Computer Simulation Model: Construction Analysis for Pavement Rehabilitation Strategies

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Abstract: Most state highways in the United States were built during the 1960s and 1970s with an infrastructure investment of more than $1 trillion. They now exceed their 20 year design lives and are seriously deteriorated. The consequences are high maintenance and road user costs because of degraded road surfaces and construction work zone delays. Efficient planning of highway rehabilitation closures is critical. This paper presents a simulation model, Construction Analysis for Pavement Rehabilitation Strategies (*CA4PRS*), which estimates the maximum amount of highway rehabilitation/reconstruction during various closure timeframes. The model balances project constraints such as scheduling interfaces, pavement materials and design, contractor logistics and resources, and traffic operations. It has been successfully used on several urban freeway rehabilitation projects with high traffic volume, including projects on I-10 and I-710. The *CA4PRS* helps agencies and contractors plan highway rehabilitation strategies by taking into account long-life pavement performance, construction productivity, traffic delay, and total cost.

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Introduction

Paradigm Change in Highway Construction

About 256,000 km of the National Highway System, which is 4% of the American road network (U.S. Census Bureau 1994), carries 40% of auto travel and 75% of truck traffic. It also connects 90% of the households and businesses in the nation (FHWA 1996). Many of the pavements on these highways, constructed during the infrastructure construction boom in the 1960s and 1970s, have exceeded their design lives in less than 20 years due to continuously increasing traffic demand. This is evidenced by the fact that over the last 20 years highway traffic has increased by 75% while highway facilities have expanded by only 4% during the same period (Herbsman and Glagola 1998).

In recent years state transportation agencies have shifted their focus from building new transportation facilities to "4R" projects: restoration, resurfacing, rehabilitation, and reconstruction. This shift in emphasis was driven by studies which show that maintaining federal-aid highways in their current physical condition has a financial rate of return of about 30–40%, while constructing new highways has a rate of return generally lower than 10% (U.S. Congressional Budget Office 1988). Further complicating rehabilitation project is that roughly 30% of these 4R type highway rehabilitation projects were located in urban areas in 1999–2001, where construction caused serious problems with traffic service for the communities that used these freeways (WisDOT 2002).

Innovative Highway Rehabilitation in California

The State of California, a pioneer in highway construction, is facing deteriorated highway infrastructure on a large scale. More than 90% of the 78,000 lane/km of the state highway system was built between 1955 and 1970 with 20 year design lives. This significant state of degradation adversely affects road-user safety and ride quality, and causes high vehicle operating and highway maintenance costs. In 1998, the California Department of Transportation (Caltrans) initiated the Long-Life Pavement Rehabilitation Strategies (LLPRS) program to rebuild approximately 2,800 lane/km of deteriorated urban freeways over the next 10 years. The program represented an estimated $1 billion investment over and above the regular State Highway Operation and Protection budget (Caltrans 1998). The LLPRS candidate projects were selected based upon criteria of 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 candidate freeways were Portland cement concrete (PCC) paved interstates in the Los Angeles Basin (80%) and the San Francisco Bay Area (15%).

Traditionally, urban freeway rehabilitation or reconstruction projects in California have used 7 or 10 h nighttime closures because daytime closures cause unacceptable delays to weekday peak travel. The disadvantage of nighttime closures is that they may lead to poor construction quality control which, in turn, may affect pavement life expectancy and pavement surface smoothness, and jeopardize the safety of road users and construction crews (Lee 2000). Nighttime closures may also result in longer

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total closure times, higher construction and traffic handling costs, and greater traffic delay to road users. In recognition of these drawbacks, Caltrans has adopted innovative highway rehabilitation strategies of accelerated construction with continuous (round-the-clock) operations during 55 h weekend or 72 h weekday closures for LLPRS projects.

Research Motivation and Approach

The increased need for highway maintenance and rehabilitation has led to much research on construction methods and their impact on traffic flow. However, no systematic research has been conducted, until now, with the goal of integrating pavement materials and design, construction logistics, and traffic operations. These issues are clearly essential to determine the most economical rehabilitation strategies (Anderson and Russell 2001). For rehabilitation of high volume urban freeways, three competing goals should be satisfied:

- the pavement should have a service life of at least 30 years,
- construction schedules should be fast, and
- traffic delays resulting from construction closures should be minimized.

To meet design life and constructability goals, pavement design must focus on: (1) thinner structural sections and (2) materials and curing times that can shorten construction without sacrificing quality and performance (Roesler et al. 1999). Construction planning should focus on hastening the construction process and making it more predictable by incorporating such concepts as contingency (risk) management, incentives/disincentives (I/D), and cost plus schedule ($A+B$) bidding (Arditi et al. 1997). Traffic planning should focus on minimizing traffic delay impact without sacrificing construction productivity.

The integrated analysis of design, construction, and traffic requires a construction production analysis model to provide a schedule baseline for highway rehabilitation projects. The Construction Analysis for Pavement Rehabilitation Strategies (*CA4PRS*) software, described in this paper, is such a scheduling tool and was designed for constructability analysis of highway rehabilitation projects (Technology/Business Opportunity: *CA4PRS* 2003). It is a knowledge-based computer simulation model designed to help transportation agencies and paving contractors make sound construction project management decisions at each stage of the highway rehabilitation project: planning, design, and construction.

The input variables of *CA4PRS* are schedule interfaces, pavement design and materials, resource constraints, and lane closure schemes. These were identified by experienced Caltrans engineers and the research team. The model's formulation was reviewed and adjusted through technical committee meetings with the Southern California Chapter of the National Asphalt Pavement Association and the Western States Chapter of the American Concrete Pavement Association. The software was tested on projects throughout California. Such tests also allowed us to gather construction resource and schedule activity relationship data to calibrate and validate the software. Details of these case studies are described later in this paper.

Research Relevance and Applicability

The *CA4PRS* model was developed to provide road agencies and the transportation industry with a systematic construction engineering and management tool for the rehabilitation and reconstruction of highways. The model is beneficial for the highway agencies especially during the planning and design stages when the resulting analysis can be used to optimize pavement, construction, and traffic operations. It is also useful for design and construction engineers, consultants, and paving contractors in providing cost savings by comparing various alternatives during estimating and project control stages.

Software Overview

The *CA4PRS* is a production analysis tool designed to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given the various project constraints (Lee 2000). As summarized in Table 1, the *CA4PRS* model evaluates "what-if" scenarios with respect to rehabilitation production by comparing the following input variables (alternatives):

1. pavement strategy: PCC reconstruction, crack and seat PCC and asphalt overlay (CSOL), or full-depth asphalt concrete replacement (FDAC);
2. construction window: nighttime closures, weekend closure, continuous closure, or combinations of the above;
3. lane closure tactics: number of lanes to be closed for rehabilitation (i.e., partial or full closures);
4. material constraints: mix design and curing time for concrete or cooling time for asphalt;
5. pavement cross section: thickness of new concrete or asphalt concrete;
6. concrete pavement base types: lean concrete base or asphalt concrete base (ACB);
7. contractor's logistical resource constraints: location, capacity, and numbers of rehabilitation equipment available (batch plant, delivery and hauling trucks, paving machine); and
8. scheduling interfaces: mobilization/demobilization, traffic control time, and activity lead-lag time relationships, and buffer sizes.

A powerful feature of *CA4PRS* is that it can be integrated with macro- and microscopic traffic simulation models to quantify road user costs during construction. This can help planners, designers, and construction and materials engineers determine which pavement materials/structures and rehabilitation strategies maximize production without creating unacceptable traffic delays. The rehabilitation strategies and associated input variables modeled in *CA4PRS* are described in the following sections.

Rehabilitation Strategies Modeled

It is challenging yet necessary to define a typical or common pavement rehabilitation process when trying to model the process. There are numerous rehabilitation strategies that may be implemented and are contingent upon: pavement materials, lane closure tactics, and contractor's resource constraints. Consultation with agencies and contractors led us to focus on and incorporate three common rehabilitation strategies into *CA4PRS*:

1. PCC reconstruction: remove the old pavement and rebuild with PCC slab and optional pavement base structure;
2. CSOL rehabilitation: crack and seat the old PCC pavement and overlay with new asphalt–concrete (AC) pavement; and
3. FDAC replacement: remove the old pavement and replace with full-depth AC pavement.

The number of traffic lanes in one direction of a typical urban freeway was assumed to be four for the sake of simplicity. Since most passenger lanes ($P1$ and $P2$) are generally in good condi-

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Table 1. Categorized Major Parameters, Comparable in Construction Analysis for Pavenent Rehabilitation Strategies Model

Category	Options	
Rehabilitation strategies	Concrete rehabilitation or reconstruction Portland cement concrete (PCC)	
	Asphalt concrete	Crack seat and overlay (CSOL)
		Full depth ac (FDAC) replacement
Pavement cross section	PCC	203 mm slab
		305 mm slab
		User defined cross section
	CSOL and FDAC	Multiple lift of layers
Scheduling constraints	Construction windows	Nighttime closure
		Weekend closure
		Continuous closure
	Schedule relationship	Mobilization/demobilization
		Activity lead-lag relationship
	Curing time (PCC)	4 h (fast-setting cement)
		12 h (Type III PCC)
		User specified curing time
	Cooling time (CSOL and FDAC)	Function lift thickness and weather
Lane closures and rehabilitation sequences	PCC	Concurrent work method
		Sequential work method
	PCC and FDAC	Single-lane rehabilitation
		Double-lane rehabilitation
	CSOL	Partial closure
		Full closure
Contractor's logistics and resource constraints	Demolition hauling trucks	Capacity and number per hour
	Paving material delivery trucks	Capacity and number per hour
	Batch plant	Capacity and number
	Paving machines	Speed and number

tion, it furthermore was assumed that only the two outer truck lanes (*T*1 and *T*2) will be rebuilt in each direction in the PCC reconstruction and FDAC replacement strategies, as per LLPRS practice. In the case of CSOL rehabilitation, the whole freeway (i.e., main traffic lanes including median and outside shoulder) is assumed to be subject to rehabilitation. Details on rehabilitation methodologies and design variables for each rehabilitation strategy as an individual module in *CA4PRS* are summarized below.

Portland Cement Concrete Reconstruction Strategy

Pavement Design Alternatives

The PCC reconstruction module in *CA4PRS* incorporates the following pavement design-related criteria (Lee et al. 2000):

- new pavement cross-sections,
- concrete mix design for new PCC slab, and
- the width of the outside truck lane.

Three alternative new pavement cross sections—203 mm (8 in.), 254 mm (10 in.), and 305 mm (12 in.)—are included in the PCC analysis module. The existing slab is assumed to be 203 mm thick (typical California situation). The latter two PCC slab designs (254 or 305 mm) will require replacing the existing base with a new thicker (150 mm) base, as illustrated in Fig. 1. The user can also create his/her own cross-section profile if the default cross sections in the *CA4PRS* menu are not applicable for the project. The user can also enter in any additional demolition depth that might be necessary to comply with new height clearance requirements for bridge underpasses or overpasses.

In the PCC analysis module there are three default concrete mix designs to choose from: 4, 8, and 12 h curing time mixes. Fast setting hydraulic cement concrete or early-age strength Type III PCC products can quickly achieve traffic opening strengths of 2.8 MPa (400 psi) in California. This allows extra paving time that cannot be attained when using ordinary PCC. A user-defined concrete curing time is also allowed in the model.

The user has two options for the width of a new outside truck lane (*T*2): regular width (3.7 m) tied to the concrete shoulder, or widened truck lane (4.3 m).

Reconstruction Methodologies

Four combinations of construction operation sequence and lane closure tactics are included in the PCC analysis module: concurrent single-lane, sequential single-lane, concurrent double-lane, and sequential double-lane rehabilitations. The concurrent methods refer to the simultaneous undertaking of demolition of the existing slab and new slab and base paving operations. In the sequential methods slab paving starts only after the demolition and base paving are completed. When performing both operations concurrently, interruptions between construction equipment (e.g., loader, hauling trucks, paving machine, and delivery trucks) can be avoided or minimized by providing the demolition and paving activities with their own access lane. In the sequential methods the demolition and paving activities share one lane for construction access one after the other, thus leaving one more lane open for freeway traffic than in the concurrent scenario. The shoulder is not assumed to be a reliable access lane in urban environments because it may be less than 3 m wide, adjacent to sound walls, or not continuous.

The two existing truck lanes can be paved either one by one or both lanes at once. Both single-lane paving and double-lane reha-

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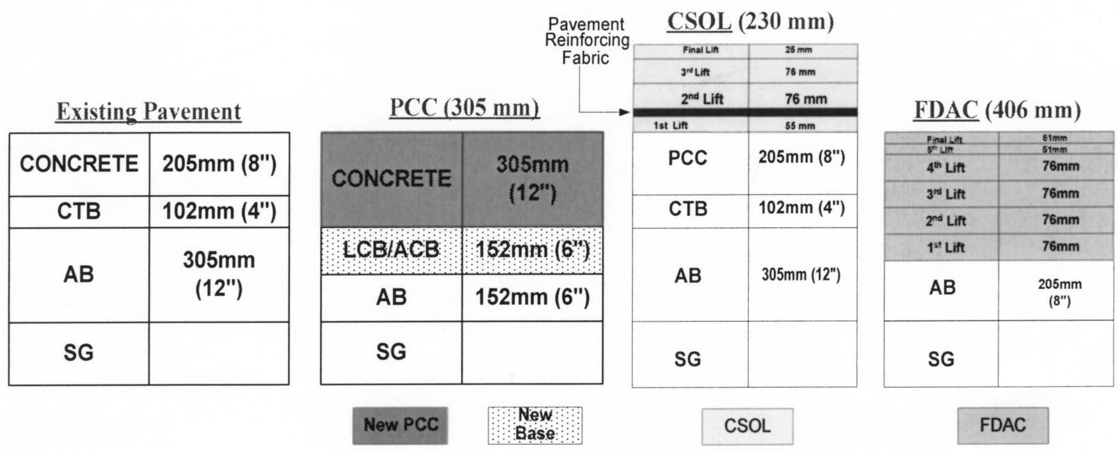

Fig. 1. Typical pavement cross-section changes modeled in Construction Analysis for Pavement Rehabilitation Strategies

bilitation are applicable for both concurrent and sequential methods. Washington State Department of Transportation reported that higher productivity was observed when two lanes were paved simultaneously (Washington State Department of Transportation 2002). Double lane paving may have other advantages: simpler installation of tie bars and better quality control and long-term performance in the longitudinal joint.

Crack and Seat Portland Cement Concrete and Asphalt Overlay Rehabilitation Strategy

Pavement Design Alternatives

In California, the crack seat and asphalt concrete overlay (CSOL) rehabilitation involves placing three to five new AC layers on top of the cracked and seated PCC pavement. To slow the propagation of cracks, it is a common practice to install a pavement reinforcing fabric saturated with tack coat while the first AC layer is still hot. The CSOL's major advantage is that it does not require removal of the existing PCC slabs, unlike the PCC reconstruction or FDAC replacement strategy. However the AC overlay cannot be placed underneath bridge overpasses unless there is adequate clearance between the freeway and the bridge. Another constraint is that CSOL usually requires that all lanes and shoulders be paved to maintain uniform elevation.

In the CSOL analysis module the user is able to create a project-specific cross section by specifying the total number of AC layers (lifts) required and the thickness of each layer. As illustrated in Fig. 1, the typical Caltrans LLPRS design calls for four AC layers with thickness varying from 200 mm (8 in.) to 250 mm (10 in.). "*MultiCool*" is a numerical simulation program that calculates the AC cooling time for multi layer AC paving. It is embedded in *CA4PRS* to check the suspension of the paving operation due to the cooling time (Timm et al. 2001).

Rehabilitation Methodologies

Two lane closure tactics are permitted in the CSOL analysis module: CSOL full-closure and CSOL half-closure (Lee et al. 2002a). In the case of CSOL full closure, one direction of the freeway is completely closed off for rehabilitation and traffic is switched to the other side of construction through median crossovers, utilizing counter-flow traffic. The main lanes and shoulders are overlaid completely layer by layer and lane by lane on one side of the freeway within a closure. Usually the paving operation alternates the sequence of paving lanes to minimize waiting time.

Half-closure CSOL requires closing down only two out of four lanes in one direction during a closure. This allows two lanes to be open to traffic in the direction of the rehabilitation and four lanes of traffic in the opposite direction. Traffic would be separated from the construction work zone by a moveable concrete barrier. This half-closure option has two suboptions: (1) CSOL half closure with full completion, where part of the AC layers are placed on two lanes, and then traffic is shifted to the newly paved lanes while the other two are paved, and this process is repeated until the section is completed; and (2) CSOL half-closure with partial completion, where the first bottom AC layers are overlaid at the first closure and the remaining top layers are completed at the subsequent closure.

Full Depth Asphalt Concrete Replacement Strategy

The FDAC replacement strategy requires complete removal of the PCC and partial trimming of the aggregate base to accommodate the specified depth of the new AC pavement. Similar to the CSOL analysis module, the FDAC analysis module allows the user to input project-specific AC cross sections. In Caltrans LLPRS projects a rich bottom AC layer will normally be placed on top of the recompacted aggregate base (AB), followed by five or six AC layers paved sequentially, with total thickness ranging from 330 mm (13 in.) to 406 mm (16 in.), as illustrated in Fig. 1.

The FDAC analysis module includes two lane closure tactics: single-lane or double-lane rehabilitation. A benefit of the double-lane rehabilitation is that the multiple AC layers are interlocked by overlapping the longitudinal joints between adjacent lanes. The single- and double-lane rehabilitation concept for the FDAC replacement is similar to the PCC reconstruction methodology. Following a common AC paving practice, the double-lane rehabilitation option for the FDAC replacement does not specify paving both lanes in one pull, unlike PCC reconstruction.

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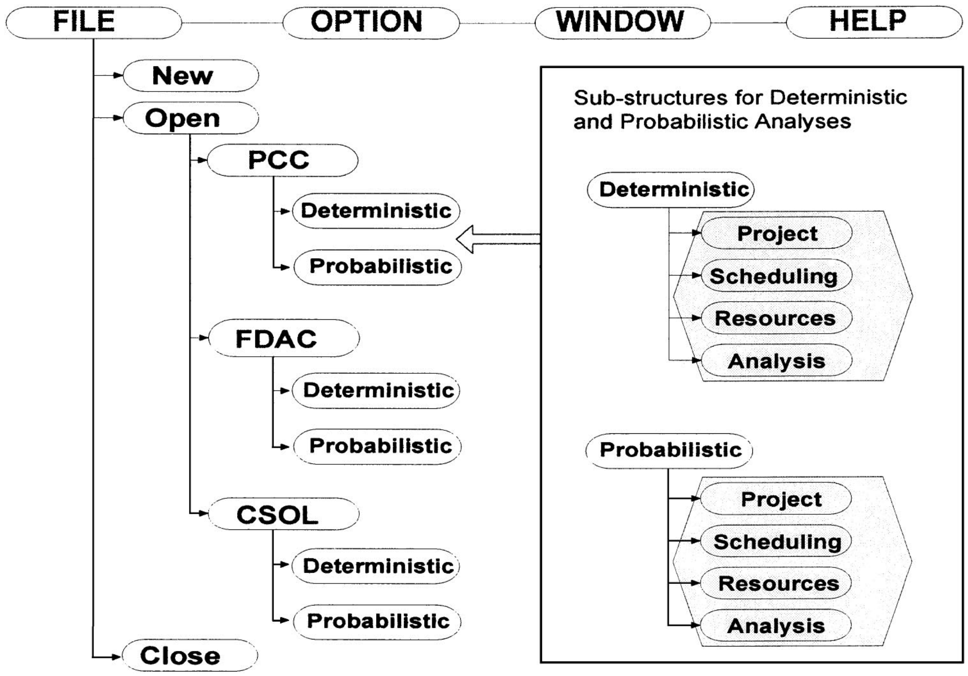

Fig. 2. Construction Analysis for Pavement Rehabilitation Strategies menu structure and analysis hierarchy

Construction Analysis for Pavement Rehabilitation Strategies Computational Background

Construction Analysis for Pavement Rehabilitation Strategies Computational Process

Typical input procedure and analytical processes of *CA4PRS* are:

1. choose the analysis mode: deterministic or probabilistic.
2. Input the total scope (lane km) of the rehabilitation project.
3. Select a rehabilitation strategy: PCC reconstruction, CSOL rehabilitation, or FD AC replacement analysis modules.
4. Define the new pavement cross section: slab and base thickness (PCC) or layer profile (AC).
5. Set the concrete curing time (PCC) or AC cooling time (or let the *MultiCool* software calculate cooling times interactively).
6. Decide a construction window (closure timing and length): for example, 10 h nighttimes, 55 h weekend, or 72 h weekday closures.
7. Define activity lead–lag relationships (start to start, finish to start, etc.) between major operations: mobilization, demobilization, and minimum time interfaces between operations.
8. Select rehabilitation sequences and lane closure tactics: concurrent versus sequential and single-lane versus double-lane rehabilitations.
9. Input contractor's logistical resources (crew, equipment, and plants) for major operations. The number of hauling and delivery trucks per hour should take into account the minimum cycle for supply and haul trucks. (Our prior research has found that loading or discharging trucks is usually the critical productivity constraint). Based on the preceding inputs and constraints, *CA4PRS* performs the following computations and continues as follows:
10. Quantify material volumes for the major operations: demolition, AC paving, or PCC paving.
11. Utilize a simplified critical path method (CPM) scheduling analysis to calculate available durations for the main operations.
12. Quantify the production capability of each resource input, and apply a linear scheduling technique to identify the constraining resource and consequently the maximum production capability.
13. Provide consistency checks on the main *CA4PRS* outputs including:
    - maximum rehabilitation production (lane kilometer) per closure,
    - total number of closures and duration needed to finish the whole project scope,
    - constraining resource and minimally needed resource profile, and
    - balanced time allocation between the demolition and paving operations.

Construction Analysis for Pavement Rehabilitation Strategies Computational Platform

The *CA4PRS* software runs on Microsoft Windows 95/NT4.098/2000/XP™ or higher operating systems. It is developed in *Microsoft Visual Basic 6.0* and utilizes a Microsoft Access 2000 database as the back-end for data storage, though it does not require Microsoft Access installed to run the software. The *CA4PRS* utilizes a number of third-party, royalty free tools to enhance the user friendliness, versatility of the user interfaces, and presentation quality of the program. It has a multiple-document interface, similar to Microsoft Excel or Microsoft Word, which enables multiple projects and analyses to be opened, viewed, and compared simultaneously. The *CA4PRS* is designed for project level analysis and each project analysis must have a unique identifier as the primary key in the *CA4PRS* database for storing and retrieving all related information.

As illustrated in Fig. 2, *CA4PRS* employs a systematic menu structure that groups menu items in an intuitive manner and provides context sensitive online help and a user manual. Its hierarchical structure provides extensive graphical and tabular outputs

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and incorporates a report feature that documents the analysis input and output for printing or saving as an Adobe Portable Document Format or Rich Text Format file. The *CA4PRS* provides seamless transition between deterministic and probabilistic analysis modes, as described in the following section, and the user can easily transfer project data between the two analysis modes.

Deterministic and Probabilistic Analysis Modes

The *CA4PRS* can perform both deterministic and probabilistic analysis. In the deterministic analysis mode the input parameters including resource and scheduling constraints (activity lead–lag time relationships) are treated as constants without any variations. This mode seeks the straightforward maximum pavement amount (distance) that can be rebuilt within the construction closure windows under the given project constraints.

The probabilistic (stochastic) mode treats input parameters as random variables. Each variable can be described using an appropriate statistical distribution; the options are uniform, normal, log normal, beta, geometric, triangular, truncated normal, and truncated log normal. This mode permits the user to review the likelihood of achieving different pavement rehabilitation production rates, utilizing Monte Carlo simulation.

Construction Analysis for Pavement Rehabilitation Strategies Input Windows

The user starts an analysis by either creating a new one or by opening an existing one, with four input tab window prompts:
- project details window,
- scheduling window,
- resource profile window, and
- analysis window.

The input configurations of the deterministic and stochastic modes are similar except that the former asks the user to specify absolute values for the uncertain variable (constant numbers). The stochastic model provides the user a list library of probability distribution functions to choose from.

Project Details Window

The project details window prompts the user to input the basic textural information on a proposed project, including identifying project descriptions, route name, post (station) miles, location, etc. In the project objective cell the user specifies the project scope by typing in total lane kilometer (or mile) to be rehabilitated. This user-specified project objective (goal) then acts as the baseline to compute total number of closures required based on the rehabilitation production estimation of each scenario to be calculated at the end of the analysis. When a number of alternative scenarios are considered for the same project, the distinct features of each alternative can be recorded under the "Project Notes" portion of the window.

Scheduling Window

Fig. 3 shows the probabilistic scheduling window (with the PCC analysis module shown for example). The scheduling aspects of the project are categorized into three subgroups: mobilization/demobilization variables, construction closures (windows), and activity lead–lag time relationships. A certain minimum time will be needed for mobilization and demobilization purposes such as site preparation, cleaning up, and, more importantly, traffic control for the construction.

As illustrated in Fig. 3, three alternative time frames (construction windows) are available to the user: nighttime (typically weekdays), weekend, and continuous closures. The continuous closure has two sub-options to choose from: (1) continuous closure with daytime-only shift operations, with one or two crew shift(s) for a limited number of weekdays while the freeway remains closed throughout the whole period of rehabilitation; and (2) continuous closure with continuous operations, which means fast-track accelerated construction with round-the-clock operations using two or three rotating crew shifts.

Resource Profile Window

The contractor's logistics and resource constraints are two of the most decisive factors in rehabilitation production, especially in fast-track urban highway rehabilitation where the space and access for construction equipment is often limited. The user inputs the number and capacity of the available equipment and plants. Some resource inputs will require prior knowledge, experience, and personal judgment from the user. For instance, the user should input a reasonable number of demolition hauling trucks per hour by taking account of the expected loading cycle time of the demolition and turn-around time of the trucks between site and dumping area.

Analysis Window

Fig. 4 illustrates the analysis window. Here the user selects and controls the following input categories for the PCC analysis module, as an example:
- construction windows,
- rehabilitation sequence with respect to lane closure tactics,
- concrete curing time,
- pavement cross section changes, and
- truck lane width.

For each input category, a drop-down list of values or check box options is available. To analyze and compare various options, the user can choose one or more variables. The asphalt (CSOL and FDAC) analysis window also allows the user to enter estimated cooling times for each AC lift or choose the option to run the *MultiCool* software instead.

Construction Analysis for Pavement Rehabilitation Strategies Outputs

As mentioned earlier, *CA4PRS* produces either a single or multitude of analysis results, depending on the number of input options the user selects. For example, if the user elects to consider two concrete curing time options (4 and 12 h), two rehabilitation sequence options (sequential single lane and concurrent double lane), and two cross section profiles (203 mm and user defined) for the 55 h weekend closure in the PCC analysis module, a total of eight ($2 \times 2 \times 2$) analysis results, each in a separate output window, will be generated once the user clicks the "Analyze" button.

Deterministic Outputs

In deterministic mode, the output is presented in two parts: "Production Details" and "Production Chart". Included in the produc-

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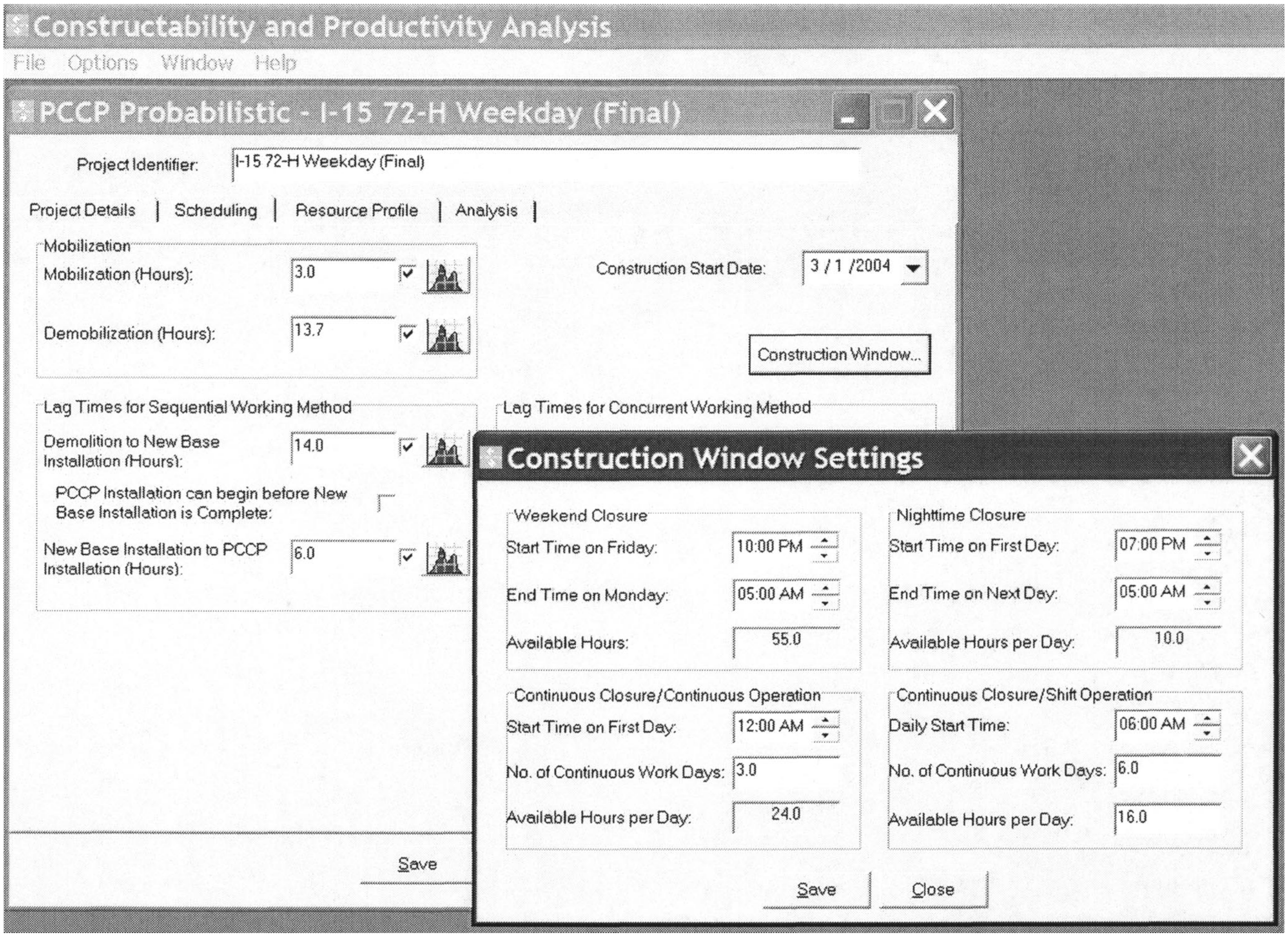

Fig. 3. Scheduling input window in Portland cement concrete probabilistic mode

tion details screen are the user input summary and the main analysis results (see Fig. 5). The main results are the maximum production of each rehabilitation scenario analyzed in terms of lane kilometer, and the total number of closures to finish the whole rehabilitation project scope (objective) based on the maximum production of the each scenario. Some additional information is also provided in the outputs, including a summary of material volumes for the major operations like demolition, slab paving, and base paving. The main results of the CPM scheduling analysis are provided as well; i.e., the optimally balanced maximum duration of the demolition and paving activities within a given closure time limit. The production chart screen contains a "line of balance schedule" where the linear progress of the main rehabilitation operations is plotted against the time.

One of the most useful features of the *CA4PRS* outputs, especially from the contractor's point of view, is identifying which input equipment constrains the operations. A list of input resources, with a comparison of the input number and number minimally needed, is tabulated in the project details output window (see Fig. 5).

When the user checks multiple options in each category in the analysis window, the number of output windows could be too large for effective comparison of all the analyzed scenarios at once. To avoid this inconvenience, a simplified comparison table can be generated. It summarizes the main inputs and outputs in a hierarchical manner: starting with the construction window, then the cross section profile, the rehabilitation sequence, etc.

Probabilistic Outputs

One main difference between the probabilistic and deterministic modes is that the probabilistic outputs shows a plot of the distribution of maximum production as a result of the Monte Carlo simulation (see Fig. 5). The probabilistic output, as a normalized distribution according to the Central Limit Theorem (Moder et al. 1983), represents the most likely maximum production as a mean, and productions at −0.5 SD and +0.5 SD as lower and upper bounds, respectively. Despite requiring more input information and more time to run, the stochastic formulation provides a more realistic estimation and comprehensive description of the rehabilitation production. One other advantage of the probabilistic analysis is that it permits the user to see the relative contribution of the probabilistic input variables to the rehabilitation production as a whole, in the sensitivity "tornado" chart.

Construction Analysis for Pavement Rehabilitation Strategies Case Studies

The *CA4PRS* software has been verified and applied on several numbers of Caltrans LLPRS projects, as summarized below.

Construction Analysis for Pavement Rehabilitation Strategies Validation on I-10 Project

A case study was performed for the validation of *CA4PRS* on the first concrete LLPRS project on Interstate 10 near Pomona. This

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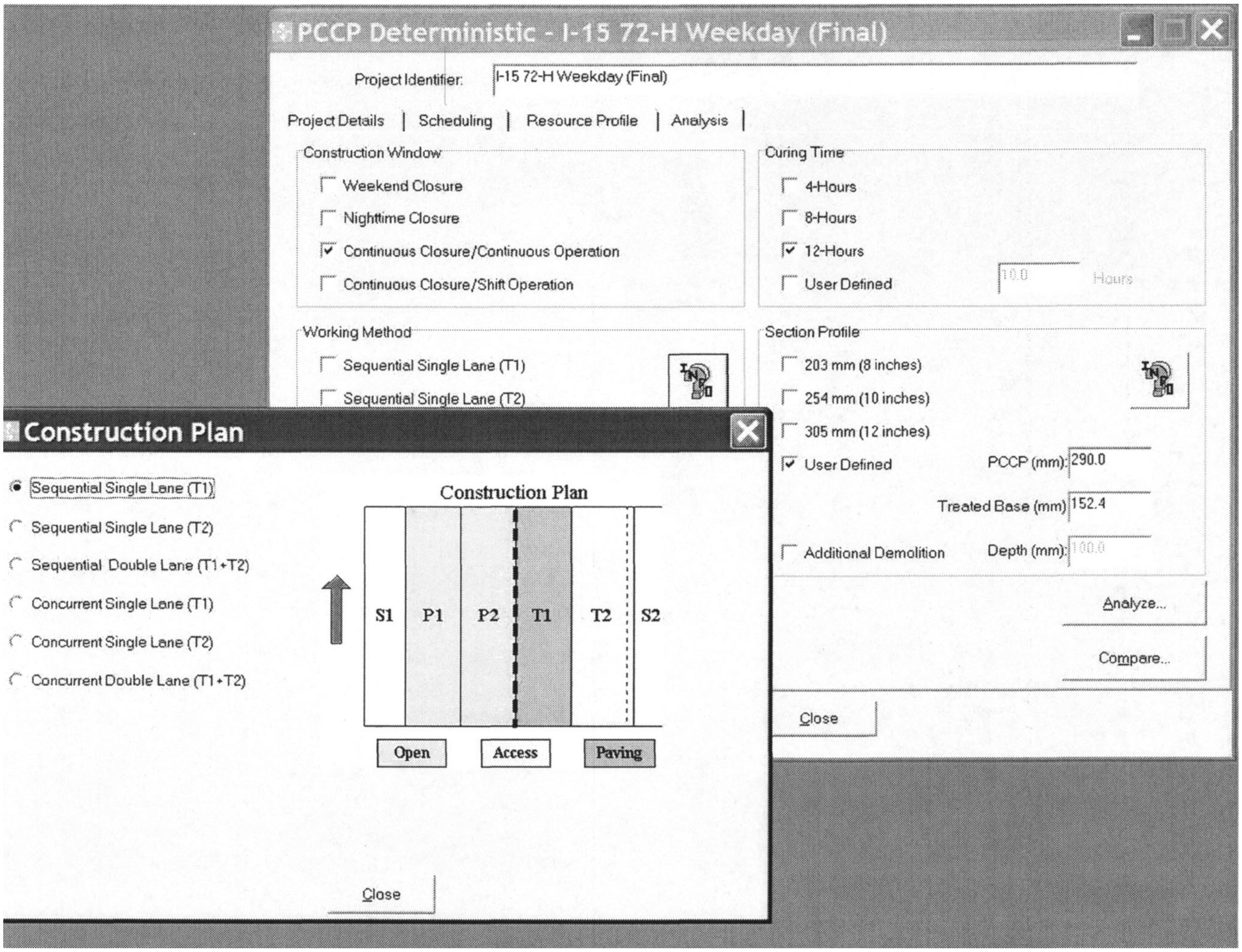

Fig. 4. Analysis input window in Portland cement concrete deterministic mode

job consisted of 2.8 lane km successfully rebuilt with one 55 h weekend closure (Friday 10 p.m.–Monday 5 a.m.) in late 1999 (Lee et al. 2002b). The highway segment, having four lanes in each direction, was built in the early 1960s and had a high concentration of deteriorated concrete pavement due to traffic volumes of 240,000 ADT with approximately 9% heavy trucks. Two of the four lanes remained open while the inner truck lane ($T1$) in the eastbound direction was rehabilitated. The outer truck lane ($T2$) was used for construction access. The contractor used the "PCC concurrent single-lane paving" method. Demolition and concrete paving occurred simultaneously to replace the 230 mm of old slab with a new slab using fast-setting concrete. Under the incentives/disincentives clause in the contract, the contractor was awarded a $500,000 bonus payment for successful completion of the PCC rehabilitation within the 55 h weekend closure.

The lower bound production of 2.8 lane km, predicted with the confidence level of 68% in the *CA4PRS* probabilistic mode, was identical to the actual production performance monitored by the research team during the weekend closure. The contractor encountered the lower production limit of 2.8 lane km only because of several resource problems, including a main batch plant breakdown for about 4 h. The *CA4PRS* probabilistic analysis estimated a best case (upper bound) scenario of 3.4 lane km production.

Construction Analysis for Pavement Rehabilitation Strategies Application on I-710 Project

The *CA4PRS* software was next tested on an asphalt LLPRS project on Interstate 710 in Long Beach, Calif. A 4.4 km stretch of the freeway (total of 26.3 lane km) was rehabilitated successfully with long-life AC in eight 55 h weekend closures, two weekends earlier than initially planned by Caltrans District 7 (Lee et al. 2003). First opened in 1952, this stretch of I-710 carries more than 164,000 ADT, including 13% heavy trucks during weekdays. The project had four FDAC sections located under the four bridge overpasses, where the existing PCC pavement structure was excavated and removed to a depth of 625 mm, and replaced with 325 mm of AC. The pavement between the FDAC sections received 230 mm of CSOL. During construction, Caltrans applied "counter-flow traffic" controls ("full-closure and full-completion AC rehabilitation" method).

For this scenario *CA4PRS* estimated that the maximum production capability of a 55 h weekend was about 1.3 km of the CSOL section and one FDAC section (about 0.4 km). Prior to starting construction, the *CA4PRS* analysis results confirmed that the contractor's goal of completing the main rehabilitation work in eight weekend closures was realistic. However, the *CA4PRS* analysis also warned that the contractor's initial plan of rehabili-

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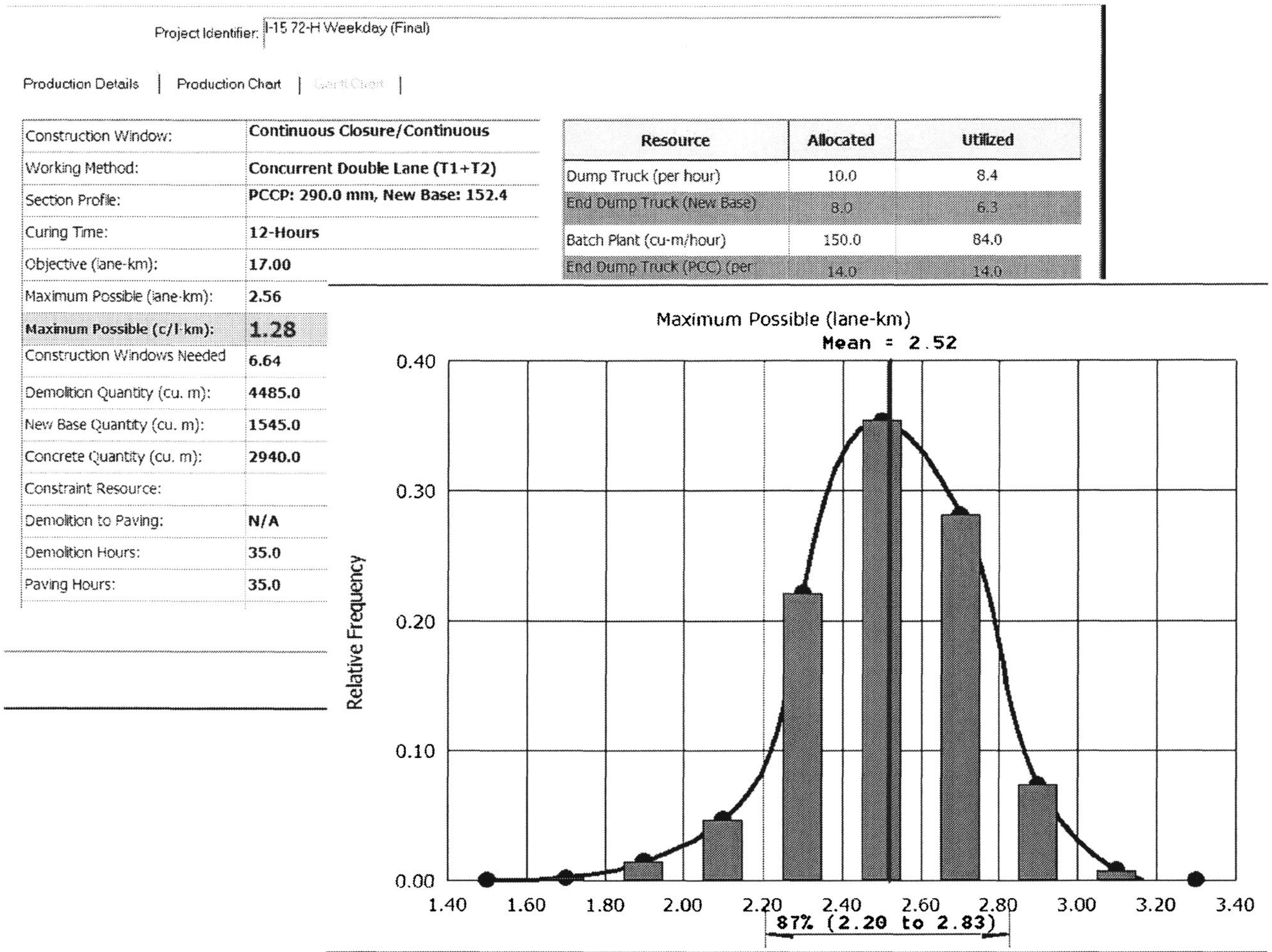

Fig. 5. Output screens for Portland cement concrete deterministic (table) and probabilistic (graph) analysis

tating about two FDAC section (about 0.8 km, basically two overpasses) and 1.3 km of the CSOL section per weekend was overly optimistic. (This optimism may have been encouraged by an incentive provision that offered the contractor $100,000 per unused weekend closure, cap at $500,000.) The contractor revised his production plan based on the production levels recommended by the researchers.

The contractor's actual production performance measured in the construction monitoring study by the research team was within about 5% of the *CA4PRS* production estimates. In addition, the number of demolition hauling trucks (an average of 10 trucks/h) and hot mix asphalt delivery trucks (12 trucks/h on average) predicted by *CA4PRS* was similar to the contractor's eventual fleet.

Construction Analysis for Pavement Rehabilitation Strategies Integration on I-15 Project

The next case study is on the third Caltrans LLPRS project to rebuild a 4.2 km stretch (total of 17 lane km, two truck lanes in both directions) of Interstate 15, scheduled to begin fall 2004. This highway, near Devore in San Bernardino County, Calif. carries 110,000 ADT on weekends (leisure traffic between Los Angeles, Calif. and Las Vegas, Nev.). A full closure approach ("concurrent double-lane rehabilitation") strategy was selected. The Berkeley research team was involved at the outset to assist in preparing an integrated analysis of pavement materials and design, construction logistics, and traffic operations. The goal was to determine the most economical reconstruction closure scenario (Lee et al. 2005). The existing pavement structure consisted of 203 mm (8 in.) PCC slabs, 102 mm (4 in.) cement treated base, and 450 mm (18 in.) AB. This old pavement is to be replaced with 290 mm (11.5 in.) of plain, jointed, and doweled concrete slabs utilizing the early strength Type III PCC (so-called "12 h mix") and 152 mm (6 in.) of ACB.

The concept of total cost, integrating closure schedule, road user cost, and construction and traffic handling costs, was used as the evaluation criteria for the most economic closure strategy. The *CA4PRS* software was used for scheduling analysis as a baseline. The demand-capacity model (*Highway capacity manual*), and macroscopic (*FREQ*) and microscopic (*Paramics*) traffic simulation models were utilized for traffic delay analysis. Caltrans decided to implement eight 72 h weekday closures with round-the-clock operations based on the *CA4PRS* schedule analysis. The analysis demonstrated that the 72 h closure scenario had 77% less total closure time, 34% less road user cost, and 38% less agency cost when compared with the traditional nighttime closures (Lee et al. 2005).

Conclusions

Construction Analysis for Pavement Rehabilitation Strategies software is structured and designed to predict the maximum

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amount (distance) of highway that can be rehabilitated or reconstructed given various parameters, such as pavement materials and design, lane closure tactics, schedule interfaces, and contractor's logistics and resources. The software is a useful constructability analysis tool for transportation agencies and contractors who want to evaluate "what-if" scenarios at each stage of the pavement rehabilitation project: feasibility/planning, design, and construction. It provides a construction schedule baseline for the integration of design, construction, and traffic, all of which are essential for the selection of the most economical pavement rehabilitation strategies. The *CA4PRS* software can be integrated with traffic analysis tools. When combined with traffic analysis models, *CA4PRS* can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating unacceptable traffic delays.

The software has been verified on the Caltrans I-10 Pomona project where concrete long-life pavement was built in a 55 h weekend closure. It has been used to evaluate plans for the Caltrans I-710 Long Beach project where asphalt long-life pavement was built in eight 55 h weekend closures. Further enhancements and upgrades are currently underway so that the enhanced *CA4PRS* model will cover even more rehabilitation strategies such as a continuous reinforced concrete pavement strategy.

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