Knowledge-based Scheduling Analysis Software for Highway Rehabilitation and Reconstruction Projects

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ABSTRACT
Most of California's highway infrastructure was built between 1955 and 1970. These pavements had 20-year design lives and many now require frequent maintenance. In 1998, the California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategies (LLPRS) program to rebuild approximately 2,800 lane-kilometer (lane-km) of high traffic volume urban freeway in the 78,000 lane-km state highway network over a 10-year period. Priorities identified for the successful implementation of LLPRS projects are the selection of construction schedules and the development of traffic management plans that minimize road user and agency costs. This paper presents a construction simulation program, called CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies), developed as a scheduling and production analysis tool for LLPRS projects for use during the planning and design stages. CA4PRS estimates the optimized distance and duration of highway rehabilitation projects, taking into account the constraints of scheduling interfaces, pavement design, lane closure tactics, and contractor logistics. As a knowledge-based computer system on a Microsoft Access database, it uses Monte Carlo simulation, critical path method (CPM) analysis, and linear scheduling technique. CA4PRS is designed to help highway agencies and paving contractors make construction schedule decisions that balance rehabilitation productivity, traffic inconvenience, and agency cost. Application of the CA4PRS model to urban freeway rehabilitation projects in California, including the Interstate-10 (I-10) Pomona, Interstate-710 (I-710) Long Beach, and Interstate-15 (I-15) Devore projects, has demonstrated its value in saving millions of dollars for both Caltrans and road users.

RESEARCH BACKGROUND
California Long-life Pavement Rehabilitation Strategies
Most of the highway system in the United States became operational between 1950 and 1980, and most of its pavements were designed to last 20 years before requiring major rehabilitation or reconstruction. The importance of the 256,000 km National Highway System (NHS) in moving people and goods increased tremendously in that time period, and continues to grow today. NHS currently carries 75 percent of all truck traffic and connects 95 percent of businesses and 90 percent of the households in the United States (1).

In California, as elsewhere in the United States, a major objective of public and private organizations is to rehabilitate or reconstruct damaged pavements to provide service lives of 30 years or longer. A pioneer in the construction of a state highway network, the California Department of Transportation (Caltrans) in particular faces a significant backlog of aging pavements. More than 90 percent of the 78,000 lane-km in the state network were built between 1955 and 1970. Most of these reached their design number of axle loadings before the end of their 20-year design life. Problems caused by damaged pavements include decreased road user safety, poor ride quality leading to increased vehicle operating costs, increased maintenance activities and agency cost, and more frequent traffic delays, which increase fuel usage and environmental pollution.
To resolve these pavement problems, Caltrans launched its Long-Life Pavement Rehabilitation Strategies (LLPRS) program in 1998. Based on a preliminary life cycle cost analysis and evaluation of the agency’s future cash flow management, approximately 2,800 lane-km were selected as initial candidates for LLPRS. An additional $1 billion budget was assigned to the existing State Highway Operation Protection Program (SHOPP) for LLPRS for 1998 to 2008 (2).

The LLPRS program is California’s approach to “long-lasting, lower-maintenance pavement,” a concept promoted by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and other state transportation agencies. The goal is to design and construct pavements that last longer (30-50 years) and require less maintenance than those provided by current rehabilitation and reconstruction strategies. Life cycle costs decrease for heavily trafficked pavements as the period between major rehabilitations is extended, costing the highway agency less than standard pavement designs and providing a more efficient investment of public funds (3). The purpose of LLPRS is to implement in California the slogan of “Get-in, Get-out, and Stay-out” for urban highways with high traffic volume by providing “long-lasting, lower-maintenance pavement” (4).

Selection criteria for LLPRS candidate projects were poor pavement structural condition and ride quality, and a minimum 150,000 Average Daily Traffic (ADT) or 15,000 Average Daily Truck Traffic. Most of the LLPRS candidates selected in 1998 were Portland cement concrete (PCC) freeway pavements in Southern California and the San Francisco Bay Area that were 25 to 45 years old and had not yet had any major rehabilitation or reconstruction. Caltrans has placed priority on developing construction and traffic management plans for LLPRS projects on the following:

- minimizing traffic disruptions and road user cost
- providing a safe construction work zone environment for crew and road users
- reducing impacts on the local business community and the environment

**LLPRS Planning Tool: CA4PRS**

The increase in highway maintenance and rehabilitation has emphasized the need for research to improve construction methods and reduce their impact on traffic flow. Recent research has separately focused on specific areas such as pavement materials, construction, and traffic operations. Most of the recent research has not taken a systems approach to the integration of pavement materials and design, construction logistics, and traffic operations, which would provide more useful evaluations of highway rehabilitation alternatives.

*QuickZone* was developed as key component software for the FHWA’s Strategic Work-Zone Analysis Tools (SWAT) program to evaluate traveler delay due to construction work zones (5). It provides a complete and realistic view of total construction costs based on estimation and quantification of work-zone delays and resulting road user cost. However, the *QuickZone* user must provide input values for the construction schedules of different rehabilitation alternatives in terms of the closure number and duration, which is a crucial
component in calculating traffic delay, based on assumptions or personal experience rather than on an analytical scheduling module.

The FHWA recently released RealCost, a new life-cycle cost analysis software program to help state highway agencies more quickly and easily calculate life-cycle costs of pavement design alternatives, especially for highway rehabilitation and reconstruction projects (6). RealCost identifies cost differences between design alternatives, assuming the same level of service and performance for each of the alternatives, and taking into account both initial and future agency and road user costs. Similar to QuickZone, RealCost requires the user to input an assumed duration and number of construction closures, as it does not include a rehabilitation schedule estimation module.

The need for a scheduling and production analysis tool for highway pavement rehabilitation and reconstruction projects is the motivation for developing the CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software, as introduced in this paper. The design of the CA4PRS software resulted from the observations of engineers, with different levels of expertise and responsibility, struggling to estimate optimum rehabilitation schedules and to balance pavement design requirements, construction logistical constraints, and traffic operation limitations in their decision-making. The need for a tool of this type during the planning and design phases of rehabilitation projects was especially noted, because important and often irreversible decisions are made in these phases that later control construction productivity and traffic delay.

When used as an LLPRS planning tool, CA4PRS estimates the maximum possible distance of highway rehabilitation and reconstruction projects, and calculates the total duration and number of closures with given project specific constraints. CA4PRS evaluates “what-if” scenarios using a knowledge-based model with Monte Carlo simulation to compare the various alternatives for highway pavement rehabilitation strategies from the perspective of rehabilitation schedule and production. The main parameters compared in the CA4PRS model are categorized:

- pavement rehabilitation type alternatives
- schedule interfaces between major activities
- contractor’s resource constraints
- pavement design and material properties
- lane closure tactics

Table 1 summarizes more detailed variables according to the comparison criteria (category) in the CA4PRS model.

Added benefit comes when CA4PRS results are integrated with macroscopic and microscopic traffic simulation tools for estimating road user delay cost due to construction work zone closures. When combined with such traffic tools, various traffic lane closure strategies and pavement design alternatives can be evaluated with the goal of maximizing new pavement life expectancy and construction production and minimizing traffic delays.
delay and agency costs. This achieves the objective of integrating pavement design, construction logistics, and traffic operations.

CA4PRS also provides a schedule baseline for road agencies during the planning and design stages that can be used to determine reasonable construction productivity goals in cost (A) plus schedule (B) contracts, especially when combined with traffic simulation and cost estimate tools. Paving contractors and consultants will find CA4PRS useful for checking construction staging-plans, identifying critical resources constraining production, and calculating the probability of meeting incentives/disincentives and A+B contracts.

CA4PRS ANALYSIS MODULES
The three most common highway rehabilitation strategies in California’s LLPRS program are incorporated as individual analysis modules in CA4PRS:

- **Concrete Reconstruction (PCC Module):** remove the old pavement and rebuild with Portland cement concrete slab, and optionally replace the base
- **AC Overlay Rehabilitation (CSOL Module):** asphalt concrete (AC) overlay on cracked and seated old PCC pavement
- **Full-depth AC Replacement (FDAC Module):** demolish the old concrete pavement and base and replace with new full-depth AC pavement, or mill old AC and fill new AC

Although CA4PRS is designed to analyze freeway rehabilitation with any number of lanes, CA4PRS analysis assumes that a typical urban freeway segment has four main lanes in each direction. Since most passenger lanes in the LLPRS candidate freeways in California are generally in good condition, it was further assumed for the PCC and FDAC strategies that only one or both truck lanes would be rebuilt. However, for the CSOL strategy, it was assumed the whole freeway (main traffic lanes, median and outside shoulders) would be rehabilitated in one closure to maintain uniform surface elevation across all lanes after rehabilitation. CA4PRS is currently being upgraded to include more rehabilitation strategies, including placement of continuously reinforced concrete pavement (CRCP). The design variables and rehabilitation methodologies for each of the current modules are summarized below.

**Concrete (PCC) Reconstruction Module**
The PCC reconstruction strategy in California requires the complete demolition of the existing concrete pavement (including, optionally, demolition of the pavement base) and replacement with a new base and concrete slab. As a selection choice for the user, the main pavement design-related alternatives incorporated in the PCC reconstruction module are: pavement cross-section change, concrete mix design for the new PCC slab, and the width of the outside truck lane (7).
For new pavement cross-sections, three alternative new slab thicknesses, 203 mm (8 in.), 254 mm (10 in.), and 305 mm (12 in.), are available from the CA4PRS menu, or users can enter their own slab thickness. Although it does not influence the rehabilitation production, the existing slab is assumed to be 203 mm-thick concrete pavement, typical in California. Replacement slabs thicker than 203 mm require replacement of the existing base with a new base, with thickness input by the user. The user can also input any additional demolition depth necessary to lower the pavement surface elevation to meet current FHWA bridge height clearance requirements.

Three default concrete curing times to reach traffic-opening strength are available in the menu: 4, 8, and 12 hours. Mixes that reach 2.8 MPa (400 psi) third-point flexural strengths with these curing times are currently used on many Caltrans LLPRS projects, and can be achieved using Type III early-strength PCC mixes or hydraulic cement concrete mixes that do not use Portland cement. Use of these materials provides additional time for paving compared to ordinary PCC. Additionally, a user-defined concrete curing time is allowed.

For the width of the new outer truck lane, the user has two alternatives: regular width (3.7 m), or a widened truck lane (4.3 m).

Construction sequence and lane closure tactics in the PCC module include:

- Concurrent demolition and paving for reconstruction of one or both (inner and outer) truck lanes;
- Sequential demolition and paving for reconstruction of one or both truck lanes.

The use of concurrent demolition and paving increases the number of lanes that must be closed to road users because both operations require its own access lane for construction trucks. However, it increases the amount of pavement that can be reconstructed within a given amount of time. Similarly, reconstruction of both truck lanes simultaneously increases the number of lanes that must be closed, but provides benefits in terms of higher rehabilitation productivity, simpler tie bar installation, better quality control, and long-term performance of the longitudinal joint, as reported by the Washington State Department of Transportation (8).

The concurrent-method with full-closure (Figure 1) requires closure of four lanes when reconstructing both truck lanes simultaneously. The two inside lanes are used for construction access (haul trucks, delivery trucks, paving machines, etc.). Typically, a counter-flow traffic arrangement will be used for urban highways in California, in which the four lanes of the traffic roadbed on the other side of the construction are converted to two-way traffic with two lanes in each direction. Moveable concrete barriers (MCB) are used between the two lanes oncoming from each direction on the traffic roadbed.

At the other extreme, single truck-lane reconstruction with the sequential-method requires that only two lanes be closed during reconstruction. One truck lane is rebuilt while the other is used for construction access (Figure 1). The remaining two lanes on the construction roadbed are open to traffic and separated from construction by MCB. With just one lane for construction access, the sequential-method with half-closure permits the paving operation to start only after demolition and base paving have been completed.
AC Overlay (CSOL) Rehabilitation Module

The crack-seat and AC overlay (CSOL) rehabilitation strategy usually involves placing three or four new AC layers on top of the cracked and seated PCC pavement (9). In California, it is common to install an asphalt impregnated pavement reinforcing fabric between the first and second AC lifts to slow crack propagation from the bottom. CSOL rehabilitation, unlike PCC reconstruction or FDAC replacement, does not require removal of existing pavement structures. However, the AC overlay cannot be placed under highway overpasses unless there is adequate clearance.

The number and thicknesses of AC lifts in the overlay are input by the user for the project specific cross-section. MultiCool, a numerical AC cooling simulation program for multi-layer paving, is embedded in CA4PRS to calculate the schedule interruption in paving operations necessary for cooling (10).

Two lane closure alternatives are available in the CSOL module: full- or half-closure rehabilitation. In the case of CSOL full-closure, one direction of the freeway is completely closed for rehabilitation, and traffic is switched to the other side of construction through median crossovers for counter-flow traffic. The main lanes and shoulders are overlaid completely on the construction roadbed during a closure, layer-by-layer and lane-by-lane. AC paving operations usually alternate lanes (i.e., 1, 3, 2, and 4) to minimize waiting time for AC cooling.

On the other hand, CSOL half-closure requires closure of only two of four lanes on the construction roadbed, allowing the other two lanes to remain open to traffic. Typically, the first two AC layers are placed lane-by-lane on two lanes. Traffic is then shifted to these newly paved lanes so overlay can be done on the remaining two. Usually, traffic is separated from construction work by MCB. The CSOL half-closure option has two sub-options, depending on whether all AC layers are placed during a closure (half-closure with full-completion), or some layers are placed during the first closure, while the remaining layers are completed during the subsequent closure (half-closure with partial-completion).

Full-depth AC (FDAC) Replacement Module

The FDAC replacement strategy requires complete removal of the existing pavement to sufficient depth to accommodate the new AC pavement (9). In LLPRS projects, a rich bottom AC layer will likely be placed on top of the re-compactcd aggregate base, followed by various types and thicknesses of AC, each designed for specific purposes in the structure. Similar to the other modules, users can input project-specific AC cross-sections.

The FDAC analysis module includes two lane closure tactics: single- and double-lane rehabilitation. A major benefit of double-lane rehabilitation is the interlocking of multiple AC layers by overlapping longitudinal joints between adjacent lanes. The single- and double-lane rehabilitation concept for the FDAC
replacement is similar to the PCC reconstruction methodology except that FDAC replacement does not require paving both lanes in one pull.

**INPUT / OUTPUT INTERFACES**

CA4PRS runs on Microsoft Windows 95/NT/98/2000/XP or higher operating systems. It was developed with Microsoft Visual Basic 6.0, and utilizes a Microsoft Access 2000 database for data storage. Microsoft Access does not need to be installed on the operating computer. The database interface is valuable in recalling input parameters from previous analyses, and for transmitting project information to other users. CA4PRS can be installed on a PC as a stand-alone application or on a network server to allow multi-user access and database sharing.

**Computational Process**

As detailed in the following section, the typical CA4PRS input procedure is:

1. Select a rehabilitation strategy: PCC reconstruction, CSOL rehabilitation, or FDAC replacement analysis modules.
2. Choose the analysis approach: deterministic or probabilistic analysis mode.
3. Choose a construction window (closure timing and adjustable duration): 10-hour nighttime, 55-hour weekend, or 72-hour weekday closures.
4. Input the scope of the rehabilitation project measured in lane-km.
5. Define the change of pavement cross-section: slab and base thickness (PCC) or layer profile (AC), including the additional demolition, if needed.
6. Choose the properties of pavement material: set the concrete curing time (PCC) or AC cooling time (or let the MultiCool software calculate cooling times).
7. Select rehabilitation sequences (methods) and lane closure tactics: full-closure (concurrent-method) versus half-closure (sequential-method) and single-lane versus double-lane rehabilitations.
8. Define activity lead-lag relationships between major operations: mobilization, demobilization, and minimum time interfaces between operations.
9. Input the contractor’s logistical resources (crew, equipment, and plants) for major operations.

CA4PRS may be used in either deterministic or probabilistic mode. The input configuration of the probabilistic analysis mode is similar to the deterministic analysis mode except that the former provides the user with a library of probability distributions from which to choose. When used deterministically, it finds pavement amount (distance) that can be rebuilt within the closure windows under given project constraints. The probabilistic mode allows the user to model the input parameters as random variables. Uniform, normal, log normal, beta, geometric, triangular, truncated normal, and truncated log normal probabilistic distributions
are available. Utilizing Monte Carlo simulation, this mode permits analysis of the likelihood of achieving different pavement rehabilitation production rates.

Considering the parameters and constraints defined through the aforementioned input procedure, CA4PRS calculates the maximum rehabilitation production and consequent number of closures using the following analytical process:

1. Quantify material volumes for major rehabilitation operations.
2. Utilize a simplified technique of critical path method (CPM) scheduling analysis to calculate available durations for the major operations.
3. Quantify the productivity of each resource input.
4. Apply a linear scheduling technique to identify constraining resource(s).

The outputs produced by this process allow the user to evaluate the maximum rehabilitation production (lane-km) per closure (i.e., productivity of the constraining resources), and the total number of closures and duration needed to finish the entire project scope.

**Input Windows**

CA4PRS employs a menu structure that groups analysis items (analytical modules and input interfaces) intuitively, as shown in Figure 2. CA4PRS employs a multiple document interface, similar to Microsoft Excel and Word, enabling multiple projects and analyses to be viewed simultaneously. CA4PRS starts with a prompt for user input with the following four input tab windows:

- **Project Details**
- **Scheduling**
- **Resource Profile**
- **Analysis**

In the **Project Details** window, as illustrated in Figure 2, the user enters basic project information, including an analysis identifier, project descriptions, route name, post (station) miles, location, etc. The user also specifies project scope by entering total lane-km to be rehabilitated. This scope acts as the baseline for computing the total number of closures required, based on the computed rehabilitation production rates for each closure.

In the **Scheduling** window, the user enters minimum times required for mobilization and demobilization purposes, such as site preparation, clean up, and, most important, deployment and removal of traffic control. The user specifies activity lead-lag relationships and minimum-time interfaces among major operations. Three alternative closure time frames (construction windows) are available: nighttime, weekend, and continuous closures. Continuous closure has two sub-options: (a) daytime operations, with one or two crew shift(s) while the freeway remains closed; and (b) round-the-clock operations using two or three rotating crew shifts.
In the Resource Profile window, the user specifies contractor logistics and resource constraints, which are two of the most significant factors in rehabilitation production, especially in urban highway rehabilitation where space and access for construction equipment are often limited. Figure 3 illustrates the Resource Profile window for the PCC analysis module in the probabilistic mode. Resource inputs rely on the user’s knowledge of project conditions, experience with similar projects, and personal judgment. For instance, the user should input a reasonable number of demolition hauling trucks per hour by taking into account expected truck loading and turn-around cycle times between the site and the dumping area.

In the Analysis window, the user can select from the following multiple input categories:

- construction windows
- rehabilitation sequence with respect to lane closure tactics
- mix design in terms of concrete curing and AC cooling time
- pavement cross-section changes
- truck lane width (PCC only)

The Analysis window in the FDAC analysis module is shown in Figure 4. A drop-down list of values or check box options is available for each input category.

Outputs and Reports

The hierarchy of CA4PRS provides extensive graphical and tabular outputs, and incorporates a report feature that allows input and output information to be printed in PDF or RTF format. CA4PRS simultaneously produces results for the combinations of options the user selects for each input category in the analysis window. For example, if the user elects to consider two concrete curing times (4- and 12-hour), two rehabilitation options (sequential single-lane and concurrent double-lane), and two cross-section profiles (203 mm and user-defined) for the 55-hour weekend closure in the PCC analysis module, CA4PRS generates a total of 8 (2 × 2 × 2) analysis results, each in a separate output window.

In deterministic mode, the output windows present the analysis results in two parts: Production Details and Production Chart. Included in the Production Details are the principal analysis results and a user input summary (Figure 5). The principal analysis results are the maximum production of each rehabilitation scenario, analyzed in terms of lane-km, and the total number of closures required to finish the project scope based on the maximum production of each scenario. Production Details also lists a summary of material volumes for major operations and a tabulated list of input resources.

The software identifies the minimum required resources including those that constrain production. The principal results of the CPM scheduling analysis are presented, i.e., the optimally balanced maximum duration of demolition and paving activities within a given closure time limit. The Production Chart shows a line of balance schedule illustrating the linear progress of the main rehabilitation operations plotted against time,
shown in the Figure 5 FDAC example. The user can also generate a comparison table that summarizes the main inputs and outputs relative to combinations of various production variables, e.g., construction window, section profile, rehabilitation sequence, etc.

The probabilistic mode output windows are similar to those of the deterministic mode. In addition, the software generates a distribution plot showing the range of production generated by the Monte Carlo simulation, which is a more realistic production estimate. The software also produces a sensitivity analysis chart, called a “tornado chart,” which permits the user to see the relative sensitivity of production to each input variable. More stable production is best achieved by paying greater attention to the input variables with the highest sensitivity.

**CA4PRS EXPERIENCE IN CALIFORNIA**

**Validation on LLPRS Pilot Projects**

*CA4PRS* has been validated and successfully implemented on several urban freeway rehabilitation / reconstruction projects in California. The first case study was on I-10 in Pomona (concrete LLPRS pilot project), where 2.8 lane-km of deteriorated truck-lane was rebuilt during one 55-hour weekend closure from Friday 10 p.m. to Monday 5 a.m. (11). PCC slabs, 200 mm thick, were replaced with fast setting hydraulic cement concrete (FSHCC), which developed the flexural strength of 2.8 MPa (400 psi) in 4 hours. The freeway was built in the early 1960s and has four lanes in each direction. It had a high percentage of cracked slabs and faulting, and has an ADT of 240,000 and approximately 9 percent heavy trucks. Two of the four lanes remained open while the inner truck lane was rehabilitated, as half-closure. The outer truck lane was used for construction access.

The *CA4PRS* production best estimate (probabilistic mode) of 2.8 lane-km was identical to the contractor’s actual production measured by the research team during the closure (11). The contractor was awarded a $500,000 incentive payment for completing more than 2.0 lane-km of the contractual threshold.

The software was then used to evaluate the I-710 Long Beach project, as the asphalt LLPRS pilot project (12). The deteriorating PCC pavement was replaced with a long-life asphalt concrete pavement in eight 55-hour weekend closures. The design for FDAC sections under four freeway overpasses required excavation and removal of the existing pavement to a depth of 625 mm, and replacement with 325 mm of AC. The pavement design between the FDAC sections called for cracking and seating of the old PCC slabs and 230 mm AC overlay (CSOL). During construction, Caltrans applied counter-flow traffic controls (the full-closure and full-completion AC rehabilitation method).

*CA4PRS* estimated that the maximum production capability during a 55-hour weekend would be one CSOL section (about 1.3 centerline-km) and one FDAC section (about 0.4 centerline-km). Prior to construction, *CA4PRS* analysis results confirmed that the contractor’s goal of completing the main rehabilitation work (26 lane-km) in eight weekend closures was realistic. However, the *CA4PRS* analysis
warned that the contractor’s initial plan of rehabilitating two FDAC sections (about 0.8 km) together with one CSOL section (1.3 km) per weekend was overly optimistic. The contractor revised his production plan based on the production levels estimated by CA4PRS. Actual production performance was within 5 percent of the CA4PRS estimates (12).

Implementation on the I-15 Devore Project

Most Economical Closure Scenario

The CA4PRS software was used during the initial planning and design stages of a reconstruction project on I-15 at Devore, near San Bernardino (13). The project, scheduled to start in the fall of 2004, will rebuild a 4.2-km stretch of the deteriorated truck lanes using full-closure of the construction roadbed (counter-flow traffic), and applying the concurrent-method that permits demolition and paving to be conducted simultaneously. With three or four lanes in each direction, this corridor carries approximately 110,000 ADT with 12 percent trucks on weekdays and 7 percent on weekends. Unlike typical urban freeways that have peak rush-hour traffic on weekday mornings and afternoons, the Devore corridor also has a high volume of leisure traffic on weekends (northbound Friday afternoon and southbound Sunday afternoon) between Los Angeles and Las Vegas.

The existing pavement structure has 203 mm plain-jointed concrete slabs, 102 mm cement-treated base (CTB), and 450 mm aggregate base (AB). The new pavement will have 290 mm (11.5 in.) plain-jointed concrete slabs with dowels, and 152 mm (6 in.) of asphalt concrete or lean concrete base. The slabs will be made of early-strength Type III PCC with special admixtures to achieve 2.8 MPa (400 psi) third-point flexural strengths in 12 hours.

Analysis of the 55-hour weekend closures identified traffic delay problems because of the unique weekend traffic patterns and the construction staging-plan. Accordingly, a strategy of 72-hour weekday closures was compared with (a) 10-hour nighttime weekday closures, (b) 55-hour weekend closures, and (c) one-time continuous-until-completion closures. Caltrans decided to implement repeated 72-hour (three weekdays) continuous closures with round-the-clock operations, based on the following:

- rehabilitation production schedule estimated with CA4PRS
- traffic delay (road user cost and maximum queue length per closure) estimated with several traffic analysis tools, including the “Highway Capacity Manual” (14), macro- and microscopic traffic simulation software
- agency cost based on engineer’s estimates

The preliminary analysis concluded that the 72-hour weekday closure scenario was the most economical from the perspectives of both agency and road user (traffic delay) costs. The construction/traffic integrated analysis indicated that the 72-hour closure results in 7 percent less total closure time, 60 percent less
road user cost, and 14 percent less agency cost than the 55-hour weekend closure. Furthermore, compared to
10-hour nighttime closures that are standard closure practice in California, the 72-hour closure results in 77
percent less total closure time, 34 percent less road user cost, and 38 percent less agency cost. It is estimated
that this strategy will save millions of dollars for both Caltrans and road users.

Constructability Check with CA4PRS

Upon selection of the 72-hour weekday strategy as the most economical, further constructability check using
CA4PRS compared the following pavement design-related alternatives from a production (scheduling)
perspective, with the assumption that the alternatives would provide similar pavement performance and life
expectancy:

- Concrete mix design: 12-hour Type III PCC versus 4-hour FSHCC
- Pavement base type: asphalt concrete base (ACB) versus lean concrete base (LCB)
- Outer truck lane width: widened truck lane (4.3 m) versus normal truck lane (3.7 m) with tied concrete
  shoulders

FSHCC’s 8-hour time advantage over 12-hour Type III PCC is offset by higher concrete slump and
material stickiness, the need for more delivery trucks and a smaller paving machine, and the coarse finished
surface that frequently requires diamond grinding after curing. In addition, FSHCC costs about twice as much
as Type III PCC 12-hour mix in California. A production analysis with CA4PRS indicated that the two
materials take approximately the same overall project completion time (closure numbers). It was therefore
concluded that the use of FSHCC was not as economical as the use of the 12-hour mix.

The CA4PRS model estimated that at least two more 72-hour closures would be needed if LCB were
used instead of ACB, because LCB requires 12 hours of curing time before PCC paving starts. District practice
also requires placement of a bond-breaker, such as 25 mm of AC, between the LCB and PCC to reduce friction
that can cause early-age cracking. The selected ACB scenario permits parallel production of the base and slabs,
with each operation utilizing its own resources. This permits elimination of two 72-hour closures, thus
reducing traffic delay and construction costs.

The CA4PRS schedule analysis indicated that only about 8 percent more construction time would be
needed for the widened outer truck-lane option, compared to the regular truck-lane tied to the new concrete
shoulder scenario. Caltrans decided to use the widened outer truck-lane option. With effective construction
staging, the project could still be completed with this option with the same number of closures as for the tied-
concrete shoulder alternative.

Finally, for the I-15 Devore project Caltrans adopted the strategy of using (a) Type III 12-hour PCC
concrete slab mix, (b) asphalt concrete base, and (c) a widened truck-lane, based on the above-mentioned
CA4PRS constructability analysis.
CONCLUSIONS

The CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software, a Microsoft Windows application on Access database, was developed as a scheduling and production analysis tool for highway pavement rehabilitation projects in California, especially high traffic urban segments. CA4PRS estimates the distance (lane-km) and duration of pavement rehabilitation or reconstruction given project constraints, utilizing Monte Carlo simulation, critical path method (CPM) analysis, and linear scheduling technique.

CA4PRS provides a baseline schedule for road agencies during the planning and design stages to achieve their goal of selecting the most economical highway rehabilitation strategy by integrating pavement design, construction logistics, and traffic operations. CA4PRS allows agencies to develop and evaluate “what-if” scenarios for each stage of a pavement rehabilitation project: feasibility, planning, design, and construction. The CA4PRS model can also facilitate teambuilding among engineers from design, construction, and traffic operations to mutually arrive at an optimal solution for pavement rehabilitation.

CA4PRS can be used with macro- and microscopic traffic simulation tools to estimate road user inconvenience (delay) due to construction closures. With this integrated analysis, various traffic lane closure strategies and pavement design alternatives can be evaluated with the goal of maximizing new pavement life expectancy and construction production, and minimizing traffic delay and agency costs.

Agencies and paving contractors will find the CA4PRS scheduling estimation useful for development of construction staging-plans and evaluation of risk management plans. CA4PRS can be used for developing reasonable production goals for cost (A) plus schedule (B) contracts, and for calculating appropriate schedule incentive/disincentive specifications.

CA4PRS has successfully demonstrated its value on several urban freeway rehabilitation projects with high traffic volume in California.

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15. California Department of Transportation, Division of Research and Innovation. “CA4PRS”.

LIST OF TABLE

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