# Innovative Approach to Rapid Rehabilitation of Concrete Pavement on Urban Highway

Eul-Bum Lee[1], John T. Harvey[2], Kunhee Choi[3] and David Thomas[4]

## Abstract

This case study presents an innovative fast-track reconstruction approach applied to a heavily trafficked LLPRS project on Interstate-15 (I-15) in southern California. A 4.5-km stretch of badly damaged concrete truck lanes, two in each direction, was rebuilt in only two 210-hour (about 9 days) one-roadbed continuous closures, using counter-flow traffic and around-the-clock operations as accelerated construction, an undertaking estimated to take 12 months using traditional nighttime closures. This post-construction case study validated pre-construction estimates of productivity and traffic delay, which closely matched performance data measured during construction. The I-15 Devore project provided a unique opportunity to validate, fine-tune, and enhance highway analysis tools for future LLPRS projects. The use of CA4PRS schedule analysis and other traffic models presented in this study facilitates teambuilding amongst engineers involved in the design, construction, and traffic phases to mutually arrive at an optimal solution.

## Introduction

***California Highway Reconstruction.*** A More than 90 percent of the 80,000 lane-km (55,000 asphalt and 25,000 concrete) of the state highway system in California were built between 1955 and 1970 during the construction boom of transportation infrastructure. A pioneer in highway construction, California is now facing large-scale highway deterioration as this generation of pavements has far exceeded their original 20-year design lives and experienced increased traffic demands well beyond those initially considered. Pavement degradation adversely affects road user safety, ride quality, vehicle operation and highway maintenance costs, and rehabilitation of these pavements inevitably creates expensive traffic

[1] Research Engineer (Ph.D., PE, PMP), University of California at Berkeley, Institute of Transportation Studies, Bldg. 452 (PRC), 1353 S. 46th Street, Richmond, CA 94804, email: eblee@berkeley.edu
[2] Associate Professor, Dept. of Civil & Environmental Engineering, University of California at Davis, 3139 Engineering III, 1 Shields Avenue, Davis, CA 95616, email: jtharvey@ucdavis.edu
[3] Graduate Student Researcher, Dept. of Civil & Environmental Engineering, University of California at Berkeley, 213 McLaughlin Hall, Berkeley, CA 94720, email: kunhee@ berkeley.edu
[4] Chief Design Engineer, California Department of Transportation (District 8), 464 West 4th Street, San Bernardino, CA 92401, email: david_k_thomas@dot.ca.gov

delays (Leather 1987). In response, Caltrans launched the LLPRS program in 1998 with the purpose of providing “long-lasting with lower-maintenance pavement”, putting into practice the concept of “Get-in, Get-out, and Stay-out” embraced by the Federal Highway Administration (FHWA) and the Transportation Research Board (TRB 2000a). Caltrans’ commitment to the “Get-in, Get-out, and Stay-out” philosophy includes building roads with 30-plus years of life expectancies that will reduce the need for future repair projects, limit traffic congestion associated with roadway maintenance and rehabilitation, and ultimately save money for future generations of road users.

Based on a preliminary life cycle cost analysis and evaluation of the agency’s future cash flow, approximately 2,800 lane-km were selected as initial LLPRS candidate projects to be rehabilitated over a period of 10 years. LLPRS candidate projects were selected from among highways with poor pavement structural condition and ride quality, and a minimum average daily traffic load of 150,000, or an average load of 15,000 heavy trucks (Caltrans 1998). Most LLPRS candidate sections are Portland cement concrete (PCC) pavements on interstate freeways in urban networks, 80 percent within the Los Angeles basin, and 15 percent in the San Francisco Bay area.

Urban highway rehabilitation projects under high traffic volumes often create undesirable effects for state highway agencies, motorists, and commercial enterprises, including congestion, safety problems, and limited property access. Especially, severe traffic disruption for motorists and business in the construction work zone closures comes into conflicts between state highway agencies and abutting communities. To mitigate these problems, highway planners, designers, and traffic managers have a need to expedite rehabilitation schedules through the use of comprehensive construction and traffic management plans (de Solminihac and Harrison 1993). Caltrans, mindful of the challenges posed by high traffic volumes experienced during LLPRS closures, has placed a particular focus on: 1) minimizing traffic disruptions and road user cost (RUC); 2) providing a safe construction work environment for crew and road users; and, 3) reducing impacts on the business community and the environment (Lee et al. 2000).

The experience of pavement engineers in California has been that nighttime closures, still a typical practice for pavement repair and maintenance activities in the state’s urban highway networks, are not generally applicable for LLPRS projects. Construction access constraints associated with short-timeframe nighttime closures limit the ability of contractors to deliver the large volumes of hauling and delivery materials needed for the construction of long-life pavement, which contributes to low construction productivity relative to what can be achieved during extended closures.

In recognition of the limitations of nighttime closures, Caltrans has experimented with innovative pavement rehabilitation strategies for its LLPRS projects, using accelerated construction approaches such as multiple (repeated) extended 55-hour weekend or 72-hour weekday closures and 24-hour operations. The concept of the 55-hour extended weekend closure (Friday, 10 p.m. through Monday, 5 a.m.) was validated in 2000 on the first concrete LLPRS demonstration project on Interstate-10 (I-10) in Pomona (Lee et al. 2002), and in 2003 on the first asphalt LLPRS demonstration project on Interstate-710 (I-710) in Long Beach (Lee et al.

2005b). The construction monitoring study on the I-10 Pomona project showed that, on average, construction during the 55-hour weekend closure was 40 percent more productive, measured in linear meter rebuilt per hour, than productivity achieved during traditional nighttime closures.

***Objectives and Approach.*** The question of how to economically rebuild deteriorating highways in metropolitan areas, while minimizing disruptions to the commuting public and surrounding business is a challenging task for state transportation agencies. Most state highway agencies are under increased pressure to complete their highway construction projects ahead of schedule. Further, the public has demonstrated a willingness-to-pay (WTP) to avoid severe traffic disruptions during highway construction, with the expectation of the benefits from accelerated project completion (FDOT 1997). In addition, increases in highway maintenance and rehabilitation have brought to the fore the need for research to improve current construction practices to reduce adverse impacts on motorists and adjacent communities. Until recently, no systematic research has been conducted with the goal of integrating pavement materials and design, construction logistics, and traffic operations, all of which are essential in determining the most cost-effective rehabilitation practices (Anderson and Russell 2001).

Transportation agencies and contractors can use the results of this study for developing sound pavement rehabilitation strategies that maximize construction productivity, minimize traffic delay, and mitigate the total cost for high traffic volume highways. The advantages of using this method of accelerated construction were: shortest period of disruption for the traveling public; greater life expectancy for the new pavement than could have been obtained using nighttime closures; improved safety for motorists and workers; and significantly reduced construction costs. California now has a unique opportunity to validate and further calibrate the processes, tools, and expertise used on fast-track pavement reconstruction projects under heavy traffic volumes in urban highway networks. This post-construction report was prepared to gather "lessons learned" from the I-15 Devore project for use on future LLPRS projects, especially focusing on state-of-practice features to (1) accelerate construction, (2) mitigate traffic delay impacts, and (3) propagate project information to the public.

## I-15 Devore Project

***Project Overview.*** In October 2004, Caltrans reconstructed 4.2 km of aging concrete pavement on the two truck lanes of I-15 from Sierra Avenue to the I-215 junction in Devore. (Figure 1). This was a section of pavement typical of 1970s-era Caltrans design, i.e., 200 mm of (undowelled plain jointed) concrete slabs over 100 mm of cement treated base.

According to Caltrans traffic statistics, I-15 is one of the state's most heavily traveled routes. The Devore corridor carries average daily traffic (ADT) of approximately 110,000 vehicles, about 10 percent of which are heavy trucks. In contrast to typical urban freeways in California, which have high traffic volumes during rush-hour weekday peak periods and lower traffic volumes on weekends, the Devore corridor has consistently high weekday commuter peaks and even higher leisure traffic volume on weekends. The two highest peak traffic volumes are northbound (NB) on Friday afternoon and southbound (SB) on Sunday afternoon, when leisure travelers in the Los Angeles area are going to and from Las Vegas and to resort locations along the Colorado River. I-15 is also a main route used by truckers transporting goods across the state.

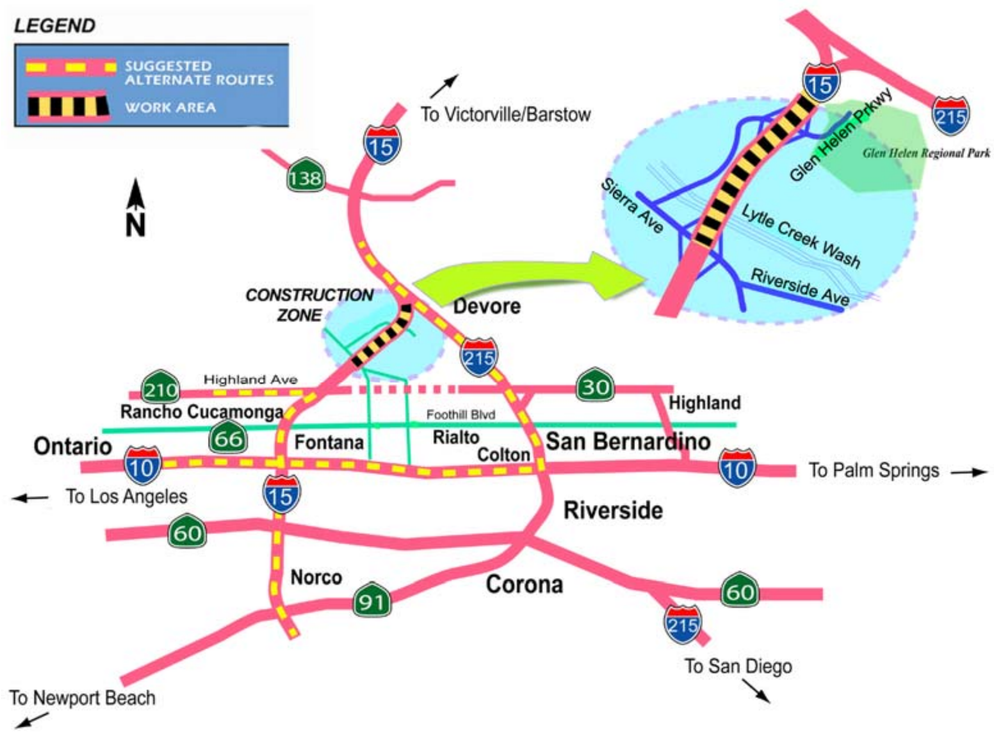


**Figure 1. The I-15 Devore reconstruction project site**

Since the initial construction of these pavements, between 1969 and 1975, increases in automobile and heavy truck traffic along I-15 had resulted in damage for which an AC overlay or slab repair as routine maintenance could not provide an effective long-term solution. Caltrans pavement management engineers estimated that the road surface would not survive even another winter without severe breakdown of the roadbed, and determined that rehabilitation was needed from the gravel base up.

Reconstruction was split into two segments. Segment 1 consisted of a 2.5-km stretch with four lanes in each direction between the Sierra Avenue and Glen Helen Parkway intersections. Segment 2 consisted of a 2.0-km stretch from the Glen Helen Parkway intersection to the I-215 system interchange with three lanes in each direction. The objective was to replace the damaged concrete pavements with a new cross-section of 290-mm doweled slabs using rapid strength concrete (RSC), including placement of a 150-mm AC base on the top of the remaining aggregate base. (Figure 2).

The construction staging required the NB freeway to be closed for reconstruction first, switching traffic to the SB side through the median crossovers at the ends of segments 1 and 2. Construction occurred on the two truck lanes while the two inside lanes were used for access by construction trucks and other equipment. (see Figure 3). The two directions of traffic shared the southbound lanes as “counter flow traffic” separated by a quick changeable moveable barrier (QMB). Ramps in the work zone were closed to traffic other than construction equipment. The outside shoulder was used as a traffic lane in Segment 2 to allow two lanes for each direction of traffic. The same process was repeated for the reconstruction of the SB direction.

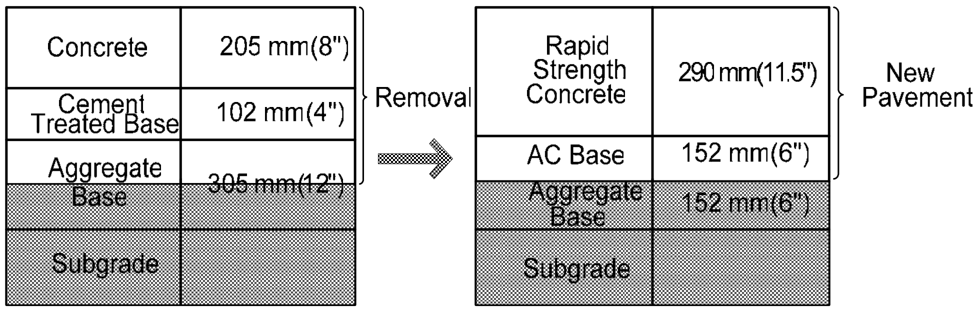


**Figure 2. Pavement cross-section change**

***Pre-construction Analysis.*** An integrated approach was applied in the pre-construction analysis for the I-15 Devore project with the goal of selecting the most economical closure scenario from the perspective of construction schedule, traffic inconvenience, and agency cost. Four construction closure scenarios (72-hour weekday, 55-hour weekend, one-roadbed continuous [24/7], and 10-hour nighttime) were compared from those above mentioned perspectives and each was found to have strengths and weaknesses. Some scenarios were deemed unacceptable to either Caltrans or the public. An integration of these construction, traffic, and cost evaluation criteria was developed to select the most economical closure scenario for the LLPRS project.

The integrated analysis concluded that the one-roadbed continuous closure scenario was the best strategy in terms of schedule comparison and road user and agency costs (Table 1). The analysis showed that the one-roadbed continuous closure scenario required 81 percent less total closure time, 29 percent less road user cost due to traffic delay, and 28 percent less agency cost for construction and traffic control compared to traditional 10-hour nighttime closures (Lee et al. 2005c).

The outer truck lane was to be 600 mm wider than the existing configuration as part of a long-life pavement design intended to reduce edge loading of trucks on the outer edge of the slab. Replacement of all bridge approach and departure slabs was also included. AC shoulders were also planned for rehabilitation within the same closure period and were to be cold-planed (milled) to approximately 60 to 75 mm of the existing AC shoulder and overlain with the new pavement.

**Table 1. The Comparison of Alternative Closure Scenarios from the Perspective of Estimated Schedule, Delay, and Cost**

| Closure Scenario (1) | Schedule comparison | | Traffic comparison | | Cost comparison | |
|---|---|---|---|---|---|---|
| | Closure number (2) | Closure hours (3) | Road user cost ($M) (4) | Peak delay (minute)* (5) | Agency cost ($M) (6) | Total cost+ ($M) (7) |
| One-roadbed continuous | 2 | 400 | 5 | 80 | 15 | 20 |
| 72-hour weekday | 8 | 512 | 5 | 50 | 16 | 21 |
| 55-hour weekend | 10 | 550 | 10 | 80 | 17 | 27 |
| 10-hour nighttime | 220 | 2,200 | 7 | 30 | 21 | 28 |

+ Total cost = road user cost + agency cost (per row)
* Peak hour maximum queue delay based on the assumption of 20 percent traffic demand reduction

***Dynamic Response to Challenge.*** The I-15 Devore project location presented difficult challenges for Caltrans in terms of meeting the needs of the area's daily commuters, who normally travel an average of 1 to 2 hours each way to work destinations in San Bernardino, Los Angeles, and Orange County. The only alternate route around the CWZ through I-10 and I-215 added 22 miles and 45 minutes to the daily commute both ways.

There was a lot of skepticism about the initial approach of the 72-hour weekday closures scenario among the public and that skepticism was often covered by the local news media. As reported in the media, public feedback from community meetings indicated that people's biggest fear was being late for work and losing their jobs. Caltrans responded with a commitment to reduce the inconvenience (delay) of road users through the CWZ during one-roadbed continuous closures (called "extended closures" hereafter) through the implementation of innovation and technologies. With the state-of-practice features to achieve the goal of minimizing the impact of this accelerated construction project on traffic delay, described in the following section, Caltrans' focus was on: (1) increasing roadway capacity through the CWZ with the temporary conversion of the rehabilitated shoulder to the main lane; (2) diverting more traffic demand through the I-15 Devore corridor to neighboring detour freeways; and (3) deploying a proactive public outreach effort that included regular project updates. It was observed that the direct cost increase for the implementation of the additional features, usually related to contract change orders, was eventually repaid through the value of time saved to road users and improvements in the public perception of Caltrans and the accelerated construction approach, as discussed in the later section.

Caltrans' solution was to implement a one-roadbed continuous closure scheme, with a 24 hour per day/7 day per week by combining weekday and weekend closures. This accelerated construction compressed the original 6-week project schedule with 72-hour weekday closures to less than 4 weeks and allowed project completion by the end of October 2004. Caltrans' responsiveness to the public's concerns received much praise from the public and politicians alike and proved instrumental in saving the project and setting high standards for what can be accomplished under the "Rapid Rehab" slogan.

## Innovation and Technology

***State-of-Practice Features.*** This innovative highway reconstruction process – known as the "Rapid Rehab" approach – is the latest effort by transportation agencies to devise accelerated construction techniques that compress construction schedules without increasing maximum peak-hour delays.

The I-15 Devore "Rapid Rehab" project utilized an integrated process to evaluate project alternatives based on the scenario comparison framework for LLPRS. Through the evaluation process, the most economical reconstruction scenario from the perspective of schedule, traffic, and cost was selected. "Rapid Rehab" benefits compared to traditional nighttime closure approach include:

- Faster construction and project delivery (4 weeks versus 12 months for the traditional night-time method).
- Shorter period of disruption to commuters and the traveling public.
- Pavement doubled lifespan expected to last 30 years instead of the average 15 years.
- Separating traffic from the work zone improves safety for workers and motorists.
- Reduced construction costs (25 percent on I-15 Devore, resulting in $6 million in savings).
- Improved safety factor: The "Rapid Rehab" approach provides an added safety benefit for both construction workers and motorists. With all traffic confined to the adjacent roadbed, construction traffic and workers are not directly exposed to an active roadway.

The I-15 Devore project combined conventional construction materials and operations with the state-of-practice technologies to expedite construction and to minimize traffic delay impact, including:

- Reducing the extended weekday only closure period from 6 to 4 weeks by working continuously to balance impacts on weekday commuters and weekend recreational travelers.
- Providing three lanes with a temporary additional lane converted from the shoulder for the peak weekday morning commute guaranteeing minimal delays for one commute direction with the QMB dynamic lane configuration by movements in the live traffic twice a day. (Figure 3).
- Providing Automated Work Zone Information Systems (AWIS) for travelers in the construction zone with near real-time travel time and detour route information displayed on changeable message signs.
- Equipping a project command center with Closed Circuit Television (CCTV) capability for traffic and construction monitoring.
- Writing incentive/disincentives (I/D) into the construction contract to accelerate the contractor's work and minimize impacts on the traveling public.
- Providing an Internet project web page featuring real-time traffic map and project updates.
- Utilizing rapid strength concrete with Type III cement for achieving a 12-hour opening strength to traffic.

- Establishing a High Desert Commuter Advisory Committee (HDCAC) to meet twice during the construction period to share information and receive constructive input from the public.
- Funding a free commuter bus service from the High Desert through the construction zone to promote ridesharing.

Details of the above-listed features are described in the following sections.

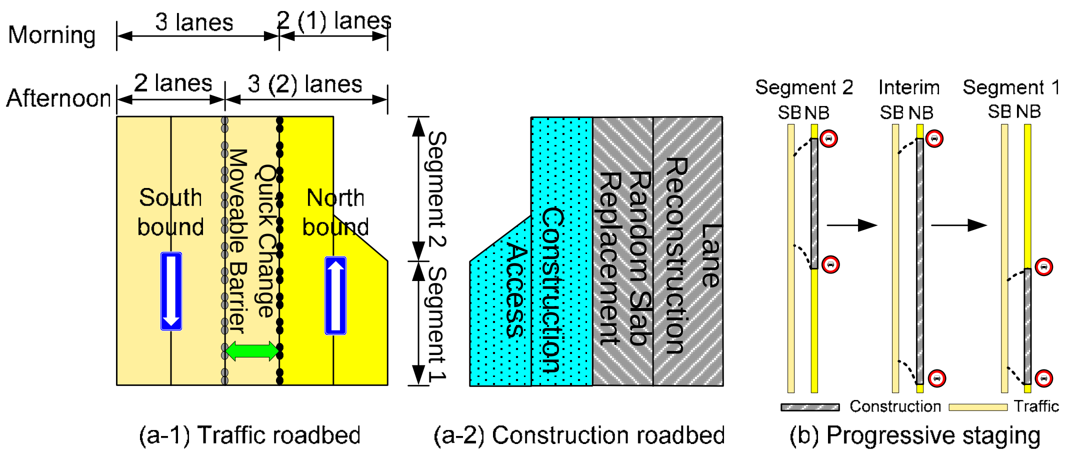


**Figure 3. Dynamic lane configuration on traffic roadbed with QMB and progressive-staging on construction roadbed**

***Incentives Provisions.*** Construction planning for urban highway rehabilitation must focus on speeding up the construction process by incorporating such concepts as contingency management, incentives/disincentives (I/Ds), and cost (A) plus schedule (B) (A+B) bidding by balancing the traffic needs of road users on one side of the lane closure barrier and construction access with equipment on the other (Arditi et al. 1997). With high traffic volume through the CWZ, three levels of time value provisions were specified for the contractor in the contract to ensure the completion of closures on time: (1) incentives/disincentives requirement for the extended closures, (2) late opening penalty for the segment with 3-lane section, and (3) A+B contracting for the entire project.

The Devore project incorporated the unique approach of using the additional cost associated with road user traffic delay to develop the I/D requirement. The assessment of I/Ds was based on the CA4PRS production schedule and traffic simulation analyses (Lee et al. 2005a). Due to a high demand of traffic volume during closures, and the public desire for early completion of the reconstruction, Caltrans decided to apply two types of I/D provisions to encourage the contractor to complete the closure ahead of the engineer's estimated schedule. The primary incentives were to minimize the duration of each one-roadbed closure. The secondary provision incentives were to minimize the total closure days of the extended closures.

The projected RUC, determined by using the demand-capacity spreadsheet based on the Highway Capacity Manual (HCM) model, was used as the baseline for the I/Ds calculation for the one-roadbed closures. However, only one-third of the

RUC was factored into the I/D calculation, a practice commonly used in other states. The incentives were limited by the realities of the budget limitations of the State of California, and a value of $600,000 was used for the incentive cap.

The contractor was eligible for a closure incentive bonus of $300,000 if one-roadbed continuous closure was completed in equal or less than two units of time segment (111 hours per unit), and was subject to a closure disincentive penalty without a limit if the closure took longer than three units of time segment (one extra was given for realistic flexibility). In addition to this closure incentives requirement, the contractor was eligible to receive a daily incentive bonus of $75,000 if the entire major reconstruction was completed in fewer than 19 days (a total of 456 hours), and was subject to a daily disincentive penalty (without a limit) if the reconstruction took longer.

The overall contract was also eligible for A+B, though this had little impact on the extended closures or the reduction of impacts on the traveling public for the extended closure period. The A+B contracting method is applied to the overall construction period of the contract, which was beneficial to this contract because there was a desire to complete the entire contract as soon as possible. In this case, liquidated damages for the overall contract were established at around $12,000 if the total working days in the bid were exceeded. The A+B contracting method allowed the contractor to bid on the number of total working days and get credit towards the bid for the working days that were estimated. Before and after the extended closures, miscellaneous nighttime rehabilitation activities were performed with some lane closures.

***Project Website.*** The project website linked as the first headline on the District 8 home page provided a valuable tool for road users through the CWZ corridor. A project website was created to provide information to those in the target audience with Internet access. The website was launched in July 2004, 3 months before the construction started, and updated regularly with the following features:

- Schedule update and lane closure scheme information
- Traffic control plan including detour routes with traffic road maps
- Benefits to the public of extended closures compared to nighttime closures
- Press releases and fast-fax for project update
- Scheduled public meetings
- Frequently asked questions (FAQs)
- Project progress photos and innovative features
- Real-time travel information
- Before- and during-construction surveys.

The web statistics analysis by Caltrans information systems indicated that the number of hits on the Devore project website started with a total of about 75,000 in the month of August, 2004, when the website was finally opened. Due to a restriction of the server security, hits were calculated based on each page visit, rather than on unique visitors. The hit numbers on the project website increased significantly to about 225,000 in October when extended closures were in process. That number represents three times higher linear expansion in just two months since August. The hit numbers diminished sharply after the extended closures were completed, but some road users still have a habit of checking even nighttime closure situations, as shown in hits in November (100,000) and December (50,000).

**Work-Zone Traffic Management**

The construction staging plan required the NB freeway to be closed for reconstruction first, switching traffic to the SB side through the median crossovers at the north and south ends of the construction boundary. The two directions of traffic shared the SB lanes as "counter flow traffic," separated by a QMB. (Figure 4). Some on-ramps in the CWZ were closed to traffic other than construction equipment. The outside shoulder was rehabilitated with AC during the nighttime prior to the extended closure to be used as an additional main traffic lane in Segment 2, which had three main lanes. The same process was repeated for the reconstruction of the SB direction.

**Figure 4. Pavaing operation on construction roadbed and counter-flow traffic with QMB on traffic roadbed**

***Demand-oriented Control.*** The traffic sensitivity analysis during the planning stage predicted a 92-minute maximum peak delay during weekdays even if there were to be a 10 percent reduction in traffic demand as a combination of "no show" (motorists avoiding the area) and diversion (motorists using alternative routes). Caltrans suggested commuters avoid the CWZ during peak hours (i.e., from 6 to 9 a.m. on the SB lanes, and from 3:30 to 6 p.m. on the NB lanes). If 20 percent of commuters were to change their commuting times, and also take I-10 and I-215 as an alternate route weekday maximum, delay times were expected to be cut in half (45 minutes).

***Capacity-oriented Control.*** Unlike most freeways in the region, traffic on I-15 remains heavy on the weekend because of motorists traveling to Las Vegas. Monday through Thursday, a projected 57,000 vehicles on average traveled I-15 SB through Devore in each 24-hour period, while 54,000 vehicles passed through NB. The numbers are greater on weekends: NB traffic on Friday averages 65,000 vehicles, and

SB traffic on Sunday averages 63,000 vehicles per day. The plan to balance the traffic impacts between the commuters and weekend travelers required a dynamic lane configuration, with the additional one lane converted from the AC shoulder rehabilitation temporarily during the extended closure. QMB allowed a lane configuration change within 30 minutes if need arose. Segment 1, which had five lanes on the traffic roadbed during construction, temporarily maintained three SB by two NB (3 x 2) in the morning, and reversed to the two SB by three NB (2 x 3) configuration in the afternoon. (see Figure 3).

Caltrans had the flexibility to change construction staging on a daily basis to best accommodate traffic conditions through the use of a QMB system similar to what is used permanently on the Coronado Bridge in San Diego, CA. This specialized equipment (transformer) picks up the barrier and shifts it to the next lane without major disruption to live traffic. As the transformer drives with live traffic at a speed of about 15 km per hour (kph), it takes only half an hour to shift the 5-km segment of the barrier. The barrier was moved twice a day to accommodate peak directional traffic. This traffic-handling plan was subject to change if safety became a concern. The breakdown of the project budget showed that $1.5 million was allocated to the one-month rental of the QMB system during the extended closures. Caltrans believed that this extra cost item, which is not needed for traditional closures, was paid off by the time savings of road users through the CWZ.

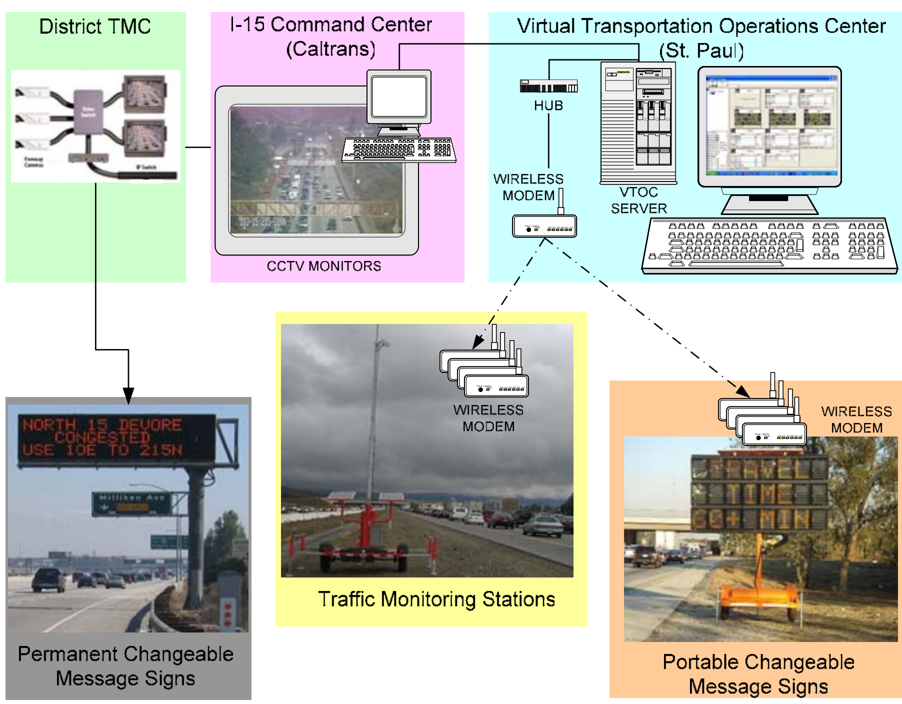


**Figure 5. AWIS network structure**

***Real-time Travel Information.*** This project provided the first implementation of the AWIS in LLPRS project. The AWIS monitored traffic data (count and speed) in several locations using Remote Traffic Microwave Sensor (RTMS) traffic surveillance units, roadside radar devices that were situated about 1.5 km apart. Wireless communication relayed the data back to a server in St. Paul, Minnesota, which put the information through an algorithm and AWIS displayed the real-time travel information on the portable Changeable Message Signs (CMS) that were strategically located at key decision making points for the traveling public. (Figure 5). A format of 10-minute increments to display travel time information between two known points (the junction with I-210 on the south and the junction with I-215 on the north) proved easier for the public to understand than overall delay time. Temporary CMS provided additional information when project engineers wanted to emphasize a detour route. This utilization of CMS minimized the amount of time the permanent message signs (PMS) were activated allowing those permanent signs to be used as other incidents came up.

**Pre-construction Schedule Analysis**

***CA4PRS: Scheduling Tool.*** *CA4PRS* is a planning tool designed for use during the planning, design, and construction stages of accelerated highway rehabilitation projects to select the most economical strategies. The software was developed by the Institute of Transportation Studies in the University of California at Berkeley with support from the State Pavement Technology Consortium (California, Minnesota, Texas, and Washington), an FHWA pooled-fund program. Utilizing CPM and a linear scheduling technique, the *CA4PRS* software estimates the optimized distance and duration of highway rehabilitation or reconstruction projects under a given set of constraints, such as scheduling interfaces, pavement design, contractor logistics, and traffic operations (Lee and Ibbs 2005). When combined with traffic analysis models, *CA4PRS* software can help agencies and paving contractors minimize costs by determining which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating unacceptable traffic delays.

*CA4PRS* was used for this Devore project to provide pre-construction productivity analysis, especially to compare the estimated closure durations between the closure alternatives of one-roadbed, 72-hour weekday, 55-hour weekend, and 10-hour nighttime closures. The *CA4PRS* model estimated that about 200 hours of main operations with lead-lag time relationship between main activities were needed to finish 5.1 lane-km (including the random slab replacement) of each roadbed closure (one complete direction finished in each closure), with a total closure time of 210 hours when mobilization and demobilization were included.

As summarized in the following sections, resource constraints in the *CA4PRS* inputs and its estimated closure schedule of about 210 hours matched closely with the eventual as-built resource mobilization and actual closure duration of about 215 hours for each one-roadbed construction.

***Constructability Review.*** For the I-15 Devore project, detailed constructability and productivity analyses were performed using the *CA4PRS* model after selection of the most economical reconstruction closure scenario. From the production and scheduling point of view, the constructability review compared the technical features of new pavement such as: (1) concrete mix design (PCC with Type III cement versus FSHCC); (2) pavement base type (asphalt concrete base versus lean concrete base); and (3) outer truck lane width (widened truck lane versus tied concrete shoulder).

The scheduling analysis with *CA4PRS* answered the question of how quickly the whole project could be completed for each permutation of the three variables by estimating the maximum production (distance) per closure and the total number of closures to complete the entire project. Based on the constructability analysis results, Caltrans decided to use (1) Type III concrete mixes, (2) asphalt concrete base, and (3) a widened truck lane. Details of the constructability analysis are summarized in the following section.

Two concrete mix designs were compared for the slabs in the design stage: rapid strength concrete (Type III PCC) that allows opening to traffic within 12 hours of placement, and fast-setting hydraulic cement concrete (FSHCC) that allows traffic opening within 4 hours. Caltrans and construction experts confirmed that the extra 8 hours of curing time pays off in the long run because the rapid strength concrete provides better long-term performance, requiring fewer repairs and road closures, compared to the FSHCC that was used on the previous I-10 Pomona project and costs two to three times more in California. In addition, the 8-hour time advantage of FSHCC is offset by higher concrete slump and material stickiness, the need for more delivery trucks and a smaller paving machine, the restriction to single-lane paving, and a typically rougher finished surface that frequently requires diamond grinding after curing. The *CA4PRS* production estimate indicated that use of either of the two materials results in approximately the same overall completion time, with the time saving advantage of the extended closures being evened out by the lower paving operation productivity with FSHCC.

Rapid strength concrete with Type III PCC was eventually used for the new slab and for much of the pavement reconstruction, but to save material cost the contractor also used Type II PCC, with a 24-hour curing time mix, for approximately 50 percent of the pavement, especially for the initial part of the segment.

One of pavement design preferences for Caltrans concrete LLPRS projects includes approximately a 290-mm thickness of PCC separated with an AC bond breaker of approximately 25 mm, then a 150-mm lean concrete base (LCB), and finally additional base material as needed depending on the R value of the underlying soil. However, during the design of this project, Caltrans evaluated other base types primarily to look at the constructability and to find a way to reduce the time to construct the overall pavement design without significantly affecting the long life pavement design. It was determined that instead of using LCB, an AC base (150-mm thick using rich bottom AR-8000 mix) could be placed in two lifts of 75 mm, eliminating the need for an AC bond breaker, thus eliminating an additional operation. One of the benefits to placing an AC base and a PCC top layer was that two separate subcontractors with separate materials supplies could be employed. This increased the capability of the prime contractor to construct with the two different pavement types.

The existing structural section consisted of approximately 210 mm of PCC over 100 mm of cement-treated base, in most cases placed directly on native ground. Some areas installed a coarse aggregate base of underlying material as a part of an edge drain system that was installed where there was a high groundwater table. To construct the new structural section, the existing pavement section had to be removed and a portion of the native material, or the course aggregate in the under-drained areas, had to be removed in order to construct the thicker structural section.

Caltrans held discussions with the American Concrete Paving Association to discuss the feasibility of leaving the AC shoulder in place, saw cut adjacent to it, and pave the PCC pavement to match the existing asphalt pavement. They decided this would create a poor final product since the existing pavement would then control the profile. The shoulder was cold-planed prior to construction of the PCC pavement to leave a lip for the new concrete pavement and it was overlaid with AC thereafter during the extended closures. The concrete pavement was controlled by wire placement, providing its own profile control.

**Post-construction Productivity Evaluation**

***As-built Reconstruction Process.*** The Devore reconstruction project involved three main operations: closure mobilization, pavement reconstruction during main closure, and closure demobilization. Primary pavement reconstruction activities during the one-roadbed continuous closure included: demolition of the existing old pavement structure; paving AC base; paving PCC slab; and cold plane and AC overlay of the outside shoulder.

The contractor performed these four major operations concurrently, though equipment could not be used concurrently at the same locations. Based on the linear scheduling technique, one activity followed the other while maintaining a distance and time buffer to avoid interference between activities. A rehabilitation technique known as the “concurrent double-lane paving method” with a slip form paver was used since two passenger lanes were available for construction access to rebuild two truck lanes at once. This allowed demolition, asphalt concrete base (ACB) paving, and PCC paving to proceed simultaneously.

The detailed activities were operated with the following process within one-roadbed closure (about 215 hours):

- Set up MCB on the traffic roadbed
- Traffic break (about 1 hour) for stripping on the median crossover
- Full closure of construction roadbed and switching of traffic to the traffic roadbed
- Saw-cut old PCC slabs
- Cold plane (milling) old outside AC shoulder
- Demolition of old PCC slabs
- Excavation of CTB and part of aggregate base (AB)
- Grade and compact AB
- Pave new AC base (76-mm thick by 2 lifts)
- Compaction and cooling of AC base
- New PCC slab paving
- Finishing and spreading the curing compound
- Saw-cut new PCC slab joints
- AC overlay of outside shoulder
- Clean-up of the newly constructed pavement

- Mark lanes (striping) on the new pavement
- Open the construction roadbed to traffic with about 1 hour traffic break
- Remove QMCB from the traffic road bed

As the *CA4PRS* production analysis estimated, each segment during the one-roadbed closure was subdivided into equal sections, approximately 500 m long for construction convenience. ACB paving began following demolition once the demolition and excavation operations progressed far enough (about 500 m) that equipment interferences minimized and ACB operations would not catch up with the demolition activities. Similarly, PCC paving began and followed ACB paving once ACB paving progressed sufficiently.

***Construction-Productivity Monitoring.*** The reconstruction project, with two one-roadbed continuous closures and around-the-clock operations, was successfully completed in October 2004. More specifically, the NB construction was completed in 216 hours between October 3 and October 13, 2004, and the SB construction was completed in 210 hours between October 23 and November 3, 2004, excluding a couple of non-working days due to inclement weather. As part of life-cycle analysis framework of LLPRS projects, the monitoring study is a partnership between Caltrans and the University of California's Pavement Research Center. The research team was in charge of monitoring and analyzing how quickly major highway construction could be done and how traffic impacts could be minimized.

This construction monitoring study provided a good opportunity to construct a productivity-rate database that can be utilized for the planning of future LLPRS projects. In addition, the hourly truck data collected in the construction monitoring study were useful in verifying the accuracy of the *CA4PRS* software schedule and production estimation. It was observed that the trucks numbers per hour linearly govern the productivity, as they are the main input into the *CA4PRS*. In summary, the average number of hauling trucks turned around per hour for the slab removal was 17 (with two crews), and the average for concrete delivery trucks for paving was 18. The minimum cycle time of loading and discharging typically controlled the hourly truck numbers, i.e., the average cycle time of slab removal loading per truck was about 7 minutes and discharging concrete cycle time was 3 minutes.

***Contractor's Learning Curve.*** During reconstruction of both the NB and SB lanes, researchers tracked the number of hauling and delivery trucks per hour, as well as truck turn-around time for the major reconstruction operations measuring progress and productivity for: slab removal, base excavation, AC base paving, and PCC paving. The overall progresses of the four primary reconstruction operations measured during the first one-roadbed continuous closure (NB construction) are shown in Table 2.

**Table 2. Summary of Truck Operations and Progress of Major Operations Measured During Reconstructions**

| Operation | Average truck number per hour | Average truck turn-around time (min) | Total operation hours per closure for 210 hours | Hourly progress (meter) | | |
|---|---|---|---|---|---|---|
| | | | | Northbound | Southbound | Average |
| Slab Removal | 17 | 62 | 49 | 84.8 | 104.9 | 95 |
| Base Excavation | 13 | 55 | 29 | 144.8 | 142.1 | 144 |
| AC Base Paving | 12 | 107 | 28 | 145.5 | 158.9 | 153 |
| PCC Paving | 17.7 | 42 | 45 | 93.1 | 114.2 | 102 |

As illustrated in Figure 6, significant learning-curve effect on the contractor production rates occurred on this project. Majority of the reconstruction operation during the SB reconstruction (second closures) showed more progress than those of the NB reconstruction (first closure). The operation with the same crew and equipment resources that gained the biggest effect is the slab removal activity, which showed 28 percent more productivity increase; that is, 85 m progress per hour in average with two demolition crews in the first closure (NB construction) and 105 m per hour in the second closure (SB construction). The concrete paving operation showed a similar learning effect of 22 percent productivity increase from 93 m per hour for NB construction to 114 m per hour for SB construction. AC base paving showed a nine percent productivity increase (146 m → 159 m) and base excavation (milling) showed the least productivity increase of five percent (142 m → 145 m).

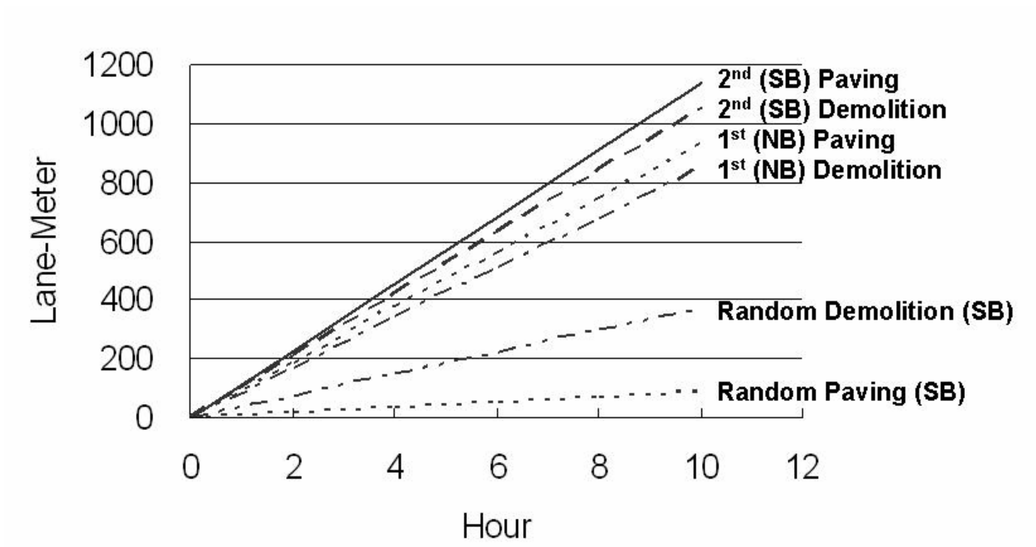


**Figure 6 Contractor's learning curve: lane-reconstruction vs. random-slab replacement**

Initially, on the NB construction the contractor mobilized a conveyor, similar to a shuttle boggie, to feed concrete from the delivery truck (end dump) in front of the paving machine. The production with the conveyor was slow (57 m per hour) compared to the NB average production of 93 m. Eventually the delivery truck achieved greater delivery speed by dumping the concrete directly on top of the AC base. However, the direct dump sometimes (infrequently) dislocated the dowel basket, which was nailed down to the ACB to withstand the high pressure from the dumping.

Considering that both slab removal and PCC paving are two major key factors to determine the success of construction, this improvement is attributed to the contractor's better logistics management in the second closure. In other words, the contractor, who would have learned that both activities were most critical, was obliged to make an extra commitment from both the resource and scheduling standpoints to ensure the timely completion of the project.

The study confirmed that the overall as-built performance, with respect to construction process and progress, followed the estimated schemes in the *CA4PRS* pre-construction analysis. It is attributed largely to the fact that the number of hauling and delivery trucks turned around per hour for the major reconstruction operations closely matched the assumed resource inputs in the *CA4PRS* model.

***Lane-reconstruction Versus Random-Slab Replacement.*** An average of 10 percent of the severely damaged slabs on the inner truck lane were rebuilt as random slab replacement with the new AC base placement, a result of downsizing the reconstruction scope from continuous lane reconstruction at the initial stage. Through the construction monitoring study, it was obvious that the operation of the continuous-lane reconstruction on the outer truck lane represented higher productivity, compared with the operation of random-slab replacement on the inner truck lane. For example, slab removal by the continuous-lane reconstruction operation on the SB construction showed about two times higher productivity than random-slab removal (90 m per hour versus 37 m per hour). Because the blade of the excavator could not get into the space between the slabs, the random slab was lifted by the excavator with a sling hooked to eyeholes drilled into the slab.

Usually, the random slabs were paved together with the continuous outer truck lane as a double-lane paving by the slip form. The exceptions were random slabs at the end section of Segment 1, which were paved manually by extra crews without the slip form, working separately from the main paving crew to make up for project delays and ensure meeting the deadline for traffic opening. This manual paving process is similar to the traditional nighttime paving operations. The continuous-lane paving with the slip form was about 10 times more productive than the random-slab paving with manual equipment (100 m per hour versus 9 m per hour). Another factor contributing to the lower productivity with the random slabs, for both slab removal and paving operations, was that the operations crew spent a significant amount of additional time to move around the random slabs and to set up equipment, compared to that which was required for the continuous lane-reconstruction.

## Outreach and Public Perception Changes

To inform commuters, truckers, and recreational travelers about potential delays and the availability of alternative routes around the construction, Caltrans implemented an extensive public outreach program. Outreach materials included a comprehensive project brochure, construction flyers, a construction advisory electronic bulletin, Fast-fax through email, a project information help hotline, and several public meetings for local communities. The project website was created with the cooperation of local agencies and the surrounding three Caltrans District Offices (Los Angeles, Orange, and San Diego) to provide up-to-date comprehensive project information. The project website had a total of about 500,000 requests for three months before and during the extended closures and played an important role as an interactive tool to gain input from the public.

Pre- and post-construction traffic web surveys with about 400 respondents were conducted to examine the public perception of the 'Rapid Rehab' approach. Most survey respondents showed initially strong reluctance to the extended closures, as shown 64 percent expressed an initial preference for the traditional nighttime or weekend closures and 14 percent requested even to cancel the project. However, public perception substantially changed because of the public outreach efforts. Of the respondents to the post-construction survey, 70 percent expressed support for 'Rapid Rehab' projects. This result indicates that with the expectation of the benefits from accelerated project completion, the public is willing to bear increased construction cost in exchange for reduced construction schedules, thus mitigating the inconvenience of traffic disruption.

**Conclusions**

Since 1998, Caltrans has been developing LLPRS to address the state's need for cost-effective approaches to rebuilding its network of aging pavements. Because of high traffic volume on urban highway networks in California, a priority for highway rehabilitation/reconstruction projects is selecting construction schedules and developing traffic management plans that will minimize road user and agency costs.

This paper introduces the techniques and technologies used in the fast-track concrete pavement reconstruction of two deteriorated truck-lanes (4.5 centerline-km) on I-15 at Devore, part of a high traffic volume urban highway network, in which one-roadbed continuous closures and around-the-clock operations (24/7) were used to complete the reconstruction in about 210 hours for each of the two lanes. This project is the first large-scale implementation of Caltrans' LLPRS program using state-of-practice features to implement innovation and technology based on experience and lessons-learned from the recently completed I-10 Pomona (concrete) and I-710 Long Beach (asphalt) LLPRS demonstration projects.

As validated with as-built construction data and traffic performance monitored during construction, the integrated pre-construction analysis concluded that, from the perspective of production schedule, traffic inconvenience, and agency costs, the one-roadbed continuous closure was the most economical scenario when compared to traditional nighttime or weekend closures. Compared to traditional 10-hour nighttime closures, the pre-construction integrated analysis concluded that the one-roadbed continuous closure scenario would require about 80 percent less total closure time, about 30 percent less road user cost due to traffic delay, and about 25 percent less agency costs for construction and traffic control. The advantages of using this method of fast-track (accelerated) reconstruction, known as "Rapid Rehab" in California, included the shorter period of disruption for the traveling public (1 month versus 10 months), 30-year life expectancy for the new pavement, improved safety for motorists and workers, and construction costs that were reduced by 25 percent ($6 million) compared to those of traditional repeated nighttime closures.

The I-15 reconstruction project turned out to be successful in achieving a 20 percent reduction in traffic demand through the CWZ (attributed to motorists avoiding the CWZ through use of alternative routes, and travel time and mode changes) and minimized inconvenience to motorists, homeowners, and abutting businesses during construction. To achieve the reduction in traffic demand, a critical, extensive proactive public outreach effort was undertaken to inform commuters, truckers, and recreational travelers about potential delays and the availability of alternative routes around the construction.

The overall impact of reconstruction closures on traffic was “acceptable” according to a traffic measurement study and web-surveys conducted during and after the construction. The maximum peak hour delay (although infrequent) was measured at about 75 minutes on weekends (NB) and about 45 minutes on weekdays (SB) during the extended closures, compared to the expected 90 minutes delay during weekdays with the initial assumption of 10 percent reduction estimated in the pre-construction traffic analysis and project TMP. The 10 percent (in total 20 percent) more reduction in actual traffic demand (volume) through the CWZ was attributed to Caltrans’ proactive public outreach and traffic control efforts.

The use of QMB helped to balance traffic impacts to commuters and weekend travelers by activating a dynamic lane configuration with one additional lane converted temporarily from the rehabilitated AC shoulder. The barrier was moved twice a day to accommodate peak directional traffic without a significant disruption on live traffic. Three SB lanes were open for the daily morning commute, which reduced delays with additional roadway capacity estimated in the pre-construction analysis.

AWIS, first implemented in California for LLPRS projects, played a useful role in informing motorists traveling through the CWZ of real-time travel and detour route information, as indicated by the results of before- and during-construction surveys managed through the project website. That AWIS information was posted on the permanent and changeable message signs, as well as on the traffic roadmap on the project website that was used in mounting an effective public outreach campaign.

The website was created with the cooperation of transportation partners (local agencies) and the surrounding three Caltrans District Offices (Los Angeles, Orange, and San Diego) to provide up-to-date comprehensive project information. The website also played an important role as an interactive tool to gain feedback from the public. By utilizing the project website, two traffic surveys were undertaken to compare commuters’ expectations of potential traffic delays prior to construction with their actual experience during the extended closures, as well as to study their overall perceptions of the “Rapid Rehab” approach of the extended closures.

This project provided a unique opportunity to validate, fine-tune, and enhance highway analysis tools for LLPRS projects. Construction and traffic monitoring studies by the research team during reconstruction confirmed that the overall performance of the reconstruction was consistent with the outlined schemes in the pre-construction analysis with respect to construction process and progress. The CA4PRS software program, developed as a scheduling and production analysis tool for LLPRS projects, underestimated the as-built production by about five percent, which is tolerable for a planning tool. The number of hauling and delivery trucks per hour turned around for the major reconstruction operations were similar to the assumed resource inputs in the CA4PRS model. The Devore project incorporated the unique approach of using the additional costs associated with road user traffic delay in determining the amount of I/D. The assessment of I/D amounts was also based on the CA4PRS production schedule and traffic simulation analyses.

This study of post-construction analysis with the validation of the pre-construction estimates can provide important technical ideas for transportation agencies and contractors to balance the maximization of rehabilitation productivity with the minimization of traffic delay, while also minimizing total costs and achieving long-life pavement performance.

**References**


Anderson, A.D. and Russell, J.S. (2001). "Guidelines for Warranty, Multi-Parameter, and Best Value Contracting." Research Reports (Series: NCHRP (National Cooperative Highway Research Program) Report 451), Transportation Research Board, Washington, D.C.

Arditi, D., Khisty, J., Yasamis, F. (1997). "Incentive/Disincentive Provisions in Highway Contracts." Journal of Construction Engineering and Management, ASCE, 123 (3), 302-307.

California Department of Transportation (Caltrans) (1998). "Ten-year State Highway System Rehabilitation Plan 1998-99 through 2007-08." <http://www.dot.ca.gov/hq/transprog/reports/tnyrplan.pdf> (June 10, 2004).

Florida Department of Transportation (FDOT) (1997). "Alternative Contracting User's Guide Draft." <http://www.ic.usu.edu/search/doc/156.pdf> (February 2, 2005).

Leather, R.C., (1987). "FHWA Perspectives: A Comprehensive Approach to Major Highway Rehabilitation Projects." Transportation Management for Major Highway Reconstruction, Transportation Research Board, Special Report 212, Washington, D.C.

Lee, E.B., Ibbs, C.W., Roesler, J., and Harvey, J.T. (2000). "Construction Productivity and Constraints for Concrete Pavement Rehabilitation in Urban Corridors." Journal of the Transportation Research Board, Transportation Research Record No. 1712, National Research Council, Washington, D.C., 13-22.

Lee, E.B., Roesler, J.R., Harvey, J.T., and Ibbs, C.W. (2002). "Case Study of Urban Concrete Pavement Reconstruction on Interstate 10." Journal of Construction Engineering and Management, ASCE, 128(1), 49-56.

Lee, E.B. and Ibbs, C.W. (2005). "A Computer Simulation Model: Construction Analysis for Highway Rehabilitation Strategies (CA4PRS)." Journal of Construction Engineering and Management, ASCE, in press.

Lee, E.B, Thomas, D., and Bloomberg, L. (2005a). “Planning Urban-Highway Reconstruction with Traffic Demand Affected by Construction Schedule.” Journal of Transportation Engineering, ASCE, in press.

Lee, E.B., Lee, H.J., and Akbarian, M. (2005b). “Accelerated Pavement Rehabilitation and Reconstruction with Long-life Asphalt Concrete on High-trafficked Urban Highway.”, Journal of the Transportation Research Board (84rd Annual Meeting), Transportation Research Board, National Research Council, Washington, D.C., Approved for publication (in press).

Lee, E.B., Harvey, J.T., Thomas, D. (2005c) “Integrated Design/Construction/Operations Analysis for Fast-track Urban Freeway Reconstruction.” Journal of Construction Engineering and Management, ASCE, Approved for publication (in press).

Transportation Research Board (TRB). (2000a). “Get In, Get Out, Stay Out.” Proceedings of the Workshop on Pavement Renewal for Urban Highway, The Beckman Center, Irvine, CA.
<http://gulliver.trb.org/publications/sp/getin_getout_stayout.pdf> (June 2, 2004).