,520	2,631	6.38	11.80	10.30

Table 5.8: Simulation results on the six-hour emissions for the 110-day A+B lane closure plan (morning peak 6:00am-12:00pm)

Stage	Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
1	SB/1L	291,249	2,585	6.33	11.53	10.13
2	NB/1L	291,756	2,589	6.37	11.47	10.10
3 ∼ 5	SB/2L	291,990	2,591	6.31	11.60	10.16
6 ∼ 8	NB/2L	291,834	2,590	6.65	11.10	10.01
9	J St. off	295,836	2,625	6.28	11.82	10.29
10	W50 on	296,309	2,629	6.36	11.78	10.28
11	E50 on	295,099	2,619	6.28	11.80	10.27
12	P St. on/off	296,520	2,631	6.38	11.80	10.30

A comparison of the emissions for all three plans during the NB closures in the morning peak is presented in Table 5.9, and SB closures in Table 5.10. The results for the 110-day A+B and 195-Day plan are represented by the stage with two-lane closures. In comparing all three closure plans, the 110-day A+B plan does indeed have the lowest emissions output as a result of highest demand reduction. The directional closure plan yields a slightly higher fuel consumption, thus more CO2 emissions, than the lane closure plans, and it does not reduce the emissions of CO and NOX as much as the lane closure plans do.

Table 5.9: Simulation results on the six-hour emissions for all three plans under NB closure (morning peak 6:00am-12:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	293,937	2,608	6.22	11.80	10.27
Actual	294,876	2,617	6.72	11.55	10.28
A+B	291,834	2,590	6.65	11.10	10.01
195-DAY	293,885	2,608	6.76	11.31	10.17

Table 5.10: Simulation results on the six-hour emissions for all three plans under SB closure (morning peak 6:00am-12:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	293,937	2,608	6.22	11.80	10.27
Actual	297,479	2,640	6.64	11.59	10.28
A+B	291,990	2,591	6.31	11.60	10.16
195-DAY	294,865	2,617	6.44	11.60	10.22

5.1.3 Overall assessment

Table 5.11 summarizes the total/average traffic delay, average travel distance, VMT, VHT and emissions in average for the six-hour morning peak of all three plans, with their percentage changes compared to the baseline scenario. The overall changes over the baseline scenario in the morning peak for all three plans are shown in Table 5.12. The numbers in Table 5.12 describe how those indicators during the morning peak would change over the entire work zone horizon, if a plan is used to fix the “Boat Section”.

The two lane closure plans produce slightly less daily traffic delay (including the daily average delay, the daily six-hour delay, daily six-hour delay cost and daily six-hour VHT) than the directional closure in the six-hour morning peak. For instance, the daily average traffic delay is 11.94 min per trip and 10.87 min per trip for the 195-day plan and the 110-day A+B plan, as compared to the 12.05 min per trip for the directional closure. While the daily six-hour total delay cost is 0.86 million dollars and 0.78 million dollars for the 195-day plan and the 110-day A+B plan, as compared to the 0.88 million dollars for the directional closure. However, the total delay (as well as the VHT) over the entire work zone horizon brought by the two lane closure plans is significantly greater than the directional closure plan, as indicated by the numbers in Table 5.12. Compared to the directional closure, both lane closure plans increase the average travel distance per trip. Since the 195-day plan has the same demand reduction as the directional closure plan, it certainly yields greater daily VMT, as well as total VMT. On the other hand, the 110-day A+B is assumed to have a higher demand reduction than the directional closure plan, and as a result, it produces less daily VMT and less total VMT. In addition, the daily emissions caused by all three work zone plans seem to not differ as much in terms of percentage changes, except for the HC emissions.

As for the overall changes in the morning peak, the 195-Day lane closure plan has a significantly larger impact on traffic and emissions compared to the baseline numbers in 7 of the 9 categories, yet has the lowest figures for the CO and NOX categories. The directional closure plan has the lowest increase in total traffic delay and VHT. The additional total delay cost caused by the work zone is 13 M for the directional closure, which is almost 80% less than 67 M for the 195-day lane closure. The directional closure also results in approximately 80% less VHT and 14% less VMT than the 195-day plan. Aside from ranking in the middle of the pack for total delay and VHT, the 110-day lane closure plan brings about lower fuel consumption, CO2, CO, and NOX emissions than even that of the baseline values.

Table 5.11: Network performance and emissions in average for the six-hour morning peak of all three plans, with their percentage changes compared to the baseline scenario (morning peak 6:00am-12:00pm)

Plan	Baseline	Directional closure		110-DAY lane closure		195-DAY lane closure	
Number of Days		36		110		195	
Average delay(min)	7.07	12.05	70.44%	10.87	53.80%	11.94	68.88%
Average distance(mile)	25.15	25.23	0.30%	25.44	1.16%	25.44	1.13%
6-hr delay(thousand hrs)	42.6	72.5	70.44%	64.3	51.02%	71.1	67.06%
6-hr delay cost(million $)	0.51	0.88	70.44%	0.78	51.02%	0.86	67.06%
VMT (thousand veh*mi)	9,084	9,108	0.27%	9,028	-0.62%	9,089	0.06%
VHT (thousand veh*hr)	196	231	17.85%	220	12.02%	228	16.26%
Fuel (thousand gallon)	294	296	0.76%	293	-0.43%	295	0.23%
CO2 (ton)	2,608	2,629	0.79%	2,598	-0.40%	2,615	0.27%
HC (ton)	6.22	6.68	7.40%	6.42	3.26%	6.54	5.19%
CO (ton)	11.8	11.57	-1.95%	11.48	-2.75%	11.52	-2.41%
NOX (ton)	11.27	10.28	0.10%	10.13	-1.32%	10.21	-0.61%

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

5.2 Afternoon peak

5.2.1 Daily network performance

The simulation results for the afternoon peak of the actual directional closure, presented in Table 5.13, show that there is a greater impact imposed upon the traffic during the directional SB closures than the directional NB closures. The directional SB closures brought about the highest average travel distance, delay, and speed, along with the lowest average travel speed. It increases the average travel delay up to 12.30 min, while the directional NB closure yields an average delay of 9.82 min. In combination with the amount of trips made, the directional SB closures result in the largest six-hour VMT and VHT, a 6% increase in VMT and 2% in

Table 5.12: Additional delay/VMT/VHT/fuel/emissions over the baseline case (all the morning peak periods of the entire work zone project)

Plan	Directional closure	110-DAY lane closure	195-day lane closure
Number of Days	36	110	195
Total delay(thousand hr)	1,079	2,388	5,565
Total delay cost(million $)	13.0	28.8	67.2
VMT (thousand veh*mi)	868	-6,180	1,008
VHT (thousand veh*hr)	1,261	2,596	6,224
Fuel (gallon)	79,938	-137,496	134,511
CO2 (ton)	738	-1,151	1,350
HC (ton)	16.56	22.32	63.01
CO (ton)	-8.28	-35.70	-55.43
NOX (ton)	0.36	-14.95	-12.25

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

VHT compared to the baseline scenario. There are a variety of reasons why the directional SB closure led to a higher impact than the directional NB closure. In the afternoon peak, with the presence of the SB closure, outbound traffic to the Southern Area has to take the arterials, e.g. 10 St. or 16 St., and take the US 50 ramps to finally get on the I-5 SB. The traffic data showed that a further detour to Riverside Blvd. or Freeport Blvd. is not as common as occurred by the inbound traffic in the morning peak. Therefore, the queues on US-50 ramps are significant, and can further block the traffic on both the major arterials and the US-50 freeway. The queues on US-50 ramps together with the queues on US-50 freeway are much longer in the directional SB closure than the directional NB closure, which in fact induces significant detour. On the other hand, if the directional NB closure is applied, the outbound traffic to the Southern Area is not affected as much, while the traffic to the Northern Area can still take I St. or Richards on-ramps to I-5 NB. Consequently, the increase in the travel distance of this detour is not as prominent as that in the directional SB closure. With longer detour routes, the directional SB closure generates a higher VMT than the directional NB closure.

Similar to the morning peak analysis, the demand reduction in travel demand is taken as 1% for the 195-Day lane closure plan and 2% for the 110-day A+B lane closure plan. The simulation results for each of the stages in the 195-Day plan and the 110-day A+B plan are displayed in Table 5.14 and 5.15.

One-lane or two-lane SB closures of the freeway led to longer travel distances and travel delays than the baseline scenario, but as much as the directional SB closure in the actual plan.

Table 5.13: Simulation results for the directional closure plan (afternoon peak 2:00pm-8:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Open	335,346	42,161	25.62	33.78	7.54	45.50	8,590,459	188,782
NB	331,990	54,326	25.32	36.40	9.82	41.63	8,405,769	201,435
SB	331,990	68,047	26.65	40.35	12.30	39.62	8,847,134	223,268

Table 5.14: Simulation results for the 195-day lane closure plan (afternoon peak 2:00pm-8:00pm)

Stage	Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
1	SB/1L	331,990	49,934	25.69	35.42	9.02	43.51	8,527,220	195,980
2	NB/1L	331,990	38,464	25.58	33.06	6.95	46.43	8,492,903	182,934
$3 \sim 5$	SB/2L	331,990	52,953	25.76	36.20	9.57	42.70	8,552,282	200,289
$6 \sim 8$	NB/2L	331,990	76,740	25.76	41.07	13.87	37.63	8,551,663	227,261
9	J St. off	335,346	43,033	25.62	33.87	7.70	45.38	8,591,510	189,312
10	W50 on	335,346	50,363	25.56	35.19	9.01	43.58	8,571,577	196,701
11	E50 on	335,346	38,665	25.55	32.98	6.92	46.47	8,567,057	184,349
12	P St. on/off	335,346	87,780	25.78	42.38	15.71	36.50	8,646,109	236,890

Table 5.15: Simulation results for the A+B lane closure plan (afternoon peak 2:00pm-8:00pm)

Stage	Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
1	SB/1L	328,635	39,532	25.60	33.27	7.22	46.18	8,414,562	182,222
2	NB/1L	328,635	37,821	25.58	32.98	6.91	46.54	8,407,548	180,652
$3 \sim 5$	SB/2L	328,635	49,794	25.73	35.59	9.09	43.38	8,456,656	194,937
$6 \sim 8$	NB/2L	328,635	72,221	25.76	40.43	13.19	38.23	8,465,311	221,435
9	J St. off	335,346	43,033	25.62	33.87	7.70	45.38	8,591,510	189,312
10	W50 on	335,346	50,363	25.56	35.19	9.01	43.58	8,571,577	196,701
11	E50 on	335,346	38,665	25.55	32.98	6.92	46.47	8,567,057	184,349
12	P St. on/off	335,346	87,780	25.78	42.38	15.71	36.50	8,646,109	236,890

With the I-5 SB partially open, outbound traffic is likely to continue using the freeways, and the capacity reduction of 25% and 50% seems not differ as much. On the other hand, NB closures generate some interesting phenomena. The traffic delay caused by the one-lane NB closure is minimal compared to the baseline, but the two-lane NB closure, however, can create as high as

13.87 min average delay and a 15% increase in VHT. A review on detailed simulation animation reveals the reason. The outbound traffic still uses the I-5 NB to head for the Northern Area as the American River limits the route choices. Those vehicles form a long queue at those on-ramps which backs up all the way to the downtown area. More importantly, the capacity reduction also leads to a long queue on I-5 NB as well as WB US 50. This actually can block thousands of vehicles taking US 50 to the Western Area and Southern Area. Therefore, the network is overall worse off than the directional NB closure during the afternoon peak.

It is then not surprising to see that the closure of the P St. on- and off-ramps causes the greatest increase in travel distance and travel delays, even greater than the case with two-lane NB closures. This is because there is no demand reduction, and thus outbound travelers detour to other ramps and could form long queues that block even more travelers. The average travel delay is up to 15.71 min, while the closure of other ramps, J St. off-ramp or WB/EB US 50 on-ramp, only generates minor congestion.

Simulation results for the 110-day A+B plan follow many of the same patterns of the 195-Day Plan. The two-lane NB closure causes longer delays and longer detours than both the two-lane SB closure and the one-lane NB closure. Due to the greater decrease in the number of trips, the VMT and VHT are lower overall for this lane closure plan than the 195-day lane closure plan.

A comparison of the network performance indicators during the afternoon peak for all three plans during NB closures is presented in Table 5.16, and SB closures in Table 5.17. The results for the 110-day A+B and 195-Day plan are represented by two-lane closures. Figures 5.3 and 5.4 plot the average travel delay and VMT among those three plans, respectively.

In comparing all three plans under NB closures for the afternoon peak (two-lane NB closure for the alternative plans), the alternative plans cause longer detours, longer travel times and lower average travel speeds. The average travel distances for the actual directional closure were actually lower than that of the baseline numbers. This finding may have been a result of detour routes via downtown could be shorter than the freeway, but those detour routes definitely take longer time. For the SB closures in the afternoon, on the other hand, both lane closure plans bring in less congestion, thus less VMT/VHT, than the actual directional plan. This indicates that the SB I-5 plays an important role in transporting outbound traffic in the afternoon.

Both the directional closure plan and the lane closure plans reduce the six-hour VMT slightly, except for the directional closure plan during the SB closures where a 3.0% increase in VMT is obtained. The directional SB closure, as we discussed before, could lead to longer detour routes and the average travel distance is increased by nearly 1 mile per trip. Therefore, the resultant VMT is significantly greater than other scenarios. Overall, the demand reduction can be a dominant way of reducing VMT as all the work zone plans yield less VMT than the baseline.

Table 5.16: Simulation results for all three plans during the NB closure (afternoon peak 2:00pm-8:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Baseline	335,346	42,161	25.62	33.78	7.54	45.50	8,590,459	188,782
Actual	331,990	54,326	25.32	36.40	9.82	41.63	8,405,769	201,435
A+B	328,635	72,221	25.76	40.43	13.19	38.23	8,465,311	221,435
195-DAY	331,990	76,740	25.76	41.07	13.87	37.63	8,551,663	227,261

Table 5.17: Simulation results for all three plans during the SB closure (afternoon peak 2:00pm-8:00pm)

Configuration	Six-hour trips (veh)	Six-hour queuing delay (veh*hr)	Average travel distance (mile)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	Six-hour VMT (veh*mile)	Six-hour VHT (veh*hr)
Baseline	335,346	42,161	25.62	33.78	7.54	45.50	8,590,459	188,782
Actual	331,990	68,047	26.65	40.35	12.30	39.62	8,847,134	223,268
A+B	328,635	49,794	25.73	35.59	9.09	43.38	8,456,656	194,937
195-DAY	331,990	52,953	25.76	36.20	9.57	42.70	8,552,282	200,289

5.2.2 Daily Emission

Simulation results on the emissions for the actual directional closure plan during the afternoon peak are presented in Table 5.18. During the directional closure, SB closures caused the largest consumption of fuel among the afternoon scenarios by a 6.5% increase due to the additional congestion, longer travel distances and longer travel times it brings. The corresponding emission values for CO2, HC, CO and NOX are the highest for the SB closure as well. Fuel consumption

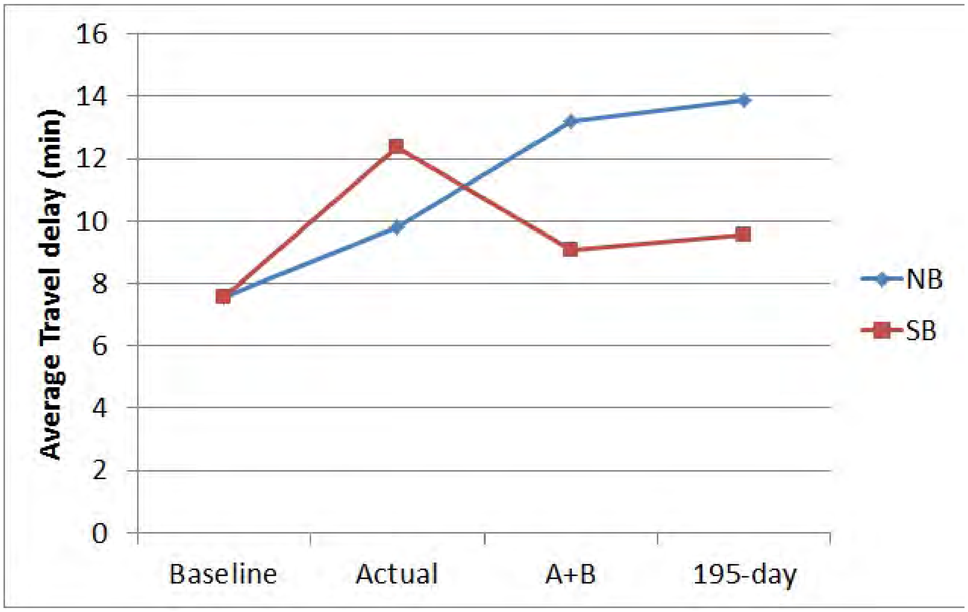


Figure 5.3: Average Travel Delay of the directional closure plan and lane closure plans in the afternoon peak

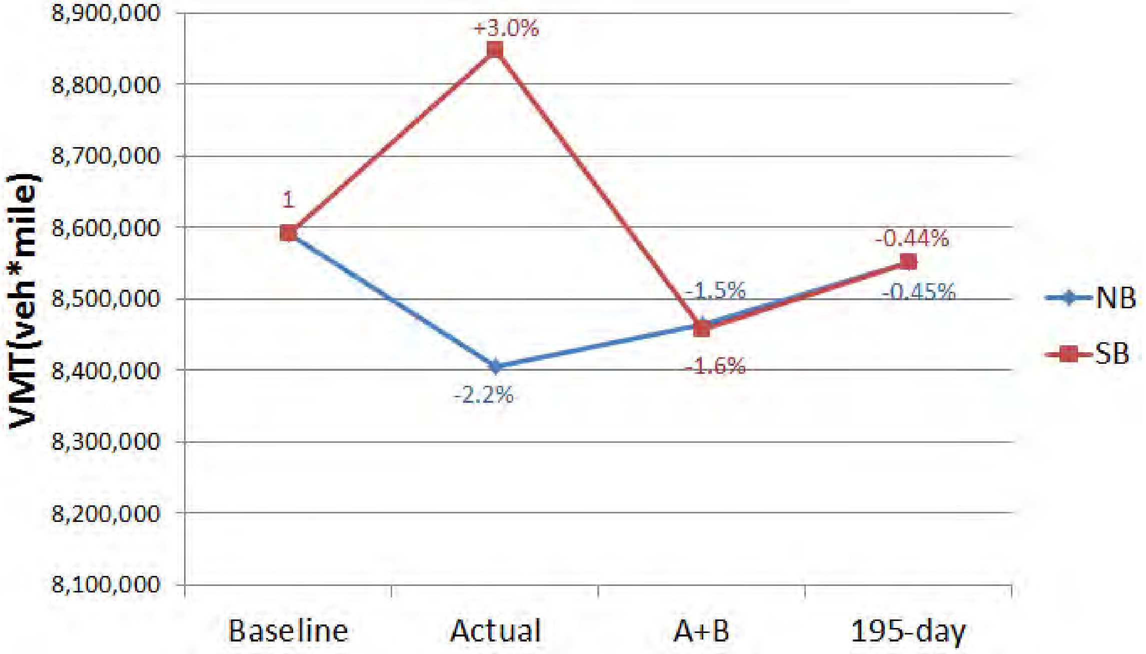


Figure 5.4: Vehicle Miles Traveled (VMT) of the directional closure plan and lane closure plans in the afternoon peak

during NB closures was actually lower than that of open weeks by 2,000 gallons, mainly due to a less demand and a less VMT while the overall network congestion remain approximately the same as the open day.

Table 5.18: Simulation results on the emissions for the actual directional closure plan (afternoon peak 2:00pm-8:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	278,181	2,469	5.91	11.00	9.63
NB	276,834	2,457	6.11	10.80	9.61
SB	295,874	2,626	6.73	11.40	10.20

Table 5.19 presents emissions during the afternoon peak for the 195-Day lane closure plan. The one-lane closures in stages 1 and 2 result in lower fuel consumption and emission values than the two-lane and on/off-ramp closures. The shut down of the P St. ramps is the most impacted of the closures, with the highest values in fuel consumption, CO2, HC, and NOX, thanks to its contribution to the heaviest congestion of all the scenarios. The simulation results for the 110-day A+B plan, shown in Table 5.20, display similar patterns to the 195-Day plan, but it produces less overall fuel consumption and emissions than the 195-day plan. In this case, the shut down of the P St. ramps also results in the largest values for every emission category.

When comparing all three NB/SB closure scenarios together, the emission values are roughly the same with a change of less than 1.5%, as displayed in Table 5.21 and 5.22. The only exception is that the directional SB closure consumes the most fuel and produces the greatest emissions on CO2, HC and NOX. Overall, there is less fuel consumed and less CO2, CO and NOX emissions for the A+B plan during the afternoon peak.

Table 5.19: Simulation results on the emissions for the 195-day lane closure plan (afternoon peak 2:00pm-8:00pm)

Stage	Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
1	SB/1L	276,921	2,458	5.98	10.89	9.57
2	NB/1L	274,836	2,439	5.80	10.89	9.53
$3 \sim 5$	SB/2L	278,576	2,473	6.15	10.92	9.64
$6 \sim 8$	NB/2L	277,176	2,460	6.27	10.85	9.66
9	J St. off	277,918	2,467	5.89	11.01	9.64
10	W50 on	277,808	2,466	6.00	11.02	9.67
11	E50 on	276,905	2,458	5.82	11.02	9.62
12	P St. on/off	282,760	2,510	6.52	11.18	9.91

Table 5.20: Simulation results on the emissions for the 110-day A+B lane closure plan (afternoon peak 2:00pm-8:00pm)

Stage	Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
1	SB/1L	272,380	2,417	5.73	10.83	9.45
2	NB/1L	271,899	2,413	5.74	10.80	9.44
3 ∼ 5	SB/2L	274,809	2,439	6.02	10.82	9.53
6 ∼ 8	NB/2L	274,750	2,438	6.25	10.70	9.55
9	J St. off	277,918	2,467	5.89	11.01	9.64
10	W50 on	277,808	2,466	6.00	11.02	9.67
11	E50 on	276,905	2,458	5.82	11.02	9.62
12	P St. on/off	282,760	2,510	6.52	11.18	9.91

Table 5.21: Simulation results on the emissions for all three plans during the NB closure (afternoon peak 2:00pm-8:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	278,181	2,469	5.91	11.00	9.63
Actual	276,834	2,457	6.11	10.80	9.61
A+B	274,750	2,438	6.25	10.70	9.55
195-DAY	277,176	2,460	6.27	10.85	9.66

Table 5.22: Simulation results on the emissions for all three plans during the SB closure (afternoon peak 2:00pm-8:00pm)

Configuration	Fuel Consumption (gallon)	CO2 (ton)	HC (ton)	CO (ton)	NOX (ton)
Open	278,181	2,469	5.91	11.00	9.63
Actual	295,874	2,626	6.73	11.40	10.20
A+B	274,809	2,439	6.02	10.82	9.53
195-DAY	278,576	2,473	6.15	11.92	9.64

5.2.3 Overall assessment

Table 5.23 summarizes the total/average traffic delay, average travel distance, VMT, VHT and emissions in average for the six-hour afternoon peak of all three plans, with their percentage changes compared to the baseline scenario. The overall changes over the baseline scenario in the afternoon peak for all three plans are shown in Table 5.24. The numbers in Table 5.24 describe how those indicators during the afternoon peak would change over the entire work zone horizon.

There are benefits and drawbacks of each plan. Although the directional closure produces slightly higher daily average delay and slightly higher daily 6-hour delay than the two lane closure plans, it brought about the least total delay over the entire work zone horizon. On the other hand, the direction closure results in the largest daily and overall VMT, as well as fuel consumption values along with the highest emission values of the three plans during the afternoon peak (except for the overall HC emissions it is less than the 195-day plan). Both alternative plans are capable of reducing VMT, fuel consumptions and emissions. Of the two alternative plans, the A+B plan presents less of an impact on traffic and emissions than the 195-Day plan due to its greater demand reduction.

Table 5.23: Network performance and emissions in average for the six-hour afternoon peak of all three plans, with their percentage changes compared to the baseline scenario (afternoon peak 2:00pm-8:00pm)

Plan	Baseline	Directional closure		110-DAY lane closure		195-DAY lane closure	
Number of Days		36		110		195	
Average delay(min)	7.54	11.06	46.68%	10.22	35.57%	10.81	43.37%
Average distance(mile)	25.62	25.99	1.42%	25.69	0.29%	25.72	0.39%
6-hr delay(thousand hr)	42.2	61.2	45.13%	56.2	33.37%	59.9	42.04%
6-hr delay cost(million $)	0.51	0.74	45.13%	0.68	33.37%	0.72	42.04%
VMT (thousand veh*mi)	8,590	8,626	0.42%	8,482	-1.26%	8,550	-0.48%
VHT (thousand veh*hr)	189	212	12.49%	144	-23.64%	208	10.10%
Fuel (thousand gallon)	278	286	2.94%	275	-1.05%	278	-0.19%
CO2 (ton)	2,469	2,542	2.94%	2,443	-1.06%	2,464	-0.18%
HC (ton)	5.91	6.42	8.63%	6.05	2.43%	6.13	3.78%
CO (ton)	10.99	11.11	1.09%	10.84	-1.38%	10.91	-0.74%
NOX (ton)	9.63	9.9	2.80%	9.56	-0.69%	9.64	0.10%

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

Table 5.24: Additional delay/VMT/VHT/fuel/emissions over the baseline case (all the afternoon peak periods of the entire work zone project)

Plan	Directional closure	110-DAY lane closure	195-day lane closure
Number of Days	36	110	195
Total delay(thousand hr)	685	1,547	3,456
Total delay cost(million $)	8.3	18.7	41.7
VMT (thousand veh*mi)	1,296	-11,947	-7,987
VHT (thousand veh*hr)	849	-4,910	3,719
Fuel (gallon)	294,228	-321,449	-103,480
CO2 (ton)	2610	-2,873	-885
HC (ton)	18.36	15.79	43.52
CO (ton)	4.32	-16.72	-15.77
NOX (ton)	9.72	-7.28	1.97

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

5.3 All-day assessment

The ‘All Day” simulation results are generated by adding the results of the morning and afternoon peak together. Even though this is not a 24-hour assessment, the combination of the two peaks provides a significant amount of information for us to evaluate the differences in those closure plans. The daily delay, VMT/VHT and emissions for the 12-hour peak periods over the three plans are displayed in Table 5.25, and Table 5.26 shows the overall changes of those statistics over the entire work zone horizon.

While all the three plans produce fairly close daily average delay (11.56 min, 11.37 min and 10.55 min for the directional closure, 195-day lane closure and 110-day lane closure respectively), the directional closure causes the least total delay of all the plans. However, it yields greater average daily 12-hour VMT, daily 12-hour fuel consumption and daily 12-hour emissions than the two lane closure plans. Their percentage changes over the baseline, however, are small (less than 2% in most cases).

The lower 12-hour VMT, fuel consumption, and emissions of the 110-day plan is the direct result of the 1% more reduction in its total demand than that of the 195-day plan, because the two alternative plans have the same staging plan except that the former shortens the duration of each stage.

It is also interesting to see that less vehicle miles are traveled during the lane closures, compared to the case without the work zone, except for the morning peak travel under the 195-Day plan. This indicates that travelers do not detour as much in the lane closure plans as in the directional plan.

5.4 Summary

For the morning peak travel, NB closures have a greater impact on traffic and emissions for any of the three plans. Comparatively, delays, detours, speeds are worse in the morning peak for NB closures than SB closures. In the afternoon, SB closures have a greater impact on traffic and emissions than NB closures for the directional closure. For the two alternative lane closure plans, two-lane NB closures lead to more traffic delays and emissions than the directional NB closures.

Overall, the directional closure produced slightly higher average daily delay and slightly

Table 5.25: Network performance and emissions in average for the 12-hour peak period of all three plans, with their percentage changes compared to the baseline scenario (6:00am-12:00pm and 2:00pm-8:00pm)

Plan	Baseline	Directional closure		110-DAY lane closure		195-DAY lane closure	
Number of Days		36		110		195	
Average delay(min)	7.31	11.56	58.18%	10.55	44.39%	11.37	55.71%
Average distance(mile)	25.39	25.61	0.87%	25.57	0.72%	25.58	0.76%
12-hr delay(thousand hr)	84.7	133.7	57.84%	120.5	42.24%	131.1	54.61%
12-hr delay cost(million $)	1.02	1.61	57.84%	1.45	42.24%	1.58	54.61%
VMT (thousand veh*mi)	17,674	17,734	0.34%	17,509	-0.93%	17,638	-0.20%
VHT (thousand veh*hr)	385	444	15.22%	364	-5.46%	436	13.24%
Fuel (thousand gallon)	572	583	1.82%	568	-0.73%	572	0.03%
CO2 (ton)	5,077	5,170	1.83%	5,040	-0.72%	5,079	0.05%
HC (ton)	12.13	13.10	8.00%	12.48	2.86%	12.68	4.50%
CO (ton)	22.79	22.68	-0.48%	22.31	-2.09%	22.42	-1.60%
NOX (ton)	19.9	20.18	1.41%	19.70	-1.02%	19.85	-0.26%

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

Table 5.26: Additional delay/VMT/VHT/fuel/emissions over the baseline case (all the morning and afternoon peak periods of the entire work zone project)

Plan	Directional closure	A+B lane closure	195-DAY lane closure
Number of Days	36	110	195
Total delay (thousand hr)	1,764	3,936	9,021
Total delay cost (million $)	21.3	47.5	108.9
VMT (thousand veh*mi)	2,164	-18,127	-6,979
VHT (thousand veh*hr)	2,110	-2,314	9,944
Fuel (gallon)	374,166	-458,945	31,031
CO2 (ton)	3,348	-4,024	465
HC (ton)	34.92	38.11	106.53
CO (ton)	-3.96	-52.42	-71.20
NOX (ton)	10.08	-22.23	-10.28

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

more fuel consumption and emissions than the two lane closure plans in the extended 12-hour AM/PM peak period. Because directional closure considerably shortens the number of construction days, it reduces considerably more total delay cost than the lane closure plans. In the case of Fix I-5, the reductions are 5-fold (compared to 195-day plan) and 2.2-fold (compared to 110-day plan). This reduction can be even higher once construction cost is also considered.

Compared with travel delay cost, the directional closure plan produced slightly more emissions and consumed more fuel over the base scenario when compared with the lane closure plans. The changes over baseline figures are less than 2% in most cases. Travel delay cost (and construction cost), therefore, largely determines which plan should be used.

It should be pointed out that traffic diversion to alternative routes plays a major role to soften the impact of directional closure in the case of Fix I-5. This requires the network to have enough alternative routes and adequate capacity to absorb the diverted traffic. If this condition is not met, lane closure rather than directional closures may be more desirable.

Chapter 6

Analysis with a planning model

Part of this research is to investigate how planning models fare in assessing work zone impact when compared with a dynamic network modeling tool. The planning model does not model dynamic network queuing, but it is easy to calibrate and implement and has been widely applied in large-scale networks. There are several planning software packages to choose from: they include TransCAD, VISSUM, CUBE, EMME2, etc. Despite their many differences in appearance, all these software packages use the Wardropian User Equilibrium to assign O-D demands to the network, hence should produce the same result if the same O-D demand is loaded onto the same network. In this project, we choose TransCAD to evaluate the actual directional closure plan, and compare its results with those from NetZone, a mesocopic simulation tool. The comparison of both types of models is not for the purpose of evaluating the plans, but for the purpose of identifying the appropriate models for work zone traffic analysis. Therefore, we here use only one scenario, the directional NB closure in the actual plan during the morning peak, to illustrate such findings.

6.1 Modeling process

Recall that in a planning model, demand in the peak period is treated as constant. In order to model the varying demand in the extended peak period, we create six hourly-based time periods in the morning peak from 6:00am to 12:00pm. The time-varying traffic demand obtained from the dynamic O-D estimation is transformed to six hourly-based O-D trip matrices. This is done by aggregating the time-varying traffic demand in the morning peak with 15 min intervals to the total number of trips in each of those six hours. Meanwhile, we export the network from

NetZone to TransCAD and ensure all the network properties are the same in both tools. The network properties and the six hourly-based O-D trip matrices serve as the input of the planning model.

In TransCAD, we set up six scenarios. In each scenario, we load the network using STA with one of those hourly-based O-D trip matrices. The statistics of the assignment results in each scenario are added up to obtain the overall assessment for the baseline weekday (i.e. recurrent congestion). On the other hand, to model the directional NB closure, we estimate the 5-min O-D demands using the dynamic O-D estimator based on the real traffic count data collected during the NB closure. Then, the new time-varying demands are aggregated to the hourly-based O-D trip matrix for the NB closure in the same way we do for the open day, which is then assigned to the network where the directional NB closure plan is implemented. Therefore, we can obtain the overall statistic for the NB closure by aggregating the statistics of all six scenarios. Finally, those statistics are compared to the case obtained by the mesoscopic simulation tools.

6.2 Comparison to the mesoscopic simulation results

The statistics of the network performance resulted from both the planning model and the mescoscopic simulation models are shown in Table 6.1.

Table 6.1: The statistics of the network performance resulted from the planning model and the mescoscopic simulation models

Planning model								
Closure	Total trips (veh)	Total queuing delay (veh*hr)	Average travel distance (hr)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	VMT (veh*mile)	VHT (veh*hr)
Open	361,120	7,421	25.21	27.81	1.23	54.40	9,104,710	167,360
NB	332,230	5,491	25.14	27.70	0.99	54.46	8,351,859	153,368

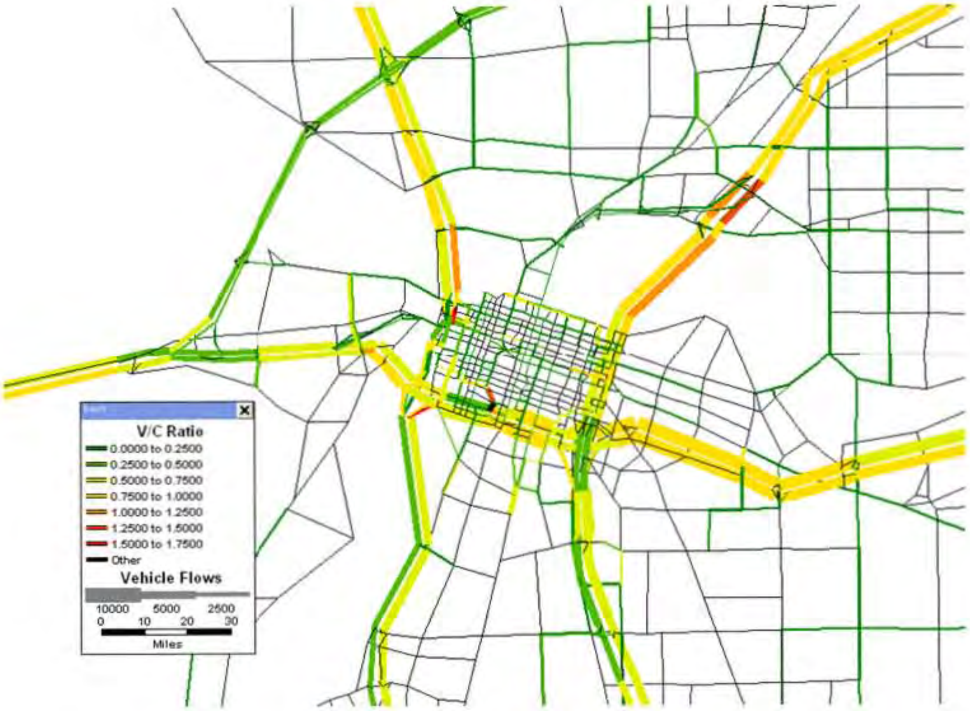
Mesoscopic simulation model								
Closure	Total trips (veh)	Total queuing delay (veh*hr)	Average travel distance (hr)	Average travel time (min)	Average travel delay (min)	Average travel speed (mph)	VMT (veh*mile)	VHT (veh*hr)
Open	361,120	42,553	25.15	32.61	7.07	46.28	9,083,748	196,285
NB	357,509	82,398	25.15	40.09	13.69	37.64	9,081,179	241,279

The results are not surprising. As compared to the simulation results from NetZone, the planning model overwhelmingly underestimate travelers' queuing delay and travel time on the network. The average travel delay is merely 1.23 min and 0.99 min for the baseline and NB closures, respectively. This is far less than the average delay of 7.07 min and 13.69 min by the dynamic simulation. Furthermore, the planning model estimates better network performance in the NB closure than the baseline, which contradicts with the real observation.

In addition, we also review the TransCAD results of each hour. Generally, the traffic flow on those key links, e.g. the freeway links and major arterials for detours, do not change significantly when the NB closure is implemented. The Volume/Capacity (V/C) Ratios of all the links over the entire network, for the 8:00am-9:00am period, can be seen in Figure 6.1. As a matter of fact, little traffic diversion can be observed, and the volume changes on several freeway links does not match the real observation. For instance, the I-5 NB section south of US 50 was seen to be heavily congested. However, by the planning model, that section is unrealistically better off during the NB closure. This is not a rare situation under the planning model, since it does not model the dynamic queuing caused by vehicle detour via downtown area. Because the BPR link performance function used in the planning model allows a higher traffic flow than the capacity and does not necessarily impose sufficiently long travel time for heavy congestion, travelers can take those local streets without being subject to long queuing delay. Therefore, it is possible that STA models the I-5 NB section in less congestion than the baseline.

In a nutshell, results obtained from TransCAD are far from accurate in assessing the recurrent traffic congestion nor the traffic impact caused by the work zone plan. In this project, the dynamic traffic simulation by the mesoscopic traffic model do indeed produce satisfactory results that approximately match observed traffic conditions, while the planning model is unable to do so.

(a) Baseline



(b) The NB closure

Figure 6.1: The view of volume capacity ratios (V/C) for the case of baseline and the NB closure (8:00am-9:00am)

Chapter 7

Conclusions

In this project, we evaluated three work zone plans for the Fix I-5 project in the Sacramento Metropolitan Area using dynamic network analysis. The three plans are: 1) the actual directional closure plan implemented from May 20 to July 28 with directional NB and SB closures; 2) the 195-day lane closure alternative plan which would last 10 months with 12 lane closure or ramp closure stages; and 3) the A+B lane closure alternative plan which would last six months with the same staging as the 195-day plan.

The modeling process involves several steps. First of all, the network of Sacramento Metropolitan Area was coded in NetZone, a dynamic work zone analysis tool. Using the 5-min PeMS traffic counts on selected 28 freeway segments and 15-min traffic counts on major arterials on the periphery of Downtown Sacramento, we estimated the time-dependent O-D demands by a Logit Path Flow Estimator for the 6-hour morning peak (6:00am-12:00pm) and the 6-hour afternoon peak (2:00pm-8:00pm), respectively. We then loaded the time-dependent O-D demands to the network where no work zone was deployed. By trial-and-error, the network properties, O-D connectors and route choice models were appropriately calibrated so as to produce the real traffic counts, travel time and queuing patterns. This serves as the baseline scenario. For the cases with the presence of work zone plans, the same method was also applied but the time-dependent demands are adjusted accordingly using a demand diversion model and engineering judgment. By network calibration and simulation, we obtained the network performance measures, link specific measures of effectiveness and emissions for all the three plans.

In order to assess if a simpler transportation planning model would be adequate to evaluate the alternative construction plans, we modeled the directional NB closure plan using TransCAD, a widely used planning software package. To have a fair comparison, the same network and O-D demand used in NetZone were also used in TransCAD, but the morning peak was divided into six one-hour periods and the demands in each period were loaded into TransCAD to give TransCAD the opportunity to capture the variation in demand and congestion. The assignment results from all six periods were added up and compared to the results obtained by NetZone.

Table 7.1 summarizes the total/average traffic delay, average travel distance, VMT, VHT and emissions in average for the 12-hour peak periods of all three plans, with their percentage changes compared to the baseline scenario. The overall changes over the baseline scenario in the peak periods of the entire work zone horizon for all three plans are shown in Table 7.2. The comparative study are summarized as follows,

Table 7.1: Network performance and emissions in average for the 12-hour peak period of all three plans, with their percentage changes compared to the baseline scenario (6:00am-12:00pm and 2:00pm-8:00pm)

Plan	Baseline	Directional closure		110-DAY lane closure		195-DAY lane closure	
Number of Days		36		110		195	
Average delay(min)	7.31	11.56	58.18%	10.55	44.39%	11.37	55.71%
Average distance(mile)	25.39	25.61	0.87%	25.57	0.72%	25.58	0.76%
12-hr delay(thousand hr)	84.7	133.7	57.84%	120.5	42.24%	131.1	54.61%
12-hr delay cost(million $)	1.02	1.61	57.84%	1.45	42.24%	1.58	54.61%
VMT (thousand veh*mi)	17,674	17,734	0.34%	17,509	-0.93%	17,638	-0.20%
VHT (thousand veh*hr)	385	444	15.22%	364	-5.46%	436	13.24%
Fuel (thousand gallon)	572	583	1.82%	568	-0.73%	572	0.03%
CO2 (ton)	5,077	5,170	1.83%	5,040	-0.72%	5,079	0.05%
HC (ton)	12.13	13.10	8.00%	12.48	2.86%	12.68	4.50%
CO (ton)	22.79	22.68	-0.48%	22.31	-2.09%	22.42	-1.60%
NOX (ton)	19.9	20.18	1.41%	19.70	-1.02%	19.85	-0.26%

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

1. While the directional closure plan produces a slightly higher daily average delay, 11.56 min, than the two lane closure plans at 11.37 min and 10.55 min respectively, the directional closure causes 1.76 million hours of total traffic delay, the least of all the three plans. The total traffic delay over the entire work zone horizon caused by the 195-day lane closure and the 110-day lane closure would be as much as 411% and 123% more than the directional closure, respectively. If minimizing total traffic delay is the goal, the directional

Table 7.2: Additional delay/VMT/VHT/fuel/emissions over the baseline case (all the morning and afternoon peak periods of the entire work zone project)

Plan	Directional closure	A+B lane closure	195-DAY lane closure
Number of Days	36	110	195
Total delay (thousand hr)	1,764	3,936	9,021
Total delay cost (million $)	21.3	47.5	108.9
VMT (thousand veh*mi)	2,164	-18,127	-6,979
VHT (thousand veh*hr)	2,110	-2,314	9,944
Fuel (gallon)	374,166	-458,945	31,031
CO2 (ton)	3,348	-4,024	465
HC (ton)	34.92	38.11	106.53
CO (ton)	-3.96	-52.42	-71.20
NOX (ton)	10.08	-22.23	-10.28

Note: The value of time at 12.07$ per hour is used to assess the queuing delay cost.

closure plan is the best. People may be willing to put up with the inconvenience of an accelerated construction schedule, rather than spreading out the delays over a longer period, if completion is significantly faster.

2. Compared to the baseline weekday (i.e. recurrent congestion), directional closure increases the daily 12-hour VMT by 0.34%, while the 195-day plan and the 110-day plan can reduce it by 0.20% and 0.93%, respectively. Over the entire work zone project, the 195-day plan can save the total VMT by nearly 7 million vehicle miles, and the 110-day plan would save more by 18 million vehicle miles. However, the directional closure, due to its intensive and large disruption to the traffic, would increase the total VMT by 2 million vehicle miles. In addition, the lane closure plans tend to produce slightly less daily 12-hour emissions and fuel consumption than the directional closure (less than 2% except for the HC emissions), as well as less total emissions and fuel consumption over the entire work zone horizon. Therefore, if the goal is to reduce VMT, fuel consumption and emissions, the lane closure plans are better, especially the 110-day A+B plan where more demand reduction is assumed.

3. Among lane closure plans, the demand reduction plays the most important role in achieving the least VMT, fuel consumption and emissions. This is shown by the results that the larger reductions brought about from the 110-day A+B plan is mainly due to the higher deduction in demand of 2%. This indicates that the travel demand is one of the most important

factors in designing a work zone plan. A variety of demand management measures, media campaign and any other ways of reducing the travel demand will be the key of improving the network performance, as well as to reduce the emissions and fuel consumption.

4. During the morning peak travel, NB closures cause more traffic delay and more emissions than SB closures of all the three plans. In the afternoon peak, SB closures have a greater impact on traffic and emissions for the directional closure only. For the two lane closure plans, two-lane NB closures lead to more delay and emissions than the two-lane SB closures, even than the directional NB closure. This indicates that freeway closures on different directions will have significantly different effects on the traffic and emissions and for different time periods. An efficient way of designing work zone plan is to develop time-of-day stages and have the construction implemented on the appropriate direction and appropriate time that causes the least delay and emissions.

5. We see that lane closure, e.g. two-lane NB closure, can lead to more congestion than a directional (full) closure, even with the same demand reduction. This is because travelers may still use the freeway if it is not fully closed. This can produce a long queue on the freeway. Such a queue not only increases the delay for travelers taking the freeway, but also make it difficult for them to plan or find detour routes. More importantly, a queue on the freeway can block the ramps, and further block the vehicles on the major arterials, which in fact can affect thousands of other travelers. On the other hand, if travelers are notified that the freeway is fully closed prior to their trips, then they may prepare to take alternative routes in the first place. This can avoid flow concentration on the freeway since the freeway, with lane closure, cannot provide adequate capacity. Therefore, we should definitely pay more attention to the capacity reduction when designing a lane closure plan. A lane closure does not necessarily produce better daily network performance than a directional (full) closure, especially when the capacity reduction is significant and when the alternative routes to the freeway are plenty. This also indicates that efficient detour guidance can play important role in reducing the network delay during the work zone construction. Therefore, a lane closure may better suit the network with few major arterials serving as the alternative routes to the freeway, while a full directional closure of the freeway may be appropriate in the case where alternative routes are plenty.

6. It is sometimes important to know the length of those possible alterative routes to the freeway. If those routes are significantly longer than the freeway, then they, used by a significant amount of travelers can, can contribute significant part of VMT to the network, as well as to increase the fuel consumption and CO2 emissions. The directional SB closure during the afternoon peak has been an example of that. In the afternoon peak, with the presence of directional SB closure, outbound traffic to the Southern Area has to take the arterials, e.g. 10 St. or 16 St., and take the US 50 ramps to finally get on the I-5 SB. The traffic data showed that a further SB detour to Riverside Blvd. or Freeport Blvd. is not as common as occurred by the inbound traffic in the morning peak. The detour via US-50 to I-5 SB generally increase the travel distance significantly, and there contributes to a greater total VMT, fuel consumption and emissions. Therefore, we should pay special attention to the length of alternative routes when pursuing the goal the VMT/fuel consumption/CO2 reduction.

7. Based on the fuel consumption models and emission models adopted in this project, it seems that the emissions produced by different work zone plans are fairly close with the change of less than 2% (except for the HC emissions up to 8% change), and the total fuel consumption also does not differ as much (less than 1% change). This is essentially because all emission models used here have a flatter portion in the middle speed range where our traffic conditions fall, so unless a work zone plan produces drastically different average speeds, the resultant emissions and fuel consumption may not differ much. Though it deserves further investigation using more refined emission models, our preliminary conclusion is that fuel consumption and emissions may not be as important factors to consider as the traffic delay and VMT for preparing work zone plans.

8. Compared to the simulation results obtained from NetZone, the results from the planning model indicates that it overwhelmingly underestimates travelers' queuing delay and travel time on the network. Also, the traffic flow on key links does not change significantly when the directional NB closure is implemented. Little traffic diversion can be observed and the volume changes on several freeway links do not match the real observation. This is mainly due to the inability of the planning model to capture dynamic queueing and unrealistic link performance function. Clearly, a planning model is not appropriate for analyzing both

recurrent congestion and work zone impact in large-scale work zone projects and dynamic models are highly recommended for similar studies.

From these findings, the following conclusions/lessons can be drawn, and should be used as a guideline to develop future work zone staging and TMP plans:

1. Considered for the whole project duration, the 36-day directional closure plan is more preferable because the total additional delay cost caused by the work zone was 80% less than the traditional 195 day plan, \$21M compared to \$109M. The A+B plan is still preferable to the 195 day plan with more than 50% less total delay cost than the 195 day plan, \$47.5M compared to \$109M.

2. Adequate number of alternative routes and amount of reserve capacity are prerequisites for using directional closures, because traffic diversion plays an important role in softening the traffic impact of directional closures.

3. Demand reduction is likely to be minor in work zone projects with predominantly commuting trips. The specific levels of reduction largely depend on the availability of alternative modes and the extent of public awareness. Before enough data are assembled to reliably predict demand reductions, the level of demand reduction is the biggest unknown in any large work zone project.

4. A well executed TMP plan for work zone projects can increase disaster preparedness because it makes the traveling public become more aware of travel alternatives and reveal the vulnerable elements of the transportation system.

5. Good data coverage and quality, as well as adequate modeling tools are essential to the development of effective transportation management plans (TMPs).

Bibliography

Bell, M. G. H., Shield, C. M., Busch, F. & Kruse, K. (1997), 'A stochastic user equilibrium path flow estimator', *Transportation Research Part C* **5**, 197–210.

Daganzo, C. F. (1994), 'The cell transmission model: a dynamic representation of highway traffic consistent with the hydrodynamic theory', *Transportation Research Part B* **28**, 269–287.

Daganzo, C. F. (1995), 'The cell transmission model, part II: Network traffic', *Transportation Research Part B* **29**, 79–93.

EPA (2001), Final facility specific speed correction factors, m6.spd.002, Technical report.

FHWA (2009), Us department of energy, transportation energy data book, Technical report.

Friesz, T. L., Bernstein, D., Smith, T. E., Tobin, R. L. & Wei, B. W. (1993), 'A variational inequality formulation of the dynamic network equilibrium problem', *Operation Research* **41**, 179–191.

Kuwahara, M. & Akamatsu, T. (2001), 'Dynamic user optimal assignment with physical queues for many-to-many od pattern', *Transportation Research Part B* **35**, 461–479.

Lebacque, J. (1996), 'The godunov scheme and what it means for first order traffic flow models', *Procedings of International Symposium of Transport and Traffic Theory* pp. 79 – 102.

Myers, C. (2009), Inc. past projects, http://www.ccmyers.com/completedprojects.cfm (accessed september 15, 2009), Technical report.

Nie, Y. (2006), A variational inequality approach for inferring dynamic origin-destination travel demands, PhD thesis, University of California Davis.

Schwarzenegger, A. (2009), Governor's executive order s-04-08. http://gov.ca.gov/executive-order/9629, Technical report.

Zhang, H. M., Nie, Y., Shen, W., Recker, W. W. & Chen, A. (2006), Development of a time-dependent path flow estimator for deriving steady-state and time-dependent origin-destination trip tables, Technical report, Final Report TO 4135/5502, University of California, Davis.

Zhang, H. M., Qian, Z., Chen, Y. R., Carpenter, R. & Lim, R. (2010), Evaluation of the i-5 closure in downtown sacramento, Technical report, Final Report to California Environmental Protection Agency, University of California, Davis.

Zhang, H. M., Shen, W., Nie, Y. & Ma, J. (2007), Integrated construction zone traffic management, Technical report, Final Report TO 5300, University of California, Davis.