Title

Construction and Traffic Analysis of Interstate 15 (Devore II) Concrete Pavement Reconstruction Project

Authors

Monismith, Carl L.
Kim, C.
Lee, E.B.

Publication Date

2008-10-01

Peer reviewed

March 2008
Research Report: UCPRC-RR-2008-05

Construction and Traffic Analysis of Interstate 15 (Devore II) Concrete Pavement Reconstruction Project

Authors:
C. Kim, E.B. Lee, and C. L. Monismith

Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.6:
Development of Rehabilitation Construction Productivity Analysis Products

PREPARED FOR:

California Department of Transportation
(Caltrans) District 8

PREPARED BY:

University of California
Pavement Research Center
UC Davis and Berkeley

DOCUMENT RETRIEVAL PAGE	Report No: UCPRC-RR-2008-05

Title: Construction and Traffic Analysis of Interstate 15 (Devore II) Concrete Pavement Reconstruction Project

Authors: C. Kim, E.B. Lee, and C. L. Monismith

Prepared for:	**FHWA No.:**	**Date**:
Caltrans District 8	CA081070B	March 2008
Contract No.:	**Client Reference No.:**	**Version No:**
0A4233 (D-8)	SPE 4.6	Stage 6, Final approved version

Abstract:
The California Department of Transportation (Caltrans) replaced about 5 kilometers (total 20 lane-kilometers) of concrete pavement on Interstate 15 in Devore, California. The I-15 Devore II rehabilitation project was completed in six weekend closures with around-the-clock construction in early 2007, with partial or full closures of one direction of the freeway. A traffic monitoring study with surveillance systems was conducted to validate the project's transportation management plan (TMP), and to utilize the collected data for a better understanding of traffic flow characteristics at the work zone and traffic demand/capacity changes on highly trafficked urban highway projects. In addition, a construction productivity monitoring study was conducted to analyze productivity for the four construction activities; demolition, milling, Asphalt Concrete (AC) paving, and Portland cement concrete (PCC) paving. The traffic study showed that the overall impact of the work zone closure on the traveling public was manageable in most closures due to the efficient implementation of the project TMP. For example, a reduction of up to 70 percent of traffic demand during peak hours was achieved in on e weekend closure. Different lane closure configurations yielded different work zone capacity values. The construction study investigates productivity progress by comparison of gross rate, operating rate, and truckload for each construction activity. This study can help guide state agencies and transportation engineers in establishing adequate TMPs and construction stage plans to improve mobility and productivity on future highway rehabilitation projects

Keywords:
Highway reconstruction; Traffic monitoring; Traffic management plan; Work zone capacity; Construction productivity; "Rapid Rehabilitation"; Devore 2, Devore II, Interstate 15 (I-15)

Proposals for implementation:
Continue use of the approach described in this report for planning, designing and executing long-life reconstruction projects. Monitor and document results from at least several more projects with different scenarios to develop database and knowledge which will lead to future cost savings.

Related documents:
UCPRC-RR-2005-14

Signatures:

C. Kim **First Author**	E. B. Lee **Technical Review/ Co-Principal Investigator**	D. Spinner **Editor**	C. L. Monismith **Principal Investigator**	M. Samadian **Caltrans Contract Manager**

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

This study was funded be the California Department of Transportation, which is gratefully acknowledged. The research team would also like to acknowledge the information and coordination support by Caltrans District 8, especially from the I-15 Devore II Project Team, including Dr. Ramakrishna R. Tadi, Assistant District Traffic Manager.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) completed replacement of concrete pavement for about 5 kilometers (total 20 lane-kilometers) on Interstate 15 in Devore, California. The I-15 Devore II rehabilitation project was completed in six weekend closures with around-the-clock construction in early 2007, with partial or full closures of one direction of the freeway.

A traffic monitoring study with surveillance systems was conducted to validate project's transportation management plan (TMP) and to utilize the collected data for traffic flow characteristics at the work zone and traffic demand/capacity changes on highly trafficked urban highway projects. In addition, a construction productivity monitoring study was conducted to analyze productivity for the four construction activities; demolition, milling, Asphalt Concrete (AC) paving, and Portland cement concrete (PCC) paving.

Traffic monitoring analysis results indicate that Caltrans successfully implemented the traffic management plans (TMPs) and detailed strategies the agency developed for its 2007 I-15 Devore II Rehabilitation Project with six weekend closures. The proportion of traffic using detours was higher on Sundays than Saturdays, indicating that the unique characteristics of Interstate 15 traffic to and from Las Vegas gave Sunday travelers more scheduling flexibility. Peak northbound traffic headed to Las Vegas appeared on Fridays and peak southbound traffic returning from the city appeared Sundays. The TMP implemented during weekend closures led to an up to 70 percent demand reduction through the construction work zone (CWZ) and a 28 percent traffic increase on detour roads (the fourth closure, Stage 3C), compared with preconstruction conditions. This large shift in traffic emphasizes the importance of proper TMP implementation.

The research team collected construction data for four different construction activities; demolition of PCC slab, milling, AC Paving, and PCC paving. During each stage, these construction activities were completed on time or earlier than originally scheduled. The construction activities were conducted processed in a parallel fashion where there were two or more lanes available for construction truck access. Where there was only one lane available for construction trucks, construction activities were processed sequentially. The construction study investigates productivity progress by comparison of gross rate, operating rate, and truckload for each construction activity.

Caltrans' massive public outreach efforts contributed to the achievement of large reductions in traffic demand, as did the public's increased willingness to follow Caltrans' travel guidance regarding travel during the project.

This study can help guide state agencies and transportation engineers in establishing adequate TMPs and construction stage plans to improve mobility and productivity on future highway rehabilitation projects.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Asphalt Concrete
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
AWIS	Automated Workzone Information System
CA4PRS	*Construction Analysis for Pavement Rehabilitation Strategies*
Caltrans	California Department of Transportation
CHP	California Highway Patrol
CMS	Changeable Message Sign
COZEEP	Construction Zone Enhanced Enforcement Program
CWZ	Construction Work Zone
DTM	District Traffic Manager
FHWA	Federal Highway Administration
FSHCC	Fast-setting Hydraulic Concrete Cement
FSP	Freeway Service Patrol
LLPRS	Long-life Pavement Rehabilitation Strategies
PCC	portland cement concrete
PCMS	Portable Changeable Message Sign
pcph	Passenger car per hour
pcphpl	Passenger car per hour per lane
PeMS	Freeway Performance Measurement System
QMB™	Quickchange® Moveable Barrier
RTMS	Remote Traffic Microwave Sensor
TMP	Transportation Management Plan
UCPRC	University of California Pavement Research Center

1.0 INTRODUCTION

1.1 Work Zone Safety and Mobility Rule

With the number of U.S. highway reconstruction projects increasing, improving the safety of construction work zones has become an increasingly serious concern. In 2004, a total of 1,065 fatalities and more than 40,000 injuries resulted from work zone accidents (1). In addition to the suffering caused by these accidents, the reduced operational capacity on a work zone results traffic delays and increases road user costs and air pollution.

On September 9, 2004, the Work Zone Safety and Mobility Rule was published in the Federal Register by the Federal Highway Administration (FHWA) to mitigate problems caused by work zone impacts. A 2006 revision of the rule requires all state and local governments receiving federal funding to comply with the provisions by October 12, 2007. Under the new rule, transportation agencies are required to consider the impacts of work zone safety and mobility on project development and implementation. These provisions are aimed at helping transportation agencies overcome current and future work zone safety and mobility challenges.

The Work Zone Safety and Mobility Rule requires state and local agencies to create systems that consider and manage work zone impacts in addition to establishing processes and procedures that implement and sustain work zone policies. The rule includes provisions for developing agency-level processes and procedures to manage work zone impacts systematically during the course of project development. The rule also calls for the development of project-level procedures to address the work zone impacts of individual projects. The project-level procedures require implementation of transportation management plans (TMPs) for all federal-aid highway projects. Lastly, the rule requires state and local agencies to develop project-specific procedures to access and manage the impacts of individual projects.

1.2 California Highway Rehabilitation

About 90 percent of the 78,000 lane-kilometers of state highways in California were constructed between 1955 and 1975 with 20-year design lives. Most of the pavements on these highways have been exposed to heavier traffic volumes and loads than they originally designed for and consequently they have deteriorated significantly. The deterioration of these pavements has resulted in marginal road user safety and poor ride quality, increasing vehicle operation and agency highway maintenance costs, and frequent, inconvenient traffic delays (road user cost) due to maintenance activities.

In light of these problems, the California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategies (LLPRS) Program in 1998. Approximately 2,800 lane-km (2,740 lane-mi) of the state highway system were selected as candidates for the LLPRS Program (2). Candidates for the LLRPS program had to meet the selection criteria for poor pavement structural condition/ride quality and a minimum of either 150,000 Average Daily Traffic (ADT) or 15,000 Average Daily Truck Traffic (ADTT). Most of the candidates were interstate highways in the Los Angeles and the San Francisco areas and were paved with portland cement concrete (PCC).

The basic goal of the Caltrans LLPRS program was to provide pavement with a service life of at least 40 years in order to minimize agency life-cycle costs. However, during rehabilitation closures, Caltrans has traditionally focused on minimizing traffic disruptions and road user costs, providing a safe construction work zone environment for crews and highway users, and minimizing the impact of projects on the environment and business community. This emphasis was important because most LLPRS candidate projects were located in highway networks with high traffic volume.

1.3 Pilot Projects of California Rapid Rehab

Since it initiated the LLPRS program, Caltrans has completed two LLPRS pilot projects by using 55-hour continuous weekend closures with round-the-clock rehabilitation operations. One project, which was completed in 2000, involved replacing the concrete pavement on Interstate 10 (I-10) in Pomona. The other, finished in 2003, involved reconstructing the asphalt concrete on Interstate 710 (I-710) in Long Beach. A third LLPRS project, completed in 2004, was performed using one-roadbed continuous closures to replace the concrete pavement on Interstate 15 (I-15) in Devore.

1.3.1 I-10 Pomona Project

An approximate 20 lane-km (5-km [3.1-mi]) stretch of I-10 in Pomona was successfully rebuilt with one 55-hour weekend closure (Friday 10 p.m. to Monday 5 a.m.) and 7- or 10-hour nighttime closures. Use of fast-setting hydraulic concrete cement, which sets within an hour of mixing and is ready for traffic after four hours, enabled rehabilitation of 2.8 lane-km (1.4 lane-mi) during the weekend closure and the remaining 17.2 lane-km (10.4 lane-mi) during the nighttime closures. By using the outer truck lane for construction access, two of four lanes remained open while the inner truck lane in the eastbound direction was rehabilitated. During weekend peak-hours (Saturday and Sunday, 9 a.m.–9 p.m.), adherence to the TMP reduced typical peak traffic volumes through the work zone by 30 to 60 percent (3).

1.3.2 I-710 Long Beach Project

An approximately 26.4 lane-km (4.4-km [2.7-mi]) stretch of existing PCC pavement on I-10 in Long Beach was rehabilitated with asphalt concrete (AC) during eight 55-hour weekend closures. Each closure entailed reconstruction of an entire roadbed in one direction while traffic was shifted to the other roadbed with a two-by-two lane configuration known as "counterflow traffic," which utilizes moveable concrete barriers. No congestion was observed during the entire 55-hour weekend closure. Weekend peak traffic volumes through the work zone were reduced by 36 percent on average. Traffic volumes on neighboring highways and adjacent arterials increased by 27 percent (4).

1.3.3 I-15 Devore I Project

In 2004, an approximately 17 lane-km (4.2-km [2.6-mi]) section of deteriorated highway on I-15 in Devore, California, was reconstructed. The reconstructed section was split into two segments based on the location of interchanges within the boundaries of the project: Segment 1 (built in 1975) was 2.5 km (1.6 mi) long and had four lanes in each direction from the Sierra Avenue intersection to the Glen Helen Parkway intersection, and Segment 2 (built in 1969) was 1.7 km (1.0 mi) long and had three lanes in each direction from the Glen Helen Parkway intersection to the I-215 system interchange. During two nine-day continuous closures, an automated work zone information system (AWIS) was implemented to decrease traffic demand and increase diversions. During the construction period the ADT volumes decreased by 19 percent on SB I-15 and by 16 percent on NB I-15. The ADT volumes increased by 15 percent on the detour highway and by 2 percent on adjacent major arterials. The AWIS operation led to reductions in traffic flow through the work zone corridor (5).

2.0 DEVORE II RAPID REHAB

The Devore II Rapid Rehabilitation Project involved the rehabilitation of pavement near the I-15/I-215 junction in the Cajon Pass near Devore, California. This project, a continuation of the I-15 Devore I rehabilitation completed in 2004, rebuilt approximately 16 lane-km (10 lane-mi) of pavement using six weekend closures between October 2006 and January 2007 (Table 1). The project boundaries on I-15 were from Station 201+40 (KP 20.1/PM 12.5) to Station 10,291+57 (KP R29.2/PM 18.12) and on SR 215 to Station 283+28 (KP 28.2/PM 17.5). The project rebuilt (as so-called "continuous lane replacement") existing concrete pavements with new 290-mm portland cement concrete (PCC) slabs and a new 60-mm asphalt concrete (AC) base on the outside lanes and bridge deck connectors from Sierra Avenue to the Cleghorn Creek Bridge. The project included continuous lane replacement of 290-mm portland cement concrete (PCC) pavement and a new 60-mm asphalt concrete (AC) base replacing the concrete slabs on the outside lanes and bridge deck connectors from Sierra Avenue to the Cleghorn Creek Bridge.

Unlike the Devore I continuous closures, the Devore II Project employed weekend closures because of complaints from local communities that they valued their commute traffic time more than their weekend leisure traffic time. During the weekend closures, connectors and ramps were closed and mainline traffic lanes were either closed or reduced in number. Motorists heading into the construction work zone (CWZ) experienced significant delays and were forced to take detours.

To counteract these delays and Caltrans' anticipated 30-to-40 percent traffic-demand reduction (based on the results of the two nine-day continuous closures used in the Devore I rehabilitation), the agency conducted a public awareness campaign and developed alternate routes to help motorists avoid delays. The public awareness campaign was so successful that on most weekends the traffic demand reduction was nearly 50 percent, exceeding the agency's expectations.

Road users, after experiencing additional delays and inconvenience, were rewarded with a new smooth-riding pavement (6).

2.1 Construction Staging Plan

The Devore II Rehabilitation Project consisted of six weekend closures along with six different construction staging plans. The first and second closures (for reconstruction of the SB I-15 connector) were completed in two 52-hour weekends. The third and fourth closures (for reconstruction of the NB I-

15 connector) were completed in two 44-hour weekends. The fifth closure (for reconstruction of the NB I-215 connector) was completed in one 55-hour weekend, and the sixth closure (to further reconstruct the SB I-215 connector) was completed in one 20-hour weekend (TABLES 1 and 2). The hours for the weekend closures were decided based on levels of traffic through work zone.

2.1.1 Stage 2A1: Weekday Construction

Construction Stage 2A1 began at 12:00 a.m. on October 4, 2006, and ended at 9:00 a.m. on October 14, 2006. Construction location on Stage 2A1 was the Number Four lane on SB I-15 between Kenwood exit and I-15/I-215 junction split (Figure 1). The Number One, Two, and Three lanes remained open while the Number Four lane was closed. In addition, the E-S connector, N-W connector, N-W connector, SB Kenwood on-ramp, and NB Kenwood off-ramp were reconstructed. There was no specific detour plan for this stage because both SB I-15 and SB I-15 were opened to traffic. A Remote Traffic Microwave Sensor (RTMS) trailer was located at roadside of the I-15/I-215 junction split to collect traffic data, separating it into traffic heading towards SB I-15 and traffic heading towards SB I-215. Data concerning traffic heading towards SB I-215 were collected in the numbers One, Two, and Three lanes, and the data concerning traffic heading towards SB I-15 were collected in the numbers Four, Five, and Six lanes.

2.1.2 Stage 2C: First Weekend Construction

The first weekend closure (Stage 2C) began at 9:00 a.m. Friday, October 13, 2006, and ended at 1:00 p.m. Sunday, October 15, 2006 (52 hours). The numbers Three and Four lanes were closed from the Kenwood exit to the I-15/215 junction and all three lanes after the I-15/215 junction of SB I-15 were closed during Stage 2C (Figure 2). The length of the reconstruction of the two outer truck lanes, from Station 263+00 to 269+00 (near where Station 267+80 merges with Station 10.227), was about 660 m (2,165 ft). The traffic on SB I-15 was detoured to SB I-215, and drivers were to take the Palm exit to return to NB I-215 and SB I-15. The length of the detour was about 8.1 km (5.0 mi). An RTMS trailer located at the roadside of the SB I-15/I-215 junction split collected through-traffic volumes during Stage 2C. Although all four lanes on SB I-15 at Kenwood were scheduled to open at 1:00 p.m. on Sunday, October 15, 2006, due to a construction delay only the Number Three lane was open to traffic as scheduled. The Number Four lane was closed until 2:00 a.m. on Monday, October 16, 2006.

2.1.3 Stage 2B: Second Weekend Construction

The second closure (Stage 2B) began at 9:00 a.m. on Friday, November 10, 2006, and ended at 1:00 p.m. on Sunday, November 12, 2006. For 52 hours the truck lane on the SB I-15 connector between the I-15/215 junction split and Glen Helen Parkway was reconstructed (Figure 3). The reconstruction length for

the two truck lanes on the I-15 to I-15 NB connector on the I-15/I-215 system interchange was 310 m (1,017 ft), falling approximately between stations 256+60 and 260+20. Lane closure began at the mainline right after the Kenwood exit, at the same location as Stage 2C. The numbers Three and Four lanes were closed from the Kenwood exit to the I-15/215 junction and all three lanes after the I-15/215 junction were closed during Stage 2B. To bypass the closure, SB I-15 traffic was detoured to SB I-215 and WB I-10 in order before it could return SB I-15 (Figure 4). The length of the detour was about 40 km (25.0 mi). Unlike Stage 2C, the connector from NB I-215 to SB I-15 was closed, making the 8-km (5-mi) Palm Avenue/NB I-215 detour unavailable.

2.1.4 Stage 3B: Third Weekend Construction

The third closure, Stage 3B, began at 8:00 a.m. on Saturday, November 18, 2006, and ended at 4:00 a.m. on Monday, November 20, 2006. For 44-hours the truck lane on the NB I-15 mainline between the I-15/215 junction split and Glen Helen Parkway was reconstructed (Figure 5). The reconstruction distance was 260 m (853 ft) between Station 10,260+20 and 10,262+80. Lane closure began at the mainline right after the Glen Helen exit. During Stage 3B all three lanes for NB I-15 were completely closed and all traffic was detoured to the SB I-215 connector (Figure 6). The NB I-15 traffic was detoured to SB I-215 and drivers took the Palm exit and entrance to return to NB I-15 through NB I-215. The detour length was about 8.0 km (5 mi). One RTMS trailer was located at the roadside of SB I-215 connector to collect through-traffic volumes and work zone capacity during Stage 3B.

2.1.5 Stage 3C: Fourth Weekend Construction

The fourth closure, Stage 3C, began at 8:00 a.m. on Saturday, January 6, 2007, and ended at 4:00 a.m. on Monday, January 8, 2007. During this 44-hour closure, the truck lane on the NB I-15 mainline between the I-15/215 junction split and the Cajon Creek Bridge was reconstructed. The reconstruction distance was 160 m (525 ft) between Station 10,256+60 and 10,258+20. During this time, NB I-15 was reduced to one lane and the connector from NB I-15 to SB I-215 was closed (Figure 7). The traffic heading on NB I-15 was expected to experience substantial delays because of the lane-drop on Saturday and Sunday afternoons. In addition, because the NB I-15/SB I-215 connector was closed, traffic heading north to the Devore area from Ontario was rerouted to EB I-10 and NB I-215, a distance of about 40.0 km (25.0 mi) (Figure 8).

2.1.6 Stage 3A: Fifth Weekend Construction

Construction on Stage 3A began at 9:00 a.m. on Friday, January 19, 2007, and ended at 4:00 a.m. on Monday, January 22, 2007. During this 55-hour closure the truck lane on the connector from NB I-215 to NB I-15 between SB I-15 exit and I-15/NB I-215 merging point was reconstructed. Lane closure began at the connector right after SB I-15 exit and ended before the Kenwood Avenue (Figure 9). The reconstruction length of Stage 3A was 1,000 m (3,300 ft) between Station 10,219+30 and 10,229+90, excluding 50 m (164 ft) of bridge span. This location showed two different types of post mile numbering since it combined the mainline with the connector. To simplify the post mile numbering, the post mile on the connector was converted to the equivalent value of the post mile on the mainline. CA post mile 10,283+20 was regarded as 10,219+30. Both of the two lanes for NB I-15 were completely closed. Motorists were detoured to the NB I-15 connector and took NB I-15 through the Glen Helen Parkway until 2:30 p.m. on Sunday, January 21, 2007 (Figure 10). The contractor completed construction earlier than originally planned (a 55-hour closure) and opened the left lane at 2:30 p.m. on Sunday, January 21, 2007 (a 41-hour closure). After the left lane was opened, motorists were able to progress directly to NB I-15 without detouring. During Stage 3A, an RTMS trailer was located at the roadside of the NB I-215 connector (3.2 km (2.0 mi) upstream of the work zone) to collect through-traffic volumes and work zone capacity.

2.1.7 Stage 2D: Sixth Weekend Construction

Construction for Stage 2D began at 10:00 p.m. on Friday, January 27, 2007, and ended at 6:00 p.m. on Saturday, January 28, 2007. During this 20-hour closure, the truck lane on the SB I-215 connector between the I-15/215 junction split and the Devore Road exit was reconstructed (Figure 11). Lane closure began at the mainline right after Kenwood Avenue exit. All three lanes for NB I-15 were completely closed and all traffic was detoured to the SB I-215 connector during Stage 3B (Figure 12). The traffic heading toward NB I-15 was forced to detour to SB I-215 and take the Palm exit and entrance to return to NB I-15 through NB I-215. The detour length was about 8.0 km (5.0 mil). One RTMS trailer was located at the roadside of SB I-215 connector to collect through-traffic volumes and work zone capacity during Stage 2D.

2.2 Productivity Monitoring Methodology

Major activities during the construction period included demolition of existing pavement structures, milling, paving the AC base, and paving the PCC slab. These four operations were performed simultaneously with minimal access space between them and with at least two lanes available for

construction access. When only one lane was available and space was limited, the four activities were performed sequentially.

The UCPRC has developed a software program called *CA4PRS* that estimates pavement rehabilitation production and calculates work-zone traffic delay for LLPRS projects, and that aspect of the Devore II project allowed for the collection of data to be used to refine the software. To enhance the productivity database in the *CA4PRS* software for use in future LLPRS projects, the research team monitored overall progress in all major operations, including tracking the cycle time and the number of hourly hauling and delivery trucks. The reconstruction productivity monitoring tracked progress on demolition, the milling process, AC paving, and PCC paving during each stage, providing the following measurements:

- Truckloads: Total number of trucks used during an activity;
- Un/load time: Average truck usage time;
- Gross rate: End time minus start time, divided by section length;
- Adjustment gross rate: Excludes major delays (rain, breakdown, traffic) which result in delays of 20 min or more; and
- Operating rate: Excludes major delays as well as vehicle realignments and typical back-up delays. Only includes time periods with physical progress and truck delays less than 20 min.

2.3 Traffic Management Plans and Monitoring Methodology

2.3.1 Traffic Management Plans

Fast-track construction such as the I-15 Devore II Rapid Rehab project required Caltrans to coordinate with other agencies to accommodate a number of large-scale social events taking place in surrounding areas during construction. Caltrans closely worked with the Las Vegas Convention and Visitors Authority, the Glen Helen Hyundai Pavilion, and management of the California Speedway during the project period. The largest impact on the above venues was the full closure of the I-15/I-215 connectors. One or both of these connectors closed for each weekend of work and as a result, peak direction traffic had to be detoured to alternative routes.

However, utilizing the rapid rehabilitation strategy with weekend extended closures (instead of traditional nighttime closures) allowed a large amount of rehabilitation work to be completed within a limited amount of time, resulting in a higher quality and longer lasting pavement.

Although it was important that the project resulted in higher quality roads, Caltrans' highest priority was motorist and worker safety during construction. For this reason, the following strategies were implemented:

- The Freeway Service Patrol (FSP) was available to ensure motorist and worker safety. FSP patrolled the construction corridor and assisted malfunctioning vehicles by relocating them outside of the work zone.
- The California Highway Patrol (CHP) assisted with traffic control and law enforcement.
- Changeable message signs (CMSs) were utilized to provide information for motorists. Portable Changeable Message Signs (PCMSs) were utilized to warn motorists of delays. There was also extended use of CMS signage in relevant state highways, such as I-10, I-15, and I-215, to alert motorists of alternative options.
- Caltrans and its contractor developed an incident plan in the event of an emergency.

2.3.2 Traffic Monitoring Methodology

Traffic monitoring plans were established to investigate traffic impact on the traffic network, including the I-15 rehabilitation corridor and neighboring highways. Traffic data collected included traffic volumes and travel times on the I-15 corridor, on neighboring highways, and an local detours, as well as queue length, speeds upstream of lane closure, and work zone traffic capacity.

Collection of traffic data required the use of several types of traffic surveillance devices. The traffic data was collected before, during, and after each construction stage.

A pair of Remote Traffic Microwave Sensors (RTMSs) were located downstream of the lane closure section to collect through-traffic volumes and work zone capacity data for each stage. The RTMSs were designed to be mounted on 6-m high portable flexible trailers so they could be relocated without interrupting traffic and construction. The sensors, operating twenty-four hours per day, seven days per week, collected data in five-minute increments on traffic volume, average speed, lane occupancy, and vehicle classification on each lane. This data was used to assess traffic volume reduction through the CWZ during each stage by comparing it with the data set collected before the closure. In addition, traffic volume data in the I-15 work zone corridor and neighboring highways (I-10, I-215, and I-210) were collected from the Caltrans RTMS database (accessible through the Freeway Performance Measurement System [PeMS] web site) (7). This data was used to assess traffic changes on neighboring highways during each stage by comparing it with the data set collected before closure.

During each stage, a probe vehicle measured travel times between two points, one of which contained a work zone and the other containing an upstream traffic queue. This data was used to assess additional traffic delays due to lane closure and construction activity.

The traffic volume data on local detour roads were collected by rubber tube detectors installed in major local intersections to find traffic changes during the different stages.

2.4 Alternate Detour Routes

Alternative routes parallelling the I-15/I-215 corridor were so far from the construction area that they were impractical as detours. For example, an alternate 130-km (80-mi) route for travelers from Orange County and the southern part of the L.A. basin to Barstow (using EB SR-91, NB I-215, EB I-10, NB SR-62, NB SR-247, and I-15, respectively) would have taken approximately 4 hr and 20 min. Alternatively, travelers could have taken NB SR-247 NB to WB SR-18 to Apple Valley and Victorville..

Similarly, an alternative 300-km (186.4-mi) route for travelers from San Diego (using NB I-15, NB NB I-215, EB I-10, NB SR-62, NB SR-247, and I-15, respectively) to Barstow would take approximately 4 hr and 40 min.

Lastly, similar 160-km (100-mi) alternative routes for travelers from Riverside and San Bernardino Counties (EB I-10, NB SR-62, and NB SR-247, respectively) to Barstow would have taken about 3 hr and 20 min. (These motorists could have also taken NB SR-247 to WB SR-18 to Apple Valley and Victorville.)

3.0 PRODUCTIVITY ANALYSIS RESULTS

To analyze the productivity of the I-15 Devore II project, the research team designed a monitoring study that spanned the six-weekend closures. The following sections provide an overview of the construction during each weekend closure, productivity measures taken during the closures, and information on truck-loading during each stage of the rehabilitation.

3.1 Stage 2C: the First Weekend Construction

3.1.1 Construction Overview

The first weekend closure (Stage 2C) began at 9:00 a.m. on Friday, October 13, 2006, and ended at 1:00 p.m. on Sunday, October 15, 2006 (52 hr). The location of construction Stage 2C was on the SB I-15 mainline from the Kenwood exit to Cajon Pass (Figure 2). The reconstruction length for the two outer truck lanes, from Station 263+00 to 269+00 (about where Station 267+80 merges into Station 10.227), was about 660 m (2,165 ft). This location showed two different types of station numberings because the I-15 NB merges into the I-15/I215 junction interchange on the section. In the middle of reconstruction, some unexpected rainfalls delayed AC paving activities by about 140 min.

3.1.2 Productivity Progress

On October 13, 2006, the traffic closure on the site began at 9:00 a.m. and demolition began at 10:26 a.m. Mobilization time was about 1.5 hr for two demolition crews (including excavators and hauling trucks). Demolition activities were simultaneously executed at two locations, the north and south ends of the construction site. Milling activity started at 2:06 p.m. (while demolition was still on going) and ended at 10:40 p.m. Overlapping the two construction operations was possible because of the access available with the full closure. AC paving began at 8:30 p.m. and ended at 1:30 a.m. (Figure 16).

During milling on October 14, 2006, rain, which began at approximately 11:15 p.m. and ended at approximately 12:45 a.m., caused a 140-min milling delay and 90-min AC paving delay.

For demolition activities, the average gross rate was 51.5 m/hr (169.0 ft/hr); the operating rate was equal to the gross rate because no major delays occurred during demolition. For milling activity, the gross rate was 77.0 m/hr (252.6 ft/hr) and the operating rate was 126.9 m/hr (416.3 ft/hr). The 140-min rain delay during milling was excluded from calculation of the operating rate (as defined earlier). For AC paving activities, the average gross rate was 118.3 m/hr (388.1 ft/hr) and the average operating rate was 153.9

m/hr (504.9 ft/hr); the 90-min rain delay was excluded from the operating rate calculation. For PCC paving, the gross rate was 94.3 m/hr (309.4 ft/hr), and was equal to the operating rate because there were no major delays (Table 4).

3.1.3 Truckloads

Truck-loading cycles were monitored during each stage to measure how fast trucks returned to the site after dumping demolished materials. A truck-loading cycle is the time measured between each of a truck's arrivals on-site and it was obtained by observing trucks' license plates.

Two demolition activities were simultaneously conducted at two segments: at the first segment, which was 340 m (1,115 ft) long, 71 truckloads were observed with an average loading time of 4.3 min; at the second segment, which was 320 m (1,050 ft) long, there were approximately 10 more truckloads observed with an average loading time of 5.0 min. For milling activities of the entire section of 660 m (2,165 ft), 137 truckloads were observed with an average loading time of 1.9 min. For AC paving activity, 34 and 35 truckloads respectively were observed at the two AC paving segments, with an average unloading time of 2.2 min. Lastly, during PCC paving activity, 152 truckloads were observed, with an average unloading time of 3.9 min.

For 6 hr of demolition activity, the average truck-number per hour was 11. The highest truck frequency per hour was between 10 and 12 (Figure 17). For 9 hr of milling activity, the average truck-number per hour was 15.11. The two highest truck frequencies per hour were between 13 to 15 and 19 to 21. For the two AC paving activities spanning 3 hr, the average truck-number per hour was 10.67 and the two highest truck frequencies per hour were between 7 to 9 and 13 to 15. For the two PCC paving activities spanning 7 hr, the average truck-number per hour was 10.86 and the highest truck frequency was between 10 and 12 trucks per hour. The average truck-number per hour (10.86) was lower than average-truck numbers (19.50 on Stage 3B and 14.00 on Stage 3C) because rain interrupted PCC paving activity during Stage 2C.

3.2 Stage 2B: Second Weekend Construction

3.2.1 Construction Overview

The second closure (Stage 2B) began at 9:00 a.m. on Friday, November 10, 2006, and ended at 1:00 p.m. on Sunday, November 12, 2006. For 52 hr the truck lane on the SB I-15 connector between the I-15/215 junction split and Glen Helen Parkway was reconstructed (Figure 3). The reconstruction length of the two truck lanes on the I-15 to I-15 NB connector, approximately between stations 256+60 and 260+20, was

310 m (1,017 ft). Lane closure began at mainline right after the Kenwood exit, at the same location as Stage 2C.

3.2.2 Productivity Progress

The traffic closure on the reconstruction site began at 9:00 a.m. and demolition began at 9:50 a.m. on November 10, 2006. Mobilization time was about 50 min for two demolition crews and trucks. Demolition activities were executed simultaneously at two locations: 10,260+28 (north side) and 10,256+64 (south side). Approximately 190 m (623 ft) of bridge span between 10,258+40 and 10,260+30 was excluded on Stage 2B. Milling activity data was not collected on Stage 2B due to a lack of resources. AC paving began at 11:30 a.m. and ended at 2:16 p.m. (Figure 18). For demolition activities, the average gross rate was 27.8 m/hr (91.2 ft/hr) and was equal to the operating rate because there were no major delays. The gross and operating rates for milling activity were not obtainable. For AC paving activities, the average gross rate was 135.9 m/hr (445.9 ft/hr) and the average operating rate was 160.9 m/hr (527.9 ft/hr). For PCC paving, the gross rate was 66.5 m/hr (218.2 ft/hr) and the operating rate was 68.1 m/hr (223.4 ft/hr) (Table 4). The operating rates of demolition and PCC paving during Stage 2B were lower than those of Stage 2C, but the operating rate of AC paving was close to that of Stage 2C.

3.2.3 Truckloads

Demolition activities were conducted simultaneously at two segments: at the first segment, which was 220 m (720 ft) long, 34 truckloads were observed with an average loading time of 6.2 min; at second segment, which was 176 m (577 ft) long, 51 truckloads were observed with an average loading time of 5.0 min. Truckload observations for milling activity were not collected for Stage 2B (see Section 3.2.2). For AC paving activity of 376 m (1,234 ft), 31 truckloads were observed with an average unloading time of 2.2 min. Lastly, 97 truckloads were observed during PCC paving activity with an average unloading time of 3.5 min.

3.3 Stage 3B: Third Weekend Construction

3.3.1 Construction Overview

The third closure (Stage 3B) began at 8:00 a.m. on Saturday, November 18th, 2006, and ended at 4:00 a.m. on Monday, November 20th, 2006. For 44 hr, the truck lane on the NB I-15 mainline between the I-15/215 junction split and Glen Helen Parkway was reconstructed (Figure 5). The reconstruction distance was 260 m (853 ft) between Station 10,260+20 and 10,262+80. Lane closure began at the mainline right

after the Glen Helen exit. All the three lanes for NB I-15 were completely closed and all traffic was forced to detour to the SB I-215 connector (Figure 6).

3.3.2 Productivity Progress

Traffic closure on the reconstruction site began on November 18, 2006 at 8:00 a.m. and demolition began at 8:36 a.m.. Mobilization time was about 36 min for two demolition crews and trucks. Demolition activities were executed simultaneously at two locations, the north and south ends of the construction site. Because of the site's accessibility, milling activity could start while demolition continued; hence milling was conducted between 11:22 a.m. and 3:34 p.m. AC paving began at 5:20 p.m. and ended at 9:02 p.m. (Figure 20). PCC paving began at 6:27 a.m. and ended at 10:13 a.m. For demolition activities, the average gross rate was 29.5 m/hr (96.8 ft/hr) and was equal to the operating rate because there were no major delays. For milling activity, the gross rate was 61.9 m/hr (203.1 ft/hr) and the operating rate was 75.3 m/hr (247.0 ft/hr). For AC paving activity, the average gross rate was 70.3 m/hr (230.6 ft/hr) and the average operating rate was 75.7 m/hr (283.4 ft/hr). For PCC paving, the gross rate was 69.0 m/hr (226.4 ft/hr) and the operating rate was 78.8 m/hr (258.5 ft/hr) (Table 4).

3.3.3 Truckloads

Demolition activities were conducted simultaneously at two segments: at the first segment, which was 160 m (525 ft) long, 58 truckloads were observed with an average loading time of 3.8 min; at the second segment, which was 100 m (328 ft) long, 29 truckloads were observed with an average loading time of 6.7 min. For milling activity for 260 m (853 ft), 59 truckloads were observed with an average loading time of 2.1 min. For AC paving activity, 43 truckloads were observed with an average unloading time of 2.3 min. Lastly, 78 truckloads were observed during PCC paving activity with an average unloading time was 3.4 min.

For 9 hr of demolition activity, the average truck-number per hour was 9.78 and the highest truck frequency was between 7 and 9 trucks per hour. This average truck-number (9.78) was close to the number for demolition activity (11.00) in Stage 2C. For milling activity, which spanned four hours, the average truck-number per hour was 14.25 and the highest truck frequency was between 16 and 18 trucks per hour. This average truck-number (14.25) was close to the number for milling activity (15.11) in Stage 2C. The average truck-number turned around per hour during the three hours of AC paving was 11.25. This average is close to that (10.67 trucks per hour) for the AC paving activity in Stage 2C. The highest truck frequency for AC paving was between 13 and 15 trucks per hour. For three hours of PCC paving

activity, the average truck-number per hour was 19.50. This average was higher than that (10.86) for PCC paving on Stage 2C. The highest truck frequency for PCC paving was between 22 and 24 trucks per hour.

3.4 Stage 3C: Fourth Weekend Construction

3.4.1 Construction Overview

The fourth closure, Stage 3C, began at 8:00 a.m. on Saturday, January 6, 2007, and ended at 4:00 a.m. on Monday, January 8, 2006. During this 44-hour closure, the truck lane on the NB I-15 mainline between the I-15/215 junction split and the Cajon Creek Bridge was reconstructed. The reconstruction distance was 160 m (525 ft) between Station 10,256+60 and 10,258+20 (Figure 7).

3.4.2 Productivity Progress

Traffic closure on the reconstruction site began at 8:00 a.m. on January 6, 2007, and demolition began at 8:30 a.m. Mobilization time was about 30 min for the one demolition crew and truck. Unlike stages 2C, 2B, and 3B, the demolition activity was conducted at only one location (10,256+60) because reconstruction length was only 160 m (525 ft). Milling activity started at 2:55 p.m. on the same day that demolition was about to end (at 2:57 p.m.). For demolition activities, the average gross rate was 24.8 m/hr (81.4 ft/hr) and was equal to the operating rate because no major delays occurred during demolition activities. Milling activity ended at 5:14 p.m., and AC paving began at 6:56 p.m. and ended at 10:47 p.m. For milling activity, the gross rate was 69.1 m/hr (226.7 ft/hr) and the operating rate was 90.6 m/hr (297.2 ft/hr). For AC paving activity, the average gross rate was 41.6 m/hr (136.5 ft/hr) and the average operating rate was 58.9 m/hr (193.2 ft/hr). For PCC paving, the gross rate was 33.6 m/hr (110.2ft/hr) and the operating rate was 36.3 m/hr (119.1 ft/hr) (Table 4).

3.4.3 Truckloads

Unlike the other stages, Stage 3C demolition activity was conducted for the entire segment of 160 m (525 ft), where 97 truckloads were observed with an average loading time of 3.2 min. For milling activity of 160 m (525 ft), 47 truckloads were observed with an average loading time of 1.6 min. For AC paving activity, 31 truckloads were observed with an average unloading time of 2.1 min. Lastly, 59 truckloads were observed during PCC paving activity with an average unloading time of 4.1 min.

The average truck-number per hour for the demolition, which spanned 6 hr, was 15.33. The highest truck frequency was between 16 and 18 trucks per hour. For milling activity, which spanned 2 hr, the average truck-number per hour was 20.05. The two highest truck frequencies were between 19 and 21 trucks per

hour. For the AC paving activity, which spanned 4 hr, the average truck number per hour was 7.75. The highest truck frequency was between 7 and 9 trucks per hour. For the PCC paving activity, which spanned 4 hr, the average truck number per hour was 14.00. The highest truck frequency was between 13 and 15 trucks per hour.

3.5 Stage 3A: Fifth Weekend Construction

3.5.1 Construction Overview

Construction for Stage 3A began at 9:00 a.m. on Friday, January 19, 2007, and ended at 4:00 a.m. on Monday, January 22, 2007. During this 55-hour closure, the truck lane on the connector from NB I-215 to NB I-15 between the SB I-15 exit and the NB I-15/I-215 merging point was reconstructed. The reconstruction length of Stage 3A was 1,010 m (3,314 ft) between Station 10,219+30 and 10,229+90 and excluded 50 m (164 ft) of bridge span (Figure 9). This location showed two different types of post mile numberings because it combined the mainline with the connector. To simplify the post mile numbering, the post mile on the connector was converted to the equivalent value of the post mile on the mainline. CA post mile 10,283+20 was regarded as 10,219+30.

3.5.2 Productivity Progress

Traffic closure on the reconstruction site began on January 19, 2007 at 9:00 p.m. and demolition began at 9:15 p.m. Mobilization time was about 15 min for the two demolition crews and trucks. Demolition activities were executed simultaneously at the north and south ends of the construction site. For demolition activity, the average gross rate was 53.5 m/hr (175.5 ft/hr) and the operating rate was 60 m/hr (196.9 ft/hr). Milling and AC paving activities were not observed for Stage 3A. PCC paving activity began at 9:40 a.m. and ended at 6:15 p.m. For PCC paving, the gross rate was 117.7 m/hr (386.2 ft/hr) and the operating rate was 121.0 m/hr (397.0 ft/hr) (TABLE 4).

3.5.3 Truckloads

Demolition activities were simultaneously conducted at two segments: at the first segment, which was 520 m (1,706 ft) long, 93 truckloads were observed with an average loading time of 4.4 min; at the second segment, which was 490 m (1,607 ft) long, 91 truckloads were observed with an average loading time of 5.1 min. Milling and AC paving activities were not conducted at Stage 3A. During the PCC paving activity, 128 truckloads were observed with an average unloading time of 2.2 min.

3.6 Stage 2D: Sixth Weekend Construction

3.6.1 Construction Overview

Construction for Stage 2D began at 10:00 p.m. on Friday, January 26, 2007, and ended at 6:00 p.m. on Saturday, January 27, 2007. During this 20-hour closure, the truck lane on the SB I-215 connector between the I-15/215 junction split and the Devore Road exit was reconstructed with random slab replacement (Figure 11). The first and last random slab replacement locations were at post miles 10,283+17 and 10,288+15 respectively (a distance of approximately 500 m (1,640 ft). Construction began 10:17 p.m. on Friday, January 26, 2007 and ended at 1:18 p.m. on Saturday, January 27, 2007.

3.6.2 Productivity Progress

Demolition activity began at 11:30 p.m. on Friday, January 26, 2007 and demolition of the last random slab section ended at 4:30 a.m. According to a progress log file (recorded by the progress monitoring crew), one set of approach rebar took about 2 hr to install. Concrete pouring took approximately 1 hr in the north approach region.

3.6.3 Truckloads

For the random slab replacement in Stage 2D, 23 trucks were utilized to remove demolished concrete and 28 trucks were utilized to deliver concrete. The average truck-loading time for demolition activity was about 9 min and the average truck unloading time for concrete slab activity was about 8 min. The average truck-cycle for demolition activity was about 42 min and the average truck-cycle for concrete slab activity was about 69 min.

3.7 Productivity Comparison

As mentioned in Section 2.2, truck-loading cycles and the number of trucks per hour were observed to build a database for similar future rehabilitation projects. The major reconstruction stages (Stages 2C, 3B, and 3C) were analyzed in terms of truck-load cycle and frequency of trucks per hour. For each on-site construction activity (demolition, milling, AC paving, and PCC paving), all truck arrival and departure times—as well the trucks' identification numbers—were recorded so that truck-loading cycle and truck frequency per hour could be calculated.

3.7.1 Demolition

During the Stage 2C demolition activity, 81 trucks were utilized to load demolished material from 660 m (2,165 ft) of existing pavement. The contractor used articulated trucks, which are commonly used in the

mining industry and have nearly double the capacity of normal construction trucks (Figure 13). For demolition activity in Stage 3B, 87 normal construction trucks were utilized to load demolished material from 260 m (853 ft) of existing pavement. Stage 3C demolition involved use of 97 regular demolition-hauling trucks to remove 160 m (526 ft) of existing pavement. The performance of the articulated trucks used during the first closure (Stage 2C) equaled that of the regular demolition hauling trucks (end dump trucks) despite the smaller number of trucks mobilized and the longer loading times the specialized (articulated) trucks required. The average loading time for the articulated trucks was 4.3 min (Stage 2C), while average loading times for normal construction trucks were 3.8 min (Stage 3B) and 3.2 min (Stage 3C).

Demolition activity truck-loading cycles in stages 2C, 3B, and 3C were approximately 15.2 min, 57.4 min, and 99.9 min, respectively.

Truck-loading cycles during demolition in Stage 2C were much shorter than the other two cycles (stages 3B and 3C) because trucks dumped the materials at a temporary space on the median gore, which is the triangular pavement between the meeting of on/off ramps and the existing traffic lanes. Due to the shorter demolition truck-loading cycle on the first closure (Stage 2C), the demolition operating rate (52.0 m/hr [170.1 ft/hr]) was higher than that of the other two closures, Stage 3B (35.3 m/hr [15.8 ft/hr]) and Stage 3C (24.8 m/hr [81.4 ft/hr]).

During Stage 2C the highest range for truck frequency per hour for demolition was between 10 and 12. In 3 of 6 hours of demolition in Stage 2C, 10 to 12 trucks per hour were utilized. A minimum of 9 trucks and maximum of 13 trucks per hour were utilized during demolition.

The highest range for truck frequency for demolition during Stage 3B was between 7 and 9 trucks per hour. In 5 of 9 hours of demolition during Stage 3B, 7 to 9 trucks per hour were utilized. A minimum of 7 and maximum of 15 trucks per hour were utilized during demolition.

The highest range for truck frequency for demolition during Stage 3C was between 16 and 18 trucks per hour. In 4 of 6 hours of demolition on Stage 3C, 16 to 18 trucks were utilized per hour. A minimum of 9 and maximum of 18 trucks per hour were utilized during demolition.

3.7.2 Milling

For milling activity during Stage 2C, 137 normal trucks were used for 9 hr to work on a 660 m (2,165 ft) length of the reconstruction section (Figure 14). During Stage 2C, the average truck-loading time for milling was 1.9 min. This was shorter than the average truck-loading time for demolition because milling processes use automatic loading machines to transfer materials into trucks. The truck-loading cycle for milling on Stage 2C was approximately 60 min.

For Stage 3B milling, 59 normal trucks worked for 4 hr on a 260 m (853 ft) length of the reconstruction section. During Stage 3B, the average truck-loading time for milling was 2.1 min. As with Stage 2C milling, this was lower than the average demolition truck-loading time because automatic loading machines were used. The truck-loading cycle for milling during Stage 3B was approximately 38 min.

For Stage 3C milling, 47 normal trucks worked for 2.5 hr on a 160 m (525 ft) length of the reconstruction section. During Stage 3C, the average truck-loading time for milling was 1.6 min. The truck-loading cycle for milling during Stage 3C was approximately 61 min, which is close to the truck-loading cycle for milling during Stage 2C.

The high frequencies of trucks per hour for milling during Stage 2C were observed in two categories: One category was between 13 and 15 trucks per hour and the other was between 19 and 21 trucks per hour. For three out of the nine hours of milling during Stage 2C, 10 to 12 trucks were utilized per hour. For another three out of the nine hours of milling during Stage 2C, 19 to 21 trucks were utilized per hour. A minimum of 6 and a maximum of 21 trucks were utilized per hour during milling.

The highest frequency of trucks per hour for milling during Stage 3B was between 16 and 18 trucks per hour. For two out of the four hours of milling during Stage 3B, 16 to 18 trucks were utilized per hour. A minimum of 10 and a maximum of 16 trucks were utilized per hour during milling.

Milling activity lasted 2 hours during Stage 3C. In the first hour, 20 trucks were utilized and during the second hour 21 trucks were utilized.

3.7.3 AC Paving

For AC paving activity during Stage 2C, 69 normal trucks were used for 6.5 hr to work on a 660 m length of the reconstruction section. During Stage 2C, the average truck unloading time for AC paving was 2.1

min. This was shorter than the average truck-loading time for demolition because the AC paving process used machines to automatically unload asphalt concrete onto the pavement. The truck unloading cycle for AC paving for Stage 2C was approximately 198 min.

For AC paving activity during Stage 3B, 43 normal construction trucks worked for 3.5 hr on a 260 m length of the reconstruction section. During this stage, the average truck unloading time for AC paving was 2.3 min and the truck unloading cycle was approximately 132 min. This was less than the truck-loading cycle of AC paving for Stage 2C.

For AC paving activity during Stage 3C, 31 normal trucks worked 4 hr on a 160 m length of the reconstruction section. During this stage, the average truck unloading time for AC paving was 2.1 min and the truck unloading cycle was approximately 144 min.

For two out of the six hours of Stage 2C AC paving, 7 to 9 trucks were utilized per hour. In another two out of the six hours, 13 to 15 trucks were utilized per hour. A minimum of 9 and a maximum of 15 trucks were utilized per hour during AC paving.

For two out of the three hours of Stage 3B AC paving, 13 to 15 trucks were utilized per hour. During this stage's AC paving, a minimum of 12 and a maximum of 15 trucks per hour were utilized.

For two out of the four hours of Stage 3C AC paving, 7 to 9 trucks were utilized per hour. During Stage 3C AC paving, a minimum of 6 trucks and a maximum of 10 trucks were utilized.

3.7.4 PCC Paving

For PCC paving activity during Stage 2C, 152 normal trucks worked for 6 hr on a 660 m length of the reconstruction section (Figure 15). During this stage, the average truck unloading time for PCC paving was 3.9 min, which exceeded the average truck unloading time for AC paving. The truck-loading cycle for PCC paving during Stage 2C was approximately 38 min.

For PCC paving activity during Stage 3B, 78 normal trucks worked 3.5 hr on a 260 m length of the reconstruction section. The average truck unloading time for PCC paving for this stage was 3.4 min, which was longer than the average truck unloading time for AC paving. The truck-loading cycle for PCC paving during Stage 3B was approximately 24 min.

For PCC paving activity during Stage 3C, 59 normal trucks worked 4.5 hr on a 160 m length of the reconstruction section. During this stage, the average truck unloading time for PCC paving was 4.1 min, which exceeded the average truck unloading time for AC paving. The truck-loading cycle for PCC paving during Stage 3C was approximately 58 min.

4.0 TRAFFIC IMPACT ANALYSIS

4.1 Stage 2A1: Weekday Closure

Stage 2A1, which spanned 10 days, was the only stage that included weekdays and weekends. The ADT (average daily traffic) of 81,200 from Monday through Friday during this stage was similar to the ADT (81,300) of the other two weekdays after it. No significant traffic reduction was observed during Stage 2A1.

Travel time measurement during Stage 2A1 was not included in traffic monitoring. There were no traffic detour plans or detour guide sign deployments because both SB I-15 and SB I-215 were open to traffic during Stage 2A1. No traffic change was observed on the neighboring freeways (I-10 and I-210) during Stage 2A1.

4.2 Stage 2C: First Weekend Closure

4.2.1 Traffic Volume Comparison

Traffic volumes for SB I-15 were collected at the SB I-15/215 junction split during Stage 2C and compared with traffic data collected during the nonclosure period (October 22 to November 12, 2006). The Thursday ADT during nonclosure was 82,102, while the Thursday ADT during closure (October 12) was 91,562 (TABLE 3), an increase of 12 percent. This shows that a significant number of motorists decided to travel on the Thursday before the Stage 2C weekend in order to avoid traffic congestion.

During Stage 2C, the Friday (October 13) ADT was 57,474, a 31 percent traffic reduction from the Friday ADT during nonclosure (83,425). The Saturday (October 14) ADT during closure was 42,624, or a 41 percent reduction of the Saturday ADT during nonclosure. The Sunday (October 15) ADT was 55,084 during closure, a 28 percent reduction of the Sunday ADT during nonclosure (Figure 22). Traffic reduction on the Sunday closure was less than the reduction during the Friday and Saturday closures because both construction and traffic closures ended at 1:00 p.m. on Sunday.

Before the closure (which began at 9:00 a.m. Friday, October 13 and lasted until 4:00 a.m. Monday, October 16), the maximum through-traffic volume was 5,900 passenger car per hour (pcph) at 6:00a.m. on Friday, when all four lanes were open to the public. During the two-lane closure (Figure 23), the maximum through-traffic volumes were 2,950 pcph at 4:00 p.m. on Friday and 2,880 pcph at 5:00 p.m. on Saturday. Although the contractor was supposed to open all four lanes by 1:00 p.m. Sunday, due to a

construction delay only three lanes opened and one remained closed until 4:00 a.m. Monday. The maximum hourly through-traffic volume during the one-lane closure was 4,395 pcph at 2:00 p.m. Sunday (Figure 23). For the Stage 2C period, the maximum hourly through-traffic volumes were less than the expected work zone capacity (1,600 passenger car per hour per lane; pcphpl).

4.2.2 Additional Travel Times and Traffic Detours

During Stage 2C, travel times were measured between two points, the 17.7 km (11.0 mi) from Oak Hill Avenue to Kenwood Avenue, to investigate traffic delays due to the closure. The travel time with free-flow speed during nonclosure (normal travel time) is about 9.0 min. The maximum travel time on Friday was 110 min at 6:00 p.m., when two of four lanes were closed (Figure 24). The maximum travel times on Saturday and Sunday averaged approximately 50 min at 5:00 p.m. and 60 min at 7:00 p.m. Early Saturday and Sunday mornings were the only times the Stage 2C lane closure did not cause traffic delays.

Because the SB I-15 connector was completely closed during Stage 2C, traffic on SB I-15 had to detour to SB I-215 and WB I-10 in order to continue south. The detour was about 40 km (25 mi) and required an extra 25 min at free-flow speed (90 to 110 km/h [55 to 70 mph]). Traffic monitoring on the detour highways (SB I-215 and WB I-10) was performed to investigate how many motorists used the detour routes and how the added traffic changed conditions there.

4.3 Stage 2B: Second Weekend Closure

4.3.1 Traffic Volume Comparison

Traffic volumes for SB I-15 were collected at the SB I-15/215 junction split during Stage 2B (9:00 a.m., November 10 to 1:00 p.m., November 12) and compared with the traffic data collected during nonclosure (the same time, October 22 to November 9, 2006). The Thursday ADT during nonclosure was 82,102, while the Thursday ADT during closure (November 9) was 90,891 (Table 3). This 11 percent increase shows that a significant number of motorists decided to travel the Thursday before the Stage 2B weekend to avoid traffic congestion. This pattern is similar to the variance in travel patterns during Stage 2C.

During Stage 3C, the Friday (November 10) ADT was 65,474, a 22 percent traffic reduction from the Friday ADT (83,425) during nonclosure. The Saturday (November 11) ADT during the closure was 47,598, a 34 percent reduction from the Saturday ADT (72,049) during nonclosure. The Sunday (November 12) ADT during closure was 65,484, a 14 percent reduction from the Sunday ADT (76,433) during nonclosure. Traffic reduction on Sunday was less than reductions on Friday and Saturday because

Sunday construction was completed at 1:00 p.m. with a half-day closure (Table 2). Because all four lanes opened to traffic at 1:00 p.m., Sunday traffic reduction during Stage 2B (14 percent, November 12, 2006) was less than Sunday traffic reduction during Stage 2C (28 percent; October 13, 2006).

According to hourly through-traffic volume measurements from 1:00 a.m. Friday, November 10, 2006, to 12:00 a.m. Monday, November 13, 2006, the maximum through-traffic volume Friday was 5,300 pcph at 9:00 a.m. before closure started, when all four lanes were open The maximum through-traffic volumes were 3,276 pcph at 1:00 p.m. Friday and 2,944 pcph at 11:00 a.m. Saturday during the two-lane closure (Figure 25). After all four lanes were opened to traffic at 1:00 p.m. on Sunday, November 12, 2006, the maximum though-traffic volume observed rose as high as 5,800 pcph (4:00 p.m. Sunday, November 12). For Stage 2B, maximum hourly through-traffic volumes were slightly higher than the expected work zone capacity (1,600 pcphpl).

4.3.2 Additional Travel Times and Traffic Detours

Travel times were measured during Stage 2B to investigate traffic delays due to the lane closures. During Stage 2B, travel time was measured between the start and end points of the 17.7 km (10.0 mi) closure from Oak Hill Avenue to Kenwood Avenue. The travel time with free-flow speed during nonclosure was about 9.0 min. The maximum travel time on Friday during closure was 230 min at 5:00 p.m., when two of four lanes were closed. The maximum travel time on Saturday during closure was approximately 210 min, at 3:00 p.m. There was no additional travel time on Sunday, November 12, 2006 (Figure 26).
Because the SB I-15 connector was closed during Stage 2B, traffic on SB I-15 had to detour to SB I-215 and I-10 WB in order to continue south. The detour was about 40 km (25 mi) and required an additional 25 min at free-flow speed (90 to 110 km/h [55 to 70 mph]). Traffic monitoring was performed on the detour highways (SB I-215 and WB I-10) to investigate how many motorists used detour routes and how much the additional traffic changed detour conditions.

Comparisons of ADTs between the Stage 2B closure period and the nonclosure period on the detour highways showed that ADT during the closure period was higher than that of the nonclosure period. Because of the added traffic due to the detour, there was an 8 percent increase in ADT (6,800 vehicles) on SB I-215 and a 6 percent increase in ADT (6,800 vehicles) WB I-10 on Friday. On Saturday, there was a 28 percent in ADT (21,000 vehicles) on SB I-215 and a 15 percent increase in ADT (16,500 vehicles) on WB I-10. More Saturday motorists than Friday motorists took the long-distance detour suggested by the Caltrans traffic management plan (detours SB I-215 and WB I-10). This was because more weekday than

weekend travelers used short-distance detours (arterials and local streets). Since the former are more familiar with the area, they chose their own alternate routes rather those directed by the Caltrans detour signs

4.4 Stage 3B: Third Weekend Closure

4.4.1 Traffic Volume Comparison

Traffic volumes for NB I-15 were collected at the connector from NB I-15 to SB I-215 during Stage 3B. Traffic volumes were compared with other traffic volumes collected at the same location during nonclosure (October and November 2006.) On NB I-15 the ADT on Saturday during nonclosure was 51,944 while the ADT during closure on Saturday, November 18, 2006 was 16,405. This 68 percent decrease shows that most motorists decided to travel during nonclosure rather than closure periods and/or took alternative routes to avoid congestion in the construction work zone corridor.

Figure 27 shows the hourly through-traffic volumes during Stage 3B from 1:00 a.m. on Saturday, November 18, 2006, to 12:00 a.m. Monday, November 20, 2006. The maximum through-traffic volume was 1,200 pcph at 12:00 p.m. on Saturday, when only one lane was open to traffic. At this position during nonclosure, the maximum hourly trough-traffic volume was 647 pcph. Because the connector was used as a detour road for NB I-15 traffic, the maximum hourly trough-traffic was almost double during Stage 3B.

4.4.2 Additional Travel Times and Traffic Detours

Travel times were measured during Stage 3B to investigate traffic delays due to lane closures. During Stage 3B, travel time was measured between two points, from the I-15/I-10 junction to Kenwood Ave. (24.2 km [15.0 mi]). The travel time with free-flow speed during nonclosure was approximately 13.0 min and the free-flow travel time using the detour road was about 23.0 min. During Stage 3B, the maximum travel time was 62 min at 5:00 p.m., when two of four lanes closed. The maximum travel time on Saturday was about 52 min at 5:00 p.m. Before closure on Sunday, November 12, 2006, there was no additional travel time (Figure 28).

Because the connector of NB I-15 was completely closed at the I-15/I-215 junction during Stage 3B, traffic headed toward the NB I-15 detour to SB I-215 and returned to NB I-215 using Palm Avenue. The distance of this detour was approximately 24.2 km (15.0 mi) and took an additional 10 min with free-flow speed (100 km/h [65 mph]). Traffic monitoring on detour freeways (SB I-215 and NB I-215) was performed to investigate how many motorists used detour routes and how detour traffic was affected by

additional motorists. Although the peak hour delay was not as high as those of stages 2C and 2B on the SB I-15 closure, the detour freeway was congested. This was because all the traffic heading toward NB I-15 was forced to detour to SB I-215 and NB I-215. Traffic during peak hours was congested (stop-and-go) with an average travel speed of 10 km/h (6.5 mph). Due to the narrow curve of the detour, which had a design speed as low as 72 km/h (45 mph), congestion stretched from the connector to SB I-215. Additionally, although CHP officers guided detour traffic at the Palm Avenue exit and back to NB I-215, the long queue waiting to exit onto SB I-215 interrupted the through-traffic and that upstream of the Palm Avenue exit.

4.5 Stage 3C: Fourth Weekend Closure

4.5.1 Traffic Volume Comparison

During Stage 3C (8:00 a.m., January 6, 2007 to 4:00 a.m., January 8, 2007) through-traffic volumes for NB I-15 were collected at the middle of the construction work zone—between the SB I-215 exit and the NB I-15/215 junction. The recorded volumes were then compared with traffic data collected during nonclosure. The ADT on NB I-15 on Saturday (January 6) was 39,400, while the Saturday ADT during nonclosure was 65,000. On Saturday (January 6), the first day of Stage 3C, a 40 percent reduction in traffic demand was observed in the CWZ. ADT on NB I-15 on Sunday (January 7) was 18,000. This measurement shows an approximately 70 percent reduction from the Sunday ADT of 59,200 during nonclosure (Figure 29).

Hourly traffic volumes 3.2 km (2.0 mi) upstream (south) of the Stage 3C section were collected from the Freeway Performance Measurement System (PeMS) database to investigate hourly traffic pattern changes. The data on hourly traffic volume (by time of day) shows a clearer traffic-demand reduction pattern than does the daily traffic volume. The average reduction for hourly traffic volumes was shown to be 58 percent, which is consistent with the daily traffic volume reductions. The maximum hourly traffic reduction (80 percent) was shown at 5:00 p.m. on Sunday, the second day of Stage 3C (from 3,340 to 672 vehicle per hour [vph]). On Saturday, the peak hour traffic reduction was 27 percent at 8:00 a.m. (from 3,850 to 2,580 vph), and on Sunday the peak hour traffic reduction was 70 percent at 3:00 p.m. (from 3,520 to 1,050 vph) (Figure 30).

Based on the data supplied by the Remote Traffic Microwave Sensors (RTMSs) located in the middle of the CWZ during Stage 3C, the average flow rate was about 950 pcphpl, and the work zone capacity was estimated as about 1,100 pcphpl. The research team concluded that several factors reduced work zone

capacity during this stage (these factors will be investigated in detail in further work zone capacity research):

- Only one of three lanes was open and no shoulder lane existed during Stage 3C.
- The work zone was long (8.0 km [5.0 mi] including traffic closure section).
- The lane was narrow (3.2~3.4 m [10.5-11.0 ft]) and its surface was uneven.
- Construction activity was visible to motorists.

4.5.2 Additional Travel Times and Traffic Detours

Travel times were measured during Stage 3C to find traffic delays (additional travel time) due to the lane closure. In Stage 3C, travel time was measured between two points, from the I-15/I-10 junction to the Kenwood Ave. exit (27.4 km [17.0 mi]). Travel time at free-flow speed during nonclosure was about 13.0 min. The maximum travel time was 90 min at 12:00 p.m. Saturday (January 6) and after that travel time decreased. On Sunday (January 7), the maximum travel time was about 30 min at 3:00 p.m. and remained at that level until late afternoon. Owing to the larger traffic demand reduction (70 percent) on Sunday, the maximum travel time was about one third of the maximum travel time on Saturday.

During Stage 3C, the EB I-10 and NB I-215 detour was the major alternate route both for travelers heading north of the CWZ and for those heading to the Devore area. On Saturday, the first day of Stage 3C, daily traffic volume was not significantly affected on EB I-10 but daily traffic volume on NB I-215 increased by 13 percent (7,124 vph) compared to the nonclosure ADT. On Sunday, the second day of Stage 3C, daily traffic on EB I-10 increased by 6 percent (5,600 vph) and daily traffic on NB I-215 increased by 28 percent (12,500 vph) (Figure 8). According to this detour pattern change between Saturday and Sunday, Sunday travelers showed a stronger tendency to follow the guidance regarding detours that Caltrans provided than did the Saturday travelers. Another conjecture is that some motorists who experienced the traffic delay on Saturday used the alternate routes on their Sunday trips.

On both Saturday and Sunday during Stage 3C, the increased traffic volumes on alternate routes were not equal but they corresponded to the decreased traffic volume in the CWZ corridor. Some motorists might have canceled their trips or used other alternate routes, such as local streets and/or different highways.

4.6 Stage 3A: Fifth Weekend Closure

4.6.1 Traffic Volume Comparison

Because ADT on NB I-215 was observed at less than 20,000 and was expected to achieve a more than 30 percent of traffic demand reduction through traffic control, Caltrans did not expect substantial delays during Stage 3A. Although the collection of daily traffic volumes was delayed due to technical problems in an RTMS trailer for a few hours during Stage 3A, traffic upstream of the work zone remained consistent, free-flowing, and without delays: hourly average speeds were over 90 km/h (55 mph) spanning the entire period of Stage 3A. The peak hour traffic volume during Stage 3A was less than 1,200 vph, which occurred at 4:00 p.m. on Saturday (January 20, 2007) (Figure 31).

4.6.2 Additional Travel Times and Traffic Detours

For Stage 3A, travel time measurement was conducted during the day. Because there was no congestion upstream of the work zone, average travel speeds were maintained at over 90 km/h (55 mph) with queue formation. As Caltrans expected, the average travel times were observed to be between 15 and 25 min including additional travel time (7 to 8 min) for the detour route. No additional travel time due to traffic delay was observed on the work zone in the entire period of Stage 3A.

The two lanes for NB I-15 at the NB I-215 connector were completely closed during Stage 3A. All motorists were guided toward the SB I-15 exit and returned to NB I-15 using the Glen Helen Parkway as a short-distance detour. As a result, travel distance increased 8.0 km (5.0 mi) and travel time increased 7 to 8 min. At maximum, about 1,100 vehicles per hour used the short-distance detour (3:00 p.m. to 6:00 p.m. on Saturday).

The WB I-10 to NB I-15 detour was known by motorists as the long-distance one (Figure 24).. Perhaps because of this, the daily traffic volume on WB I-10 increased by 1 percent on Saturday and by 7 percent on Sunday. Although NB I-15 between I-10 and I-215 was also designated as an alternate detour, daily traffic volumes on the highway decreased by 2 percent each on Saturday and Sunday. This may have been because Caltrans announced that the NB I-15 would be congested due to detour traffic. Even so, this pattern suggests that motorists can easily reach their destinations (e.g., shopping malls, restaurants) if they employ flexibility in choosing them, thus avoiding congested highways.

4.7 Stage 2D: Sixth Weekend Closure

4.7.1 Traffic Volume Comparison

Saturday ADT on SB I-15 was 72,049 during nonclosure. During Stage 2D, the observed ADT on SB I-15 was 60,379 and there was a 16 percent reduction of through-traffic volume. This traffic reduction was smaller than that of the previous two SB I-15 closures (41 percent for Stage 2C and 34 percent for Stage 3B) because the traffic closure at Stage 2D blocked traffic heading toward SB I-215 instead of traffic toward SB I-15.

Maximum hourly through-traffic was up to 4,500 vehicles per hour at 4:00 p.m. on Saturday, January 27, 2007 when two of four lanes were closed (Figure 32). Because the work zone length (0.1 mi) was considerably shorter than those of the previous closures, higher maximum hourly traffic was able to pass through the work zone corridor.

4.7.2 Additional Travel Times Traffic Detours

For Stage 2D, travel time measurement was conducted during the day from Cleghorn Road to Glen Helen Parkway. The average travel time without lane closure was about 7 min for 12.0 km (7.5 mi). The maximum travel time (40 min) with the maximum queue length (8.0 km [5.0 mi]) was observed at 4:00 p.m. on Saturday, January 27, 2007 (Figure 33).

Both lanes at the SB I-215 connector were closed during Stage 2D. All motorists heading toward SB I-215 were forced to take SB I-15 and EB I-10. Travel distance increased 40.0 km (25.0 mi) and travel time increased 25 min at free-flow speed (90 to 110 km/h [60 to 70 mph]). Traffic monitoring was performed on the detour highways (SB I-15 and EB I-10) to investigate the number of motorists who used the detour routes and how detour traffic was affected.

The comparison of ADT on the detour highways between the Stage 2D closure period and the nonclosure period showed that ADT during the closure period was lower on SB I-15 and higher on EB I-10 than during the nonclosure period. The comparison also indicates that some motorists in SB I-15 traffic changed their travel schedule or route to avoid work zone delays.

4.8 Traffic Behavior Through the CWZ

4.8.1 Traffic Behavior Summary

Based on data collected from six extended weekend closures, maximum traffic demand through the CWZ was reduced by up to 70 percent compared with preconstruction conditions. This reduction was shown during Stage 3C with the closure of two of three lanes on the NB I-15. The maximum increase of detour traffic volume was 28 percent during Stage 3C for the same closure. Because Caltrans' transportation management plans focused heavily on reducing traffic demand in order to avoid serious delays in the NB I-15 corridor during construction, there was high traffic demand reduction on the construction corridor and a high traffic demand increase on the detour freeway (EB I-10). Caltrans deployed portable changeable message signs and operated permanent message signs to provide travel information to motorists, including detour guidance and real-time traffic delay information for the construction corridor (NB I-15). In addition, Caltrans' radio advisory broadcasting system provided detour guidance before and during Stage 3C. Because conditions were unlike those during Stages 2C and 2B, travelers were able to take the detour freeways efficiently during stages 3B and 3C and avoid the NB I-15 closures. During Stage 3B, as with Stage 3C, traffic demand reduction for the construction corridor was about 68 percent. The high traffic demand reductions for stages 3B and 3C contributed to relatively less severe traffic delays in the construction corridor (for example, up to 62-min delays for Stage 3B and an average of 90-min delays for Stage 3C).

On the other hand, during stages 2B and 2C (or the SB I-15 closure), traffic demand reduction was 41 percent (Stage 2C) and 34 percent (Stage 2B), with maximum traffic delays of 110 min (Stage 2C) and 230 min (Stage 2B). Delays of this magnitude resulted from the absence of detours along the work zone corridor. Because of the lack of detour freeways, all traffic heading toward SB I-15/I-215 experienced traffic delays in the work zone queue and exited on SB I-15 or SB I-215. The unique topology of this area caused huge traffic delays (up to 230 min) and an 11 mi queue. As a result, motorists unavoidably experienced major inconveniences during stages 2B and 2C.

Another possible reason for the large differences in traffic patterns for the four I-15 corridor closures (in chronological order, Stages 2C, 2B, 3B, and 3C) was that motorists change traffic patterns based on their previous experience. In other words, after motorists experienced substantial traffic delays during stages 2B and 2C, a large number of them canceled or changed their travel plans for stages 3B and 3C because of an expectation of similar traffic conditions. This reduction in motorists during stages 3B and 3C contributed to the mitigation of traffic delays.

4.8.2 Comparison with the Devore I Project

The traffic demand reduction data of this project was compared with that of a very similar project: the I-15 Devore I Rapid Rehabilitation Project that was completed in 2004 south of the I-15/215 junction. Unlike the project detailed in this report—with its six extended weekend closures—the I-15 Devore I Project was completed in two nine-day one-roadbed continuous closures. This method of closure created an up to 18 percent peak-hour traffic demand reduction through the construction work zone (I-15 Devore corridor).

In comparison, the Devore II rapid rehabilitation with weekend closures created an even higher traffic demand reduction of up to 70 percent in peak-hour traffic. The obvious difference in traffic demand reduction between the two projects shows that weekend traffic (I-15 Devore II) is relatively more flexible than weekday traffic (I-15 Devore I) for work zone closures because of the unique characteristics of I-15 traffic to/from Las Vegas. The northbound peak traffic heading to Las Vegas appeared on Fridays, and the southbound peak traffic returning from Las Vegas appeared on Sundays. Unlike the I-15 Devore II closure schedule, the I-15 Devore I Project included weekday closures. The majority of traffic using the I-15 rehabilitation corridor consisted of commuters who had less flexibility in changing their travel schedule.

Although traffic demand reduction in the Devore I rapid rehabilitation project was less than in Devore II, the latter had a greater maximum traffic delay (230 min) than its predecessor (50 min). This difference is attributed to the use of the Quickchange Moveable Barrier (QMB) in Devore I, which allowed for greater traffic capacity in the peak direction. For example, QMB operation in Devore I increased to three the number of lanes of SB traffic during morning peak periods, whereas the number of lanes in the SB peak direction remained the same (two lanes) in Devore II. This result emphasizes the importance of work zone traffic capacity management along with traffic demand management. Considering the influence of work zone capacity changes on traffic delay, precise estimation of work zone capacity is essential for predicting additional traffic delays and travel times. The next chapter describes estimation of work zone traffic capacity.

5.0 MODELING OF WORK-ZONE TRAFFIC BEHAVIOR

5.1 Empirical Estimate of Work Zone Capacity

Probe vehicles were operated around the construction corridor and detouring highways for two purposes: to measure additional travel time on the CWZ corridor and detour routes, and to measure the traffic flow speed upstream of the CWZ in order to investigate through-traffic volumes and work zone capacity. First, crews in the probe vehicles recorded the time (in an hh:mm:ss format) at every kilometer from a starting point (origin) to an end point (destination). By reporting the travel time for each of their rounds through the work zone, the crew provided the command center with additional travel times between the two points. Second, the crews recorded the location of the end of the queue and observed when traffic congestion occurred and the queue was formed. Using this operation, the traffic speeds in a queue were collected. At the same time, digital photographs were taken to measure traffic density along a 0.32-km (0.2 mi) stretch of roadway. The photographs were then matched with traffic speed data and synchronized by time to calculate the average through-traffic volumes, which were then compared with the traffic volume data collected by the RTMSs.

Based on Chapter 23 of the *Highway Capacity Manual 2000,* work zone traffic capacity was assumed as 1,600 pcphpl in the preconstruction analysis stage to predict traffic delay and road user costs due to lane closures and traffic disruptions. However, work zone traffic capacity varies by site-specific road configurations and construction circumstances. In this study, the work zone traffic capacity was defined as the flow rate from the time congestion appeared to the time that it disappeared. In order to investigate the actual work zone traffic capacity per rapid rehabilitation weekend closure, RTMSs collected the through-traffic volumes in the middle of the work zone (downstream of the lane drop section) in 5-min intervals.

Here, work zone capacity was estimated by the relationship between flow density and flow speed. The flow density and speed were collected in the ways described above. The work zone capacity ($C_{m,n}$) is described with speed ($u_{m,n}$) and density ($k_{m,n}$), where *m* is the number of lanes open and *n* is the number of total lanes.

$$C_{m,n} = u_{m,n} \times k_{m,n} \quad (1)$$

where,
$C_{m,n}$ = Work zone capacity when *m* lanes open among *n* lanes (vph)
$u_{m,n}$ = Speed of queued flow when *m* lanes open among *n* lanes (kph)
$k_{m,n}$ = Density of queued flow,
number of passenger cars for *m* lanes of 1.0 km in queued flow
when *m* lanes open among *n* lanes

In the traffic queue upstream of the work zone 263 veh/4ln/km (423 veh/4ln/mi) was observed on average when three of four lanes were open and traffic conditions were stop-and-go with an average flow speed of 19.3 km/h (12.0 mph). In the traffic queue upstream of the work zone, 313 veh/4ln/km (504 veh/4ln/mi) on average were observed when two of four lanes were open and traffic conditions were stop-and-go with an average flow speed of 10.5 km/h (6.5 mph).

The work zone capacity estimated by the relationship of density and speed are 1,644 vphpl when two out of four lanes are open and 1,692 vphpl when three of out four lanes are open. The work zone capacity with two out of four lanes open was lower than the capacity with three out of four lanes open.

$$C_{2,4} = 10.5 \times 313 = 3{,}286.5 \text{ vph (through - traffic for 2 lanes)}$$
$$C_{3,4} = 19.3 \times 263 = 5{,}075.9 \text{ vph (through - traffic for 3 lanes)}$$

5.2 Estimate of Work Zone Travel Time

Lane closures at the work zone reduce operational capacity and create additional travel time (delay) when the traffic demand approaching the work zone exceeds the reduced operational capacity. Transportation agencies attempt to decrease traffic demand by providing travelers with real-time traffic information. However, there are two types of traffic-flow upstream of the work zone when demand exceeds operational capacity: *queued-flow* and *approaching flow*. Work zone travel time is estimated by known parameters such as *queue length* and *speed of queued flow*.

The Devore II Project contained either two-lane closures (4→2) or one-lane closures (4→3). The coefficient (0.75) in Eq. (2) represents travel time per kilometer under free-flow speed (80 km/h).

$$TT_{m,n}(\text{min}) = t_{m,n} \times L_q + 0.75 \times (L_t - L_q) \quad (2)$$

$TT_{m,n}$ = Travel time of L_t when *m* lanes open among *n* lanes (min)
$t_{m,n}$ = travel time per kilometer in queued flow when *m* lanes open among *n* lanes
L_t = Length of section to measure travel time (kilometer)
L_q = Length of queued flow (kilometer)

Substituting $t_{2,4}$ for the average travel time per kilometer in queued flow when two out of four lanes are open, 5.71 min, and $t_{3,4}$ for the average travel time per kilometer in queued flow when three out of four lanes are open, 3.11 min,

$$TT_{2,4}(\text{min}) = 5.71 \times L_q + 0.75 \times (L_t - L_q) \quad (3)$$
$$TT_{3,4}(\text{min}) = 3.11 \times L_q + 0.75 \times (L_t - L_q) \quad (4)$$

For example, when the queue length was 9.7 km (6.0 mi) from the work zone and two of four lanes were open, the travel time for the 17.7 km (10.9 mi) from the Oak Hill entrance to the work zone estimated by Eq. (3) is 61.4 min, close to the actual travel time measured by the probe vehicle, 64 min. This travel time estimation model can be simply used to estimate travel time through work zones in future rehabilitation sites if the queue length is known by using traffic monitoring devices, such as a surveillance camera system or loop detector.

6.0 LESSONS LEARNED

The utilization of articulated trucks (which carry double-volume capacity) enhanced operation rates in demolition activity. Due to high volume capacity, the average loading time was longer than that for standard construction trucks. However, the truckload rate (the number of trucks used per hour) was almost half that of standard truck usage. Thus, the utilization of articulated trucks can expedite demolition progress when truck accessibility to the site is impeded by heavy congestion or by other factors.

In terms of operating rates (productivity) of demolition activity, the operating rate (48 m/hr) of demolition on Stage 2C was higher than that of the other stages (i.e., 27.9 m/hr on Stage 2B and 35.3 m/hr on Stage 3B). The truck-loading cycle (or the time it takes for a truck to return to the site) for demolition activity on Stage 2C was only 15.2 min. This was shorter than other stages (57.4 min on Stage 3B and 99.9 min on Stage 3C) because the temporary dumping site for Stage 2C was located on the gore on the I-15/I-215 junction as opposed to the dumping site for other stages (located 15 mi from the CWZ in the city of Fontana). Using the junction as a temporary dumping space shortened the truck-loading cycle and thus expedited the operating rate of demolition activity.

Weather conditions were also a factor. During Stage 3C, rain delayed AC paving for 90 min. Although AC paving on Stage 2C was executed after rain abated, a quality test of the AC section paved after the rain is recommended since the base surface was very wet at the time.

In selecting the six construction weekends, Caltrans planned to avoid weekends when large-scale public events were already scheduled to be held near the construction corridor at venues such as the Hyundai Pavilion in Glen Helen or the California Speedway in Fontana. This strategy preempted the exceptionally heavy traffic demand caused by the events coupled with the freeway capacity reduction due to the work-zone closures. For example, to accommodate an unexpectedly scheduled firefighter's memorial service at the Hyundai Pavilion at 1:00 P.M. on November 5, Caltrans cancelled its second weekend closure (Stage 2B, November 3 to 5, 2006) at the last possible minute (48 hours in advance).

Traffic management plans were developed by Caltrans, the contractor, and the University of California Pavement Research Center for the Devore II Rehabilitation weekend closures. The traffic management plans provided for reduced traffic demand through the work zone, thereby reducing traffic delays and queue length over the construction period. During the Devore II Rehabilitation weekend closures, most motorists followed the transportation management plan (TMP) guide and signs to detour from the work zone. However some motorists traveled routes other than those suggested by the TMP since they seemed

to be familiar with the area and judged their routes to be more effective than those suggested by Caltrans. For example, for motorists who wanted to take SB I-15 during the first weekend closure (Stage 2C), the TMP recommended exiting I-15 at Palm Avenue, making a U-turn, and then taking NB I-215 to return to SB I-15. However, some motorists returned to SB I-15 after reaching NB I-215 via Cajon Boulevard and Devore Road north. Therefore, the traffic volume data on Devore Road north showed a 7 percent increase, while those on other directions decreased by 15 percent. In addition, California Highway Patrol (CHP) officers were located at each connector and at the interchanges to expedite the process of detouring motorists.

Other items to be considered when projects such as this one are undertaken in the future:

- Some signs were located at inappropriate locations and could not be seen well by detouring motorists.
- Due to strong winds during Stage 3C, some of the Portable Changeable Message Signs (PCMSs) fell and broke their stands, which prevented motorists at some locations from receiving relevant travel information.
- In terms of traffic monitoring devices, when the RTMS configuration was set at a 30-sec interval to collect higher resolution traffic data, battery consumption increased and some periods of traffic data were lost. In case high resolution of traffic data is needed, traffic monitoring devices need enough power resources to avoid loss of data.

7.0 SUMMARY

7.1 Construction Monitoring Study Summary

The research team collected construction data for four different construction activities; demolition of PCC slab, milling, AC Paving, and PCC paving. During each stage, these construction activities were completed on time or earlier than originally scheduled.

- The construction activities were conducted processed in a parallel fashion where there were two or more lanes available for construction truck access. Where there was only one lane available for construction trucks, construction activities were processed sequentially.
- For demolition activities, the average truck-loading cycle was 15.2 min when the temporary dumping area was at the gore while the average truck-loading cycle was 78.7 min when the dumping area was in the city of Fontana. Dumping at the gore near the construction site expedited truck-loading cycles and demolition processes compared with dumping outside the construction site.
- In demolition activities, the average loading time for articulated trucks (which have double capacity) was 4.3 min while the average loading time for normal hauling trucks was 3.5 min. Utilizing articulated trucks allowed a reduction in the number of trucks used for demolition activity. However, they required longer loading time because they carry double the capacity of normal hauling trucks. The average number of trucks was 11.7 per hour.
- For milling activities, the average truck-loading time was 1.9 min. This was less than in demolition activities because the milling process used machines that loaded materials onto trucks automatically. The average number of trucks was 15.6 per hour and the average truck-loading cycle was 53 min.
- For AC paving activities, the average truck unloading time was 2.2 min and the average number of trucks was 10.5 per hour. The average truck unloading cycle was 158 min.
- For PCC paving activities, the average truck unloading time was 3.8 min and the average number of trucks was 13.8 per hour. The average truck unloading cycle was 40 min.

7.2 Traffic Monitoring Study Summary

Traffic monitoring analysis results indicate that Caltrans successfully implemented the traffic management plans (TMPs) and detailed strategies the agency developed for its 2007 I-15 Devore II Rehabilitation Project with six weekend closures. Traffic detouring proportions on Sundays were higher than on Saturdays since Sunday travelers seemed to have more flexibility in their travel schedules.

- The TMP implemented during weekend closures led to an up to 70 percent demand reduction through the CWZ and a 28 percent traffic increase on detour roads (the fourth closure, Stage 3C), compared with preconstruction conditions. This large shift in traffic emphasizes the importance of proper TMP implementation.
- Due to heavy traffic volumes on the SB I-15 corridor, maximum travel time for through-traffic was over 230 min, and the maximum queue length was about 17.5 km (10.9 mi), although the through-traffic volume decreased by 34 percent during the second closure (Stage 2B). The traffic conditions on SB I-15 were worse than those on NB I-15 over the "Rapid Rehab" weekend, regardless of the closure direction.
- Most travelers followed Caltrans detour guidance although the detours spanned an extra distance of over 40 km (25 mi). When traffic conditions were worse (longer traffic delays), more motorists followed the detour guidance and took the detour routes. Through-traffic volume was less when construction activity was visible to motorists. Through-traffic volume (corresponding to work zone capacity) was directly related to the number of lanes.
- When two out of four lanes were open, the average queue speed was 10.5 km/h (6.5 mph) and the average density was 313 veh/4ln/km (504 veh/4ln/mi). When three out of four lanes were open, the average queue speed was 19.3 km/h (12.0 mph) and the average density was 263 veh/4ln/km (423 veh/4ln/mi).
- The capacity and travel time estimation models that were built based on traffic observation produced work zone capacity and travel time under a given traffic condition. Work zone traffic capacity was observed in the range of 1,500 pcphpl to 1,680 pcphpl, with about 9 percent heavy trucks. The work zone traffic capacity observed in this project will be utilized in the work zone capacity estimation model in the future.
- In addition, Caltrans' public outreach efforts contributed to the achievement of large reductions in traffic demand, as did the public's increased willingness to follow Caltrans' travel guidance regarding travel during the project.

8.0 REFERENCES

1. Scriba, T., and Seplow, J. 2006. "FHWA Rule on Work Zone Safety and Mobility." *Pubic Roads*, Vol. 69, No. 4.
2. California Department of Transportation (Caltrans). 1998. "Ten-year State Highway System Rehabilitation Plan 1998-99 through 2007-08." *www.dot.ca.gov/hq/transprog/reports/tnyrplan.pdf.* Accessed June 10, 2005.
3. Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. 2002. "Case Study of Urban Concrete Pavement Rehabilitation on Interstate 10. I-10 Pomona." *Journal of Construction Engineering and Management, ASCE*, Vol. 128, No. 1, pp. 49-56.
4. Lee, E. B., Lee, H. J., and Harvey, J. T. 2006. "Fast-Track Urban Freeway Rehabilitation with 55-Hour Extended Weekend Closure: I-710 Long Beach Case Study." *Journal of Construction Engineering and Management, ASCE*, Vol. 123, No. 5, pp. 465-472.
5. Lee, E. B. and Kim, C. 2006. "Automated Work Zone Information System on Urban Freeway Rehabilitation, California Implementation." In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1948*, Transportation Research Board of the National Academies, Washington, D.C., pp.77-85.
6. California Department of Transportation (Caltrans). 2006. I-15 Devore II Rapid Rehab Project. *www.dot.ca.gov/dist8/devore/.* Accessed January 10, 2007.
7. California PATH and Caltrans. 2006. "Freeway Performance Measurement System (PeMS)". *pems.eecs.berkeley.edu/Public/*. Accessed January 2007.

Table 1: Rapid Rehabilitation Extended Closure Schedule

Month		Sun	Mon	Tue	Wed	Thu	Fri	Sat
Oct. 2006		1	2	3 2A1	4	5	6	7
	1ST 52-hr	8 2A1	9	10	11	12	13 1ST 2A/2C	14
		15 2A/2C	16	17	18	19	20	21
		22	23	24	25	26	27	28
		29	30	31	1	2	3	4
Nov. 2006	2ND 52-hr	5	6	7	8	9	10 2ND 2B	11
	3RD 52-hr	12 2B	13	14	15	16	17	18 3RD 3B
		19 3B	20	21	22	23	24	25
		26	27	28	29	30		
Dec. 2006		No Construction						
Jan. 2007	4TH 44-hr		1	2	3	4	5	6 4TH 3C
		7 3C	8	9	10	11	12	13
	5TH 55-hr	14	15	16	17	18	19 5TH 3A	20
	6TH 20-hr	21 3A	22	23	24	25	26 6TH 2D	27
		28	29	30	31			

2A1 : Weekday construction on I-15 SB
2A/2C : the First construction on I-15 SB
2B : the Second construction on I-15 SB
3B : the Third construction on I-15 NB
3C : the Fourth construction on I-15 NB
3A : the Fifth construction on I-215 NB
2D : the Sixth construction on I-215 SB

Table 2: Rapid Rehabilitation Extended Closure Schedule as Built

Weekend Closure	Stage	Date and Time			Lane Closure	Construction Location
		Start	End	Duration		
n/a	2A1	11PM, Tu. 10/03/06	1PM, Fr. 10/13/06	10-days	SB I-15 reduced to 4 lanes at Kenwood Ave.	SB I-15 btw Kenwood and I-15/215 Split
1	2A/ 2C	9AM, Fr. 10/13/06	1PM, Su. 10/15/06	52-hrs	SB I-15 connector closed to SB I-15	SB I-15 connector btw I-15/215 split and Glen Helen
2	2B	9AM, Fr. 11/10/06	1PM, Su. 11/12/06	52-hrs	NB I-215 connector closed to SB I-15	SB I-15 connector btw I-15/215 split and Glen Helen
3	3B	8AM, Sa. 11/18/06	4AM, Mo. 11/20/06	44-hrs	NB I-15 connector closed to NB I-15	NB I-15 connector btw Glen Helen and I-15/215 merge
4	3C	8AM, Sa. 01/06/07	4AM, Mo. 01/08/07	44-hrs	SB I-15 connector closed to SB I-215	NB I-15 btw R/R Bridge and Cajon Creek Bridge
5	3A	9PM, Fr. 01/19/07	4AM, Mo. 01/22/07	55-hrs	NB I-215 connector closed to NB I-15	I-15/215 NB south of I-15/215 merge
6	2D	10PM, Fr. 01/26/07	6PM, Sa. 01/27/07	20-hrs	SB I-15 to SB I-215 connector	SB I-215 connector

Table 3: Daily Traffic Comparison Among Nonclosure Weekend, Stage 2C, and Stage 2B

Day of Week	Without Construction[(1)]	Stage 2C (First Weekend Closure)		Stage 2B (Second Weekend Closure)	
	Daily Traffic	Daily Traffic	Change	Daily Traffic	Change
Mon.	81,799	N/A	-	N/A	-
Tue.	77,972	N/A	-	N/A	-
Wed.	79,386	N/A	-	N/A	-
Thu.	82,102	91,562	+12%	90,891	+11%
Fri.	83,425	57,474	-31%	65,474	-22%
Sat.	72,049	42,624	-41%	47,598	-34%
Sun.	76,433	55,084	-28%[(2)]	65,484	-14%[(3)]

(1) Average Daily Traffic without construction, three sample dates for each day included.
(2), (3) Half-day constructions and closures were only operated on Sundays during Stage 2C and 2B.
Total average demand reduction is 28 percent.

Table 4: Reconstruction Productivity Progress

Weekend Closure	Stage	Length (m)	Lane Acces.	Activity	Duration (hour)	Gross Rate (m/hr)	Operating Rate (m/hr)	Truck Loads (veh/hr)
1ST, 52-hrs.	2C	660	2	Demolition	7.0	51.9	51.9	11.4
				Milling	8.6	77.0	126.9	15.9
				AC paving	6.4	132.0	147.0	10.8
				PCC paving	7.0	94.3	94.3	21.7
2ND, 52-hrs.	2B	380	2	Demolition	7.2	27.8	27.8	11.8
				Milling	-	-	-	-
				AC paving	2.8	135.9	160.9	11.1
				PCC paving	8.5	66.5	68.1	11.4
3RD, 44-hrs.	3B	260	1	Demolition	4.5	29.5	29.5	19.3
				Milling	4.2	61.9	75.3	14.0
				AC paving	3.7	70.3	75.7	11.6
				PCC paving	3.7	69.0	78.8	21.1
4TH, 44-hrs.	3C	160	1	Demolition	6.5	24.8	24.8	14.9
				Milling	2.3	69.1	90.6	20.4
				AC paving	3.8	41.6	58.9	8.2
				PCC paving	4.8	33.6	36.3	12.3
5TH, 55-hrs.	3A	1,010	1	Demolition	9.7	53.7	60.0	19.0
				Milling	Random Slab Replacement			
				AC paving				
				PCC paving	8.6	117.7	121.0	14.9
6TH, 20-hrs.	2D	500	1	Demolition	5.0	-	-	4.6
				Milling	Random Slab Replacement			
				AC paving				
				PCC paving	7.0	-	-	4.0

Table 5: Traffic Monitoring Summary

Weekend Closure	1st	2nd	3rd	4th	5th	6th
Stage	Stage 2C	Stage 2B	Stage 3B	Stage 3C	Stage 3A	Stage 2D
Closed Direction	SB I-15	SB I-15	NB I-15	NB I-15	NB I-215	SB I-215
Duration (hrs)	52	52	44	44	55	20
No. of Lanes before Construction	4	4	3	3	2	4
No. of Lanes during Construction	2	2	1	1	1	2
Max. ADT Decrease (1)	41%	34%	68%	70%	N/A	16%
Max. Hourly Trough-traffic	2,950 pcph	3,270 pcph	1,200 pcph	1,100 pcph	1,200 pcph	4,500 pcph
Max. Delay (Total Travel Time)	110 min	230 min	62 min	90 min (120 min(5))	0 min (15 min(6))	40 min (55 min(7))
Max. Queue Length	5.0 mi	11.0 mi (15.0 mi(4))	4.0 mi	5.0 mi	0.0 mi	5.0 mi
Max. ADT Increase on Detours (2)	N/A	28%	8%	28%	7%	3%
Work Zone Capacity(3)	1,600 pcphpl	1,600 pcphpl	1,200 pcphpl	1,100 pcphpl	N/A	2,150 pcphpl

(1) The traffic during each stage was compared with the ADT before construction.
(2) The traffic on detours during each stage was compared with the ADT before construction.
(3) Work zone capacity is the prevailing 15-min. flow rate.
(4) As measured by the Caltrans District Traffic Manager (DTM).
(5) Measurement by the Caltrans District Traffic Manager (DTM) includes the normal travel time of 30 min.
(6) Measurement by the Caltrans District Traffic Manager (DTM) includes the normal travel time of 15 min.
(7) Measurement by the Caltrans District Traffic Manager (DTM) includes the normal travel time of 15 min.

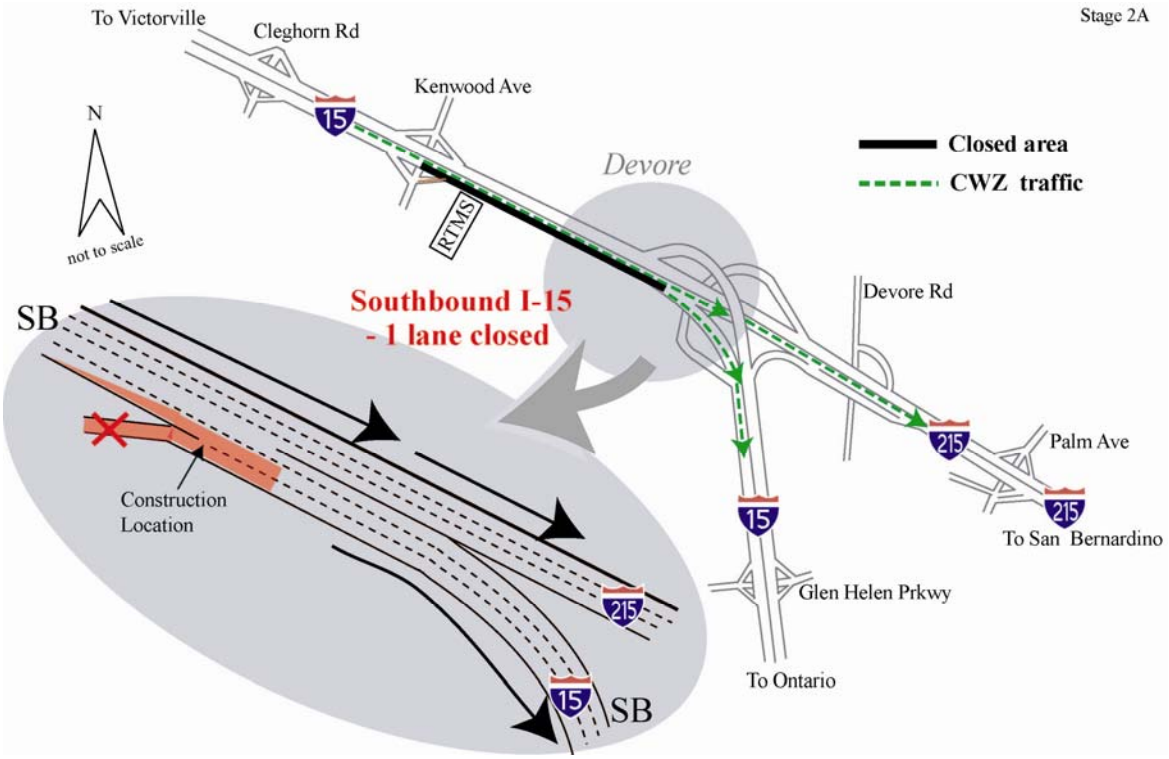

Figure 1: Stage 2A1 (Weekday Closure, I-15/215 SB).

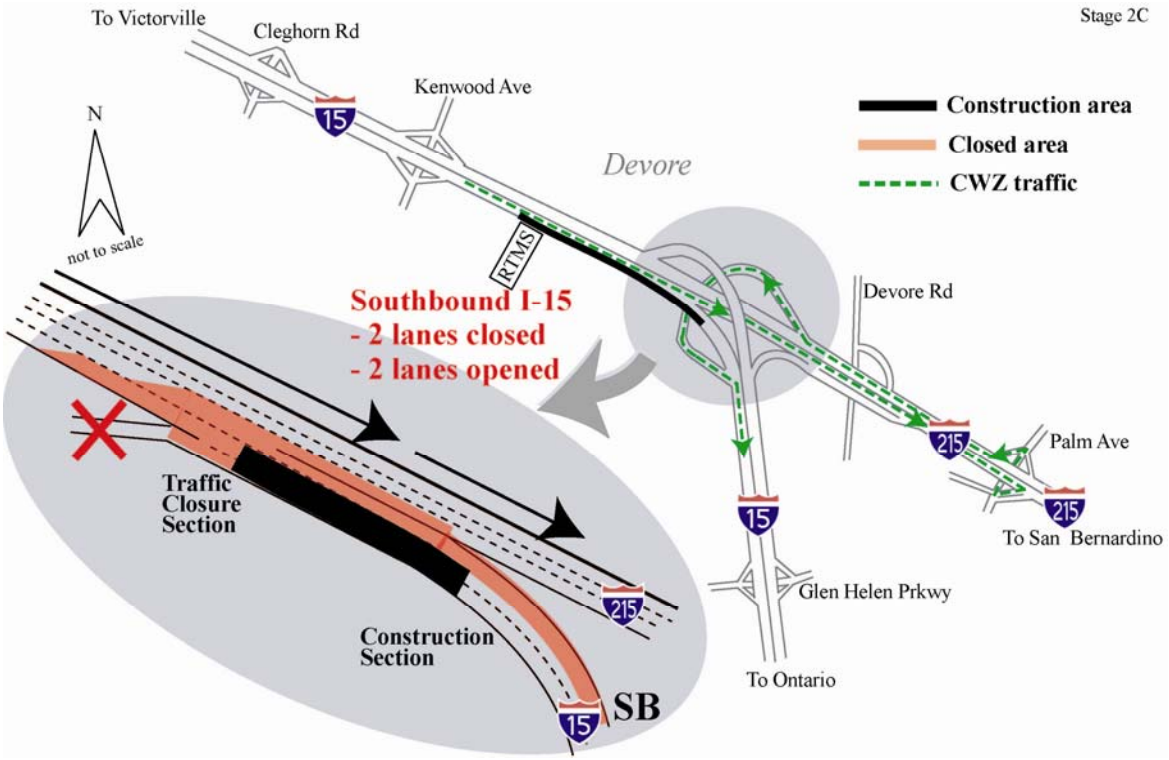

Figure 2: Stage 2C (first weekend closure, SB I-15).

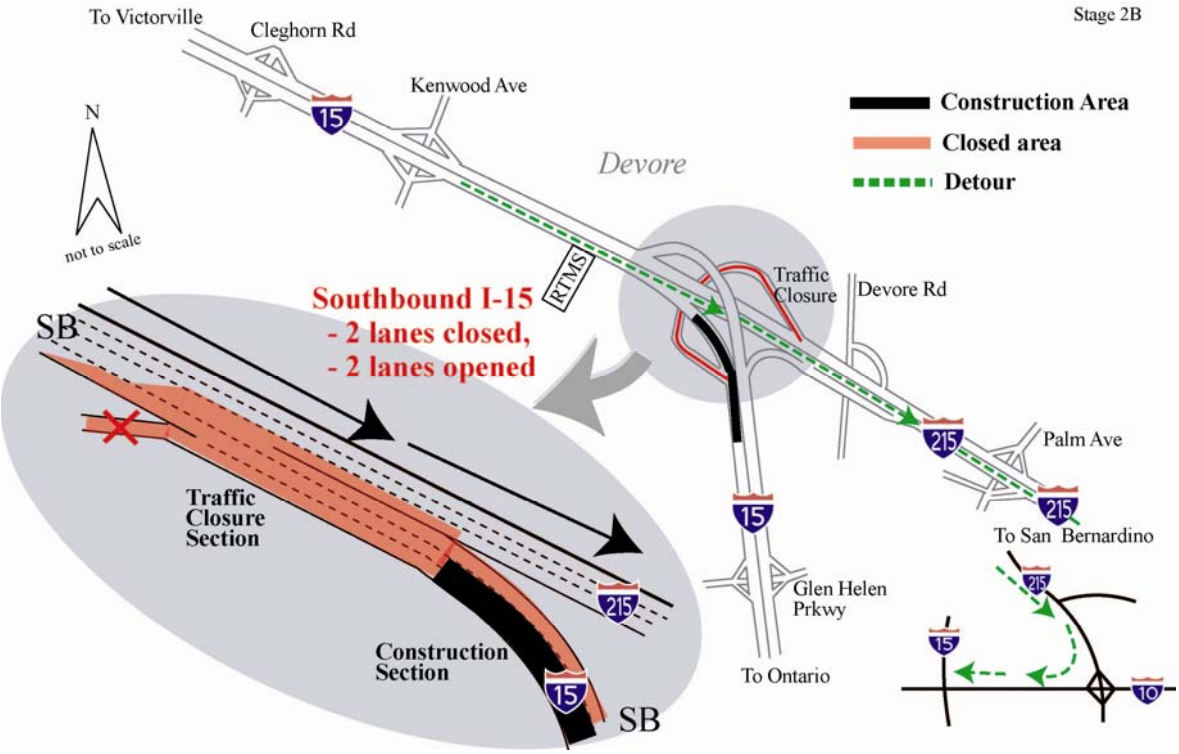

Figure 3: Stage 2B (second weekend closure, SB I-15).

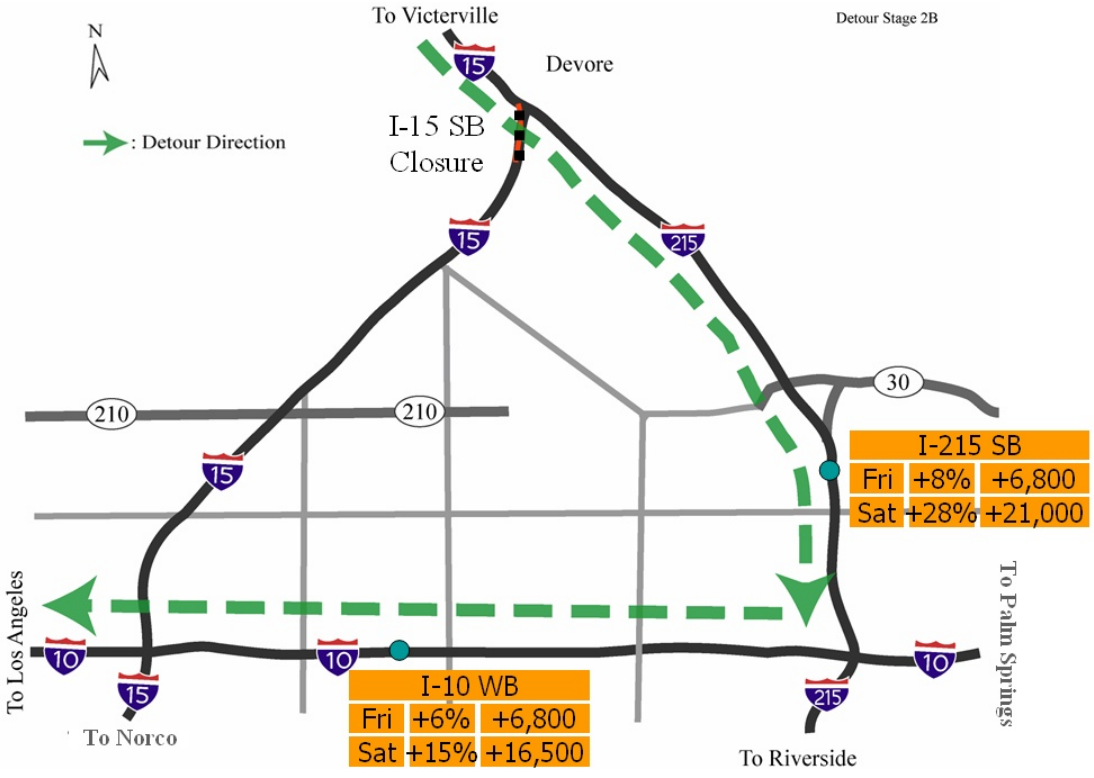

Figure 4: Traffic changes on neighboring freeways during Stage 2B (second weekend closure).

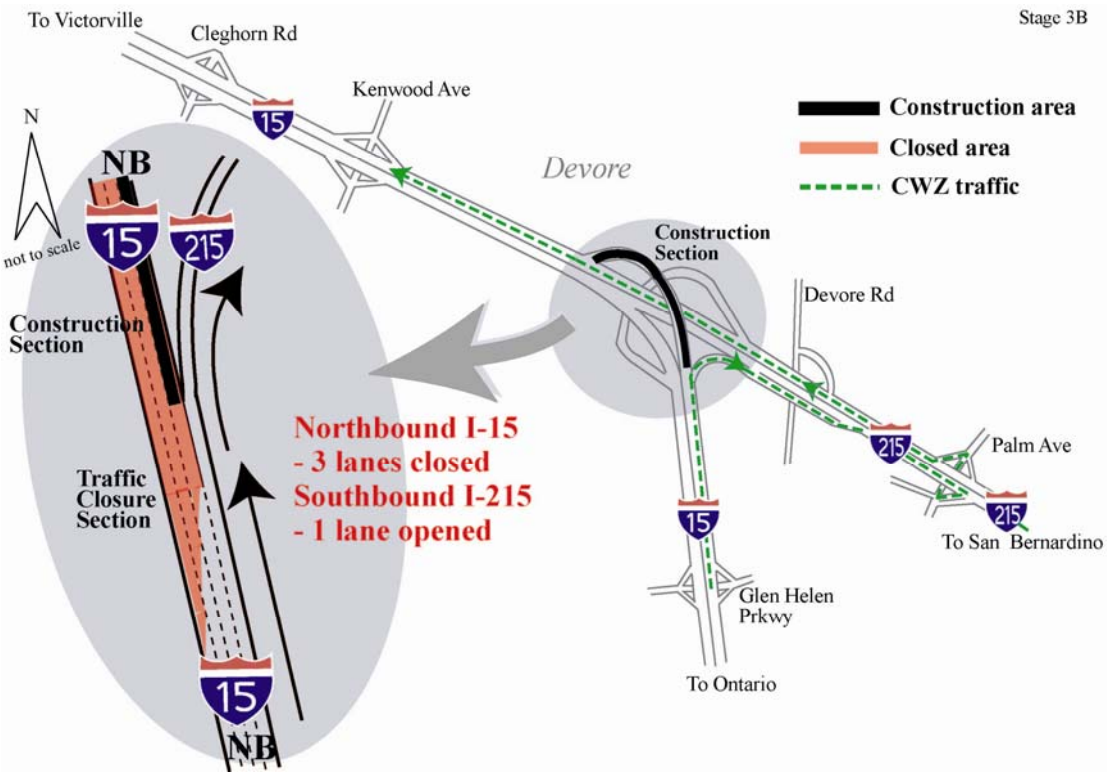

Figure 5: Stage 3B (third weekend closure, NB I-15).

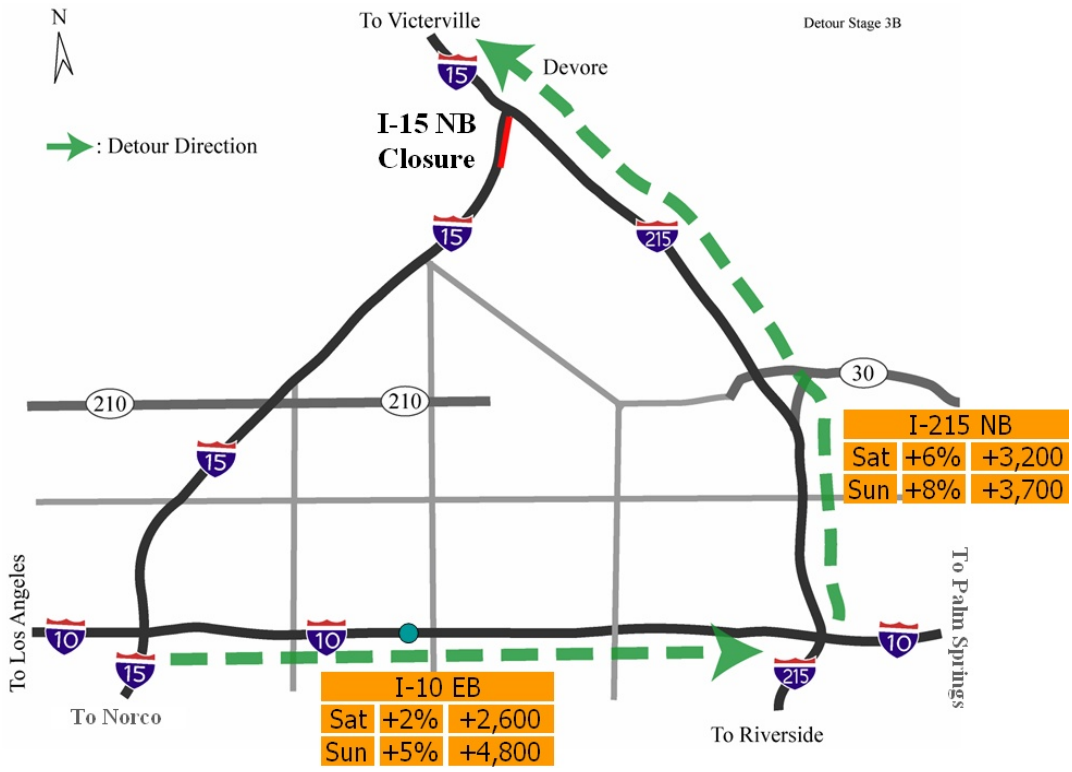

Figure 6: Traffic changes on neighboring freeways during Stage 3B (third weekend closure)

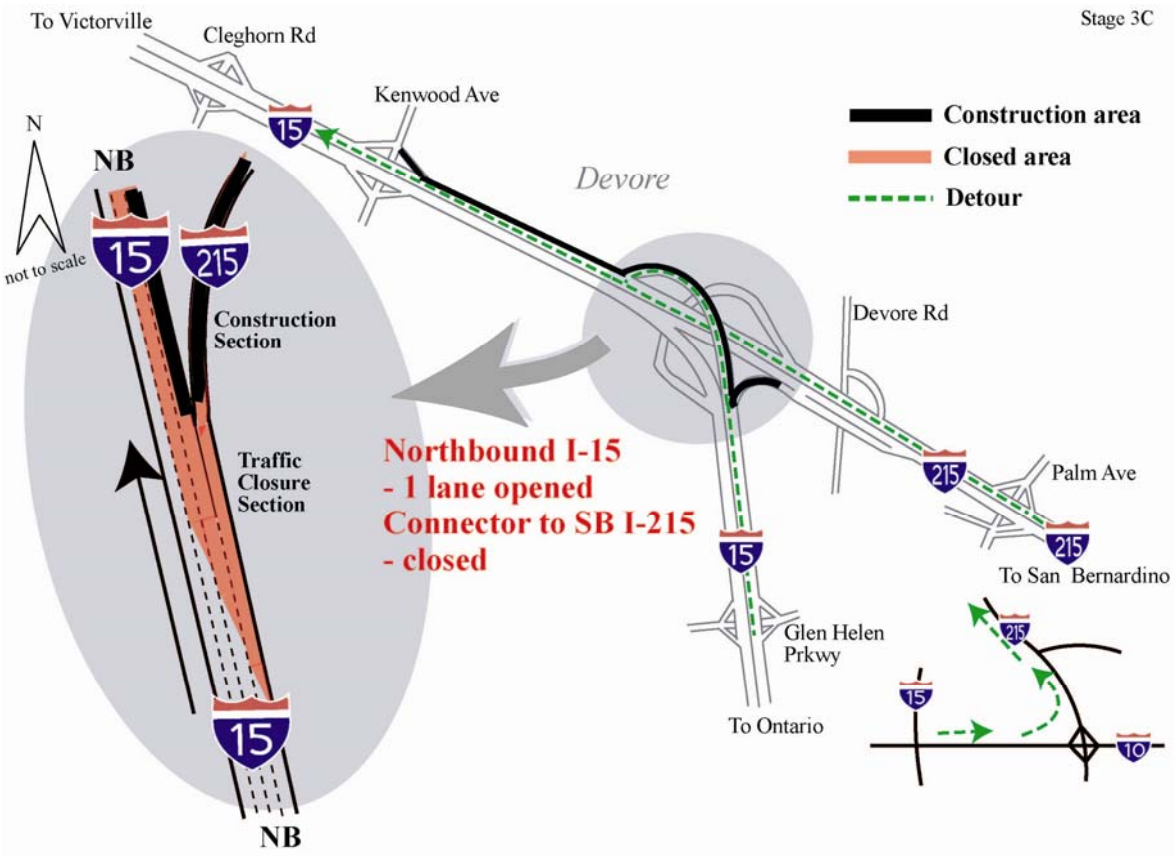

Figure 7: Stage 3C (fourth weekend closure, NB I-15, 44-hrs.).

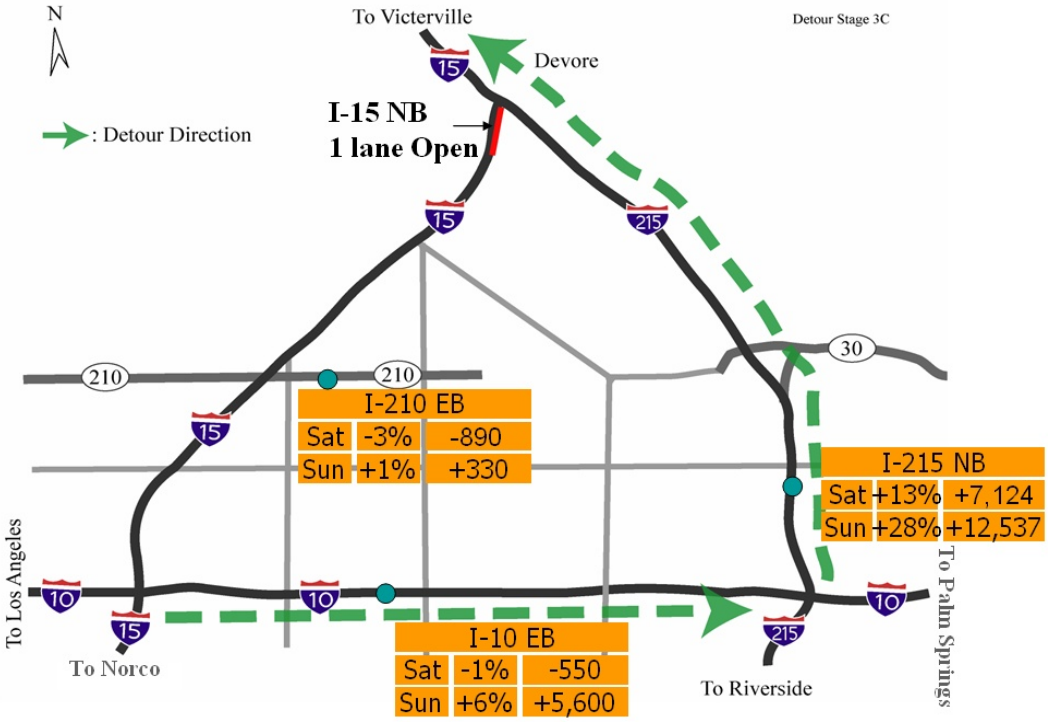

Figure 8: Traffic changes on neighboring freeway during Stage 3C (fourth weekend closure, NB I-15, 44-hrs.).

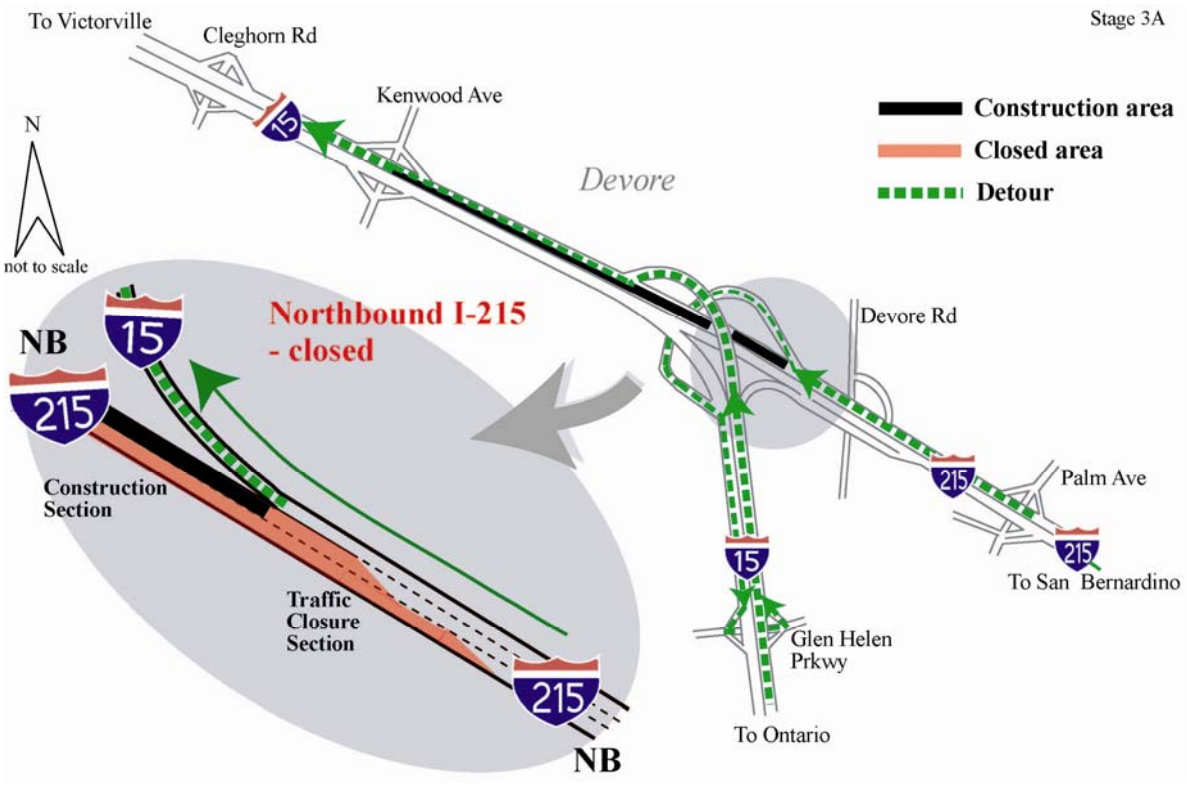

Figure 9: Stage 3A (fifth weekend closure, NB I-215, 55-hrs.).

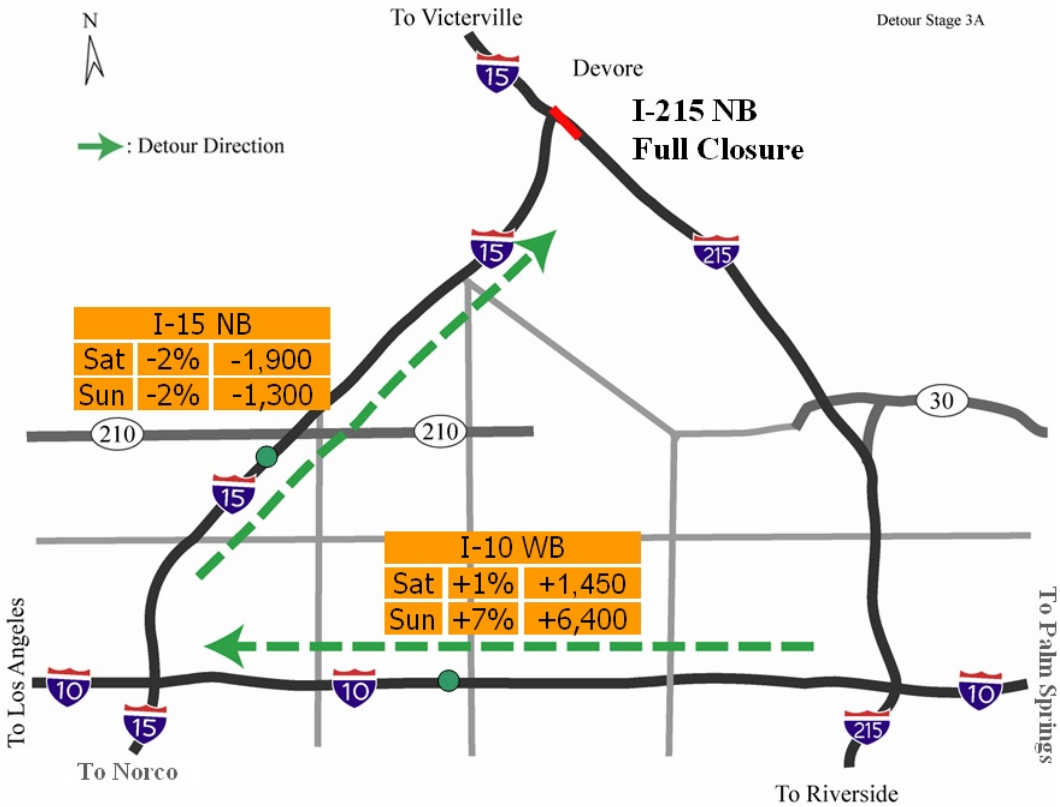

Figure 10: Traffic Changes on neighboring freeways during Stage 3A (fifth weekend closure, NB I-215, 55-hrs.).

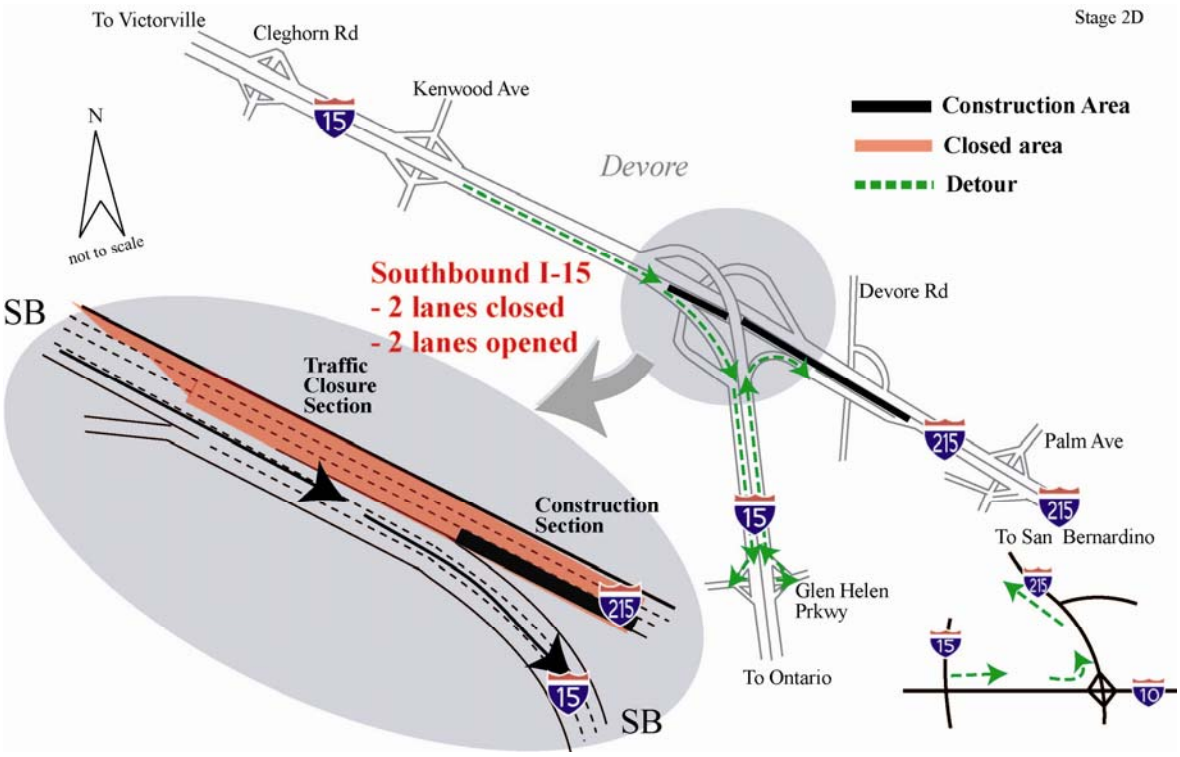

Figure 11: Stage 2D (sixth weekend closure, SB I-215, 20-hrs).

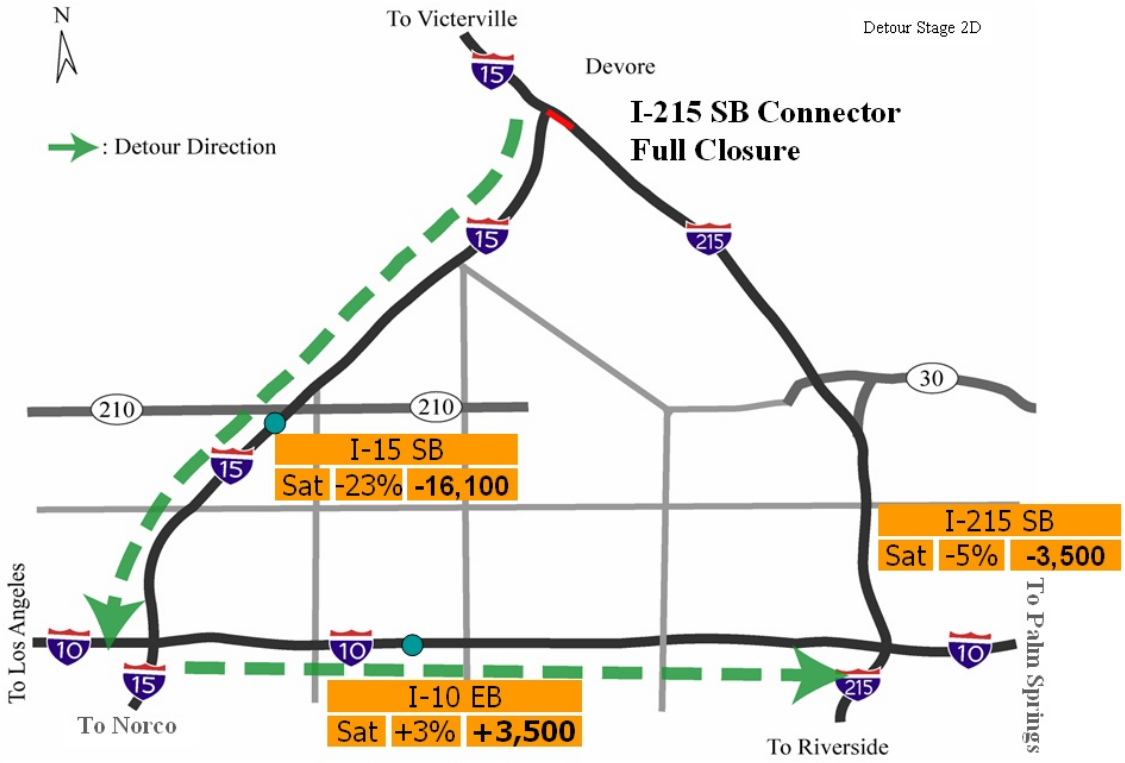

Figure 12 Traffic Changes on neighboring freeways during Stage 2D (sixth weekend closure, SB I-215, 20-hrs).

Figure 13: Demolition of PCC slab.

Figure 14: Milling of base.

Figure 15: PCC slab paving.

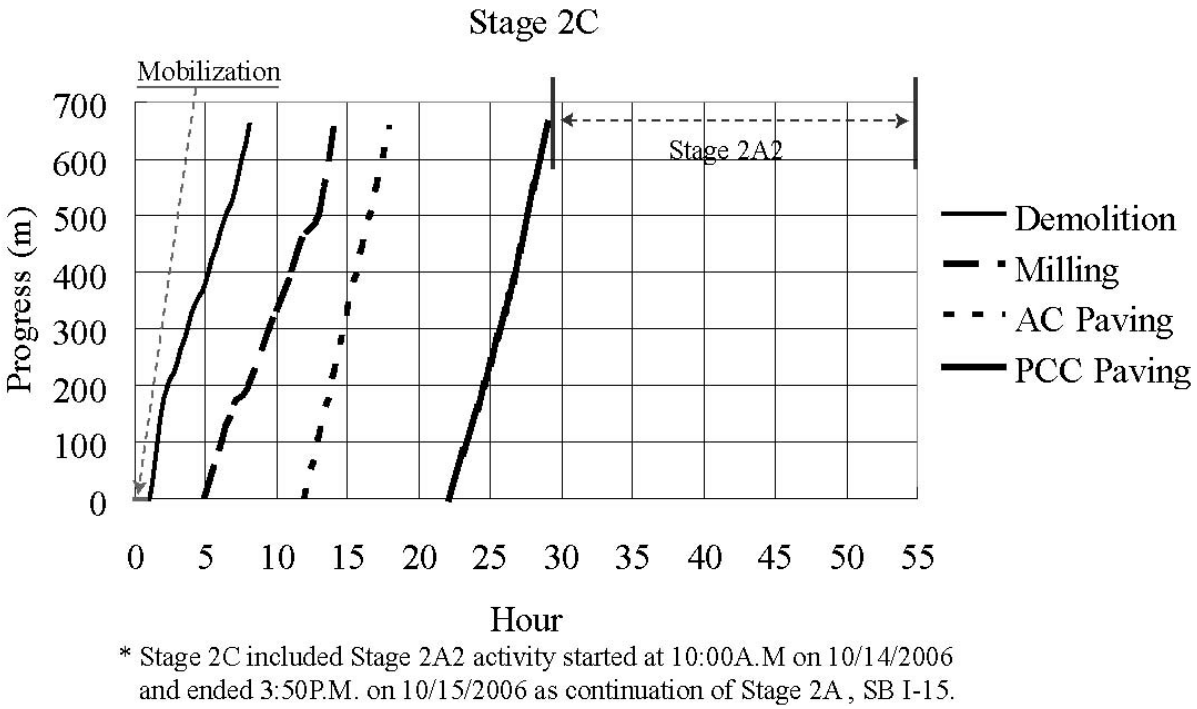

Figure 16: Productivity progress during Stage 2C (first weekend closure, 52-hrs.)

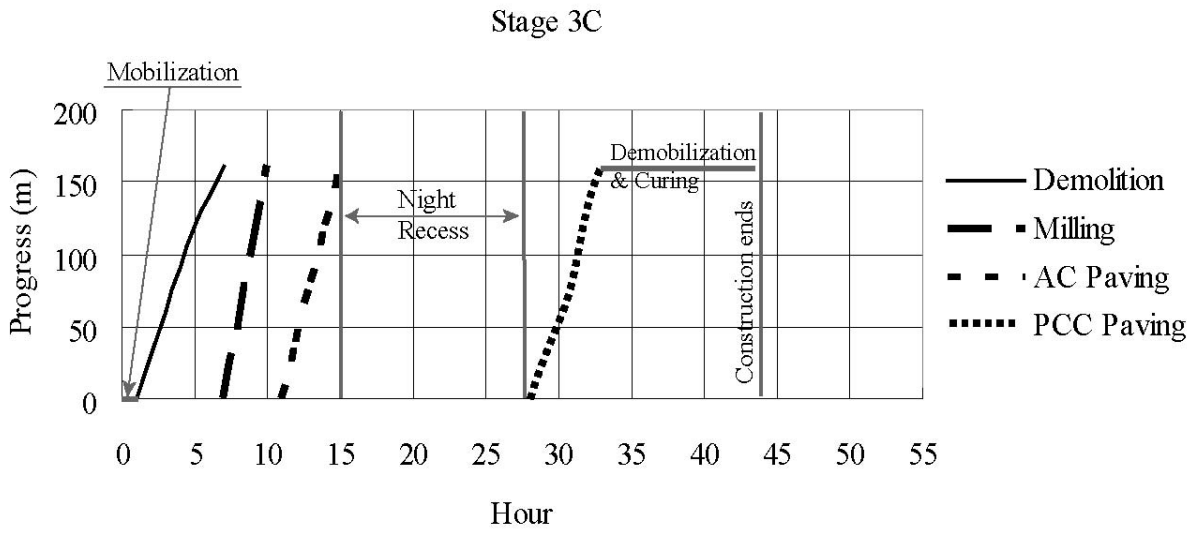

Figure 17: Truck load frequency during Stage 2C.

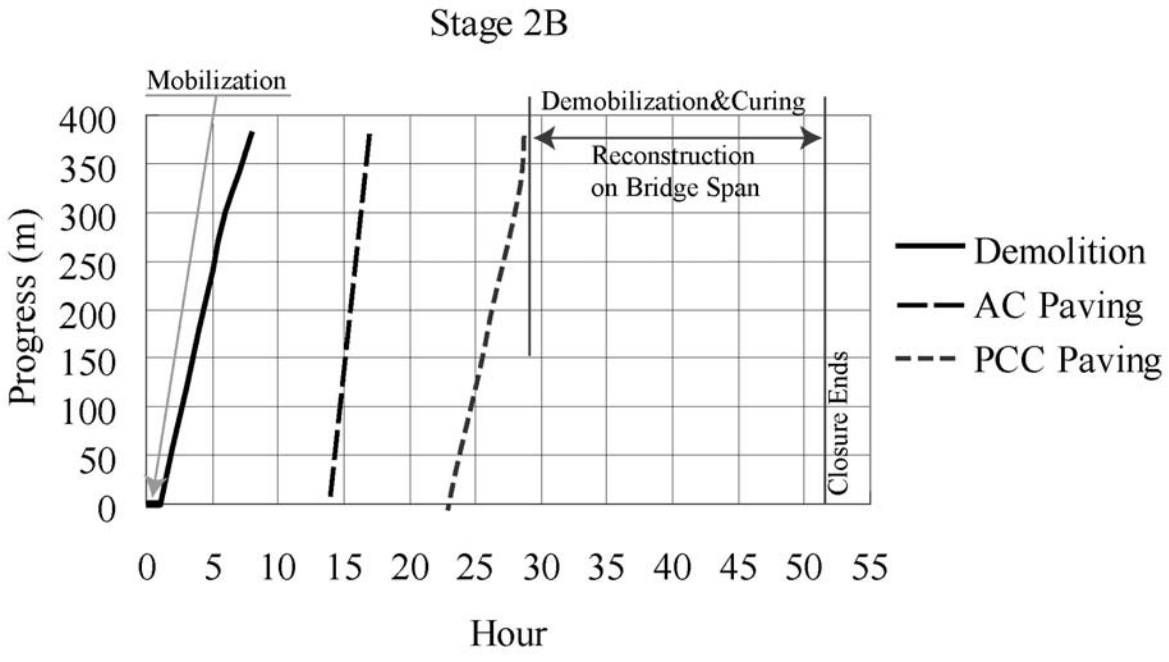

Figure 18: Reconstruction productivity progress during Stage 2B (second weekend closure, 52-hrs).

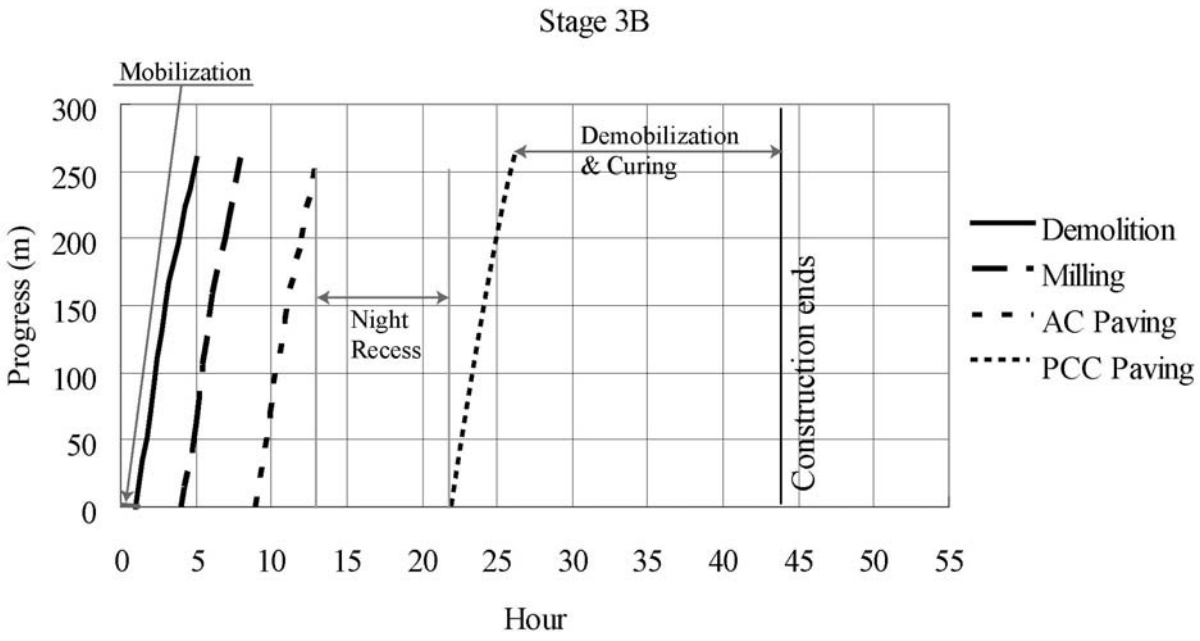

Figure 19: Reconstruction productivity progress during Stage 3B (NB I-15, 44-hrs).

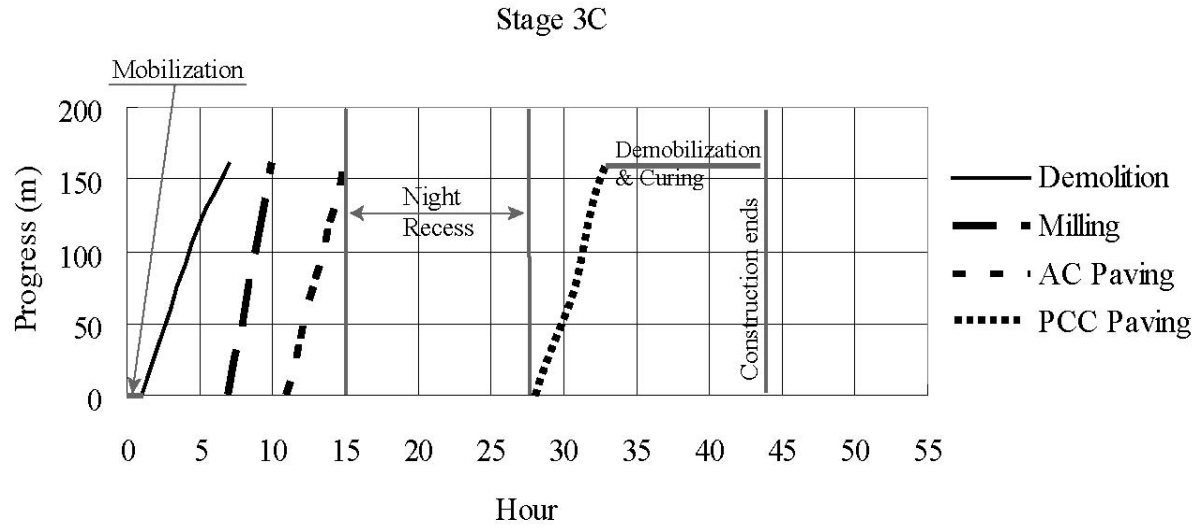

Figure 20: Reconstruction productivity progress during Stage 3C (fourth weekend closure, NB I-15, 44-hrs).

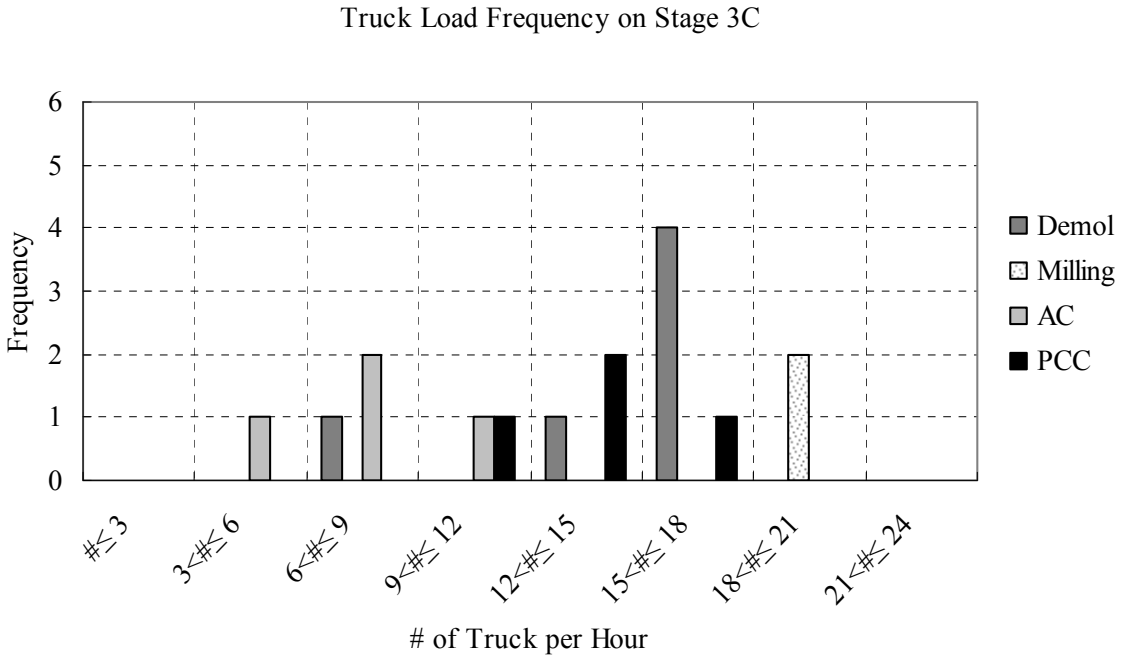

Figure 21: Truck-load frequency during Stage 3C (fourth weekend closure, NB I-15, 44-hrs).

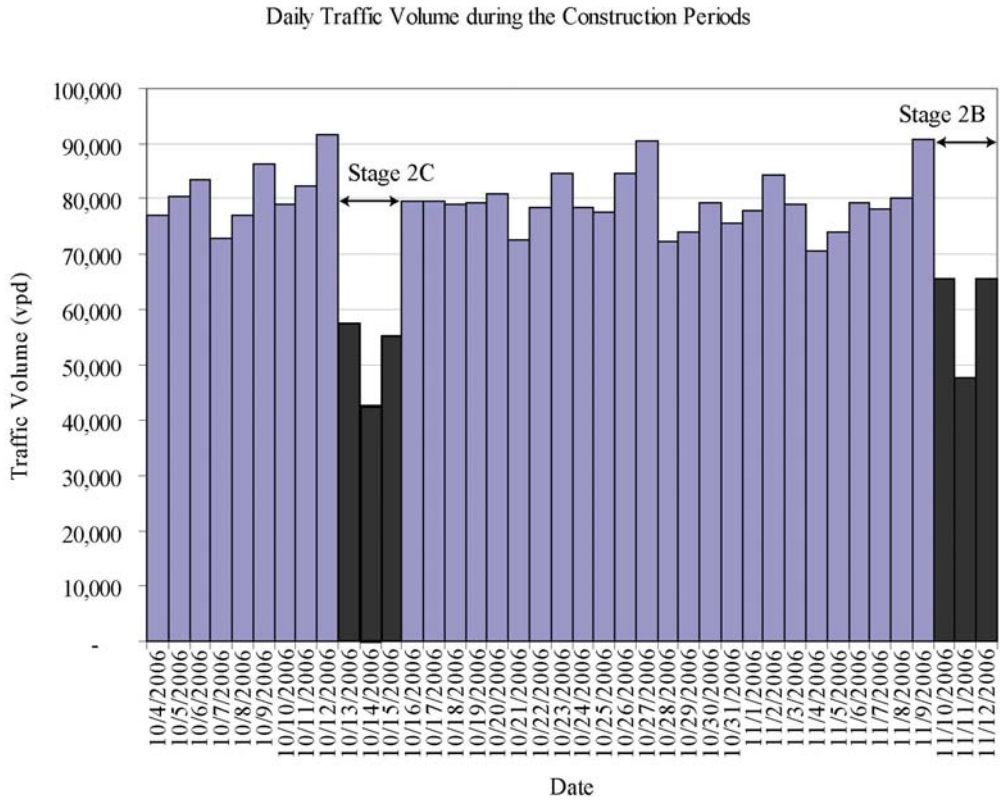

Figure 22: Daily traffic volume between 10/04/06 and 11/12/06 for Stages 2C and 2B.

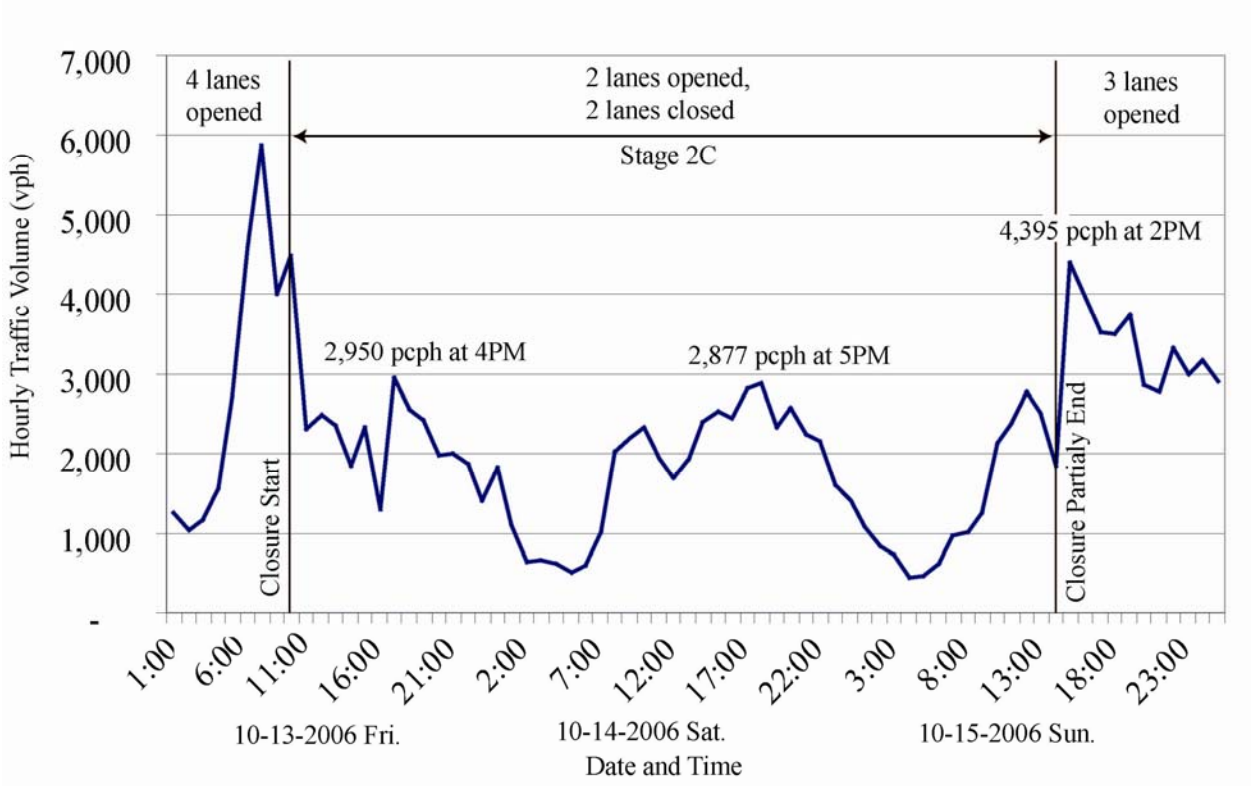

Figure 23: Hourly traffic volumes during Stage 2C (first weekend closure, SB I-15, 52-hrs).

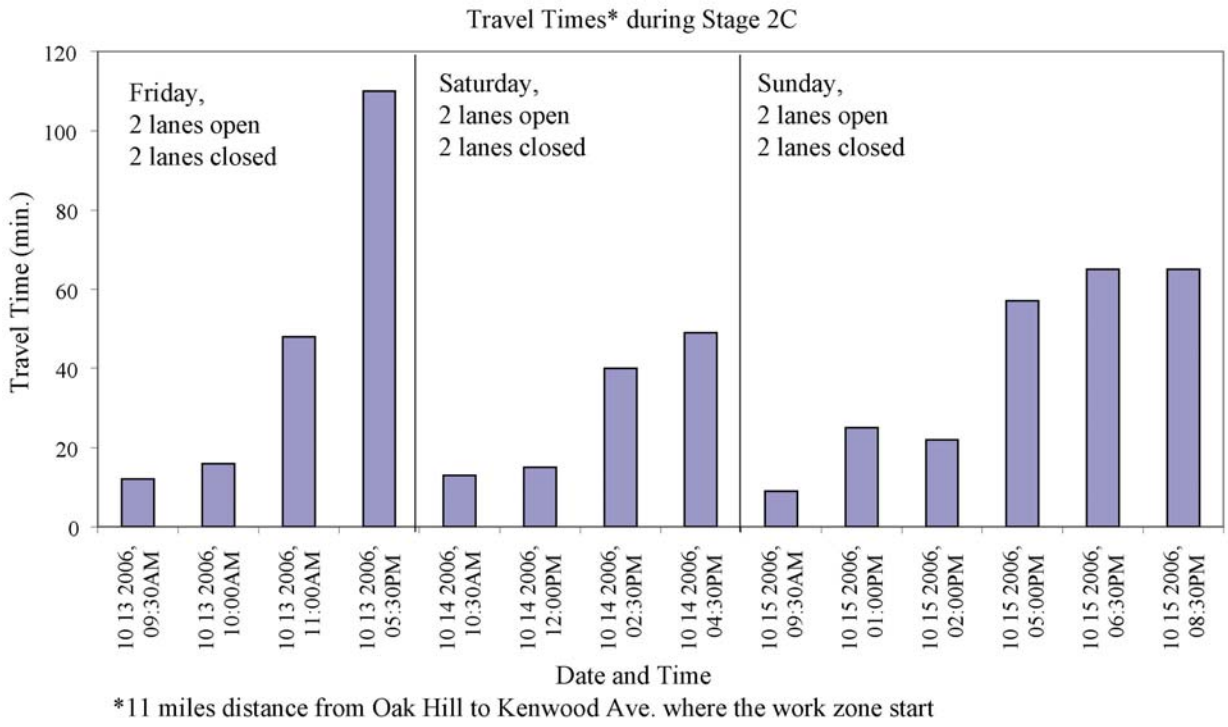

Figure 24: Travel time during Stage 2C (10/13/06~10/15/06).

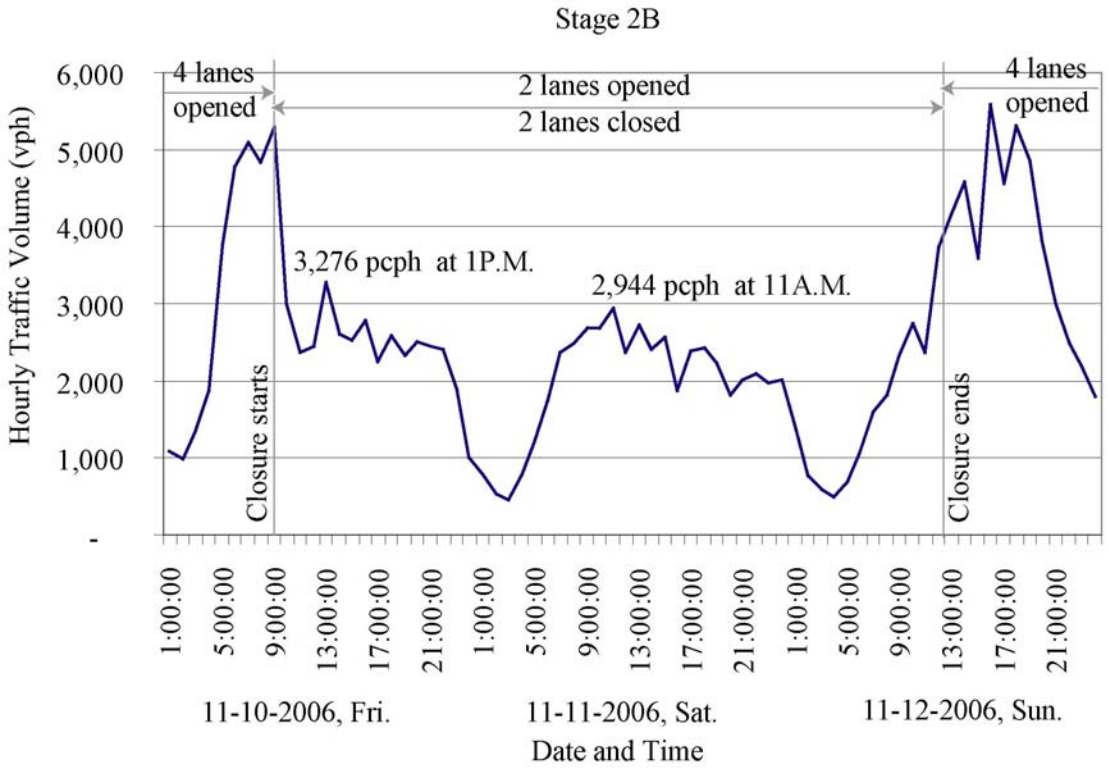

Figure 25: Hourly traffic volumes during Stage 2B.

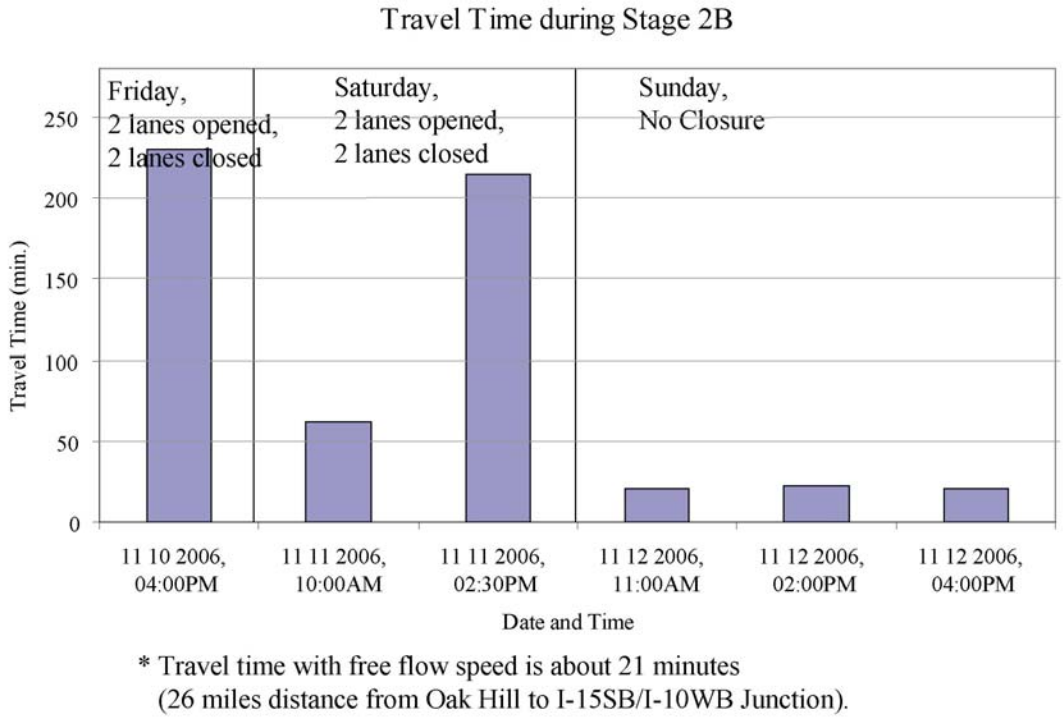

Figure 26: Travel times between 11/10/06 and 11/12/06 (Stage 2B, second weekend closure, 52-hrs).

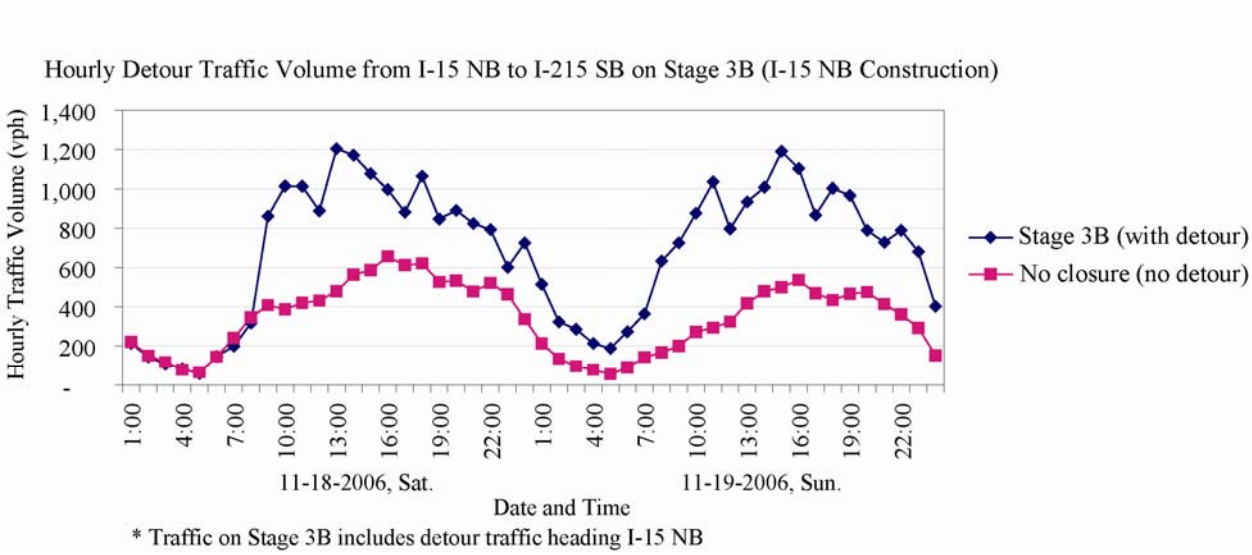

Figure 27: Hourly traffic volume comparison before- and during Stage 3B (second weekend closure, 52-hrs).

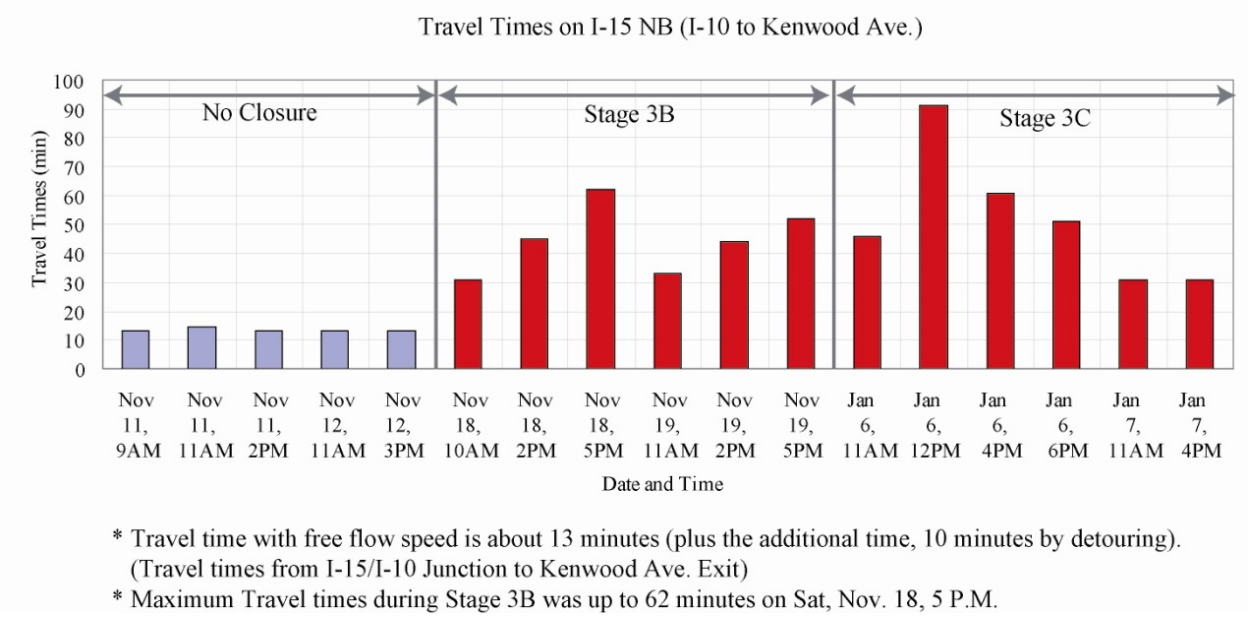

Figure 28: Travel times measured during Stage 3B and 3C.

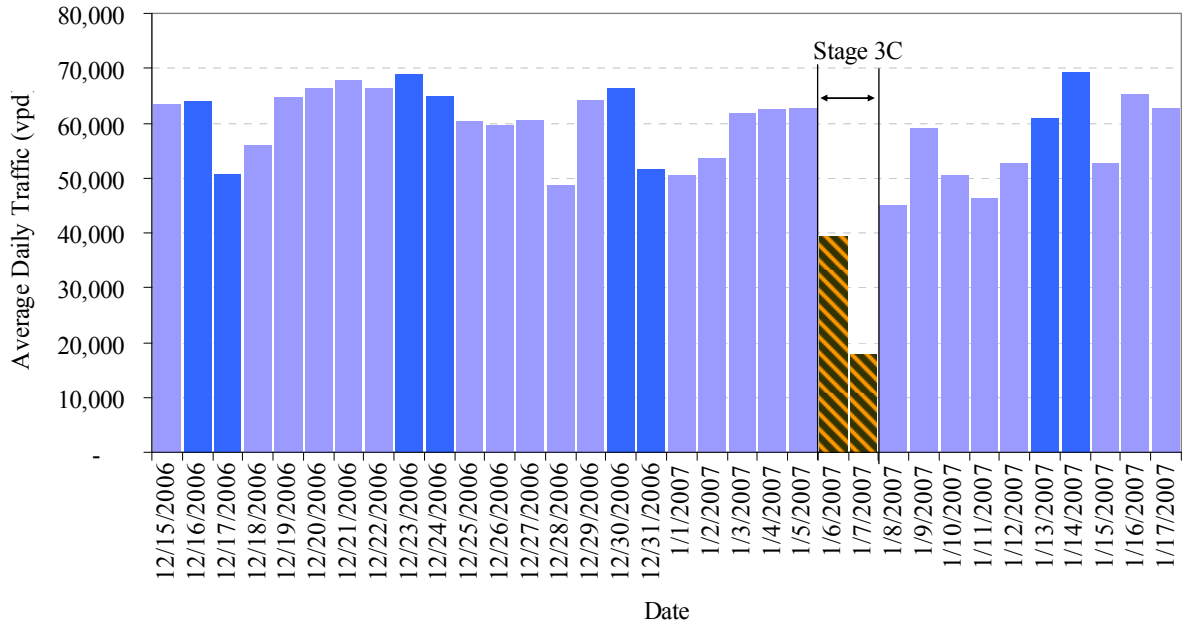

Figure 29: Daily traffic volumes during Stage 3C (fourth weekend closure, NB I-15, 44-hrs).

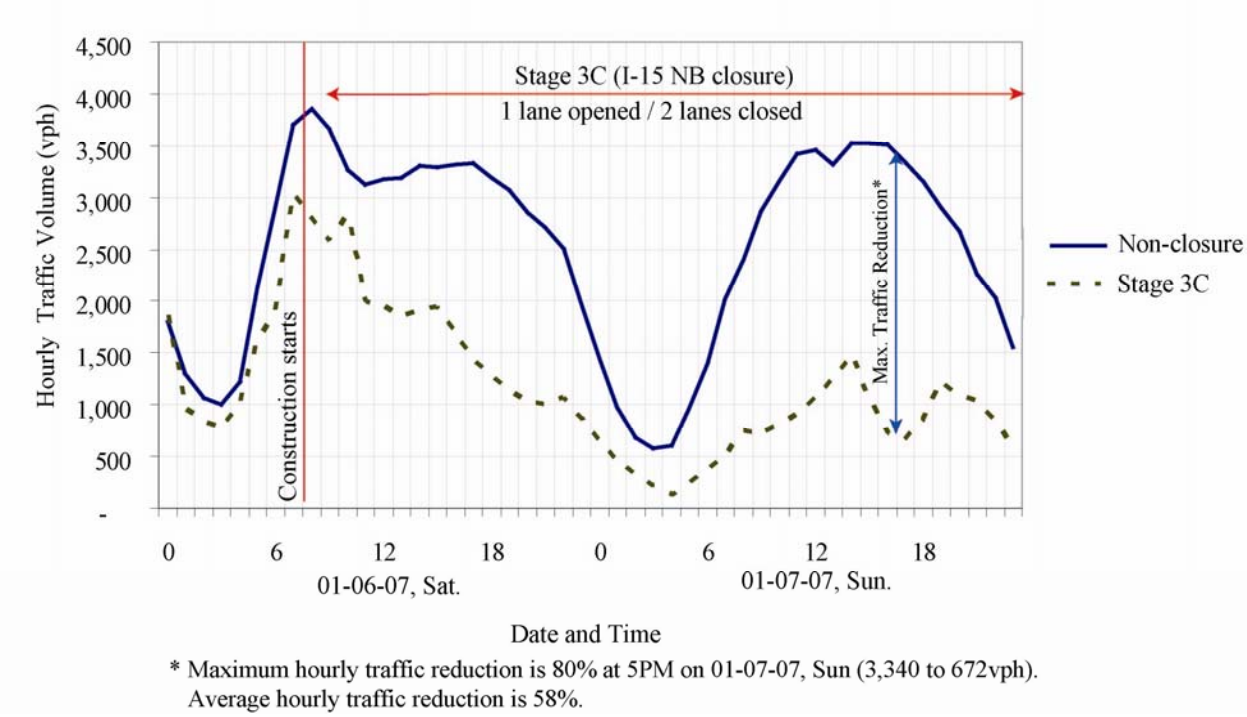

Figure 30: Comparison of hourly traffic volumes before- and during Stage 3C (fourth weekend closure, NB I-15, 44-hrs).

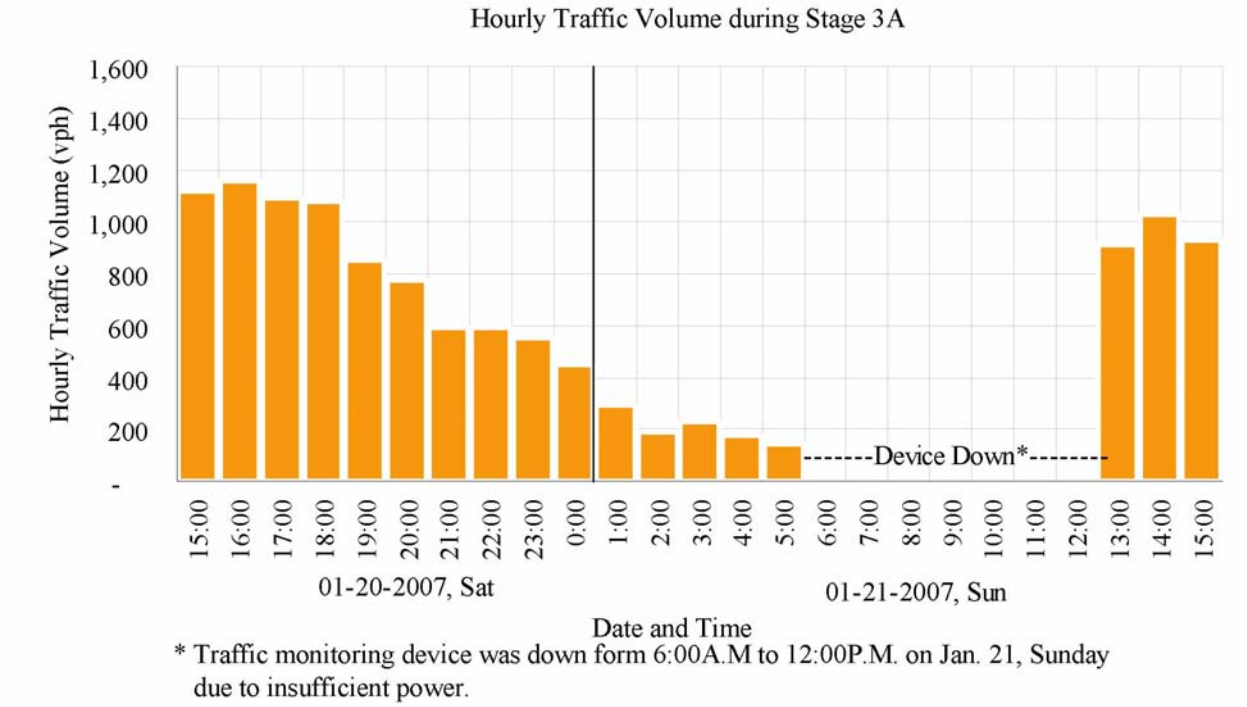

Figure 31: Hourly traffic volumes during Stage 3A (fifth weekend closure, NB I-215, 55-hrs.).

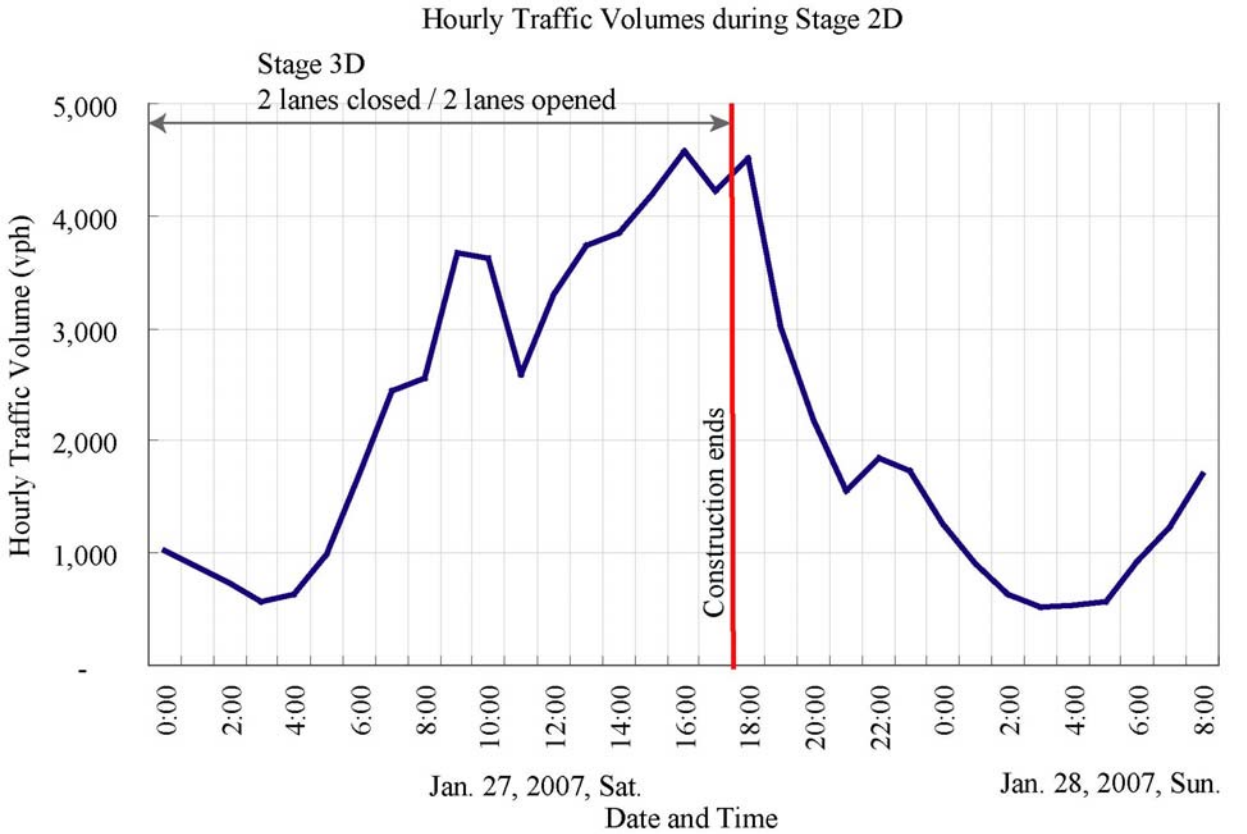

Figure 32: Hourly traffic volumes during Stage 2D (Sixth Weekend Closure, SB I-15, 20-hrs.).

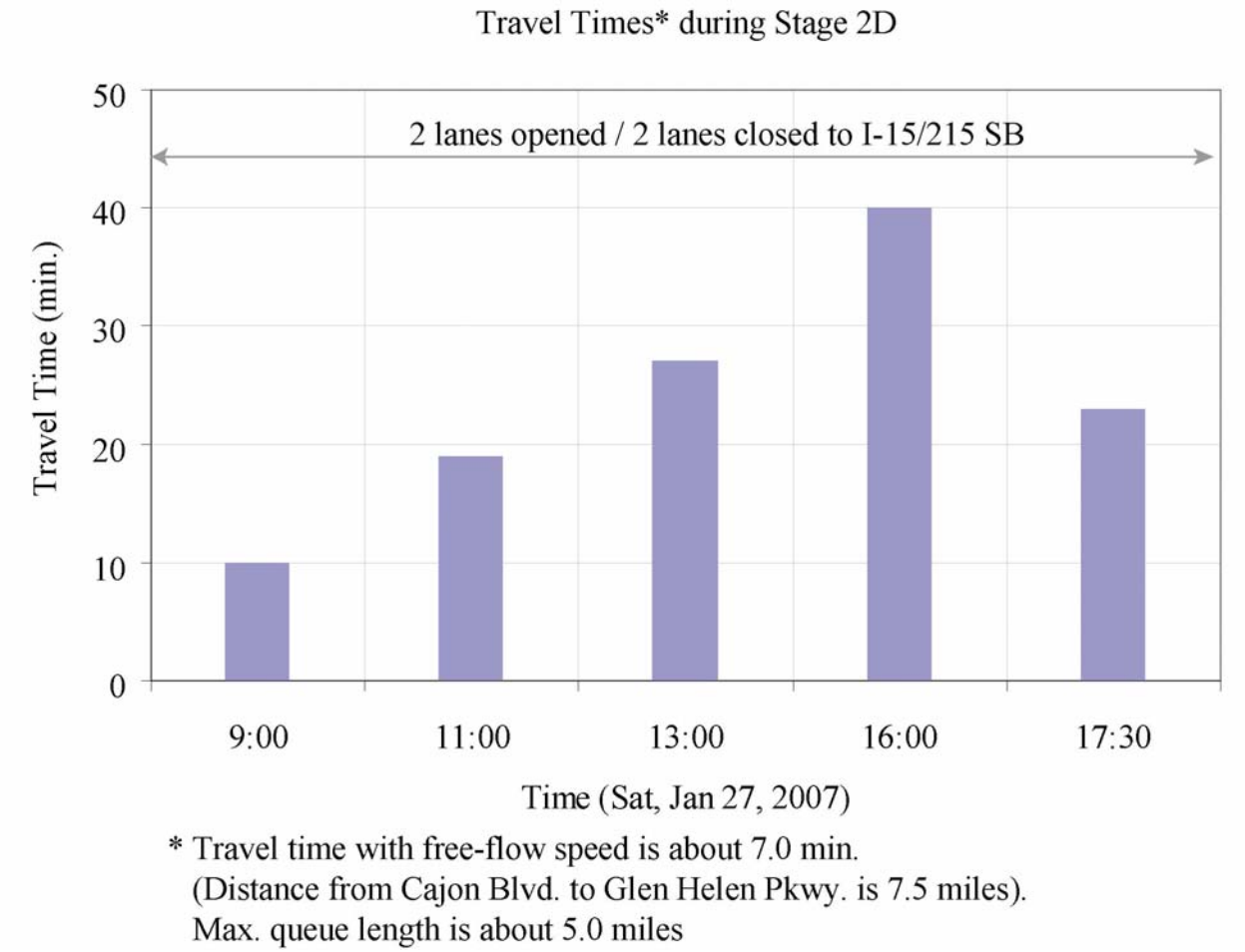

Figure 33: Travel times measured during Stage 2D (sixth weekend closure, SB I-15, 20-hrs.).