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Integrated Design/Construction/Operations Analysis for

Fast-track Urban Freeway Reconstruction

Technical Memorandum Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

By

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Most urban freeways in California and elsewhere in the United States were constructed between 1955 and 1970 with design lives of 20 years and are thus reaching the end of their serviceable lives. The California Department of Transportation is rehabilitating or reconstructing deteriorated urban freeways using Long-Life (with design lives of more than 30 years) Strategies.

This paper describes constructability and productivity analysis of the fast-track pavement reconstruction on I-15 at Devore, which is located near San Bernardino. The project uses eight 72-hour weekday closures. The integrated analysis presented in this memorandum concluded that the 72-hour closure is the most economical scenario when compared to other types of closures from the perspective of construction schedules, road user delays, and construction costs. The outline of the contingency plan, incentive contracts, and prototype lane closure charts were all developed as part of the construction management plan, utilizing the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) computer model. The results of this study are useful for transportation agencies in developing highway rehabilitation strategies that balance the maximization of construction productivity with a minimization of traffic delay.

1.0 INTRODUCTION

About 256,000 km of the National Highway System, which is only 4 percent of the nation's 6 million km of roads,(*1*) carries 75 percent of all truck traffic and connects 95 percent of businesses and 90 percent of the households in the United States.(*2*) Many of these pavements have exceeded their design lives. When an advanced state of structural damage has been reached in a pavement, routine maintenance is no longer cost effective and will no longer fix the deterioration. Thus new strategies must be found to maintain functional reliability of the highway pavement. As a result, in recent years, highway construction has shifted from building new transportation facilities to "4-R" projects: Restoration, Resurfacing, Rehabilitation and Reconstruction.(*3*) However, in 1999-2001, about 30 percent of these 4-R highway construction projects were in urban areas, where construction causes serious disruptions to traffic service.(*4*)

A pioneer when it comes to highway construction, the State of California now finds itself with deteriorated highway infrastructure on a large scale. The California highway system includes over 78,000 lane-kilometers, most of which were built between 1955 and 1975 with design lives of 20 years. A large number of the pavements in this system have been exposed to heavier traffic volumes and loads than those for which they were originally designed, and are being made to function long after their original 20-year service life. Consequently, the transportation network has deteriorated significantly, adversely affecting road user safety, ride quality, and vehicle operating and highway maintenance costs. As traffic volumes continue to rise in California, reconstruction during daytime commute hours becomes increasingly unpopular.

In 1998, the California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategy (LLPRS) program to rebuild approximately 2,800 lane-km of critical pavements for the state highway network over 10 years.(*5*) The criteria for LLPRS candidates were poor structural condition and ride quality and a minimum of 150,000 Average Daily Traffic (ADT) or 15,000 Average Daily Truck Traffic (ADTT). The main goals of LLPRS are to provide new pavement with at least 30 years of design life requiring minimal maintenance.(*5*) Most of the candidate projects are Portland Cement Concrete (PCC) pavements on interstates in urban corridors of Southern California (Los Angeles area) and the San Francisco Bay Area.

1.1 Innovative Construction Closure Strategies

Traditionally, urban freeway rehabilitation or reconstruction projects in California have used short-term nighttime closures, such as a 10-hour closure from 8 p.m. to 6 a.m. However, using these conventional nighttime closures for LLPRS candidate projects could potentially cause negative results,(*6*) such as:

- low pavement life expectancy (10-15 years) due to limits on the type of pavement structure that can be constructed and opened to traffic in 8 or 10 hours; these limits are largely imposed by the compaction, curing, or cooling time needed for the materials before traffic can be put on the pavement;
- rough pavement surface due to the poor quality control under the tight time constraint;
- volumes of materials larger than can be handled in a short period of time;
- compromised safety of road users, agency staff, and contractor’s crew; and
- environmental problems such as noise and habitat disturbance due to increased repetitions of mobilization/demobilization.

In addition to these disadvantages, longer total closure times with the traditional nighttime closure pattern would result in higher construction and traffic handling costs as well as potentially greater inconvenience to road users due to traffic delay, compared to the extended closure strategies. Therefore, Caltrans has developed fast-track reconstruction methods such as extended weekend (55-hour) or weekday (72-hour) closures with 24-hour operations for LLPRS projects. The concept of the 55-hour extended weekend closure was validated on the first concrete LLPRS demonstration project on I-10 in Pomona, CA, completed in 2000,(*7, 8*) and on the first asphalt LLPRS demonstration project on I-710 Long Beach, CA, completed in 2003.(*9*) The time savings of fast-track highway reconstruction with extended closures are offset to some degree by the potential for traffic disruption if the project schedule slips. Nevertheless, the study on the I-10 Pomona project showed that construction during the 55-hour weekend closure was about 40 percent more productive on average than the traditional nighttime closures.(*8*)

These pilot studies form the baseline for the construction management plan used for the I-15 Devore reconstruction project, as discussed in this memorandum. This project is the second Caltrans concrete LLPRS project and differs from the previous two demonstration projects because it employed an integrated schedule/traffic/cost approach at each stage of the project: feasibility and planning, pavement design, and construction.

1.2 Integrated Approach to LLPRS Projects

The lane closures required to move huge volumes of demolition and paving materials and to allow the large numbers of heavy equipment to operate during urban freeway rehabilitation often cause substantial traffic delays. Therefore, from the viewpoint of minimizing traffic delays, the most desirable pavement is one that provides at least 30 years service life.(*5*) These longer-life pavements require advanced pavement concepts, including new materials and pavement analysis procedures, to arrive at optimal slab thickness and minimal construction time.

To meet design life and constructability goals for LLPRS projects, pavement design must focus on thinner structural sections, as well as materials that shorten construction and curing time, without sacrificing quality and performance.(*10*) Construction planning should focus on speeding the construction process by incorporating such concepts as contingency management, incentives/disincentives (I/D), and cost (A) plus schedule (B) bidding.(*11*) The integration of pavement design and materials, construction, and traffic analyses provides the basis for an efficient project management plan that minimizes life cycle costs within project constraints.

1.3 Research Objectives and Scope

A joint research team from the University of California at Berkeley and Davis campuses conducted pre-construction analyses to help Caltrans refine methods for fast-track pavement reconstruction on part of Interstate 15 in San Bernardino County, California. The purpose of this study was to develop the best construction management plan by building on and adding to the lessons learned from the first two LLPRS studies: I-10 Pomona and I-710 Long Beach.

Phase I of the research study was conducted in two stages:

- **Stage 1: Selection of the most economical closures scenario.** Four construction window options (55-hour weekend, 72-hour weekday, 10-hour nighttime, and single continuous until completion closures) were evaluated and compared. The objective was to select the most economical construction closure scenario in terms of construction production, traffic delay, and total costs—combining construction cost and road user cost. Because of the space limit, only the conclusion of the Stage 1 analysis is summarized later in this paper, and details are in the project report.(*12*)

- **Stage 2: Pre-construction analysis for the selected scenario.** Caltrans decided to implement the I-15 Devore project with the 72-hour weekday closures based on the conclusions of the Stage 1 analysis.(*12*) The researchers then continued the analysis of the selected scenario (72-hour closures) in more detail, which is the focus of this technical memorandum. The analysis was performed to:
  - Define optimum reconstruction procedures
  - Develop prototype CPM schedules
  - Identify logistical resource constraints
  - Outline incentives and disincentives
  - Configure contingency plans.

Caltrans implemented the results of these analyses in the specifications of the construction contract, in particular the Special Provisions (SP) for the I-15 Devore project.

Phase II of the study will continue the research with monitoring of construction, which starts in spring 2004. The Phase II study will compare the contractor's as-built construction performance to predictions from the Phase I studies. Outcomes of all the studies will help Caltrans and other transportation agencies throughout the country develop and refine methods for managing fast-track highway rehabilitation with high traffic volume in the most timely and cost-effective manner.

1.4 CA4PRS Computer Model

This innovative approach for the I-15 Devore project required a sophisticated construction and production analysis model to develop a schedule baseline for integration of construction and traffic. The University of California Pavement Research Center (UCPRC), with pooled research funding from the state departments of transportation of California, Minnesota, Texas, and Washington, developed a program called Construction Analysis for Pavement Rehabilitation Strategies.(*13*) CA4PRS is a planning tool designed to be used during the planning and design stages of a highway infrastructure rehabilitation project. It predicts the amount (lane-km) of pavement that can be rebuilt within various windows of closure time under given project constraints.(*6*)

The software was validated on the Caltrans I-10 Pomona project, where a concrete long-life pavement was built during one 55-hour weekend closure and a repeated number of nighttime closures.(*7, 8*) It has also been used to evaluate construction management plans for the I-710 Long Beach project where asphalt long-life pavement was successfully constructed in eight 55-hour weekend closures.(*9*)

The CA4PRS model evaluates the following input variable alternatives:

- Pavement strategy: Portland Cement Concrete (PCC), cracking and seating PCC and asphalt overlay (CSOL), or full-depth asphalt concrete replacement.
- Construction window: 7- and 10-hour nighttime closures, 55-hour weekend closures, continuous weekday closures, or combinations of these options.
- Lane closure tactics: number of lanes closed for construction, i.e., partial or full closures.
- Material constraints: mix design and curing time for concrete pavement or cooling time for asphalt pavement.
- Pavement cross section: thickness of concrete slab or the thickness of asphalt concrete layer.

- Concrete pavement design: different base types (lean concrete base (LCB) or asphalt concrete base (ACB)).
- Contractor's logistical resource constraints: location, capacity, and available rehabilitation equipment (plants, delivery and hauling trucks, pavers).
- Scheduling constraints: mobilization, demobilization, traffic control time, and activity lead-lag time relationships.

A powerful additional attribute of the CA4PRS model is that it can be integrated with traffic analysis tools. With the goal of integrating construction production and traffic delay analyses, the software provides quantitative schedule baselines to planners, designers, and traffic, construction, and materials engineers so they can develop balanced construction management and traffic control plans for highway rehabilitation projects. When combined with a traffic model, CA4PRS software can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating unacceptable traffic delays. This information is vital to balancing the three competing goals of: longer-life pavement, faster construction, and less traffic delay during closures.

2.0 I-15 DEVORE RECONSTRUCTION PROJECT

The I-15 Devore pavement reconstruction project is located on Interstate 15 between Interstates 10 and 215 in San Bernardino County, CA, near the city of Devore. Caltrans (District 8) plans to rebuild a 4.2-km section of the deteriorated freeway between the Sierra Avenue intersection and the I-215 system interchange, with construction starting in spring of 2004.

For efficient traffic detours during construction, Caltrans decided to split the project into two segments. Segment 1, built in 1975, is an eight-lane, 2.5-km section from the Sierra Avenue intersection to the Glen Helen Parkway intersection. Segment 2, built in 1969, is a six-lane, 1.7-km section from the Glen Helen Parkway intersection to the I-215 system interchange. The passenger lanes are still in good condition, as is common on California's urban freeways, so Caltrans decided to rebuild only the outer two truck lanes in each direction, which have extensive cracking, faulting, and patches. Consequently, the scope of the project includes about 17 lane-km: 4.2 centerline-km × 2 truck lanes × 2 directions. A detailed layout of the segments and the staging construction plan is illustrated in Figure 1.

The freeway through the Devore corridor carries approximately 110,000 Average Daily Traffic (ADT), about 10 percent of which is heavy trucks. In contrast to typical urban freeways in California which have rush hour peak traffic in the weekday morning and afternoon and relatively low traffic volume over the weekend, the I-15 Devore corridor not only has very high commuter peaks on weekdays, but also has high leisure traffic volume on weekends. The two highest peak traffic volumes are northbound on Friday (68,000 ADT) afternoon and southbound

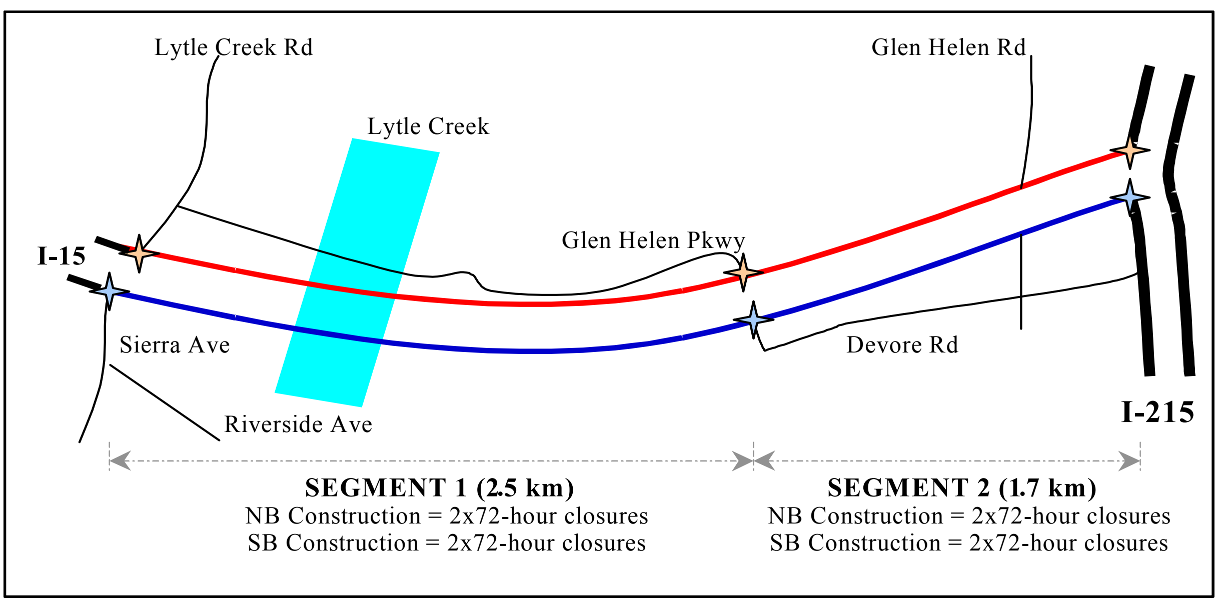

Figure 1. I-15 Devore project staging construction plan.

on Sunday (62,000 ADT) afternoon, when leisure travelers in the Los Angeles area are going to and from Las Vegas. As discussed in Section 2.3, this clearly necessitated analysis of lane shutdown impacts.

2.1 Pavement Reconstruction Scheme

The existing pavement structure has a 203-mm (8-inch) concrete slab, a 102-mm (4-inch) cement treated base (CTB), and a 450-mm (18-inch) aggregate base (AB) layer, which was typical Caltrans urban freeway design for the 1970s. This pavement structure is being replaced with a 290-mm (11.5-inch) concrete slab and 150-mm (6-inch) asphalt concrete base (ACB) or Lean Concrete Base (LCB). Figure 2 illustrates the pavement cross section changes for the I-15 project. The CA4PRS model estimates the total rehabilitation volume of major materials by type for the whole project: demolition and excavation of old pavement (29,055 m^3), new concrete slab paving (19,063 m^3), and new AC base paving (23,980 tonnes).

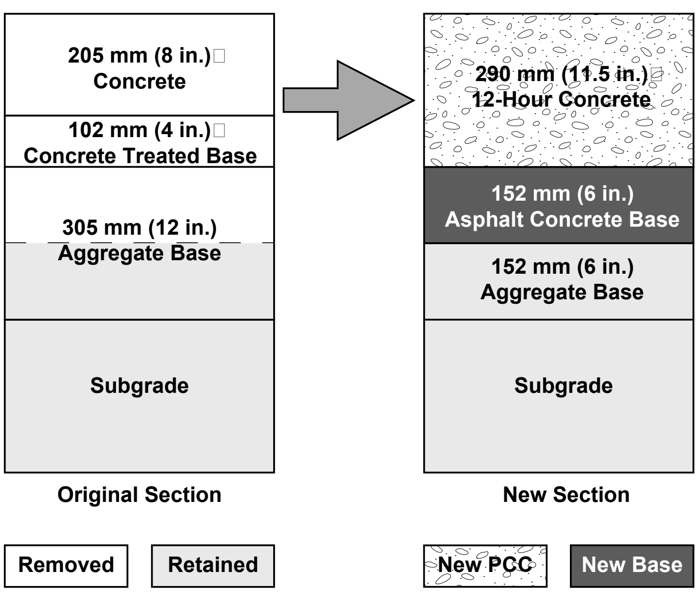

Figure 2. I-15 Devore concrete pavement cross-section change

The reconstruction project is divided into several segments for traffic control purposes. One segment for each direction of the freeway will be reconstructed per closure period. For example, Segment 1 of the northbound freeway (construction roadbed) will be closed for reconstruction by switching traffic to the other side (traffic roadbed) through the traffic crossovers at the south and north ends of the construction work zone (CWZ). Construction will occur on the two outside truck lanes (T1 and T2) of the construction roadbed while the two inside lanes are used for construction access (hauling trucks, delivery trucks, paving machines, etc.). The four lanes of the traffic roadbed will then be converted for two-way traffic (two lanes in each direction) as a "counter flow traffic" control system. Moveable concrete barriers (MCB) will be set up between the two lanes of each direction on the traffic roadbed. During reconstruction, various on and off ramps will be closed for work zone traffic control. The outside shoulder will be used as an additional traffic lane for Segment 2, which has only three lanes per direction.

2.2 Most Economical Closure Scenario

The benefits of using a 55-hour weekend closure scenario instead of the traditional weekday nighttime closure scenario, which are obvious for most urban freeways in Southern California, were not as clear for the I-15 Devore project because of its unique traffic patterns and segment layout. Therefore, a comprehensive analysis was conducted to identify the most economical closure strategy by comparing construction schedule, total traffic delay (road user cost), maximum queue length, and total cost among the following four basic closure scenarios:

72-hour weekday closure: 12:01 a.m. Tuesday through 11:59 p.m. Thursday

- 55-hour weekend closure: 10 p.m. Friday to 5 a.m. Monday
- One-time continuous closure until the completion of each direction: 12:01 a.m. Monday through 12 midnight Tuesday of the following week
- Traditional 10-hour nighttime closure: every weekday night 8 p.m. to 6 a.m.

2.2.1 Evaluation of Construction Closure Scenarios

Construction scheduling and production analysis calculated the total number and duration of closures based on the maximum possible distance of reconstruction estimated by the CA4PRS model for each closure scenario. Traffic analysis, using a demand-capacity (D-C) model based on the Highway Capacity Manual (*14*) with hourly traffic data collected on freeways and ramps on March 2002, was performed for each closure scenario as the next step to evaluate the impact on traffic delay in terms of road user cost and maximum delay (queue length) per closure.(*15*) A macroscopic traffic simulation with the FREQ model was applied to validate the traffic analysis performed with the HCM model.(*16*)

The Stage 1 analysis found that the 72-hour closure scenario had acceptable total traffic delay and maximum queue length, although not the best for either, and greatly reduced the construction duration, and therefore, the construction and road user costs. In summary, the 72-hour weekday closure strategy selected had significantly reduced total traffic inconvenience, construction duration, and construction cost compared to the traditional weekday nighttime closures and 55-hour weekend closures, as summarized in the following section.(*12*)

2.2.2 Most Economical Closure Scenario

Cost should be one of the major selection criteria for pavement rehabilitation strategies. Caltrans has previously emphasized reduction in lifecycle cost for long-life strategies as compared to conventional strategies for projects with very high traffic. Traditionally, cost projections have included only agency cost (construction and traffic handling). However, road user cost (RUC) is seldom incorporated into cost comparisons for highway construction projects in California.(*17*) Caltrans recognized that at least for LLPRS projects, this indirect cost (RUC) is as important to the traveling public as agency cost.

The concept of total cost as the sum of the agency cost and road user cost was applied to select the most economical closure scenario for this project. Road user costs and agency costs were equally incorporated for decision-making on this project with the effect that $1 of agency cost was treated as equivalent to $1 of user cost in this analysis. The road user cost was calculated using typical values for commercial ($24) and private ($9) vehicle hourly costs in California, but combined with the lower range of traffic input parameters. Table 1 shows the result of the comprehensive comparison from the perspectives of schedule, traffic delay, and total cost used to select the most economical closure scenario.(*12*)

Table 1 Schedule, Traffic, and Cost Comparison for Closure Scenarios

Closure scenario (1)	**Schedule Comparison**		**Traffic Delay**		**Cost Comparison**	
	Closure Number	Closure (hr.)	Road User Cost ($M)	Max Delay (min.)	Agency cost ($M)	Total cost[a] ($M)
72-hour Weekday	8	512	6.6	75	12.6	19.2
55-hour Weekend	10	550	12.7	196	15.1	27.8
One-time Continuous	2	400	6.1	196	9.9	16.0
10-hour Nighttime	220	2,200	10	36	20.4	30.4

[a]Total Cost = Road User Cost + Agency Cost

The Caltrans Lane Closure Review Committee approved the 72-hour extended weekday closures based on the recommendations made by the research team. The one-time continuous closure, the best candidate strategy in terms of agency, user, and total cost, was not selected because of unacceptable estimated maximum traffic delay per closure.

3.0 CONSTRUCTABILITY ANALYSIS

Once the 72-hour weekday closure was selected as the most economical construction closure scenario from the Stage 1 study, further constructability and productivity analyses were performed using the CA4PRS model. The constructability analysis compared the following alternatives for the new pavement from the production and scheduling point of view:

- Concrete mix design (cement strength gain time)
- Pavement base type (asphalt concrete base versus lean concrete base)
- Widened truck lane option versus tied concrete shoulder

The underlying assumption in the constructability analysis, based on earlier studies and laboratory and field tests for LLPRS projects, was that using these three comparison criteria in all alternatives would provide similar pavement performance and life expectancy.(*10*) For each alternative, the scheduling analysis with CA4PRS provided an answer to the question of how quickly the whole project could be completed by estimating the maximum production (distance) of the rehabilitation and the total number of closures for each option.

Based on the constructability analysis results, Caltrans decided to adopt the strategy of 1) Type III concrete mix with 12-hour needed to reach traffic opening strength for the main concrete slab, 2) asphalt concrete base, and 3) widened truck lane. Details of the constructability analysis are summarized in the following section.

3.1 Concrete Slab Mix Design Issue

Two concrete slab mix designs were compared: 12-hour early-age Type III PCC and Fast-Setting Hydraulic Cement Concrete (FSHCC). FSHCC typically provides the minimum flexural strength, required to open to traffic, of 2.8 MPa (400 psi) four hours after placement, as demonstrated on the I-10 Pomona project.(*8*) However, the 8 hour time advantage (over the 12-

hour Type III mix) 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 the coarse finished surface which frequently requires diamond grinding after curing. In addition, FSHCC is about twice as expensive as the Type III PCC 12-hour mix in California. A construction schedule analysis with the CA4PRS model indicated that the two materials take approximately the same overall project completion time. It was therefore concluded that FSHCC was not the most economical solution.

3.2 Pavement Base Type Issue

Two types of base material were considered for the I-15 project: Asphalt Concrete Base (ACB) and Lean Concrete Base (LCB). The CA4PRS model estimated that at least two more 72-hour closures would be needed if LCB was used instead of ACB because the LCB requires a 12-hour curing time before PCC slab paving. The LCB scenario also requires placement of a bond-breaker such as 25 mm of AC between LCB and the concrete slabs to reduce friction that can cause early cracking.

The ACB scenario, which was selected, permits parallel production of the base and slabs with each operation utilizing its own resources. This allows for the elimination of two 72-hour closures, which reduces traffic delay and construction cost.

3.3 Pavement Structure Design Issues

Two options were considered for the width of the outside truck lane (T2): regular width (3.7 m) tied to a new concrete shoulder; or a widened truck lane (4.3 m). According to a previous survey within the project area, the outside shoulder is seriously deteriorated due to trucks in the outside truck lane tracking into the AC shoulder. The strength of the shoulder is not designed for heavy truck traffic, and widening the outside truck lane to 4.3 m will keep trucks off the shoulder in the future. Since the CA4PRS analysis indicated that only about 8 percent more construction time is needed for widening the truck lane, and the whole reconstruction project can still be completed in the same eight 72-hour closures, Caltrans decided to use this option in the project. In addition, the widened truck lane strategy could save a significant amount of the Caltrans budget because future shoulder reconstruction will be eliminated. The schedule analysis showed that tied concrete shoulder with the regular width truck lane would slow down the reconstruction, and therefore require additional closures. The remaining outside AC shoulder will be "cold planed" (milled) to 60 mm depth and 2.44 m width. A new AC overlay of 60 mm thickness will be placed on the cold planed shoulder, as part of 72-hour closure operations.

Caltrans practice for concrete LLPRS projects is to install dowel bars and tie bars in the transverse and longitudinal joints, respectively, as a means of a load transfer between the jointed slabs to slow pavement deterioration. Because of mismatching of old and new slab joint spacing, Caltrans decided to install isolation longitudinal joints instead of using tie bars between old (passenger lane) and new (inside truck lane) pavements. This decision underscores the fact that constructability has first priority in the fast-track LLPRS project to speed construction as long as performance is not compromised.

3.4 Reconstruction Process

The I-15 reconstruction project involves three groups of operations: closure mobilization (3 to 4 hours), pavement reconstruction during main closure (72 hours), and closure demobilization (4 to 5 hours). Although the main closure will theoretically start at 12:01 a.m. Tuesday, mobilization can begin once the evening peak hours have passed and traffic volume has diminished—perhaps as early as 8 or 9 p.m. Monday. Similarly, while the main closure operation will be finished at 11:59 p.m. Thursday, demobilization can continue until the beginning of morning peak hours, perhaps until 5 a.m. Friday.

Based on the 55-hour weekend closure experiences from the two previous LLPRS demonstration projects (I-10 and I-710), the typical reconstruction process for a fast-track 72-hour extended weekday closure, including the mobilization and demobilization operations, was defined as follows:

I. Closure Mobilization Operation (3 to 4 hours)

1) Set up construction work zone signs
2) Set up MCB (traffic barriers) on the traffic roadbed
3) Remove lane marking and temporarily re-stripe the traffic road bed
4) Partial closure of the traffic roadbed

II. Main Reconstruction Operation (72 hours)

5) Full closure of construction roadbed and switch traffic to the traffic roadbed
6) Saw-cut old PCC slabs
7) Cold plane old outside AC shoulder
8) Demolish old PCC slabs and excavate CTB and part of AB
9) Grade and compact aggregate base
10) Produce and deliver hot mix asphalt
11) Pave new AC base (75 mm thick × 2 lifts)
12) Compact and provide for cooling of AC base
13) Produce and deliver concrete
14) Pave new PCC slabs

15) Finish PCC and apply curing compound

16) Allow for PCC slabs to cure

17) Saw-cut new PCC slab joints

18) AC overlay of outside shoulder

19) Clean up newly constructed pavement

III. Closure Demobilization Operation (4 to 5 hours)

20) Mark lanes on the new pavement (striping)

21) Open the construction roadbed to traffic

22) Partial closure of the traffic roadbed

23) Remove MCB on the traffic road bed

24) Remove temporary lane marking and re-striping on traffic roadbed

25) Open both directions of the freeway

3.5 Staging Construction Plan

Main pavement reconstruction activities during the 72-hour closure include following:

- Demolition of the existing old pavement structure (PCC, CTB, and part of AB)
- Paving AC base (ACB)
- Paving PCC slab
- Cold plane and AC overlay of the outside shoulder.

These four activities can progress concurrently, although equipment cannot work at the same location. Based on the linear scheduling technique, one activity has to follow the other while maintaining a distance and time buffer to avoid interference between the activities. A rehabilitation technique known as the “concurrent double-lane paving method” will most likely be used for this project since two passenger lanes are available for construction access to rebuild two truck lanes at once.(*18*) This involves demolition and paving occurring simultaneously, on two lanes, with each operation serviced by one access lane for materials hauling and delivery.

The CA4PRS model predicted that each of the four segments could be reconstructed in two 72-hour weekday closures (as demonstrated in the later section), and therefore it was decided to subdivide each segment into two equal stages for construction convenience. AC base (ACB) paving can begin following demolition once the demolition operation has progressed far enough that equipment interferences are minimized and ACB operations will not catch up with the demolition activities. Similarly, PCC paving can begin and follow ACB paving once ACB paving has progressed sufficiently to allow time for cooling. Therefore, it is most efficient to subdivide each closure into four equal sections. Each section will be approximately 300 m long for Segment 1 and 250 m for Segment 2 based on the CA4PRS analysis.

4.0 PRODUCTIVITY ANALYSIS WITH CA4PRS

The CA4PRS software played a key role in the productivity analysis for the I-15 Devore project. The productivity analysis of the 72-hour closure, which incorporates schedule interface, material volumes, and logistic and resource constraints also used reference information from the two previous LLPRS projects.(*8, 9*) The hourly production rate and resource constraints used in the CA4PRS analysis were confirmed by Caltrans construction engineers and paving contractors (the American Concrete Pavement Association-ACPA) through a series of constructability meetings for the project.

Figure 3 shows an example output screen from the stochastic CA4PRS analysis, which calculates the likelihood of maximum production capability per closure in terms of lane-km. The

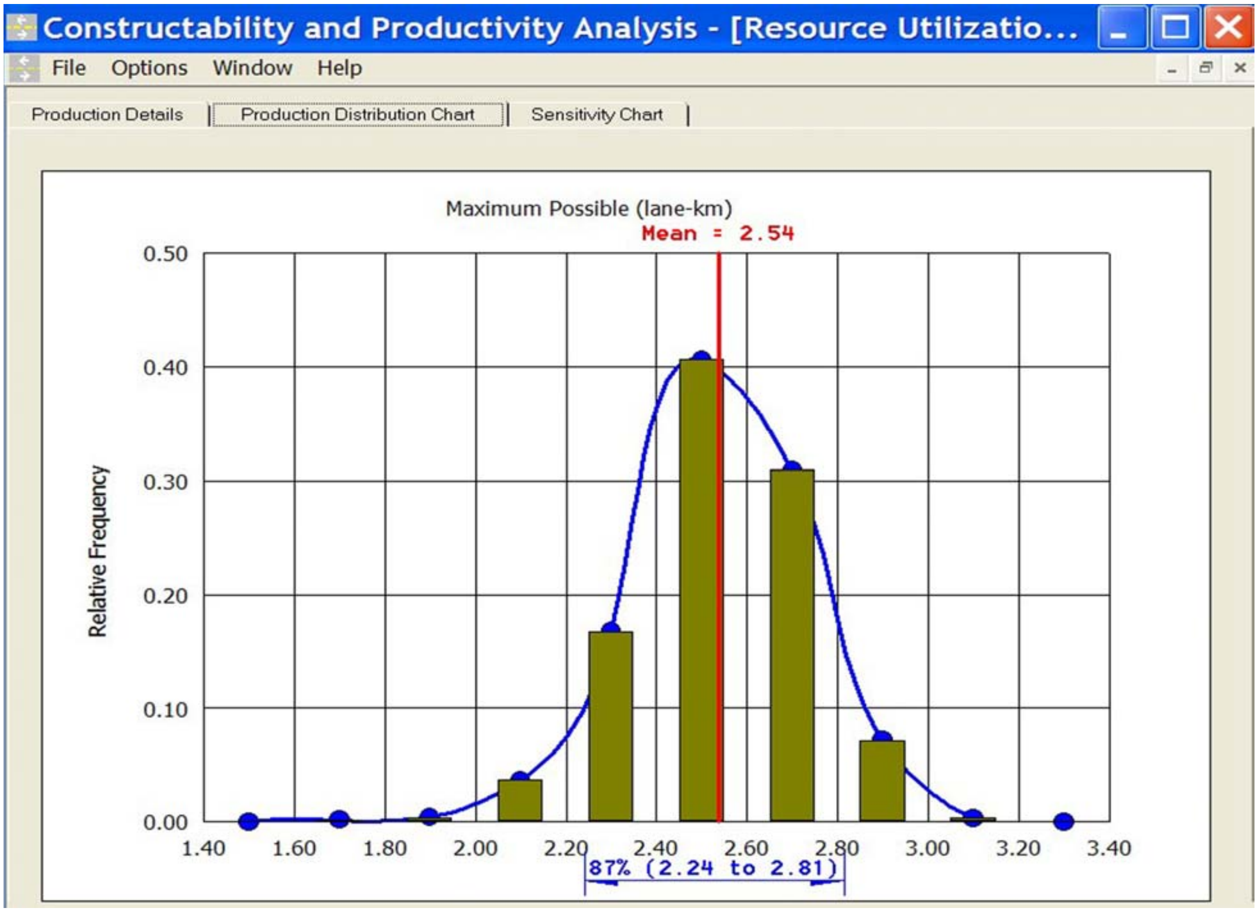

Figure 3. CA4PRS probabilistic analysis output screen.

following sections summarize the procedure of the productivity analysis for Segment 1. Only the final result of Segment 2 is discussed since the calculation process is similar for all segments.

A typical CPM schedule for the 72-hour extended weekday closure was developed based on baseline production information provided by the CA4PRS analysis, as shown in Table 2. The table lists all the major operation activities along with their duration, start and finish time for the first section (about 300 m) after a closure, and the entire closure period.

Table 2 Typical CPM Schedule for the 72-hour Closure

Activity		First Section (300 m)			Stage (1.25 km)		
		Duration (hr.)	Start (hr.)	Finish (hr.)	Duration (hr.)	Early Start (hr.)	Late Finish (hr.)
1	72-hour closure starts		0				
2	Full closure and traffic switch	1	0	1			
3	Saw-cutting of old PCC slabs	4	1	5	16	1	32
4	Cold plane old AC shoulder	6	2	8	24	2	35
5	Demolition of old slab and base	8	4	12	32	4	39
6	Compaction of the subgrade	6	10	16	24	8	43
7	Tack coating	1	16	17			
8	Paving new AC base	2	17	19	8	17	46
9	Compaction of AC base	4	17	21	16	17	48
10	New PCC slab paving	9	21	30	36	21	57
11	AC overlay of shoulder	1	42	43			
Constraint Only for Last Section							
12	PCC curing				12	57	69
13	Saw cutting				6	65	71
14	AC overlay of shoulder				1	69	70
15	Clean-up of the pavement				1	70	71
16	New lane marking				1	71	72
17	72-hour closure finishes						72

4.1 PCC Demolition Productivity

The CA4PRS scheduling analysis estimated that with the concurrent working method and the linear schedule technique, 32 hours for demolition and 36 hours for PCC paving are the optimum durations for these operations to achieve maximum production within a 72-hour closure. As discussed previously, each closure (stage) is divided into four sections of 250-300 m to avoid equipment interruption among the three major operations, i.e., demolition, AC base paving, and PCC paving. The three demolition teams (crew) will work simultaneously, and each team will work on one-third (about 100 m) of the section.

A CA4PRS Monte Carlo sensitivity analysis indicated that demolition is the most critical operation for this project. Therefore, it was recommended that the contractor pay extra attention to his demolition resources and add additional crews if needed. Typically, two types of PCC slab demolition methods are commonly used: “non-impact demolition,” in which the slab is cut into 3-4 pieces and each piece is lifted out by excavator; and “impact demolition,” in which the PCC slab is rubblized by a breaker (stomper) into small pieces and bucketed out by an excavator. Demolition experience on the previous LLPRS projects indicates that the non-impact demolition rate was 58 percent slower than that of impact demolition.(*8, 9*) However, because of environmental restrictions, the non-impact (slab lift) demolition method was selected for the I-15 project. The noise made by the slab stomper during the night could disturb residents and wildlife habitat near the site.

As indicated above, three demolition teams were used as the input in the CA4PRS analysis based on the previous LLPRS projects. Each demolition team was assumed to use an excavator (backhoe) for loading and ten 22-ton capacity end dump trucks for hauling operations. Previous case studies show that ten end dump trucks per hour per team is generally the maximum possible for non-impact demolition because at least five minutes of cycle time was required to load each haul truck.(*8*)

The CA4PRS analysis model utilizing the linear scheduling technique identified balancing resource requirements for the other two operations (AC base and PCC paving) based on the number of haul trucks as the critical resource constraint. The balanced productivity, i.e., hourly progress of the demolition calculated from the analysis with the given hauling volumes, scheduling, and resource constraints, is 41 m per hour during the total 32 hours of demolition per closure.

4.2 AC Base Paving Productivity

The CA4PRS analysis indicated that the resources required for the ACB paving and shoulder AC overlay operations to balance with the demolition and paving operation are six 24-ton bottom dump semi tractor trailers per hour on average. The AC batch plant needs to produce 150 tons per hour to keep up with paving operations. AC cooling time was calculated to check any time delays in starting PCC slab paving using the "MultiCool" cooling analysis program integrated into CA4PRS.(*19*) The productivity analysis indicated that each 300-m section of ACB can be paved in approximately four hours. Since ACB paving has to follow demolition, which will take about eight hours per section, ACB paving itself is not expected to be a production constraint.

4.3 PCC Paving Productivity

The CA4PRS analysis estimated that thirteen 6 m^3 (15 ton) dump trucks are needed each hour for concrete delivery to achieve the overall maximum production for the PCC slab paving operation. This means each delivery truck has about a five-minute cycle time for concrete charging in the batch plant and also for discharging time on site. This cycle time was validated in the previous case studies and confirmed by the industry group in the constructability meetings as the minimum practically achievable. The batch plant has to produce at least 80 m^3 per hour for 36 hours around the clock during the 72-hour closure. The paver is required to produce at least 0.6 m per minute to match production. The paver speed was confirmed to typically not be a constraint, even with the two-lane concurrent paving with the automatic dowel bar inserter, as long as there is a steady supply of dowels.

In summary, the CA4PRS analysis showed that the balanced productivity (progress) of the PCC slab paving operation with given resource constraints was estimated to be 36 m per hour during the total 36 hours of operation per 72-hour closure.

4.4 Productivity Analysis Summary

The CA4PRS analysis indicated that the maximum reconstruction production could be achieved with an ideally balanced operation, where 32 hours are allocated for demolition and 36 hours are allocated for PCC paving during the 72-hour closure. The equations for maximum production (distance) for the balanced demolition and paving operations per closure are:

- Demolition production: 41 m/hour × 32 hours = 1.3 centerline-km
- Paving production: 36 m/hour × 36 hours = 1.3 centerline-km

This analysis includes widening of the outside truck lanes as well as cold planing and overlay of the outside shoulders. In summary, the balanced maximum production of one 72-hour closure is 1.3 centerline-km for Segment 1. A similar analysis indicates 0.9 centerline-km production per closure for Segment 2. Production for Segment 2 (3-lane section) is less than that for Segment 1 (4-lane section) because there are fewer access lanes for construction, which increases interference between the operations. This access bottleneck reduces the number of hauling and delivery trucks that can operate in Segment 2.

Segment 1 (2.5 centerline-km) and Segment 2 (1.7 centerline-km) each require two 72-hour closures. Therefore, it is concluded that the I-15 Devore pavement reconstruction can be accomplished in eight 72-hour extended weekday closures, i.e., 4 segments × 2 closures per segment.

5.0 CONTINGENCY MANAGEMENT PLAN

Fast-track construction I requires specific contingency strategies to minimize the number and magnitude of unforeseen problems. Critical items for this contingency plan were determined based on the previous LLPRS case studies. Some key requirements contractually imposed on the contractor are presented in the following sections.

5.1 Poor Subgrade Replacement

As-built plans for the existing pavement structure on the construction corridor show 200 mm PCC over 100 mm CTB over 450 mm aggregate base. However, this pavement was constructed in the 1960s and 1970s. Depending on quality control at the time, it is possible that the aggregate base may be thinner than 450 mm or completely missing, and that CTB may be missing as well, as was observed on the I-710 Long Beach reconstruction project.(*9*) At some locations, poor subgrade (SG) may be encountered during demolition and excavation. Therefore, contingency plans should provide pre-planned solutions, for example, additional removal of the poor subgrade, placement of a geotextile fabric, placement of a new aggregate base, and grading and compaction.

These activities may delay the schedule and add to the project cost. To compensate for any delay, the contractor could be allowed to use FSHCC paving material, one of the faster setting but more expensive concrete mixes, for paving of some sections. Alternatively, more extended geotechnical site investigations prior to construction, including coring in the mainline and shoulder and trench investigation in the shoulder, could be performed to evaluate these site conditions. The contractor could then have appropriate treatments available to minimize production delay in advance.

5.2 Appropriate Gap between Operations

To minimize equipment interruptions, there should be a minimum allowable gap between the locations where major reconstruction operation activities (demolition, AC base paving, and PCC paving) are proceeding concurrently. As noted previously, it was recommended that each stage (72-hour closure) be divided into four equal sections (about 300 m) and that these activities occur in different sections concurrently. At the same time, the gap between demolition and AC base paving or PCC slab paving should also be limited to a certain distance that—in the event of an unforeseeable breakdown of a paving operation—will allow the amount demolished to be repaved before the end of the closure. The contingency plan can include the use of temporary paving material for that section.

5.3 Use of Two Concrete Mixes

The use of FSHCC mix on the final slabs of the 72-hour closure within 12 hours of traffic opening, the so-called “stitch,” will save paving hours. The Special Provisions for the project allow the contractor to use two concrete mixes in each closure, the 12-hour mix (PCC) on most slabs with a 4-hour mix (FSHCC) used on the stitch, either to achieve more rapid production at the end to make up for any unforeseen delay, or as a temporary paving material in case of an emergency. The contractor should arrange an appropriate set of resources, such as delivery trucks and paving machines to handle these two different mix designs.

According to the CA4PRS analysis, the hourly FSHCC paving production rate is about 23 m per hour for the two truck lanes. Consequently, an additional 138 m (23 m × 6 hours, excluding a couple of hours for switching the concrete mixes) could be finished on the stitch. Although FSHCC presents some cost and quality control disadvantages, it could be paved on the stitch from hour 50 (at the earliest) through hour 58 during 72-hour closure, and the eight hours saved could be used for other purposes such as traffic switching (striping) or for paving an additional distance, at the contractor's discretion.

5.4 Standby Paving Materials for Emergencies

Caltrans decided to retain the contractual authority to open the freeway prior to the end of closure due to emergencies, for example due to severe weather, fires, vehicle accidents, or construction-related problems that would compromise the quality of the finished product. Under such circumstances, the contractor may use FSHCC, Hot Mix Asphalt (HMA), or cold mix AC as temporary paving materials. However, the contractor should eventually replace these materials with specified materials to fulfill the contract.

5.5 Incentives/Disincentives Contract

Traditional Caltrans practice has been to rely on ad hoc estimates in assessing the amount of incentives/disincentives for highway rehabilitation projects needed to promote the production objective, often without technical justification. This I-15 Devore project incorporated the unique approach of using the additional cost associated with inconvenience to road users and the agency to outline the incentives/disincentives requirement based on the traffic analysis and cost estimation, as part of the Stage 1 analysis.(*12*) The contractor will be eligible for an incentive bonus if construction is completed in fewer than eight 72-hour closures, or be subject to a disincentive penalty if the construction takes more than eight closures. In addition, incentives or disincentives will be applied if an individual closure is completed in less than or more than three weekdays for each 24-hour increment of early or late opening.

The projected road user delay cost for one 72-hour weekday closure, using the HCM and the FREQ model as part of the Stage 1 traffic analysis, was estimated at approximately $750,000.(*15*) Calculation with an additional reduction in traffic demand of 10 percent of total traffic (the truck traffic restriction through the construction work zone during peak hours) results in a delay cost of $300,000 per closure. Based on these calculations, the recommended value is $100,000 per day or $300,000 for a full 72-hour weekday closure. The maximum allowable incentive is limited to $600,000 (i.e., two closures) because it is not realistic to assume that a contractor would be able to reduce the number of closures further. However, it was decided that there should be no limit to the amount of the disincentive if the contractor needs more than eight 72-hour closures. Because of the limit of the project budget, Caltrans adjusted these numbers and finally decided to apply $75,000 per 24-hour period (day) in each closure and $250,000 per 72-hour period (closure) with the maximum incentive being $500,000 in the contract.

6.0 CONCLUSIONS AND FUTURE RESEARCH

The conclusions and decisions based on this pre-construction study are summarized as follows:

- For the I-15 Devore project, the 72-hour weekday extended closure was selected as the most economical closure strategy in lieu of the 55-hour weekend and 10-hour nighttime closure strategies. The single continuous closure to completion strategy was not selected because of unacceptable estimated maximum traffic delay per closure. The concept of total cost, integrating closure schedule, road user cost, and construction and traffic handling costs, was used for the strategy selection criteria.

- A detailed constructability and productivity analysis for the 72-hour weekday closure was implemented using the CA4PRS model to develop a construction management plan for the project. As a result, a typical reconstruction process was defined. The CPM schedule was developed and major input resource requirements were outlined. The productivity analysis with CA4PRS estimated that the I-15 Devore project can be accomplished in eight 72-hour weekday closures.
- A contingency plan was developed for the fast-track project to minimize the impact of unforeseen problems. The contingency plan was necessary because of the project's tight schedule and production goals. A baseline for the incentives/disincentives was developed with an innovative approach based on traffic delay analysis and cost estimate.

The following recommendations were drawn from this research:

- The CA4PRS model has been shown to be an invaluable schedule analysis tool and is recommended for use on future high-volume urban freeway reconstruction projects.
- It is strongly recommended that Caltrans and the contractor involve constructability technical experts through the duration of fast-track construction to identify project constraints and to mitigate obstacles. The agency should continue the partnership and communication with the paving industry to maximize constructability benefits.

- California now has a unique opportunity to validate and further calibrate the analyses, tools, and expertise used in the design and planning of this project. Thus, Phase II of the study—monitoring during construction—should be pursued to gather "lessons learned" for future LLPRS projects.
- Construction productivity databases should be continuously updated for the three major types of pavement rehabilitation currently used in California: Portland Cement Concrete (PCC) reconstruction, Crack Seat and Overlay (CSOL), and Full-depth AC replacement.

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