Minimizing Total Cost for Urban Freeway Reconstruction with Integrated Construction/Traffic Analysis

Technical Memorandum prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

By

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EXECUTIVE SUMMARY

This technical memorandum introduces an innovative approach to development of construction and traffic management plans for the I-15 Devore project, a fast-track urban freeway reconstruction project with high traffic volume in Southern California. The goal of this approach was to determine the most economical reconstruction closure scenario by integrating construction schedule, traffic delay, and agency cost. CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software was used for scheduling analysis. The demand-capacity model (Highway Capacity Manual), and macroscopic (FREQ) and microscopic (Paramics) traffic simulation models were utilized for traffic delay analysis. Based on these analyses, the California Department of Transportation decided to implement eight 72-hour weekday closures with 24-hour operations for the project. This was found to be more beneficial for both the agency and the traveling public than the alternative closures of 1) 55-hour weekend, 2) 10-hour nighttime, or 3) a single continuous. The analysis presented herein concludes that the 72-hour closure scenario requires 77 percent less total closure time, 34 percent lower road user cost, and 38 percent lower agency cost when compared with the traditional nighttime closures.

1.0 INTRODUCTION

As most transportation agencies turn their attention from expansion (new construction) of highway systems to the 4-R approach (Restoration, Resurfacing, Rehabilitation, and Reconstruction), the need for new pavement rehabilitation strategies is emerging.(*1*) In recent years, approximately 30 percent of these 4-R type construction highway projects were in urban areas; where there are substantial challenges for both contractors and commuters as drivers struggle to get through construction work zone traffic.(*2*)

The California transportation infrastructure includes over 78,000 lane-kilometers of state highway. About 90 percent of California urban freeways were built between 1955 and 1975, with 20-year design lives. Most of these pavements were exposed to heavier traffic volumes and loads than those for which they were originally designed, and exceeded design load repetitions in less than 20 years. Consequently, the transportation network has deteriorated significantly and pavement deterioration has started to adversely affect road user safety, ride quality, vehicle operating costs, and maintenance costs.(*3*)

In 1998, the California Department of Transportation (Caltrans) launched its Long-Life Pavement Rehabilitation Strategies (LLPRS) Program to rebuild approximately 2,800 lane-km of the state highway network over 10 years, investing an additional $1 billion in the $9 billion State Highway Operation Protection (SHOP) Program.(*4*) The objectives of LLPRS were to: 1) provide 30 years of service life, 2) require minimal maintenance, and 3) achieve 6 lane-km production capability during a 55-hour weekend closure (Friday 10 P.M. – Monday 5 A.M.).(*4*) The criteria for selecting highways in need of long-life pavement rehabilitation are poor structural condition and ride quality, and a minimum of 150,000 Average Daily Traffic (ADT) or 15,000 Average Daily Truck Traffic (ADTT). Most of the LLPRS candidate projects are concrete-paved interstates in urban corridors in Southern California and the San Francisco area.

Since initiating LLPRS, Caltrans has completed two LLPRS demonstration projects. One was a concrete project on Interstate 10 in Pomona, successfully completed at the end of 2000. A total of 2.8 lane-km of 200 mm old Portland Cement Concrete (PCC) was replaced with Fast-Setting Hydraulic Cement Concrete (FSHCC) during one 55-hour weekend closure. FSHCC develops the flexural strength of 2.8 MPa (400 psi) needed to open to traffic in four hours.(*5*)

Caltrans also recently completed an Asphalt Concrete (AC) demonstration project on Interstate 710 near Long Beach.(*6*) Approximately 26.4 lane-km of existing PCC pavement was rehabilitated with AC during eight 55-hour weekend closures using fast-track construction. Two AC rehabilitation strategies were used: 1) the existing pavement was replaced with 330 mm (13 in.) of full-depth AC under four freeway overpasses; and 2) the old PCC pavement was cracked and seated, then overlaid with 230 mm (9 in.) of AC between the freeway overpasses.

1.1 CA4PRS: Pavement Rehabilitation Planning Tool

For schedule and production analysis of LLPRS projects, Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software was developed by the University of California Pavement Research Center (UCPRC), with fund support from the state departments of transportation of California, Minnesota, Texas, and Washington.(*7*) The software estimates the length of highway that can be rehabilitated or reconstructed within construction, design, and traffic constraints. The CA4PRS model evaluates “what-if” scenarios with respect to rehabilitation production and schedule by comparing the following input variables (alternatives):

- Pavement strategy: replaced with Portland Cement Concrete (PCC); cracking and seating PCC and asphalt overlay (CSOL); or full-depth asphalt concrete replacement.
- Construction windows: 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 strength gain constraints: curing time for concrete pavement or cooling time for asphalt pavement.
- Pavement structural section: thickness of concrete slab; thickness of full-depth asphalt concrete layer or thickness of AC overlay.
- AC pavement design: different lift thicknesses for AC paving
- 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.

1.2 Traffic Analysis of Construction Work Zone

Most highway segments in California requiring rehabilitation are under heavy traffic volumes in urban corridors. Because construction activities are likely to negatively influence the traffic flow of roadways that are already above or near flow capacity, rehabilitation planning and construction should be carefully considered in view of total costs, including agency cost (construction and traffic handling cost) as well as road user cost (RUC). Traffic analysis methods and tools are needed to quantify the RUC of various types of highway rehabilitation activities and to help design effective traffic management strategies in reducing this cost.

For traffic management of the construction work zone (CWZ), there are several approaches to quantify delays associated with closures. The most commonly used method is the demand-capacity approach where the demand for the CWZ is measured from historical data, and the capacity is estimated using the Highway Capacity Manual (HCM).(*8*) Occasionally, a CWZ can impact a much larger area in a road network. To quantify this CWZ delay in the larger network, more complex models are needed to assess traffic movements across the entire area.

Two types of traffic models are available to evaluate the impact of the CWZ on traffic in a general network. Static models utilize the transportation planning model which assigns time-invariant Origin-Destination demand to a road network according to certain user behavioral principles. Dynamic models include various types of dynamic assignment and traffic simulation. Software packages such as Paramics, MITSIM, VISSIM, and AIMSUN employ microscopic traffic simulation models and route assignment techniques. Both the static and dynamic models can assess the effects of the CWZ with varying levels of detail and accuracy.

1.3 Research Objectives and Approach

This study's primary purpose was to help Caltrans develop efficient construction and traffic management plans for I-15 Devore. Four construction closure scenarios—72-hour weekday, 55-hour weekend, single continuous, and 10-hour nighttime—were compared from the perspective of construction schedule, traffic inconvenience, and construction and traffic handling cost.

The HCM-based demand-capacity model was applied to compare the road user cost of the four construction closure scenarios based on schedule analysis using the CA4PRS model. After a framework integrating these construction and traffic criteria was developed to select the most economical closure scenario that minimizes the total cost for this LLPRS project.

Once the best closure scenario was selected, constructability analysis using the CA4PRS model was conducted to compare the production advantages and disadvantages of pavement-related alternatives.(*9*) Additional traffic analysis with macro- and microscopic simulation models were applied to support the project traffic management plan.

Results of this study will be useful for transportation agencies and contractors in developing pavement rehabilitation strategies that maximize construction productivity, minimize traffic delay, and reduce the total cost for highways with high traffic volume.

2.0 I-15 DEVORE RECONSTRUCTION PROJECT

The Devore project is located on Interstate 15 between Interstates 10 and 215 in San Bernardino County, California. 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. At the time of this writing, construction is scheduled to start in first quarter of 2004.

2.1 Project Overview

Caltrans decided to split the project into two segments to ease traffic control during rehabilitation. Built in 1975, Segment 1 is 2.5 km over all eight lanes from the Sierra Avenue intersection to the Glen Helen Parkway intersection. Segment 2 is 1.7 km over all six lanes, from the Glen Helen Parkway intersection to the I-215 system interchange. The passenger lanes are still in good condition and expected to provide service for at least another decade, so Caltrans decided to rebuild just the two truck lanes in each direction because they have extensive cracking, faulting, and patches. Altogether, the project includes approximately 17 lane-km (4.2 centerline-km × 2 truck lanes × both directions).

The freeway through the Devore corridor carries approximately 110,000 average daily traffic (ADT), a high percentage of which is trucks: 12 percent on weekdays, 21 percent on weekday nights, and 7 percent on weekends. The corridor is a primary freight route from

Southern California to the Midwest and northeast United States. Unlike typical urban freeways in California which have peak rush-hour traffic in the morning and afternoon and relatively low traffic volumes over weekends, 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 (NB) on Friday afternoon (63,000 ADT) and southbound (SB) on Sunday afternoon (62,000 ADT). This high traffic volume primarily consists of travelers in the Los Angeles area going to and from Las Vegas for the weekend. These traffic patterns are shown in Figure 1.

2.2 Construction Staging Plan

The existing pavement structure consists of 203 mm (8 in.) of plain, jointed, undoweled concrete slabs, 102 mm (4 in.) of cement treated base (CTB), and 450 mm (18 in.) of aggregate

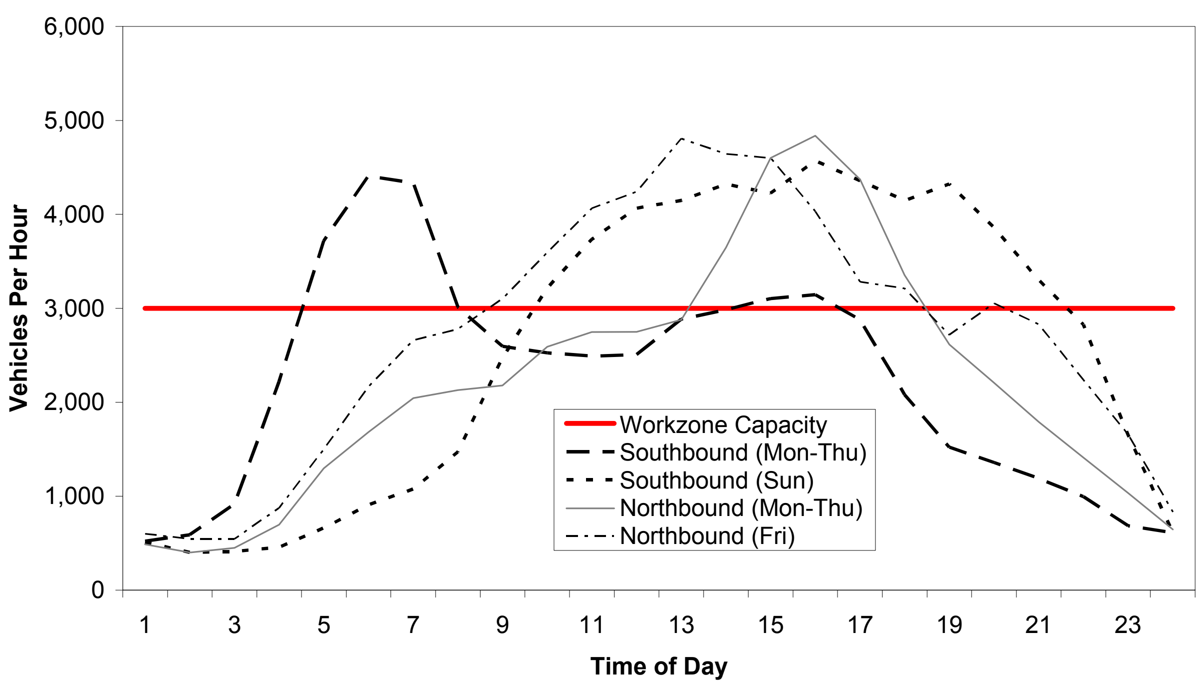

Figure 1. Daily traffic patterns for the I-15 Devore project

base (AB), which is a typical for Caltrans urban freeway design from the 1970s. The old pavement is to be replaced with 290 mm (11.5 in.) of plain, doweled concrete slabs, and 152 mm (6 in.) of asphalt concrete base (ACB) or Lean Concrete Base (LCB) to be placed on the re-compacted existing aggregate base. Caltrans chose to use the early strength Type III Portland Cement Concrete (PCC) with special admixtures to achieve the 2.8 MPa (400 psi) flexural strength within 12 hours, thus allowing the highway to open to traffic in 12 hours. This concrete is usually called "12-hour mix."

One segment in each direction of the freeway will be closed during construction per closure period. For example, Segment 1 of the northbound freeway (construction roadbed) will be closed by diverting traffic to the other side (traffic roadbed) through traffic crossovers. As Figure 2 illustrates, 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 to two-way traffic (two lanes in each direction) as a "counter flow traffic" control system during reconstruction. Moveable concrete barriers (MCB) will divide into the two lanes. During reconstruction, various on- and off-ramps will be closed for traffic control. The outside shoulder will be used as an additional traffic lane for Segment 2, which has only three lanes per direction.

3.0 EVALUATION OF THE CLOSURE SCENARIOS

The most economical closure scenario for the I-15 Devore Reconstruction Project was selected from the four basic closure alternatives using a combination of construction schedule, traffic delay, and total cost criteria.

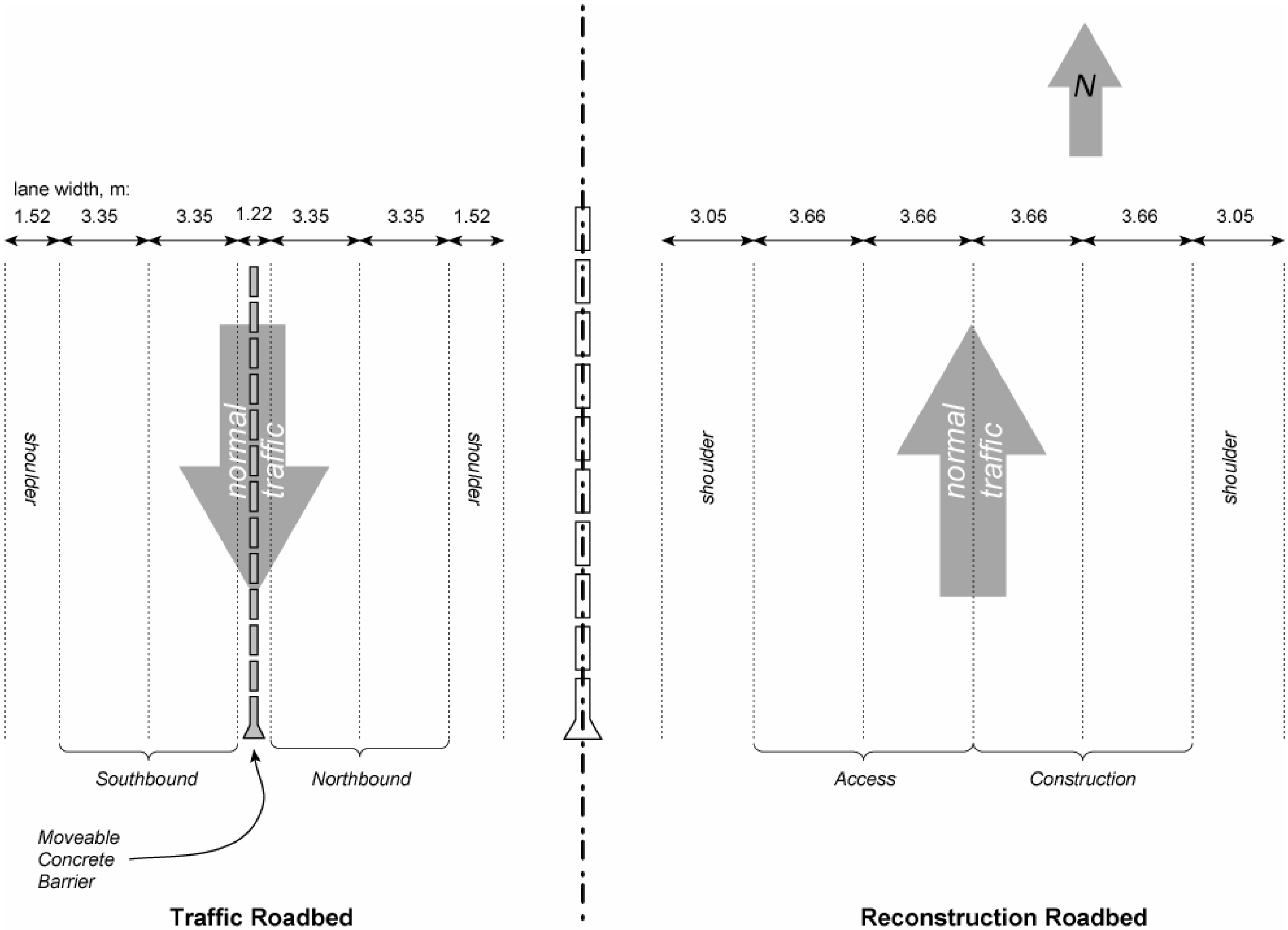

Figure 2. Lane closure tactics during construction.

3.1 Innovative Extended Closure

Caltrans initially considered a traditional approach for the I-15 project—that is, replacement of individual broken concrete slabs during repeated 10-hour nighttime closures using fast-setting type of cement concrete. However, conventional nighttime closures for LLPRS projects, especially on urban freeways, cause potential pavement management problems, such as:

- repeated risk of traffic delays if work is not completed during the nighttime closure,
- low pavement life expectancy (10-15 years) due to limits on the type of pavement structure that can be constructed in 8- or 10-hour closures and opened to traffic,
- inferior surface condition and ride quality due to reduced construction quality control under the tight time constraint,
- large volumes of materials than cannot be properly handled in a short time period,
- increased safety risk for road users, agency staff, and contractor crew, and
- environmental problems such as noise and habitat disturbance due to prolonged total construction closures.

In addition to these negative aspects, longer total construction time with the traditional nighttime closure pattern would result in higher construction and traffic handling costs as well as potentially greater total traffic delay inconvenience to road users, compared to the innovative closure strategies. These findings have led Caltrans to develop fast-track reconstruction strategies such as weekend (55-hour) or extended weekday (72-hour) closures with 24-hour operations for LLPRS projects. For example, theI-10 Pomona study showed that the 55-hour weekend closure was about 40 percent more productive than the traditional nighttime closures.(*5*)

The benefits of the 55-hour weekend closures over the traditional weekday nighttime closures stem from reduced overall traffic delays. However, these benefits seem insufficient for the I-15 Devore project because of the unique weekend traffic patterns and the layout of the construction work zones. Therefore, an innovative approach was introduced in this study that integrates construction schedule, total traffic delay (road user cost), maximum queue length, and total cost by comparing the 72-hour weekday closures to: 1) 10-hour nighttime weekday closures, 2) 55-hour weekend closures, and 3) single continuous until completion closures.

Based on the 55-hour weekend closure experiences from the I-10 Pomona and the I-710 Long Beach projects, Caltrans considered implementing the third such LLPRS project in Devore as fast-track construction with 24-hour operations while using more innovative closure strategies such as 72-hour extended weekday closures.

3.2 Scenario Evaluation Process

As illustrated in Figure 3, the four candidate construction closure scenarios were evaluated based on the comparison criteria with the following detailed processes:

- Schedule analysis was done using the CA4PRS model to calculate the number and the total duration of closures.
- Traffic analysis based on the demand-capacity model and macroscopic simulation model was conducted to quantify inconvenience to the traveling public during construction, i.e., road user cost (RUC) and maximum traffic delay (queue length) per closure.
- The agency cost as the sum of construction and traffic handling costs was derived from several sources: commercial cost databases, Caltrans historical bidding information, and pavement contractors' validation.
- Finally, the most economical closure scenario was selected based on the key criteria of total costs (the agency cost and RUC).

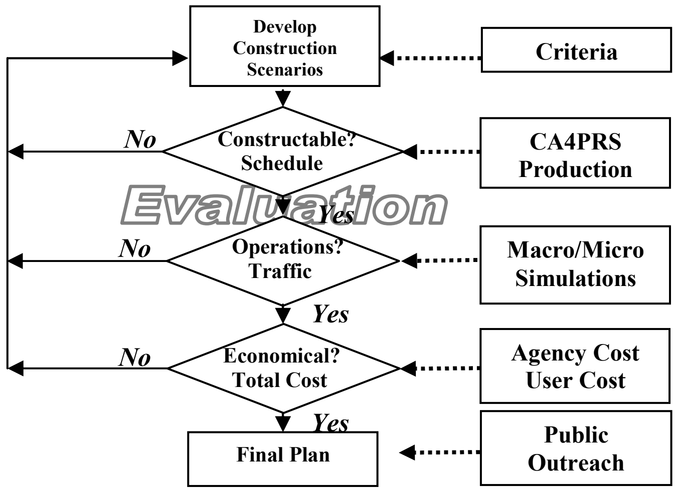

Figure 3. Integrated scenario selection process for the I-15 Devore project

Upon selection of the 72-hour closure scheme, more detailed constructability analyses were performed with the CA4PRS program to develop the construction management plan and refine pavement material and mix design issues.(*9*) Similarly, more detailed traffic analysis with a microscopic simulation model using Paramics software (*10*) was performed to support the traffic management plan.(*11*)

4.0 SCHEDULE ANALYSIS

A sensitivity study with the CA4PRS model showed that the contractor's logistical resource constraints are typically the most critical input to the construction productivity of a concrete LLPRS project.(*12*) This finding was reviewed and verified during a series of constructability review meetings with the Western States Chapter of the American Concrete Pavement Association (WSC-ACPA).

Resource constraint is dependent upon the scale and type of the rehabilitation closure and the pavement design. For example, nighttime closures require concrete that reaches opening strength in 4 hours, while 55-hour or 72-hour closures can use 12-hour mix concrete. Based upon the meetings with the agency and contractors, realistic maximum values of required resources were applied to the production analysis of each of the four closure scenarios.

4.1 Schedule Comparison with CA4PRS Model

CA4PRS was used to analyze the construction production schedule in order to compute the number of closures and the total closure hours for each closure scenario. Figure 4 illustrates a sample input screen of the CA4PRS model. The 72-hour weekday closure, (eight closures and a total of 512 closure hours) is treated as the baseline for comparison with other closure types. The ten 55-hour weekend closures require a 10 percent longer duration while the single continuous closure scenario requires the fewest closures (a total of 2) and the shortest duration (400 hours).

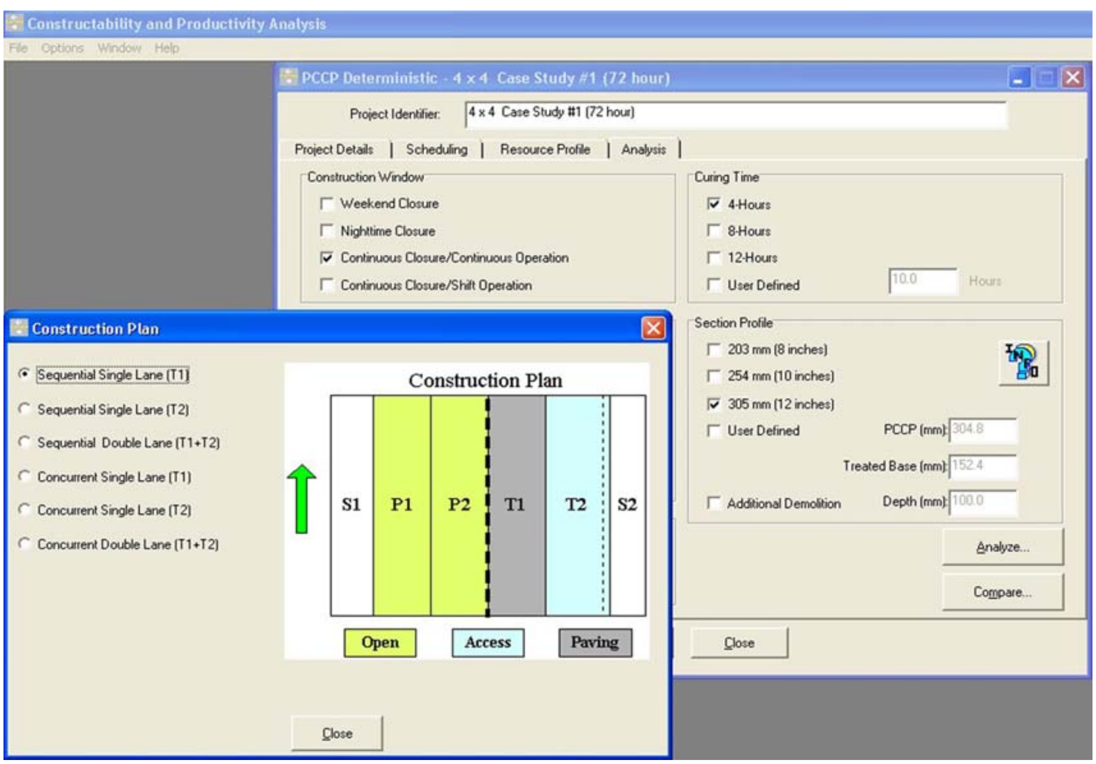

Figure 4. Input screen of the CA4PRS schedule analysis.

The traditional 10-hour nighttime closure scenario requires the greatest duration (2200 hours) and number of closures (220 weekday nights) and takes four times as long to be completed as the 72-hour weekday closures. Reconstruction would take approximately one year with traditional nighttime closures, but the construction schedule could be shortened to two months utilizing the 72-hour weekday closure scenario.

4.2 Constructability Issues

In addition to construction schedule, traffic delay, and total cost, pavement constructability issues influence the rehabilitation strategies. Three pavement-related alternatives were compared in the constructability analysis to identify the most productive rehabilitation strategies for all four closure scenarios from a production and scheduling perspective:

- Concrete mix design in respect to curing time: 4-hour versus 12-hour mix
- Pavement base type: asphalt concrete base (ACB) versus lean concrete base (LCB)
- Truck lane width: widened truck lane versus regular truck lane tied to a concrete shoulder

The effects of these three variables on the Devore project were evaluated using the CA4PRS model for the 72-hour closure scenario as the baseline case. Earlier studies and laboratory and field tests of LLPRS projects identified consistent effects of these three variables on pavement performance across all closure scenarios.

Based on the constructability analysis results from the perspective of production and schedule, Caltrans decided to adopt the strategy of 1) Type III concrete with 12-hour mix for the main concrete slab, 2) asphalt concrete base, and 3) a wide truck lane. This decision demonstrated that constructability has a priority in the fast-track urban freeway rehabilitation project to achieve high construction productivity without sacrificing the long-life performance objective. Details of the constructability analysis are summarized in the following sections.

4.2.1 Concrete Slab Mix Design

Two concrete slab mix designs, 12-hour early-age Type III PCC and Fast-Setting Hydraulic Cement Concrete (FSHCC, 4-hour curing time), were compared. The 8-hour advantage of FSHCC is offset by its higher slump and greater stickiness. These negative characteristics of FSHCC require additional delivery trucks, a smaller paving machine, and paving one lane at a time. It also produces a rough finished surface that often requires diamond grinding after paving. In addition, FSHCC is approximately twice as expensive as the Type III 12-hour mix in California. A construction schedule analysis with the CA4PRS model indicated that the two materials take approximately the same time for completion of the whole project, meaning that using FSHCC would not be the most economical solution.

4.2.2 Pavement Base Type

Two types of pavement 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 were to be used instead of ACB. These extra closures would result in an additional construction cost and greater traffic delay, as LCB requires more lead time to allow the 12-hour curing of the concrete base before PCC slab paving starts. According to previous Caltrans experience, the LCB scenario requires placement of a bond-breaker such as 25 mm of AC between the LCB and the concrete slabs to reduce friction between the PCC and LCB, and therefore reduce the risk of early cracking and increase the long-term cracking resistance. The ACB alternative, which was selected, also permits parallel production and operation of the base (ACB) and slabs (PCC) with its own resources. This increases production to the extent that two 72-hour closures are eliminated, reducing traffic delay and construction cost.

4.2.3 Truck Lane Width

Two options were considered for the width of the outside truck lane (T2): regular width (3.7 m) tied to a concrete shoulder, and a widened truck lane (4.3 m). Pavement performance analyses have indicated that the widened truck lane can provide performance similar to the regular truck lane tied to a concrete shoulder in this climate zone. The option of a 3.7 m lane with asphalt concrete shoulders was not considered because of its shorter life. The constructability analysis showed that tied concrete shoulder with the regular width truck lane option would slow the reconstruction progress, and therefore require additional closures. Only about 8 percent more construction time is needed to construct the wider truck lane compared to building a 3.7 m regular lane, and the whole reconstruction project can still be completed in the same eight 72-hour closures.

5.0 TRAFFIC DELAY IMPACT ANALYSIS

Due to high traffic volumes on the I-15 Devore section during construction, two main objectives for the traffic analysis were: 1) quantifying traffic delay during construction, and 2) design an efficient traffic management plan (TMP) to divert some mainline traffic to parallel arterial streets or neighboring freeways. This traffic analysis also helped Caltrans determine contractual incentives and disincentives to encourage the contractors to complete the project on time.

Road user cost (RUC) and maximum delay per closure were the two evaluation criteria in the traffic delay analysis for each construction closure scenario. RUC takes both queue delay and work zone delay into account. The majority of the queue delay is due to time spent in traffic queues, which is caused by demand exceeding the reduced capacity of the CWZ. Work zone delay is the additional travel time each road user experiences because of the reduced speed through the CWZ. Based on Caltrans experience, travel speed through the I-15 Devore CWZ was assumed to be reduced from 112 kph (70 mph) to 80 kph (50 mph). The work zone delay was determined by subtracting the time it would take to traverse the work zone at 80 kph from the time it would take at 112 kph.

5.1 Traffic Analysis Tools

To quantify the impact of delays caused by the closures, traffic performance was evaluated using three models: Demand-Capacity, FREQ, and Paramics. Each traffic analysis approach has its advantages and disadvantages. The Demand-Capacity approach, based on the Highway Capacity Manual is simple and efficient, but it does not take into account the impact of traffic diversion on alternate routes.(*8*)

In this case study, an approach combining use of the three modeling tools was seen as being well suited for this project. Macroscopic freeway traffic simulation (FREQ) allows for a large number of scenarios involving long simulation periods to be analyzed relatively quickly.(*13*) The microscopic tool, Paramics, provides a high level of detail in the simulation and offers high-quality graphics. Details of the macroscopic analysis with FREQ and microscopic simulation with Paramics are presented in a separate project technical report.(*11*) In summary, all three traffic models used in the analysis provided similar results for the key outputs: total road user delay and maximum queue length. Some details are presented in the following sections.

5.1.1 HCM Demand-Capacity Model

Caltrans District 8 provided traffic counts for one month (March 2002) segmented into one-hour time intervals on the I-15 corridor study area for modeling of the traffic demand in the expected construction period in the spring of 2004.

The HCM does not specifically state the capacity of a construction work zone, for example, in Chapter 22 a base capacity of 1,600 vehicles per hour per lane (vphpl) is recommended for short-term work zones. The base capacity is adjusted depending upon the geometry of the CWZ and traffic constraints such as the percentage of heavy trucks. Since bottlenecks in the CWZ are at crossover sections, a capacity of 1,500 vphpl was used as the most likely capacity for all construction scenarios except the nighttime closures. This capacity selection was based on the I-710 Long Beach case study.(*6*) A more realistic capacity of 1,170 vphpl was used for the 10-hour nighttime closures based on research reported in the 1985 HCM, which reflects the effects of narrow lanes, darkened conditions, and single-lane traffic.

5.1.2 Macroscopic Simulation Model

FREQ is a macroscopic simulation program designed for analyzing freeway systems, including ramp metering and HOV operations.(*13*) Although its basic methodologies use HCM techniques, FREQ analysis is more sophisticated than the HCM procedures because it simultaneously analyzes the entire freeway and all its ramps within a corridor. The model considers the impacts of queue spillbacks during congested periods on the freeway and provides detailed measures of overall system performance. This approach improves the model's computational performance compared to the HCM but does not provide the detailed representation of individual vehicles provided by the microscopic simulation.

5.1.3 Assumptions for Traffic Analysis

Based on previous Caltrans experience and practice with similar types of construction closures, several assumptions were used in the traffic analysis. One key parameter is the reduction in traffic demand during closures, i.e., the portion of road users who are expected to cancel their trips ("no-show" traffic) or use alternate routes (detour traffic). The assumed baseline traffic reduction percentages were as follows:

- Weekdays – 10 percent total reduction (5 percent no-show, 5 percent detour)
- Weekends – 5 percent total reduction (2.5 percent no-show, 2.5 percent detour)
- Nighttime – 5 percent total reduction (2.5 percent no-show, 2.5 percent detour)

It was assumed that traffic demand reduction would be less for the weekend and nighttime closures. Most weekend traffic consists of leisure trips, with drivers who are less likely to detour to other routes and may also be uninformed about construction activity. For nighttime closures, it was assumed that late-night drivers would be more difficult to target with public information. Traffic volumes are also lower at night and drivers are probably less familiar with the area, which also results in less traffic reduction. However, a sensitivity analysis of RUC with respect to traffic reduction and construction workzone capacity was performed and is summarized in Section 5.2.3.

5.2 Traffic Delay Comparison

5.2.1 Road User Cost Comparison

Table 1 summarizes the total RUC for each closure scenario, obtained by multiplying the delay in vehicle-hours by a dollar value of time, i.e., $9/hour for passenger cars and $24/hour for trucks per Caltrans guidelines. As shown in Table 1, the highest and lowest total RUC for the

Table 1 Traffic Delay Comparison between the Closure Scenarios

Closure Scenario	Road User Cost (RUC)				Max Delay (Minute)
	NB ($M)	SB ($M)	Total ($M)	Compared to Baseline %	
72-hour weekday (baseline)	4.3	2.3	6.6	100%	75
55-hour weekend	3.2	9.5	12.7	192%	196
Single continuous	3.0	3.1	6.1	92%	196
10-hour nighttime	1.4	8.6	10.0	152%	36

combined northbound and southbound directions was $12.7 million for the 55-hour weekend closures and $6.1 million for the single continuous closure.

As was the case for the scheduling analysis, the 72-hour weekday closure was used as the baseline to compare RUC for the four different construction closure scenarios. The 55-hour weekend closures caused 92 percent more traffic inconvenience as measured by RUC. The 10-hour nighttime closure scenario had 52 percent more traffic delay impact than the 72-hour weekday closure. Comparison indicated that it is worthwhile to pursue the I-15 Devore project as a fast-track construction with 72-hour closures because the savings in RUC equal approximately half the estimated total project budget.

5.2.2 Maximum Delay per Closure

The CWZ traffic parameter that individual drivers care most about is the maximum delay per closure. Consequently, this criterion is an important consideration for the transportation agency in its public outreach. Table 1 includes the maximum delay per vehicle during each closure period. The highest maximum delay in the northbound direction is 196 minutes per vehicle for the single continuous and 55-hour weekend closure scenarios, which is approximately

160 percent higher than the 75 minutes of maximum delay for the 72-hour closure scenario. The maximum delay on Friday and Saturday from the weekend and single continuous closure scenarios exceeds allowable limits defined by Caltrans, which reduces their viability.

5.2.3 Sensitivity Analysis for Traffic Management

A sensitivity analysis for RUC was conducted by varying the percent traffic reduction (diversion + no-show) and the CWZ lane capacity to evaluate the importance of traffic management efforts during closures. Based on previous experiences, a 10 percent traffic reduction was used as the baseline for all construction scenarios. To test the sensitivity of this critical input parameter, the RUC was further calculated for no traffic reduction and 20 percent traffic reduction.

The results indicate that RUC approximately doubles if traffic is not reduced at all (100 percent demand) during closures compared to the 10 percent reduction scenario (90 percent demand). With an assumption of 20 percent traffic reduction, the RUC is approximately two-thirds less than that of the 90 percent traffic demand. Based on this indication and further investigation with microscopic simulation with Paramics, Caltrans decided to block passage of heavy trucks through the CWZ and divert them through neighboring freeways (I-10 and I-215) at peak hours during construction.(*11*) The result of the truck detour in the microscopic simulation showed a significant benefit in overall traffic performance during construction. With this truck restriction, there is an estimated 18 percent reduction in the total travel time (vehicle-hour) and a 22 percent increase of average speed through the I-15 corridor.

For CWZ capacity, the baseline assumption for capacity was 1500 vphpl for all the scenarios except the 10-hour nighttime closure (where 1170 vphpl was used). To test the sensitivity of the CWZ capacity, the RUC was further evaluated for 1400 vphpl (1100 vphpl for the 10-hour scenario) and 1600 vphpl (1250 vphpl for the 10-hour scenario). With a capacity of 1400 vphpl (a 7 percent capacity reduction) compared to the baseline, the RUC increases by roughly 70 percent. The RUC decreases by about 40 percent compared to the baseline for a 1600 vphpl capacity (a 7 percent capacity increase). This underscores the importance of maximizing capacity through the CWZ. Examples of details that increase CWZ capacity are design of the crossovers and the shoulder areas.

The traffic measurement case study conducted by the researchers on the I-710 Long Beach rehabilitation project which had a similar traffic control scheme indicated that the CWZ capacity during repeated 55-hour extended closures stabilized at approximately 1500 vphpl. A sensitivity study in the microscopic simulation by changing parameters such as the headway factors indicated that a capacity of 1500 vphpl in the I-15 Devore CWZ is reasonable.(*11*)

5.3 Construction Cost Estimate

Agency cost was estimated based on schedule analysis (closure numbers and duration) for each closure scenario. Major operation activities involved in the pavement reconstruction costs are: 1) demolition of old pavement structures, 2) placement of new AC base, and 3) placement of new PCC slabs. Main traffic cost components are traffic control costs, such as lane marking (removal and re-striping), installation of moveable concrete barriers (MCB), and CWZ traffic signs. As part of the output of the schedule analysis, the CA4PRS model quantified the volume of materials and resources (equipment) required for each of the major processes.

The construction and traffic cost estimates for the four closure scenarios were prepared using the following three sources: 1) a commercial cost estimation database, RS Means, was used for the unit prices (*14*); 2) the unit prices in the commercial database were cross checked with historical bidding cost breakdowns for validity (*15*); and 3) preliminary third party validation by the Western States Chapter of the ACPA to confirm the research team's cost estimates. Comparison among the three cost estimates showed no significant discrepancies. Details of the cost estimate are summarized in Table 2.

Table 2 Comprehensive Comparison between Schedule, Traffic Delay, and Total Cost

Closure Scenario	Schedule Comparison		Cost Comparison ($M)			Maximum Delay (min)
	Number of Closures	Total Closure Hours	Agency Cost	User Delay Cost	Total Cost*	
72-hour Weekday	8	512	12.6	6.6	19.2	75
55-hour Weekend	10	550	15.1	12.7	27.8	195
Single Continuous	2	400	9.9	6.1	16.0	195
10-hour Nighttime	220	2,200	20.4	10.0	30.4	35

* Total cost = Agency Cost + User Delay

The construction cost estimated for each scenario indicated that the 10-hour closure scenario has the highest construction cost: $20 million. The research team's estimate of about $13 million for the agency cost for the 72-hour weekday closure scenario is close to the Caltrans engineer's initial estimate (approximately $14 million).

5.4 Agency Cost Comparison

The 55-hour weekend scenario is about 20 percent more expensive than the 72-hour weekday scenario in terms of the agency cost, mainly because of higher construction and traffic handling cost, which result from two additional closures. Although the 10-hour nighttime scenario requires a number of repeated closures (220 total), it involves the lowest traffic handling cost because rubber cones are used as a safety barrier between traffic and construction instead of

MCBs, striping and re-striping (lane marking) is not needed, and fewer construction signs are installed throughout the CWZ. Despite lower traffic handling cost, the 10-hour nighttime closure is the worst scenario, with approximately 62 percent higher agency cost than the 72-hour closure scenario.

The nighttime closures have the highest construction cost, primarily because the FSHCC mix (rapid-set type cement concrete) is approximately two times more expensive than PCC and because construction production is lower due to the material stickiness and the high concrete slump. Major resources, especially plants, equipment, and manpower, need to be on hand for a longer period of time—almost one year in this case compared to the other extended closure scenarios.

The traffic handling cost is about 20 percent of the construction cost for the extended (72-hour weekday and 55-hour weekend) closure scenarios. This is higher than the traditional nighttime closures (approximately 7 percent). This finding implies that LLPRS candidate projects on urban freeways with extended closures and fast-track construction require more traffic management effort than the traditional nighttime closures.

5.5 Total Costs Comparison

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, RUC is still seldom incorporated into cost comparisons for highway construction projects in California and other states.(*16*) But Caltrans recognizes 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. Unusually, the total costs for this analysis treated $1 of agency cost as the same as $1 of RUC because the user delay was derived with low range of traffic parameters. Table 2 summarizes the total costs, identifying the main cost components for each closure scenario. The ratio of RUC to agency cost varies depending on the closure scenario. For example, it is 49 percent for the nighttime closure, 84 percent for the weekend closure, and 52 percent of the 72-hour closure scenario.

From a total cost perspective, the 72-hour weekday closures are the second best scenario, after the single continuous until completion closure scenario. But the difference between the two scenarios is only 8 percent. As discussed previously in Section 5.2.2, the single continuous closure scenario is undesirable because the maximum delay of approximately 3 hours per closure is well over the delay limit.

The 55-hour weekend closure scenario has an intolerable delay per closure and has the highest RUC due to the unique high weekend leisure traffic flow through the I-15 corridor. This weekend scenario requires relatively high construction and traffic handling costs in addition to higher RUC. The total cost for the 55-hour scenario was 45 percent higher than the 72-hour weekday scenario. The 10-hour nighttime closure scenario had the highest total costs (58 percent higher) compared to the 72-hour closure scenario.

6.0 SELECTION OF THE MOST ECONOMICAL SCENARIO

The final step was to select the most economical closure scenario based on the results of the construction schedule, traffic delay impact, and total cost analyses. Each scenario has strengths and weaknesses, and some scenarios are not acceptable from the perspective of the agency or the public, as discussed previously. Table 2 summarizes the schedule (number of closure hours); the total costs with the breakdown of user delay, construction, and traffic handling, and maximum delay.

Based on the analytical comparisons and consultation with the agency and industry group, the research team recommended that Caltrans adopt the eight 72-hour weekday extended closure strategy. The recommendations were presented to the Caltrans Lane Closure Review Committee (LCRC) at the headquarters and district levels, and the LCRC approved the 72-hour scenario as the final reconstruction plan in the spring of 2003.

In addition to the evaluation criteria discussed above, other aspects such as 1) pavement quality in relation to pavement performance and life expectancy, 2) the safety of road users and workers during construction, 3) contractor's resource mobilization availability, 4) contingency buffer in case of an emergency, and 5) public perception was compared for each closure scenario. Because quantitative tools and analytical techniques were not feasible for analyzing these criteria, a qualitative analysis was conducted. That comparison affirmed the 72-hour weekday closures as the best scenario.

7.0 CONCLUSIONS AND FUTURE DEVELOPMENT

An integrated approach to developing construction and traffic management plans considering construction schedule, traffic delay, and total cost was applied to the I-15 Devore project, a fast-track urban freeway pavement reconstruction project with high traffic volume. The 72-hour closure scenario was selected because it is the most beneficial for both the transportation agency and the traveling public in terms of the total costs when compared to other scenarios. For example, when compared to traditional nighttime closures, the 72-hour weekday closure scenario requires 77 percent less total closure time, 34 percent less road user cost due to traffic delay, and 38 percent less agency costs for construction and traffic control.

Pavement constructability was further analyzed with the CA4PRS model for the three pavement-related alternatives to identify the most productive rehabilitation strategies from a production and scheduling perspective. Traffic analysis based on demand-capacity model as specified by the HCM, macroscopic simulation (FREQ) model, and microscopic simulation (Paramics) model was performed to support the project traffic management plan. Historical data (construction, traffic, and cost) were taken into account through a partnership between Caltrans, industry, and academia.

In summary, the I-15 Devore project will use eight 72-hour weekday extended closures, 290-mm PCC slabs with 12-hour early-age strength Type III concrete mix, a 152-mm AC base, and a 4.3-m widened truck lane. This will be the first use of the 72-hour extended weekday closures with 24-hour operations for urban freeway reconstruction in California.

The results of the study will prove invaluable in developing highway rehabilitation strategies for transportation agencies and contractors that seek to balance the maximization of construction productivity with a minimization of traffic delay, while also minimizing total cost and achieving long-life pavement performance.

As a follow-up to the construction and traffic analysis (Phase I study), the same research team will monitor: a) the construction process and progress, b) the traffic delay impact, and c) the public reactions during the construction stage (in 2004), as Phase II of the study. Data collected from construction monitoring will be used as feedback for the further calibration of the CA4PRS and the traffic analysis models as well as lessons learned for planning of future LLPRS projects with high volume traffic.

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