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Constructability and Productivity Analysis for Long Life Asphalt Concrete Pavement Rehabilitation Strategies

Report Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

By

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EXECUTIVE SUMMARY

A large portion of the highway system in the United States has exceeded its design and its service life. Deterioration of the existing highway system adversely affects the safety of road users, ride quality, the operational cost of vehicles, and the cost of highway maintenance. This report presents the results of a constructability and productivity analysis for the Caltrans Long Life Asphalt Concrete Pavement Rehabilitation Strategies (LLACPRS), focusing on optimizing the maximum production capability within a 55-hour weekend closure.

With the assistance of California asphalt concrete paving contractors, the constructability analyses explored the effects of the following parameters: rehabilitation materials, design profile [Crack Seat and Overlay (CSOL) and Full-Depth Asphalt Concrete (AC) replacement of different thickness], cooling time, number and capacity of construction resources, and alternative lane closure strategies. The experiment design consisted of a hierarchical structure of rehabilitation options based on consultation with industry and Caltrans.

Prototype constructability analysis programs running on commercial spreadsheet software were developed to interactively link all factors involved in the rehabilitation processes. The analysis programs were designed to help road agencies and paving contractors determine which rehabilitation and construction strategies were the most feasible in an urban environment with the underlying goal of balancing the maximization of production capability and minimization of traffic delay. The asphalt constructability analysis procedure has been implemented for both deterministic and stochastic analyses.

The asphalt concrete constructability analyses indicate that the proposed objective of Caltrans to rebuild 6 lane-kilometer of truck lanes within a 55-hour weekend closure has a low probability of success. Material delivery resources, especially dump trucks for demolition and delivery trucks for asphalt concrete supply, were the major constraints limiting the production.

The total layer thickness for asphalt concrete proved to be a major determining element on the production capability. For example, the production capability of Full-Depth AC Replacement is just about 60 percent of CSOL production within a weekend closure for a scenario in which the two truck lanes need to rehabilitated. However, CSOL requires rehabilitation of all lanes including shoulders on both sides, thereby limiting its effective productivity. Different rehabilitation working methods, determined by the construction access, lane closure tactics, and paving procedures, also have a significant effect on the production capability of the rehabilitation.

The comparison of different construction windows, (i.e., a weekend closure versus continuous closure) was also examined to see the effect of different construction windows on production capability. Continuous closure/continuous operation enables the CSOL project to be finished 15 percent faster and the Full-Depth AC Replacement project to be finished 12 percent faster compared to weekend-only closures. However, the total duration of the closure for continuous closure/daytime operation was longer than that for the weekend-only closure.

This study concludes that efficient lane closure tactics designed to work with the pavement profile can minimize non-working time, such as the time waiting for the AC to cool, and increase the production capability of the project. The constructability analysis for AC developed in this study will aid transportation agencies in their decision-making processes for prioritizing the number of rehabilitation projects on their backlogs, selecting optimal strategies, and effectively communicating project duration with the public and other project stakeholders, such as local governments.

1.0 INTRODUCTION

The "1995 State of the Pavement Report" indicated that 22,500 lane-km out of 78,000 lane-kilometers in the state highway system required corrective maintenance or rehabilitation, with 7,000 lane-km needing immediate rehabilitation.(*1*) Caltrans has identified 2,800 lane-km of California urban freeway as candidates for rehabilitation; most of the candidates are in urban corridors of Southern California and the San Francisco Bay Area. The criteria for long-life pavement rehabilitation candidate projects are poor structural condition and ride quality and 150,000 ADT (Average Daily Traffic) or 15,000 Average Daily Truck Traffic.

In order to complete the desired 2,800 lane-km of long-life pavement in ten years, Caltrans needs to rehabilitate approximately 6 lane-km of pavement every weekend. Initially, Caltrans developed LLPRS (Long Life Pavement Rehabilitation Strategies) for rehabilitation of existing portland cement concrete (PCC) pavement that met the following objectives: provide 30+ years of service life, require minimal maintenance, and have sufficient production capability to rehabilitate about 6 lane-km within a weekend construction window of 55 hours. Caltrans proposed the short construction window of 55 hours per weekend, i.e., 10 p.m. Friday to 5 a.m. Monday to minimize traffic disruptions during pavement rehabilitation.(*2*)

Caltrans LLPRS consists of two sub-categories: LLCPRS (concrete) and LLACPRS (asphalt concrete). In this report, PCC pavement rehabilitation with asphalt concrete is referred to as *AC Rehabilitation;* PCC pavement rehabilitation with concrete is called *Concrete Rehabilitation*.

For both strategies, the assumed existing pavement to be rehabilitated is the same: 200 to 225 mm of plain, jointed PCC; 100 to 150 mm of cement treated base (CTB); some type and thickness of aggregate subbase; and the compacted natural subgrade. The AC Rehabilitation strategies currently included under LLACPRS are: crack, seat, and overlay of the existing pavement; and removal of the concrete pavement structure at least to the aggregate subbase and replacement with an asphalt concrete structure. The crack, seat, and overlay LLACPRS strategy has a thicker overlay and different materials from the typical Caltrans crack, seat, and overlay strategy. Rehabilitation strategies currently included under Concrete Rehabilitation include removal of the concrete slabs and potentially removal of the CTB and replacement with new slabs and base (if required), as shown in Figure 1.

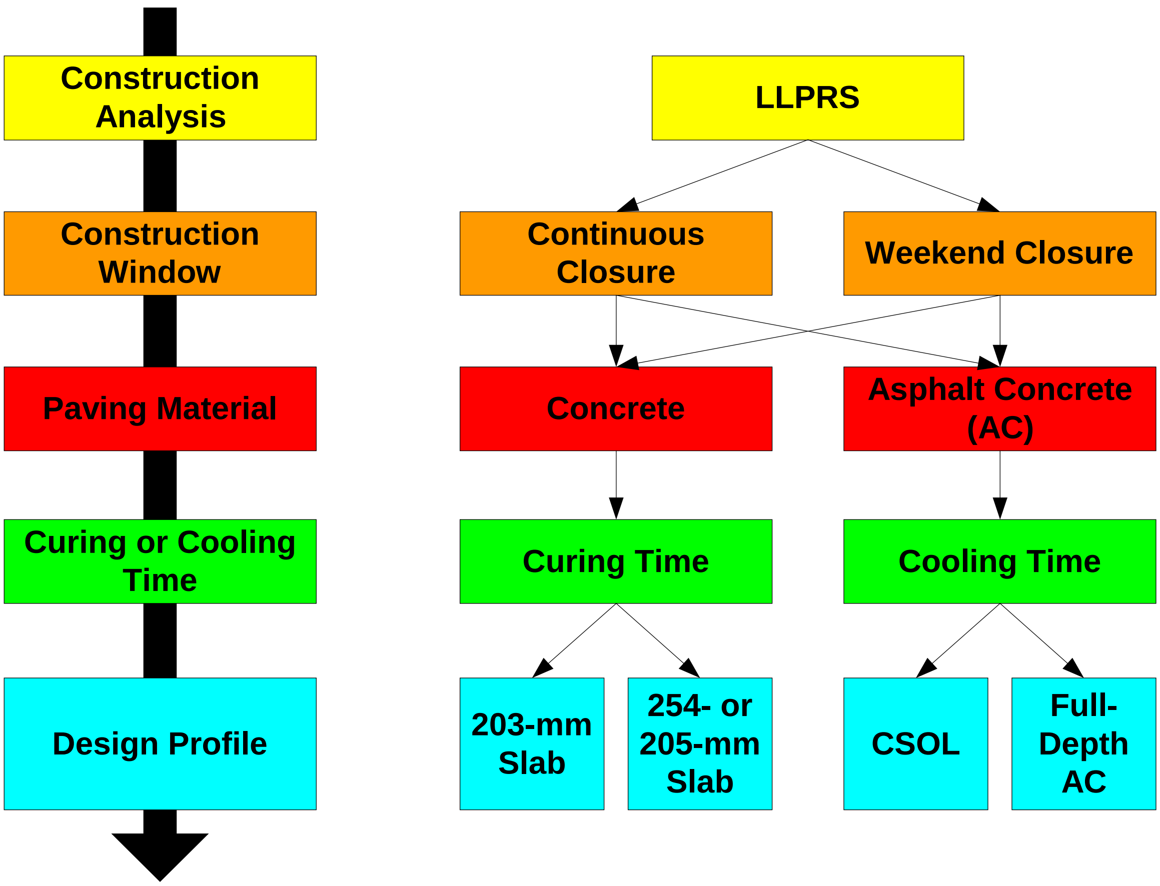


Figure 1: Overall research structure for the constructability analysis of Caltrans LLPRS.

1.1 UCB Previous Research and Future Plan for LLPRS

The research described in this report for AC Rehabilitation is a part of the five-stage study of constructability analysis of LLPRS conducted by the research team at the University of California at Berkeley (UCB). According to the Construction Industry Institute (CII), "Constructability is the optimum use of construction knowledge and expertise in planning, design, procurement, and field operations to achieve overall project objectives."(*3*) Developing a constructability analysis tool that addresses methodology, processes, and analysis models for pavement rehabilitation is a challenging task for both transportation agencies and pavement contractors, as they must consider many input variables and options involved in the rehabilitation process. Without well-developed tools for pavement rehabilitation process, transportation agencies are in a difficult situation in their decision-making processes for prioritizing the backlogged rehabilitation projects, selecting optimal strategies, and effectively communicating with the public and other project stakeholders. Consequently, the need is growing for a constructability analysis tool that can assist departments of transportation and pavement contractors in the implementation of rehabilitation strategies with multiple rehabilitation alternatives. The construction analysis tool also needs to be integrated with construction and user-delay costs in order to select the optimal rehabilitation strategy in terms of pavement design, construction schedule, and minimum inconvenience to the public. Figure 1 shows the basic structure of the Caltrans LLPRS for both concrete and asphalt concrete materials. The following list describes the previous UCB LLPRS research work, including future plans:

1. **Concrete Constructability Analysis.** The first stage of the LLPRS research, the constructability analysis for LLCPRS (Concrete Rehabilitation) was completed and reported to Caltrans.(*4, 5*) Figure 2 shows the hierarchical structure of analysis options for the concrete constructability analysis model.

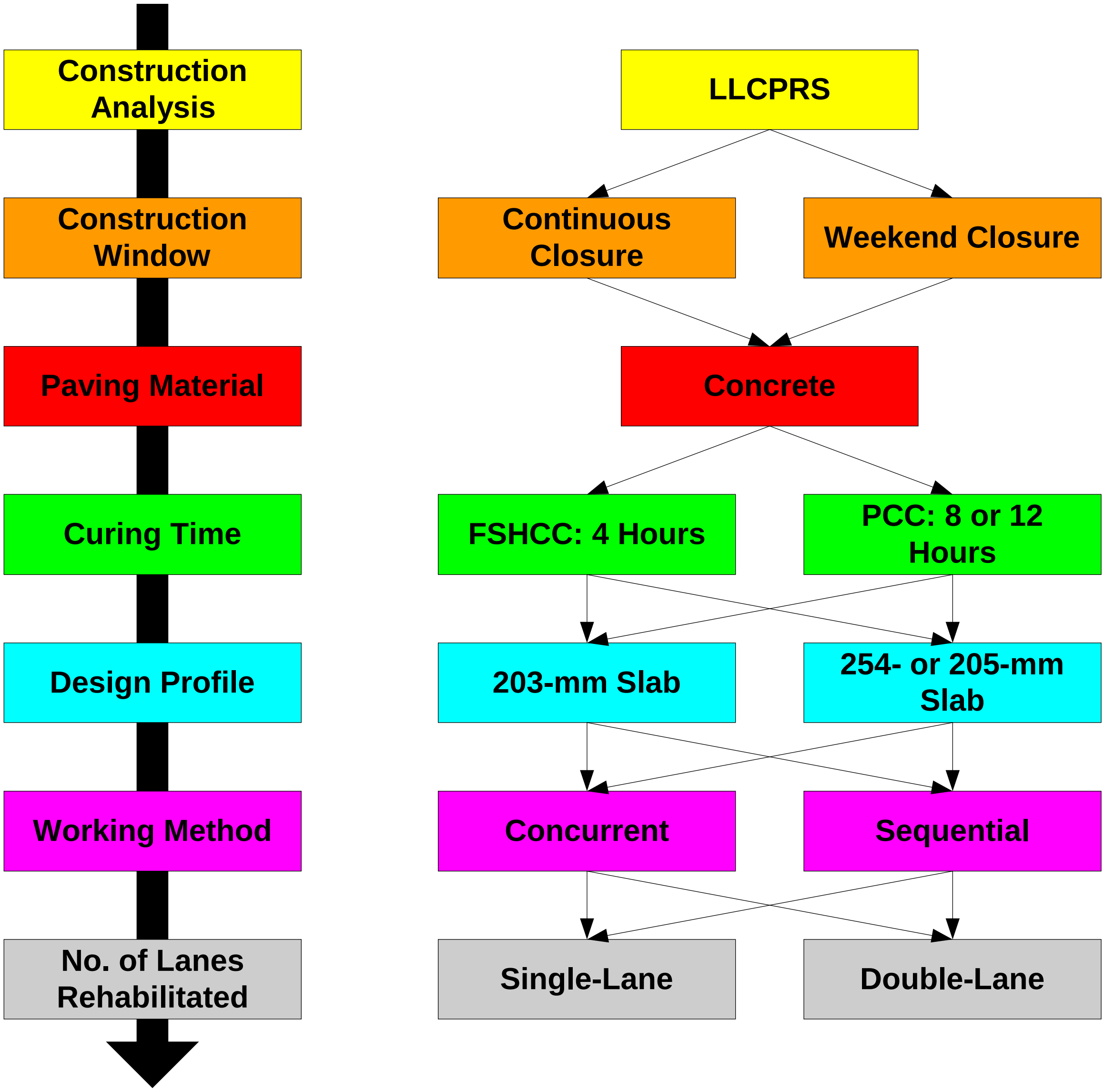


Figure 2: Research structure for constructability analysis of Caltrans Concrete LLPRS.

2. **Case Study for the Concrete Constructability Analysis.** As the second stage of the research, a case study for LLCPRS (Concrete Rehabilitation) was implemented with a Caltrans concrete demonstration project on the I-10 freeway in Pomona, California. A technical report documenting the research was submitted to published by the Innovative Pavement Research Foundation (IPRF) and the Federal Highway Administration (FHWA).(*6*, *7*) The case study played an important role in the

validation and calibration of the concrete constructability analysis model developed by the UCB team.

3. **Asphalt Concrete Constructability Analysis.** The third stage of the research, the constructability analysis for LLACPRS (AC Rehabilitation) is developed and presented in this report.

4. **Case Study for Asphalt Concrete Constructability Analysis.** In the fourth stage of this research, a case study for AC Rehabilitation is underway with a Caltrans AC demonstration project on the I-710 freeway (Long Beach Freeway) for validation and calibration of the asphalt constructability analysis model. The initial planning of the I-710 project is covered in this report with predicted production capability from the UCB asphalt constructability analysis model. A detailed technical report documenting the results of this case study will be published separately when the case study is completed.

5. **Knowledge-base Simulation Software for Constructability Analysis.** The final objective of the LLPRS constructability analysis research is professional-level knowledge-based simulation software to be used as an estimating and analysis tool. The proposed simulation software will integrate both hydraulic cement concrete and asphalt concrete models with deterministic and stochastic analysis modules. This specific research task is sponsored by four state departments of transportation (California, Minnesota, Texas, and Wisconsin). At the time of this writing, programming for the software has already begun with a tentative completion date of March 2002. The simulation software will be used by the road agencies in the construction planning of pavement rehabilitation projects.

1.2 Scope and Objective of Research

This report describes the details of the constructability analysis for Caltrans Long Life Asphalt Concrete Pavement Rehabilitation Strategies (LLACPRS), sometimes referred to as AC-Long Life Strategies, in a similar fashion to the concrete constructability analysis described in the previous report.(*4*) As inputs, the asphalt constructability analysis model used current asphalt concrete rehabilitation strategies along with typical asphalt concrete construction processes used in the asphalt paving industry. The desired output from the analysis was the maximum production capability in terms of lane-km within a short construction window such as a 55-hour weekend closure. This output was used for comparison of different rehabilitation strategies, resource constraints, design profiles, and lane closure tactics.

Two different options for AC Rehabilitation were analyzed in terms of design profile: CSOL (Crack Seat and Overlay) and Full-Depth Replacement. The analysis model developed in this research can, with slight modifications, easily be applied to other types of asphalt concrete rehabilitation. The asphalt constructability analysis procedure has been implemented for both deterministic and stochastic analyses. In the deterministic constructability analysis, input parameters involved in the rehabilitation processes, such as resource constraints, are fixed with representative values. In the stochastic approach, input parameters are treated as random variables. In addition, a 55-hour weekend closure was compared with two additional construction windows (continuous closure with continuous operation and continuous closure with daytime-only operation) to see the effect of different construction windows on production capability.

The constructability analysis is limited to the scheduling aspects of pavement rehabilitation to determine the maximum production capability. The construction scheduling analysis is a baseline for further consideration of direct construction costs and indirect costs from user delay. Long term pavement performance and then life cycle cost analysis can be evaluated in the future when the scheduling and cost aspects are integrated.

An initial part of a case study for the LLACPRS on Interstate 710 is included in this report for the validation of the asphalt constructability analysis model. The predicted maximum production capability for both CSOL and Full-Depth AC Replacement for the I-710 project are presented. The predicted production capability can be used as a guideline for the road agency and contractor to check their initial rehabilitation scheme and plan. The predicted production capability from the asphalt analysis model will be compared with the actual performance of the demonstration project when the project is completed in 2002. The details of the case study are covered in Section 5.0.

1.3 Research Approach

The asphalt constructability analysis was conducted with processes and methodology very similar in principle to those used for the concrete constructability analysis,(*4*) with some modifications to accommodate the different characteristics of asphalt materials, such as cooling time and multi-layer paving.

The basic elements of the constructability analysis, such as construction windows, paving materials, and design profiles were identified by Caltrans and experienced staff at UCB. These elements were checked and adjusted through a series of technical meetings with the Southern California Asphalt Pavement Association (SCAPA) and Caltrans pavement and material engineers.(*8–11*) A number of field trips were made to construction sites in Southern California to gather field data, especially resource constraints, scheduling aspects, and cooling time information.

Based on the information gathered from the industry (SCAPA), Caltrans, reference information from the concrete constructability analysis, and a comprehensive literature review, a hierarchical structure for the analysis options was developed. The structure included a number of options at each level of analysis. The following options are considered for the asphalt constructability analysis:

- Design profile
- Layer (paving lift) profile
- Lane closure tactics
- Completion of paving (stage construction)

A prototype simulation program linking all parameters interactively in the hierarchical structure of the analysis options was developed, which is running on commercially available spreadsheet software (Microsoft® Excel). The software was designed to determine the maximum production capability of the rehabilitation in tables and graphs. An example of the main input window of the simulation program is shown in Figure 3.

An accurate prediction of the cooling time (the time to cool the single hot mix asphalt layer to the required stop temperature) is an essential element in the scheduling of the paving operation. A cooling time simulation software was used to identify the number of hours required between paving of lifts of asphalt concrete and opening to traffic of the final lift. The cooling time analysis software used in the research was validated through a number of field calibration studies. The details of the cooling simulation program are described along with the validation results in Section 3.0.

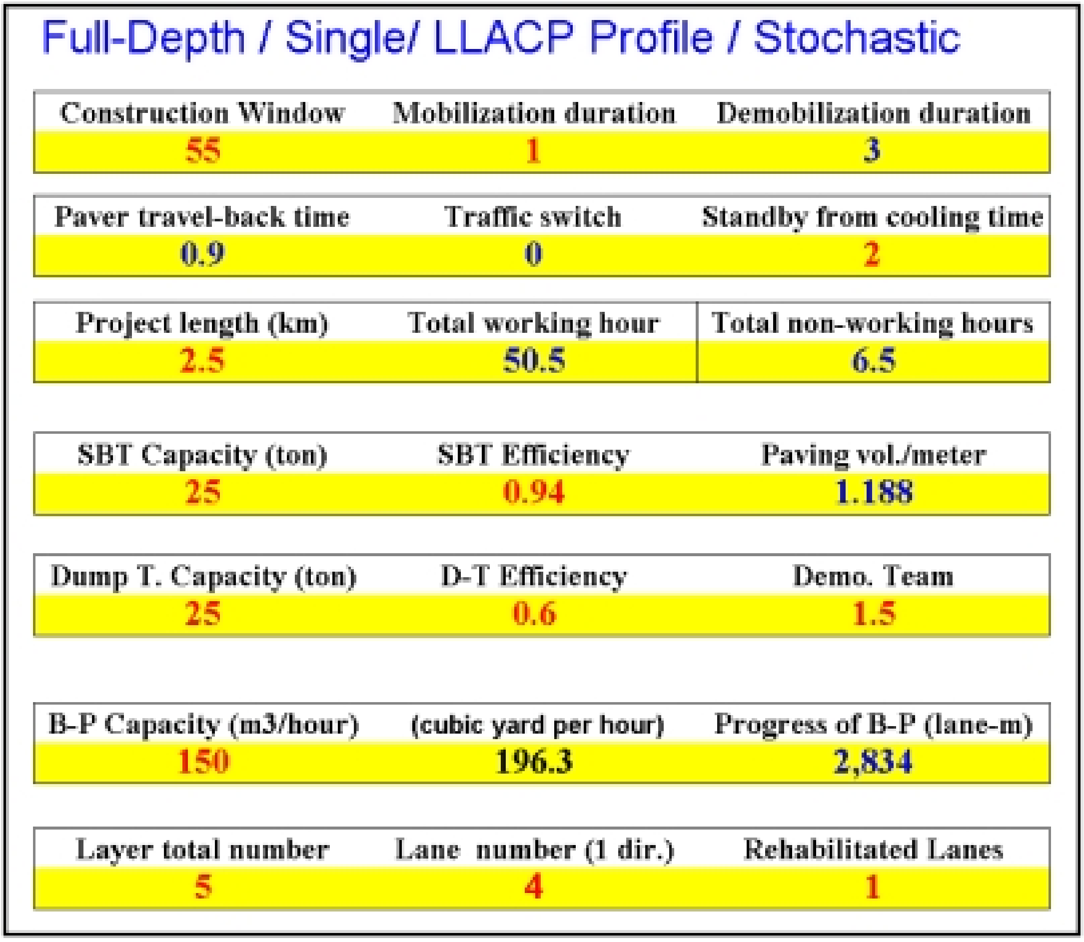


Figure 3. The input screen of the prototype analysis software for estimating asphalt concrete constructability.

2.0 EXPERIMENT DESIGN FOR THE AC CONSTRUCTABILITY ANALYSIS

This section details the experiment design for the constructability analysis for asphalt concrete rehabilitation options.

2.1 Assumptions

The following assumptions were made to decrease the number of independent parameters in the asphalt constructability analysis process:

a. As was used in the Concrete Rehabilitation constructability analysis, the weekend closure was a 55-hour construction window starting Friday at 10:00 p.m. and ending on Monday at 5:00 a.m.

b. Moveable concrete barrier (MCB) was used as the safety barrier system between traffic and the construction zone.

c. The freeway has four lanes in each direction with shoulders. The lane numbering scheme is shown in Figure 4.

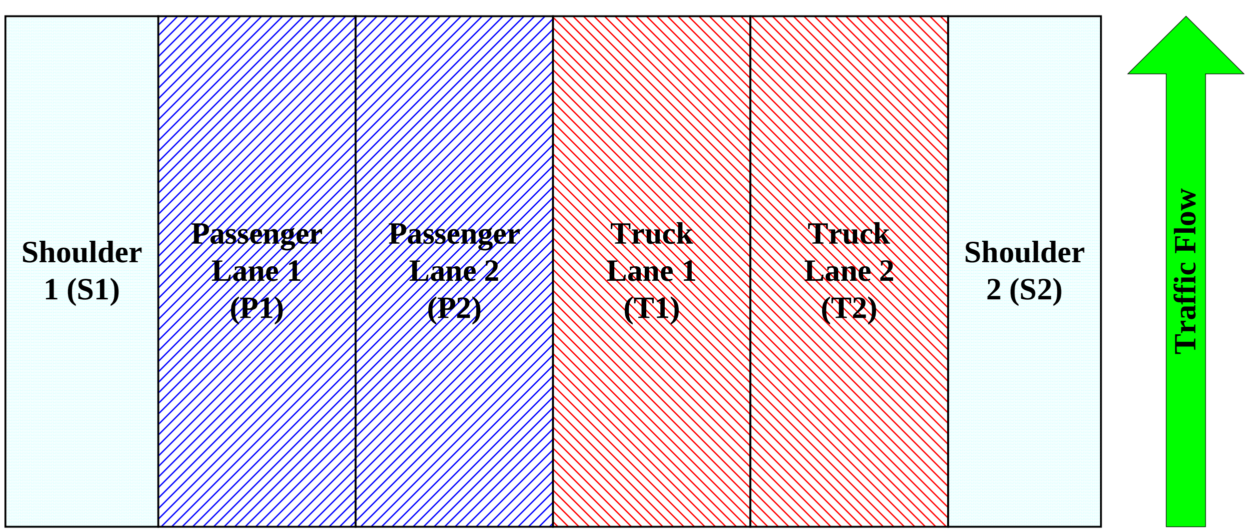


Figure 4. Typical plan view of one direction of the freeway and lane numbering.

d. For Full-Depth AC Replacement, only the truck lanes (in most cases two lanes) were replaced.

e. For Crack Seat and Overlay (CSOL), one direction of the freeway (in most cases two truck lanes and two passenger lanes) including shoulders on both sides was subjected to crack seat and overlay.

f. The outer shoulder could not be used as a major construction access lane because a sound wall was adjacent to the shoulder. The shoulder could be used as a main access lane if the width was greater than 3 meters.

g. Before the paver can begin to place a subsequent lift of asphalt concrete, the current lift must cool to a maximum temperature of 74°C (165°F).

h. The cooling time of each layer for multi-lift paving was estimated by a numeric cooling time simulation program called *CalCool*.(*12*)

i. Prior to the weekend closure, the existing PCC pavement was pre-cut and ready for removal for the Full-Depth AC Replacement case. The PCC slab was cracked and seated prior to the weekend closure for the CSOL case.

j. Daytime and nighttime operations during the weekend closure had the same productivity, except for the impact of the AC cooling time.

k. Only one paving team was used for the AC paving operation for simplicity. Consultation with the SCAPA and initial calculations indicated that it would not be practical to use multiple paving teams working simultaneously because the number of delivery trucks, the capacity of the AC plant, and construction access were maximized for a single-paving team. One AC plant was also assumed, due to conflicts between the delivery trucks, different criteria for material testing from different mixing plants, and the fact that coordination of AC cooling times between paving crews were major obstacles to manage a multi-plant team. In practice, multiple crews and plants may be used for some projects.

l. Multiple demolition teams could work simultaneously for Full-Depth AC Replacement only if enough construction access lanes were provided so that conflicts between demolition trucks could be minimized. This scenario was possible because the paving operation was planned to start only after the demolition work was completed.

m. For interlock between asphalt concrete lifts, longitudinal joints between adjacent lanes should be offset, as shown in Figure 5.

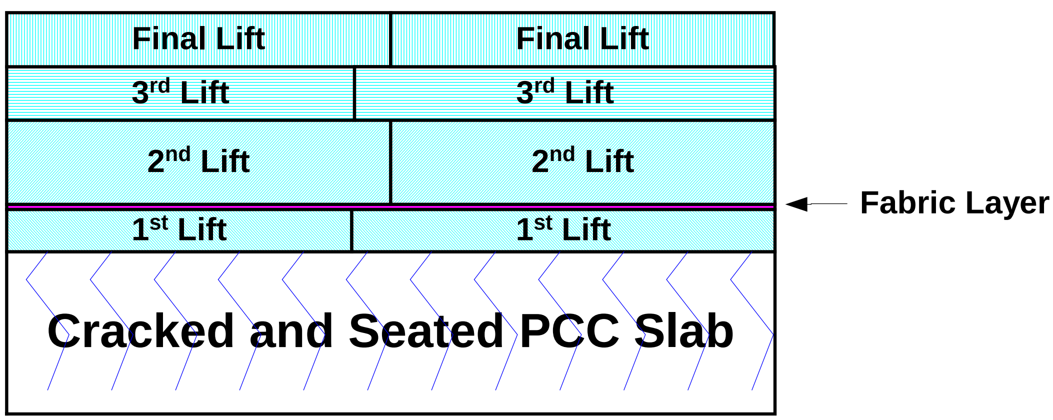


Figure 5. Overlap of longitudinal joints on multi-lift AC paving of adjacent lanes.

2.2 Hierarchical Structure of the Analysis Options

Through a comprehensive literature review and consultation with Caltrans engineers and SCAPA, the potential elements most likely to govern the production capability of an AC Rehabilitation project were identified and summarized, as presented in Table 1. Based on these elements, an experimental design for the asphalt constructability analysis was schematically developed, as shown in Figure 6. The following sections describe the factorial design that was developed and give details about each factor level.

Table 1 Major Factors Affecting the AC Rehabilitation Productivity

	Factor	Options
	Construction Window	55-hour Weekend Closure
		Continuous Closure
	Paving Material	Asphalt Concrete (AC)
	Design Profile	CSOL (Crack, Seat and Overlay)
		Full-Depth AC Replacement
	Cooling Time	Governed by the layer profile type
Affects CSOL only	Layer Profile Type	Layer Profile "A"
		Layer Profile "B"
	Lane Closure Type	Full Closure
		Half Closure
	Paving Completion Type	Full Completion
		Partial Completion
Affects Full-Depth AC Replacement only	Layer Profile Type	Layer Profile "A"
		Layer Profile "B"
	Number of Lanes Replaced	Single-Lane Replacement
		Double-Lane Replacement

2.2.1 Construction Window

Caltrans initially set the weekend closure time of 55 hours to avoid construction delays and traffic interruptions during weekday hours. The majority of the asphalt analysis was focused on the weekend closure construction window, although the comparison of different construction windows, (i.e., a weekend closure versus continuous closures) is also covered in this report. As concluded in the concrete analysis, a weekend closure strategy has some disadvantages, including repeated mobilization/demobilization and securing of resources on weekends.(*4*) The major advantage of a continuous closure is that working hours

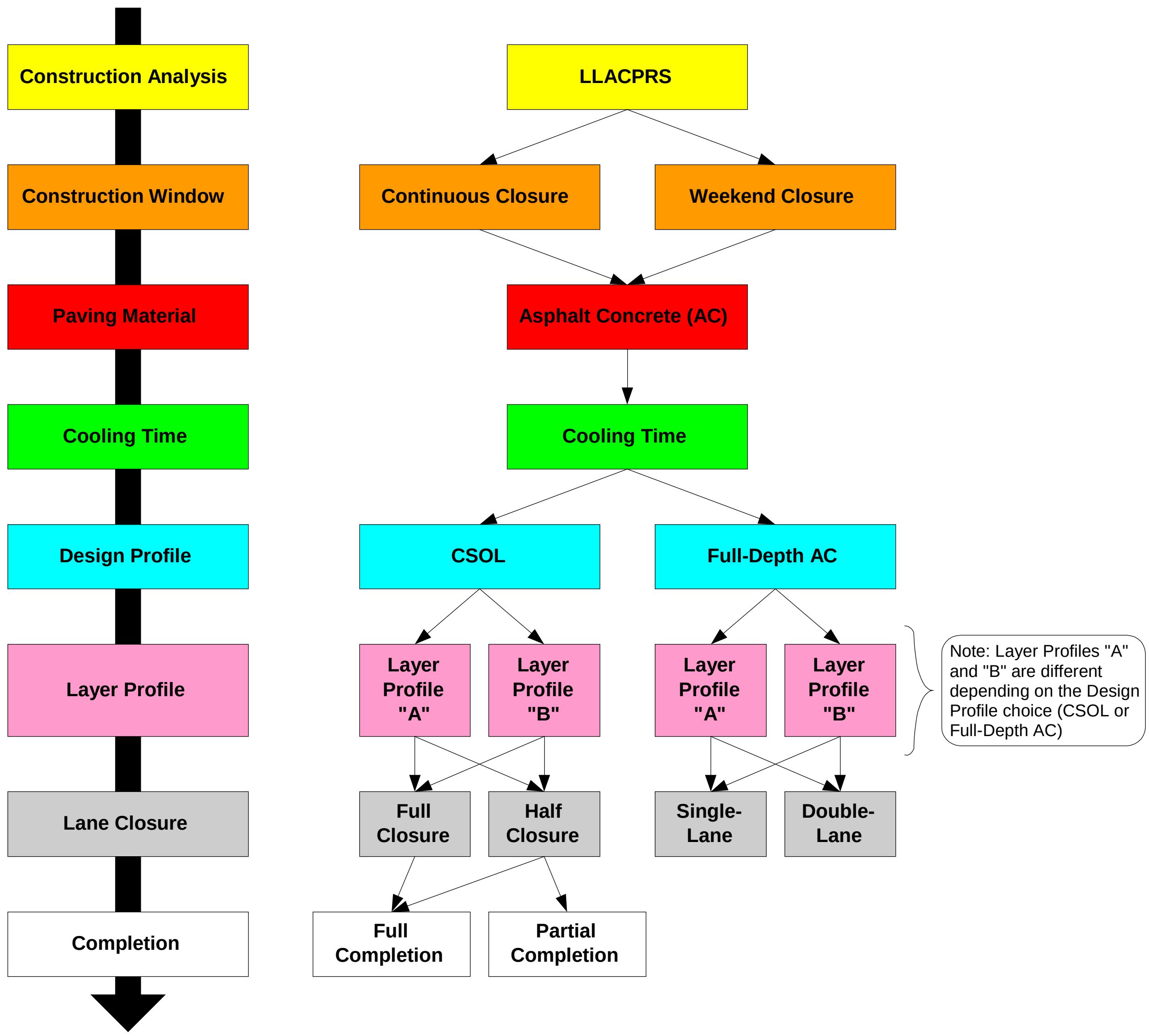


Figure 6. Hierarchical research structure for study of Caltrans LLACPRS.

are maximized without lost time for mobilization/demobilization, which may or may not reduce inconvenience to the traveling public.

2.2.2 Pavement Design Profiles

The two design profile options analyzed for rehabilitation of deteriorated PCC with asphalt concrete were:

- Crack Seat and Overlay (CSOL), and
- Full-depth replacement with asphalt concrete (Full-Depth AC Replacement)

As the choice of the pavement design profile determines the main components of AC Rehabilitation, the detailed layer profiles and work plans for each option are fully described separately in Section 2.3 for CSOL and Section 2.4 for Full-Depth AC Replacement.

2.3 Rehabilitation Options for CSOL (Crack Seat and Overlay)

Figure 7 shows the proposed pavement profile used for the CSOL option. The AC overlay is 200 mm (8 in.), which is broken down into four lifts of hot mix asphalt concrete. The existing concrete pavement was assumed to be 200 mm (8 in.), which is typical of most Caltrans rigid pavements. The major advantage of the CSOL option is that it does not require removal of the existing PCC slab, unlike PCC pavement reconstruction or the Full-Depth AC Replacement option. Consequently, with CSOL the majority of the working hours during the weekend closure can be exclusively assigned to the placement of the asphalt concrete overlay. This should result in more production capability (lane-km) relative to the other rehabilitation methods.

The disadvantage of the CSOL option from an overall production capability point of view is that the net centerline-meters of freeway that can be rehabilitated within a single weekend closure is less than half of the total rehabilitation work that could be completed if only the truck lanes required rehabilitation. This is because the shoulders (S1 and S2) and passenger lanes (P1 and P2) have to be overlaid simultaneously with the two truck lanes (T1 and T2) (Refer to Figure 4). This constraint of the CSOL option will significantly reduce its overall production capability because the other options only require replacement of the truck lanes.

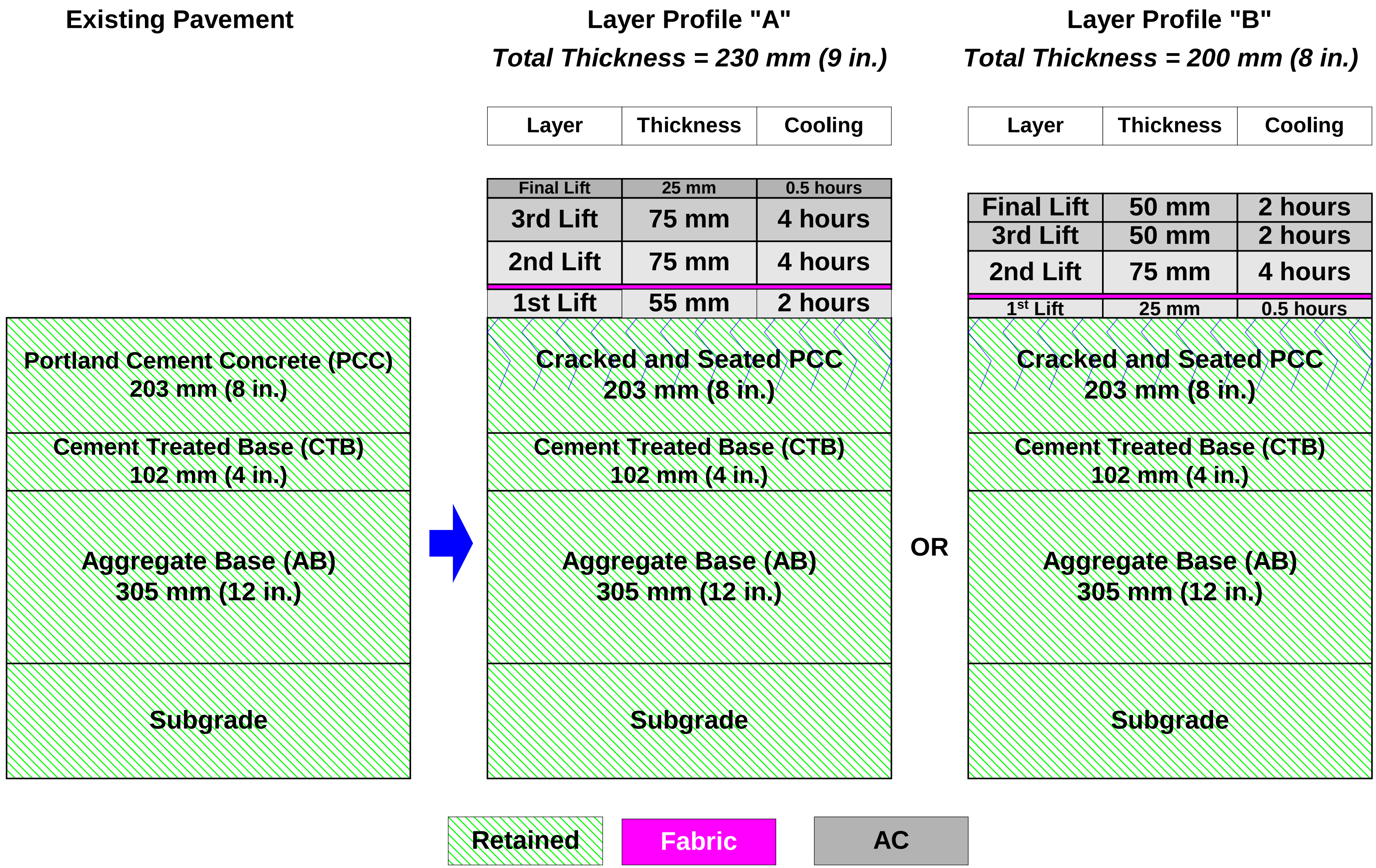


Figure 7. Two layer profiles for CSOL (Crack Seat and Overlay).

Another limitation of the CSOL option is that the overlay cannot be placed underneath bridge overpasses unless there is adequate clearance between the freeway and the bridge to accommodate the overlay. For pavements under a bridge overpass where adequate clearance cannot be achieved with the CSOL option, either Full-Depth AC Replacement or concrete slab removal and replacement(*4-7*) must be used.

2.3.1 Paving of Shoulders for the CSOL Option

The main disadvantage of the CSOL option is that the entire freeway in one direction has to be overlaid to meet adjacent lane grade criteria including the shoulders. The maximum allowable height difference between lanes is 50 mm, although differences of less than 25 mm are desirable. The shoulders outside of lanes P1 and T2 must be overlaid in addition to all of the traffic lanes (P1, P2, T1, T2), otherwise the shoulders would be 200 mm below the mainline highway elevation.

Two options are available for the overlay of the shoulders for CSOL:

- **Pre-paving.** The shoulders can be overlaid in a series of nighttime closures prior to the 55-hour weekend closure for the overlay of the main traffic lanes.
- **Simultaneous paving.** The shoulders can be overlaid at the same time as the main traffic lanes during the 55-hour weekend closure.

In the case of the pre-paving option, K-rails or Moveable Concrete Barrier (MCB) should be installed as a safety barrier between the traffic zone and the shoulders after the shoulder overlay until the weekend closure for the main traffic lane overlay.

In the case of the simultaneous paving option, the shoulders are paved at the same time as the rehabilitation of the main traffic lanes and the limited resources and limited accesses are shared among all the paving operations during the weekend closure. Accordingly, the production capability of this option in terms of centerline-meters will reduced by as much as 40 percent, assuming the width of the shoulder is 3 m and the overlay thickness is the same as the main traffic lanes.

For more direct comparison of the rehabilitation production capability of CSOL with that of other rehabilitation methods, the shoulders on both sides are assumed to be paved simultaneously with the main traffic lanes during the construction window for the CSOL analysis. More detailed production comparison of pre-paving and simultaneous paving options are covered at the end of the report (Section 6.2).

2.3.2 Layer Profiles for CSOL

After cleaning, sweeping, and tacking the concrete pavement, four lifts of hot mix asphalt will be placed on a cracked and seated existing PCC pavement surface. The following are two options for the CSOL in terms of the pavement layer profile, as shown in Figure 7:

- CSOL Layer Profile “A”
- CSOL Layer Profile “B”

Both layer profiles were selected as spanning a typical range by the UCB Pavement Research Center (PRC). The main purpose of comparing the CSOL Layer Profile “A” with the CSOL Layer Profile “B” was to evaluate the impact of different layer profiles as a sensitivity comparison on the rehabilitation production capability. Actual structural sections must be designed for each project location.

The cooling hours in the right hand column of each layer profile option in Figure 7 were calculated from a numerical cooling simulation program, *CalCool*.(*12*) The assumed environmental condition of the pavement before running the cooling time analysis was based on typical summer weather in the hotter climate regions of California: ambient temperature of 37°C (100°F); surface temperature of 43°C (110°F); wind speed of 5 kph, paving start time July 1, 10:00 a.m.; stop temperature 74°C (165°F).

In Figure 7, the interface between the first and second AC lift is a fabric helping to minimize reflective cracking in the AC overlay. The fabric is installed and compacted while the first AC lift is still hot enough to bond to it.

2.3.3 Lane Closure Tactics for CSOL

Efficient lane closure tactics are the biggest concern for any state department of transportation (DOT). The agency needs to balance inconvenience to road users and production capability of the rehabilitation. Two lane closure tactics were considered for the CSOL analysis:

- CSOL Full Closure
- CSOL Half Closure

2.3.3.1 CSOL Full Closure

In the case of CSOL Full Closure, one direction of the freeway is completely closed for rehabilitation by switching the traffic to the other side, utilizing counter-flow traffic. All four lanes of the designated segment of the freeway together with shoulders on both sides (refer to Figure 4) will be overlaid completely within the 55-hour weekend closure, lane-by-lane and layer-by-layer, sequentially.

The sequence of the operations for the CSOL Full Closure option starts with one paving machine beginning to place the first lift of hot mix asphalt from the far right lane, Truck Lane 2

(T2) (Figure 4). When the paving team completes the first lift of the overlay in lane T2, the paving team travels back to the starting point to place the first lift of the next lane, Lane 3 (T1). This process continues until the leftmost lane, Passenger Lane 1 (P1), has been paved with its first lift of AC. As soon as the first lift for all the traffic lanes are completed, the paving team begins placing the second lift at the start of lane T2. This paving process is repeated until all four AC lifts have been paved on all four traffic lanes. As mentioned previously, the shoulders on both sides are assumed to receive the overlay simultaneously with the main traffic lane overlays (simultaneous paving, as described in Section 2.3.1).

The temperature of the previously placed lift should be measured before the next lift is placed to make sure the specified stop temperature is reached. In most cases for the Full Closure option, there was no waiting time caused by slow cooling of the AC lift, even in the scenario least conducive to AC cooling (i.e., hot summer and daytime paving). The main reason for this is that the sequence of paving the large number of lanes (typically four) provides adequate cooling time for a given lane before the paving team is ready to begin the next lift. In addition, because AC delivery trucks (semi bottom dump) will use a lane next to the paving lane as the access rather than drive on the hot lane, the concern about the cooling time for construction delivery vehicles is eliminated for the Full Closure option.

One of the benefits of the CSOL Full Closure option is that it maximizes paving production without wasting time for AC lifts to cool enough to receive additional lifts. However, state DOTs are unlikely to completely close one direction of an urban freeway for rehabilitation for a 55-hour weekend.

2.3.3.2 CSOL Half Closure

Another closure option would be to close two out of four lanes in one direction while completing the CSOL rehabilitation. This would allow for two lanes to be opened to traffic in the direction of the rehabilitation and four lanes of traffic open in the opposite direction. The traffic would be separated from the construction zone by a MCB between Passenger Lane 2 (P2) and Truck Lane 1 (T1), as shown in Figure 8.

The process for the AC overlay construction would be to place the first two lifts in lanes T1 and T2. Traffic would then be switched to the paved lanes (T1 and T2), and the rehabilitation work would move to the remaining two lanes (P1 and P2). The traffic switch from T1 and T2 to P1 and P2 is needed either one or two times, depending on the CSOL paving completion option (discussed subsequently in Sections 2.3.3.2.1 and 2.3.3.2.2).

The primary negative aspect of this option is the delay caused by switching traffic. As the maximum temperature for allowing traffic on the newly paved lane is typically 50°C, which is lower than the maximum temperature for placement of the next lift [typically assumed to be 74°C (165°F) in the analysis], additional cooling time is needed before traffic can be allowed on the hot lanes.

There are two sub-categories for the CSOL Half Closure option for weekend closure construction:

- CSOL Half Closure Full Completion
- CSOL Half Closure Partial Completion

The CSOL Half Closure Partial Completion option paves two of four AC lifts over the entire four lanes of traffic in one direction of the freeway while the CSOL Half Closure Full Completion option finishes all four lifts of AC on all four lanes during the weekend closure.

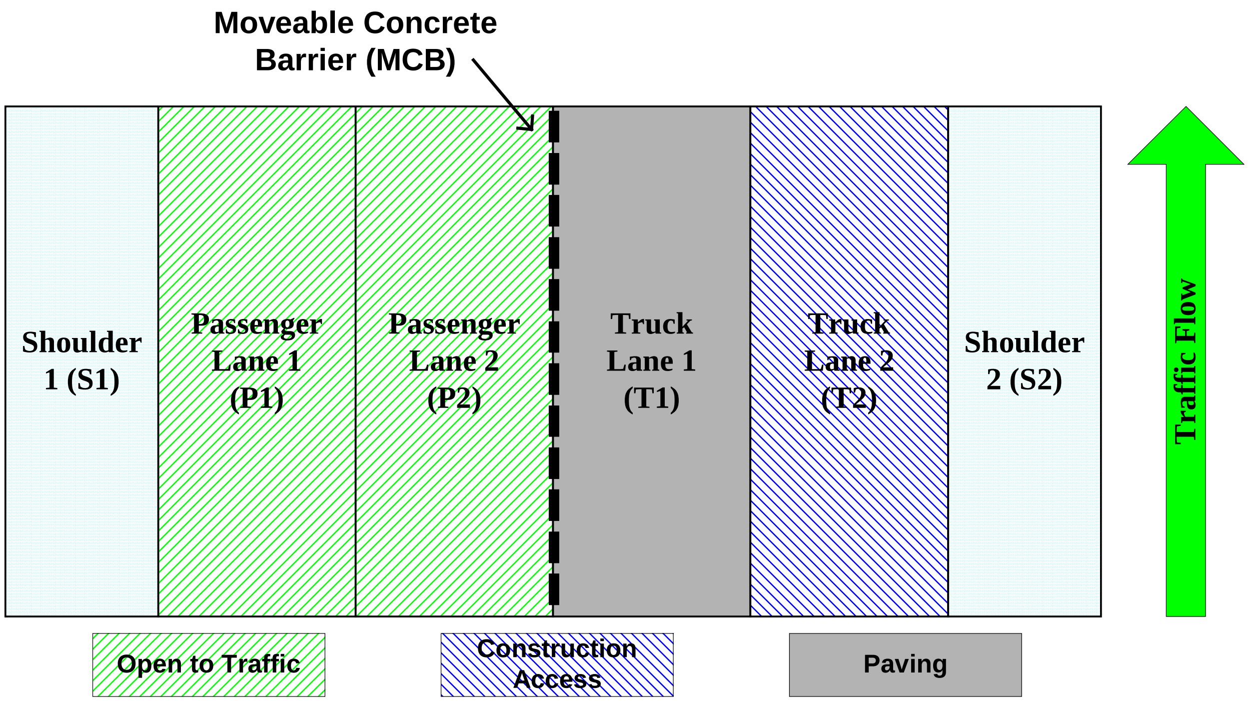


Figure 8a. Plan view of first and final stages.

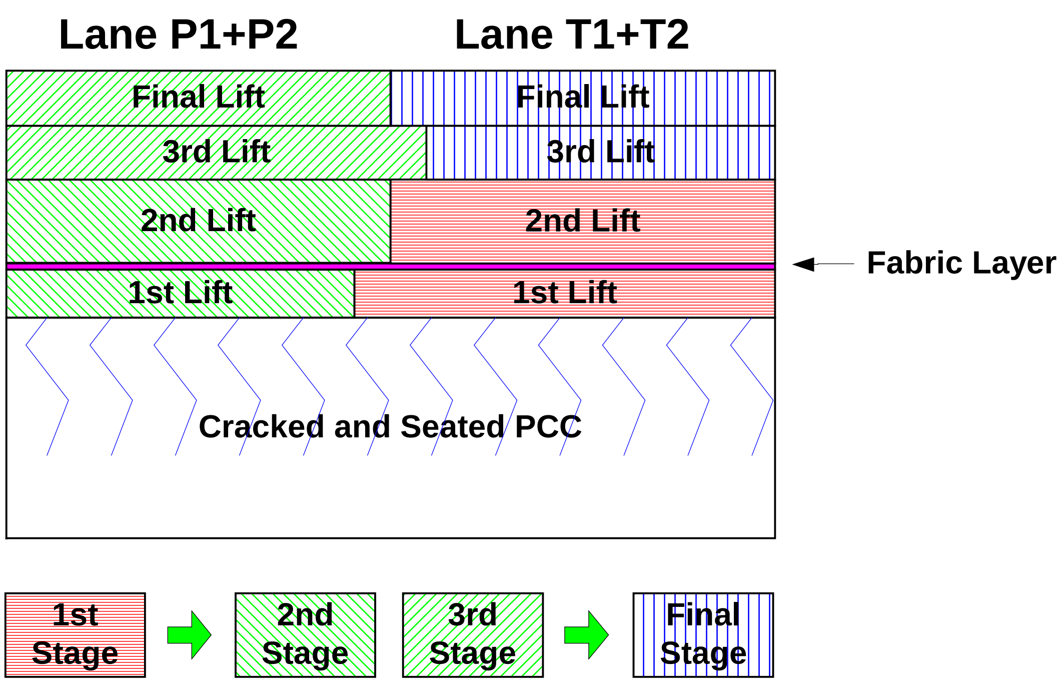


Figure 8b. Paving sequence (traffic must be switched twice during paving).

Figure 8. CSOL lane closure for CSOL Half Closure Full Completion option.

Therefore, the CSOL Half Closure Full Completion option would not finish as many centerline-km of paving as the CSOL Half Closure Partial Completion option during a given 55-hour weekend closure.

2.3.3.2.1 CSOL Half Closure Full Completion Option

The main feature of the CSOL Half Closure Full Completion option is that it completes the four-lift overlay for all four lanes of the segment being rehabilitated during one weekend closure. Figure 8 shows a schematic of the CSOL Half Closure Full Completion work plan.

Some of the advantages of this option are that two out of four lanes in one direction will always be open to traffic during the rehabilitation process and that the entire AC overlay thickness will be completed on all four lanes by the end of the weekend closure. A ramp down from the height (200 mm or 230 mm) of the overlay must be completed at the end of the weekend closure.

The first stage of this method is to overlay the first two lifts of the two truck lanes (T1 and T2). While the first lift of the Truck Lane 2 (T2) is being overlaid, the adjacent lane (T1) provides construction access. The first lift on lane T1 is then placed after completion of the first lift on lane T2. The second lift on lane T2 is then placed followed by the second lift on lane T1.

When the second lift on T1 has cooled to the required temperature (i.e., 50°C maximum to allow traffic), the two traffic lanes (P1 and P2) will be closed and the two partially overlaid lanes (T1 and T2) will be opened to traffic. In the second stage, the first two lifts on the two inner lanes (P1 and P2) will be placed with same procedure as the first stage. The third and fourth lift on the two inner lanes (P1 and P2) will be placed immediately after the second stage is done, without any traffic switch. Traffic must be then switched again to move to the traffic back to lanes P1 and P2. Finally, the fourth stage of construction completes lifts three and four on lanes T1 and T2.

Some potential problems with the CSOL Half Closure Full Completion option is that there is the possibility for wasting time during the paving operation from waiting for the AC to cool and switching the traffic flow lanes twice. In order to overcome these limitations, one alternative solution is the CSOL Half Closure Partial Completion.

2.3.3.2.2 CSOL Half Closure Partial Completion Option

The main difference between CSOL Half Closure Partial Completion and CSOL Half Closure Full Completion is that in the first weekend closure, only the first two AC lifts are placed on all four lanes. This requires only one traffic switch from lanes T1 and T2 to P1 and P2 during the weekend closure. The remaining two lifts of AC are completed during the second weekend closure with a similar single traffic switch, as shown in Figure 9.

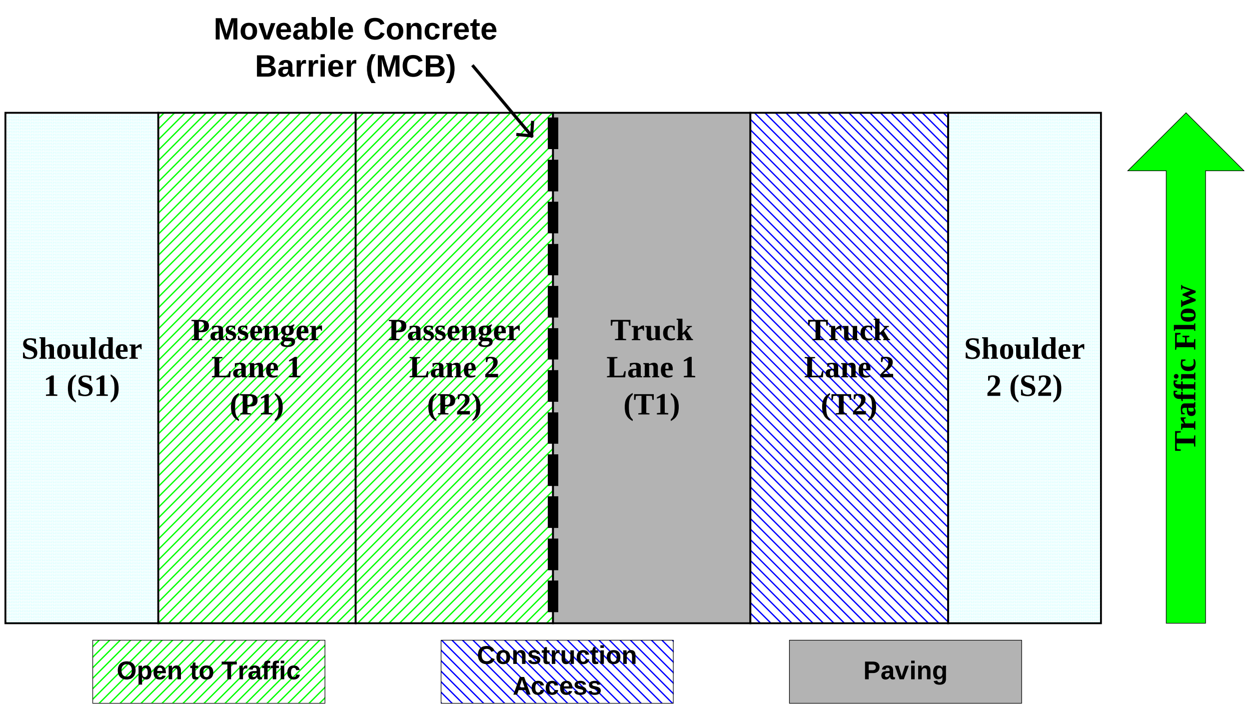
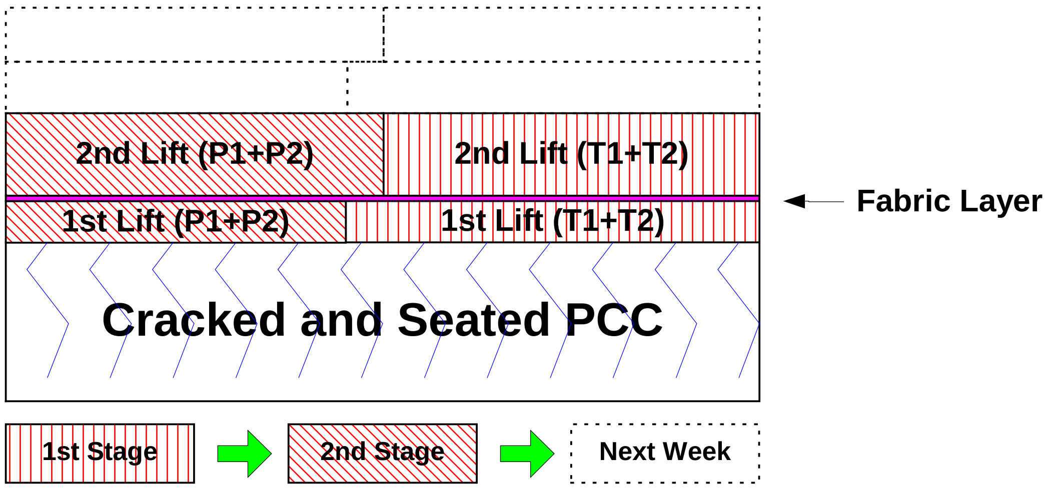


Figure 9a. Plan view of first and fourth stages.

1) First two lifts are paved during the first weekend closure:



2) Last two lifts are paved during the second weekend closure:

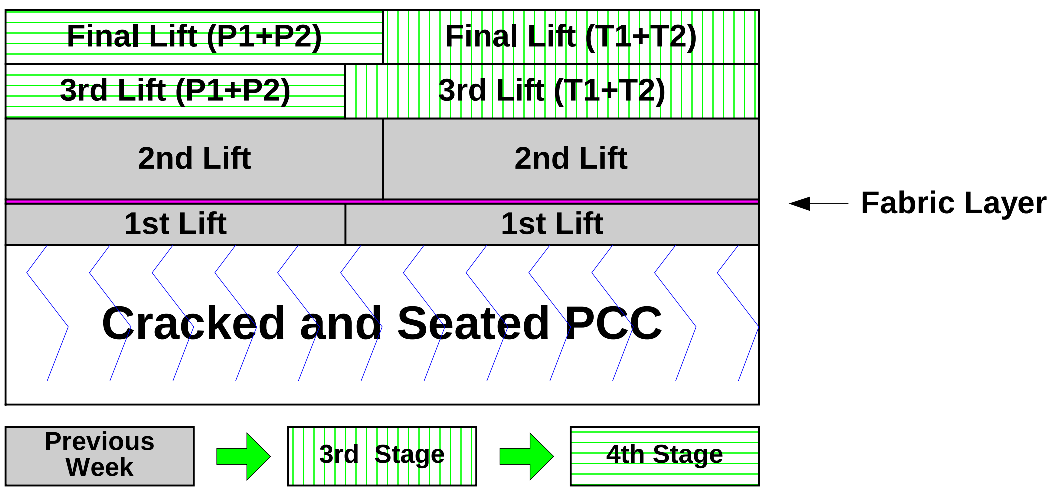


Figure 9b. Paving sequence (traffic must be switched once during each of the two weekend closures.

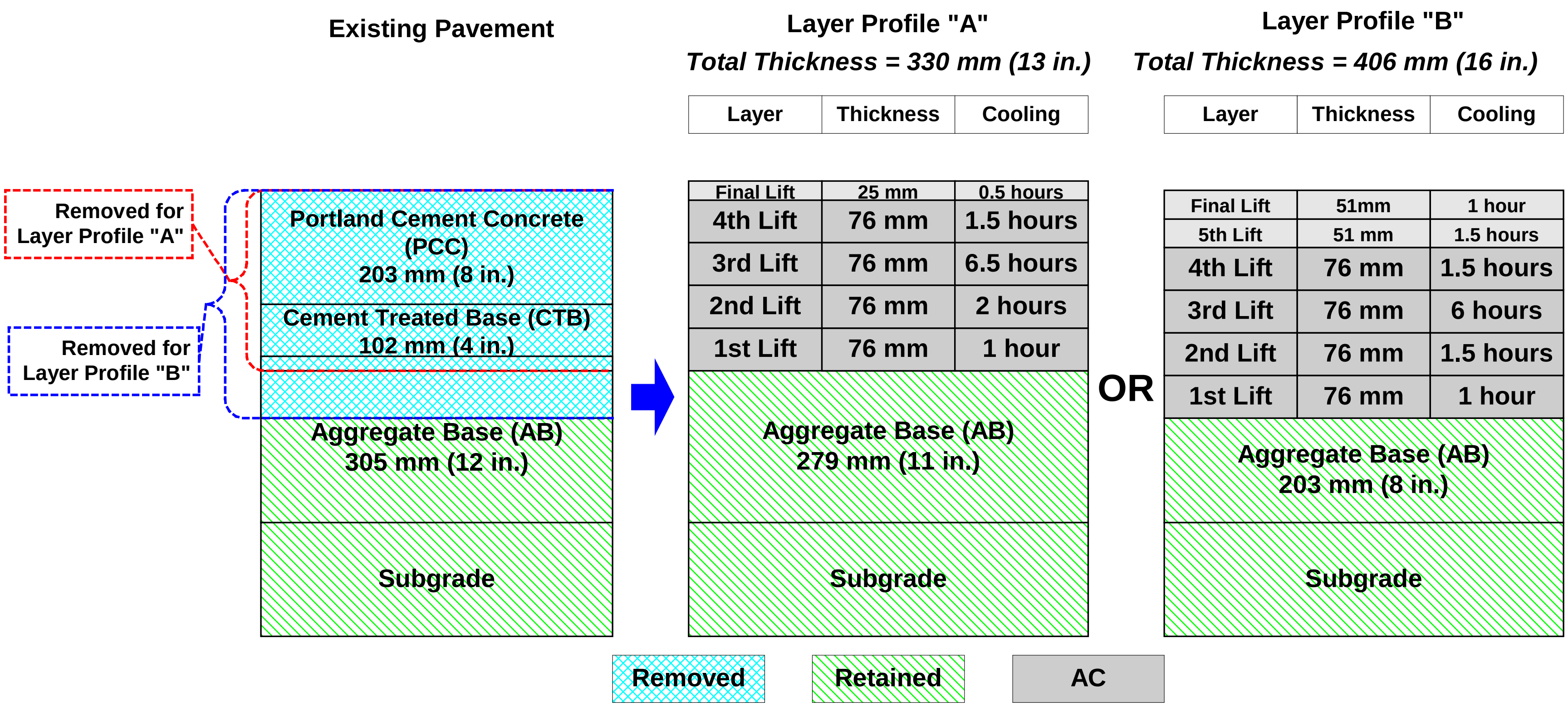
Figure 9. CSOL lane closure for CSOL Half Closure Partial Completion option.

The first stage of this method is to place the first two AC lifts on lanes T1 and T2 and then to switch traffic from the two inner lanes (P1 and P2) to the newly overlaid lanes (T1 and T2). The second stage paves the first two lifts on lanes P1 and P2. After the first two lifts have been completed, the two-lane freeway closure is opened to traffic until the following weekend. During the second weekend closure, the remaining two lifts are placed on the inner lanes (T1 and T2). In the final stage, the traffic is switched over to lanes T1 and T2 and the inner lanes (P1 and P2) are paved with their final two lifts.

Compared with the CSOL Half Closure Full Completion option, the potential benefit of the CSOL Half Closure Partial Completion option is to minimize the waiting time for asphalt concrete cooling and switching traffic compared. However, the concern with this method is the structural performance of the first two AC lifts under traffic loading for one week.

2.4 Rehabilitation Options for Full-Depth AC Replacement

In the Full-Depth AC Replacement option, the existing PCC truck lanes (T1 and T2) are replaced with new asphalt concrete. The old PCC slab and CTB will be demolished and hauled away, and part of the aggregate base (AB) will be trimmed to accommodate the required depth of the new asphalt concrete pavement, as shown in Figure 10. The first lift of asphalt concrete will be a 76-mm (3-in.) rich bottom AC layer placed on the top of the re-compacted AB. Four or five additional lifts of AC will be paved sequentially depending on the pavement profile selected. The profile of the existing PCC and new asphalt pavement (Full-Depth AC Replacement) with typical AC cooling times during summer weather in California are shown in Figure 10.



(Note: Assumed paving start time is 1:00 AM. Longer cooling time may be required for some lifts due to midday paving).

Figure 10. Layer profile of Full-Depth AC Replacement option.

The disadvantage of the Full-Depth AC Replacement option is that the production capability of this option within one weekend closure will be the least among other AC Rehabilitation options. The Full-Depth AC Replacement option is the most work intensive process, although it may provide the DOT with a better performing rehabilitation scenario compared to the CSOL options.

The following two sub-options are analyzed for the Full-Depth AC Replacement option with respect to pavement profile selection as shown in Figure 10:

- Full-Depth Layer Profile “A”
- Full-Depth Layer Profile “B”

Both layer profiles were selected as spanning a typical range by the UCB Pavement Research Center (PRC) for the purpose of checking the impact of different layer profiles on the production capability of the Full-Depth AC Replacement. This does not mean that either profile is more structurally desirable; they are considered only a sensitivity comparison. Actual structural sections must be designed for each project location.

2.4.1 Layer Profiles for Full-Depth AC Replacement

In the case of the Full-Depth Layer Profile “A” option, 330 mm (13 in.) of new asphalt concrete will replace the existing PCC slab, CTB, and 25 mm of AB. The profile has five lifts, a 76-mm (3-in.) rich bottom AC lift, three 76-mm lifts, and a 25-mm AC surface course (typically, open graded asphalt rubber), as shown in Figure 10.

The Full-Depth Layer Profile “B” option is a total of 406 mm (16 in.) of AC, consisting of six lifts. The six lifts are a 76-mm (3-in.) rich bottom AC lift, three 76-mm AC lifts, a 51-mm

AC lift, and a 51-mm top lift. The old PCC and CTB will be removed along with the top third (102 mm) of the aggregate base.

Similar to the CSOL case, the cooling hours in the right hand column of each layer profile option shown in Figure 10 were calculated from a cooling simulation program, CalCool.(*12*) The assumed environmental condition of the pavement before running the cooling time analysis was the same as for CSOL—typical summer weather for a hot climate region in California: ambient temperature of 37°C (100°F); surface temperature of 43°C (110°F); wind speed of 5 kph; paving start time July 1, 1:00 a.m.; stop temperature 74°C (165°F).

For both layer profiles the following two additional sub-options were analyzed to take into account the number of lanes rehabilitated during a single weekend closure:

- Full-Depth Single-Lane Rehabilitation
- Full-Depth Double-Lane Rehabilitation

2.4.2 Number of Lanes Rehabilitated During the Weekend Closure

Through communications with asphalt concrete paving contractors (SCAPA), two alternative lane closure tactics were defined to carry out the Full-Depth AC Replacement option:

- Full-Depth Single-Lane Rehabilitation, as shown Figures 11a and b, and
- Full-Depth Double-Lane Rehabilitation, as shown in Figure 11c.

In the Full-Depth Double-Lane Rehabilitation scheme, the two truck lanes (T1 and T2) are demolished and rebuilt during one weekend closure, while in the Full-Depth Single-Lane Rehabilitation, only one truck lane is rehabilitated during the first weekend closure and the other truck lane is completed during the second weekend closure. The single- and double-lane rehabilitation concept for AC Rehabilitation is similar to the lane closure tactics for Concrete

Rehabilitation described in Reference (*4*). Note that the double-lane rehabilitation option for Full-Depth AC Replacement does not specify paving both lanes simultaneously.

Of the two working methods used for concrete rehabilitation, only the sequential method is applicable for the Full-Depth AC Replacement option. In the sequential method, the paving operation starts only when demolition of the existing PCC pavement is finished.

The concurrent working method, in which paving and demolition activities are progressing simultaneously, is not practical for the Full-Depth AC Replacement option because placement of one AC lift (especially the first lift) only requires several hours, as shown in Figure 11. Consequently, the demolition team working in front of the pavement team would easily be caught by the paving operation if a concurrent working method were employed.

2.4.2.1 Work Plan for Full-Depth Single-Lane Rehabilitation

During the first weekend closure, two truck lanes (T1 and T2) will be closed to rebuild Truck Lane 2 (T2). Truck Lane 1 (T1) is used as the construction access for demolition and paving activities, as shown in Figure 11a. On the following weekend, T1 will be rebuilt with T2 serving as the construction access lane.

The use of one demolition team was assumed because only one construction access lane is available. In theory, multiple demolition teams can work simultaneously ahead of the first demolition team if they are properly spaced.

In the case of multiple demolition teams with one access lane, the demolition trucks from different crews will probably interact negatively if there are not multiple entrances and exits to the construction site—this is supported by observations made during the I-10 project for Concrete Rehabilitation.(*6*) In a scenario without multiple entrances and exits, the average cycle

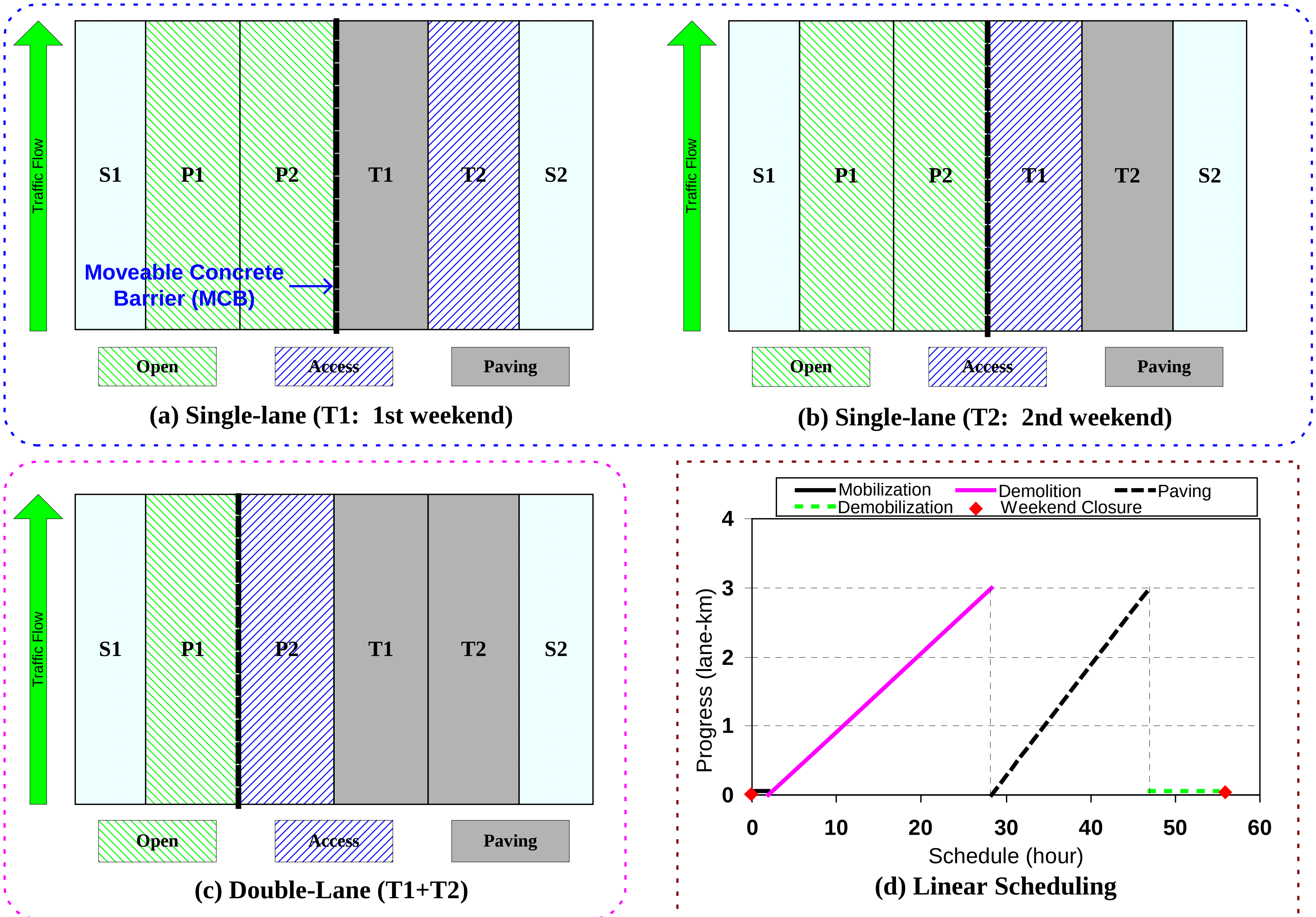


Figure 11. Work plan and lane closures for Full-Depth AC Replacement option.

time of the demolition trucks increases significantly, and the benefits of multiple demolition teams diminish significantly.

As soon as the PCC slab and CTB are removed and the AB is trimmed, five or six lifts of asphalt concrete are placed sequentially lift by lift with a single paving team. During the following weekend closure, Truck Lane 1 (T1) will be rebuilt using the same procedure—two truck lanes (T1 and T2) will be closed and Truck Lane 2 (T2) will be used as the construction access, as shown in Figure 11b.

A negative structural aspect of Full-Depth Single-Lane Rehabilitation is that the interlocking of AC lifts by overlapping of longitudinal joints between adjacent rehabilitated lanes (T1 and T2), as shown in Figure 5, is not possible. In addition, safe movement of the asphalt delivery trucks from the delivery lane to the paving lane has to be resolved because the initial elevation difference between the demolished lane and the access lane is between 330 and 406 mm. This discharging constraint is more serious with the semi bottom dump truck, which has no side dumping feature.

2.4.2.2 Work Plan for Full-Depth Double-Lane Rehabilitation

For the Double-Lane Rehabilitation option, both truck lanes (T1 and T2) will be rebuilt during one weekend closure, which requires closing three lanes (P2, T1, and T2). Passenger Lane 2 (P2) is assigned as the construction access for demolition and paving, as shown in Figure 11c. Only one demolition team and one paving team are assumed to be used in a sequential construction operation due to the availability of only one access lane. Truck Lane 2 (T2) will be used as access for paving Truck Lane1 (T1), and Passenger Lane 2 (P2) will be used as access for paving Truck Lane 1 because Truck Lane 2 will not be cool enough for delivery trucks.

Double-Lane Rehabilitation enables interlocking AC lifts along the joints between adjacent lanes. However, the Double-Lane Rehabilitation scheme also causes more traffic interruption because three lanes in one direction must be closed to traffic for the 55-hour weekend closure.

2.5 Construction Resource Constraints

In order to achieve a realistic production capability for urban freeway rehabilitation, the proper resource constraints must be recognized and established from a practical point of view. This is a slightly different approach from that used for the concrete constructability analysis. In the case of the concrete constructability analysis, maximum resource availability was initially assumed to be the maximum theoretical production capability. This was done to check whether the Caltrans production objective of 6 lane-km within one weekend closure is achievable. More realistic resource constraints were then used in the sensitivity analysis to identify the impact of resource limitations on the construction productivity.

As observed in the Caltrans LLCPRS demonstration project (I-10) case study, the maximum resource constraint assumed for the concrete constructability analysis appears too optimistic.(*6*) Accordingly, a more practical and realistic resource constraint is assumed for the asphalt constructability analysis. The following equipment resources are the major constraints limiting the production capability of AC Rehabilitation:

- Production capacity of the asphalt concrete mixing plant
- Number and capacity of hauling trucks (dump truck: DT) for demolition (for Full-Depth AC Replacement only)

- Capacity and number of asphalt concrete delivery trucks (semi bottom dump truck: SBT)
- Speed of asphalt concrete paving machine
- Speed of asphalt concrete compaction rollers in achieving required compaction

Table 2 summarizes the number and capacity of resources used in the deterministic constructability analysis. The values shown in Table 2 were used to calculate the range of the production capability of AC Rehabilitation within a 55-hour weekend closure. Based on the experience of several AC contractors, the asphalt delivery and demolition hauling trucks were found to be the primary constraints while the mixing plant and paver were the secondary constraints. The AC compaction rollers were not a major constraint for AC Rehabilitation.

Table 2 Number and Capacity of Resources Used in the Deterministic Analysis

Resource	**Quantity**	**Production Capacity**	**Units**	**Remarks**
AC Mixing Plant	1	Min.: 100 Max.: 200 Avg.: 150	m^3/hour	
Dump Truck (Demolition for Full-Depth AC Replacement option)	Min.: 8 Max.: 12 Avg.: 10	25 tons each	trucks/hour	Efficiency = 0.6 No. of Teams = 1 to 2
Semi Bottom Dump Truck (Asphalt Placement)	Min.: 9 Max.: 20 Avg.: 12	25 tons each	trucks/hour	Efficiency = 0.95 No. of Teams = 1
Paver	1	25 mm: 7.5 50 mm: 6.0 75 mm: 4.5	km/hour	Production Capacity is inversely proportional to AC lift thickness

Similar to the Concrete Rehabilitation scenario, a major concern for increasing the production capability of the project is the total number of trucks that can be mobilized. For example, if 10 demolition trucks were required every hour, approximately 45 demolition trucks would need to be mobilized for every weekend rehabilitation project (i.e., 45 trucks = 10 trucks per hour per demolition team × 1.5 demolition teams × 2 shifts × 1.5 hours per truck turnaround). Similarly, the total number of asphalt delivery trucks and the supply of aggregate to the mixing plant would also need to be sufficient to avoid delays on the production side.

The locations of the plant and the demolition dumping area with respect to the construction site are essential parameters influencing the production capability of the rehabilitation because they directly affect the turnaround time of the demolition and delivery trucks. Sufficient space is also needed at the asphalt concrete plant for the aggregate stockpiles.

Although the plant and paver are not the critical resource constraints governing production capability, contractors believe these two resources are the most crucial pieces of equipment for the success of the project. If one of these large and expensive pieces of equipment breaks down during the pavement rehabilitation, the paving operation is suspended until it is fixed or replaced, thereby causing overall productivity to drop significantly. Therefore, redundancy in the mixing plant and paving machine is essential to prevent complete loss of productivity, especially when the contract has severe incentive/disincentive clauses.

2.6 AC Rehabilitation Constructability Analysis Process

The process used for the AC Rehabilitation constructability analysis is summarized as follows:

1. Set the rehabilitation project length as a production objective: for this study, 6 lane-km.
2. Set up construction window: for this study, 55-hour weekend closure or continuous closure.
3. Select paving material: asphalt concrete.
4. Choose design profile: CSOL or Full-Depth AC Replacement.

5. Decide layer profile: Layer Profile “A” or “B” (see Figure 7).
6. Consider lane closure tactics: Full or Half Closure (applicable to CSOL option only).
7. Select paving lane strategies: Single- or Double-Lane Rehabilitation (for Full-Depth AC Replacement option only).
8. Compare Completion Option: Full or Partial Completion (for CSOL option only).
9. Introduce cooling time analysis to check waiting time between paving of sequential AC lifts.
10. Carry out a simple CPM (Critical Path Method) scheduling to calculate net working hours. From the CPM scheduling, total non-working hours are calculated first for the following operations: 1) equipment mobilization/demobilization, 2) delay for AC cooling, 3) traffic switch time, and 4) time for paver to travel back to the start point after completing a lift. The net working hours for demolition (Full-Depth AC Replacement case only) and AC paving are extracted by subtracting the total non-working hours from the construction window length.
11. Calculate quantity of materials: demolition (Full-Depth AC Replacement) and asphalt concrete.
12. Determine the required number of resources and capacity.
13. Apply resource constraints. The number of trucks per hour is limited by the minimum time for loading of old PCC slabs and the unloading of the new asphalt concrete. For example, the number of demolition trucks showing up per hour for each demolition team cannot exceed 12 in urban areas, based on the information gathered from the concrete case study on the recent I-10 reconstruction project near Pomona.(*6, 7*) The number of semi bottom dump trucks per hour for asphalt concrete

delivery is limited to 15, based on field data from several asphalt concrete overlay projects.

14. Introduce linear scheduling concept. Linear scheduling methods are applied to the constructability analysis to identify the maximum production capability of the AC Rehabilitation given the resource constraints and progress of the resources involved. Linear scheduling especially helps in the allocation of time between the paving and demolition (Full-Depth AC Replacement case only) activities. After the total paving time is calculated from the CPM scheduling (refer to Step 10 above), the paving hours for each lift are determined based on the proportion of the thickness of each lift to the total profile thickness. AC cooling time analysis is then applied to check if the AC lifts will have cooled to the stop temperature before the paver is ready to place the next lift. If the AC lift is expected not to have sufficiently cooled, the total number of working hours is decreased and the linear scheduling process is re-run.
15. Finalize maximum production capability. The prototype software picks out the most constraining resource at the calculated maximum production capability of the rehabilitation for different design profiles, lift construction strategies, and lane closure tactics.
16. Implement a stochastic analysis. Based on the same process used for the deterministic constructability analysis, a stochastic constructability analysis is run by varying the resources and scheduling parameters with an assumed Probability Distribution Function (PDF). This stochastic analysis gives a range of possible production capabilities (i.e., lower and upper bound with average) along with a confidence level (typically one standard deviation).

3.0 COOLING TIME SIMULATION

The time to cool the asphalt concrete layer to the specified maximum temperature at which the paving machine or traffic can be placed on it (cooling time) is considered a critical component for the compaction of hot mix asphalt. The cooling time permits determination of the optimal compaction time. The optimal time is between the high temperature "overstressed condition" of the mixture at which the asphalt is too soft to support compaction rollers, and the low temperature "understressed condition" at which the roller can not create sufficient shear forces to further increase density (compact the mix). Figure 12 shows a typical cooling time curve for a single hot mix asphalt lift and how the optimal compaction time is determined from the cooling temperatures.(*12*)

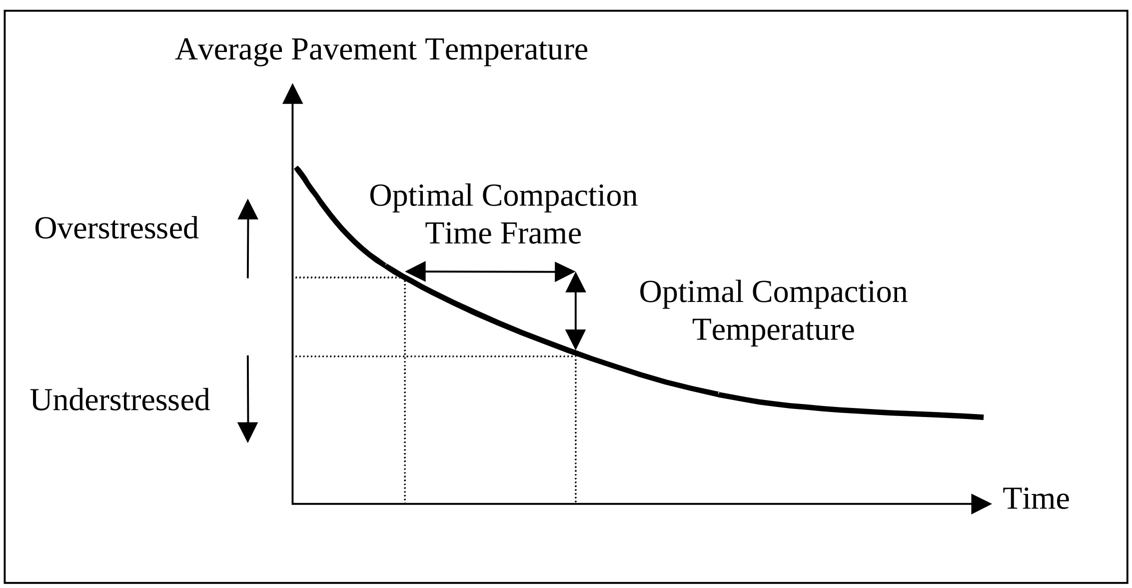


Figure 12. Typical AC pavement cooling curve for single lift paving.(*12*)

In the case of fast-track AC Rehabilitation with multi-lift AC paving, cooling time is important for a different reason, especially in moderately warm climates such as is typical in many parts of California. In multi-lift (4 to 6 lifts) construction, AC paving is scheduled for a number of lanes (typically 2 to 4 lanes) within limited weekend closure. To optimize paving time, the next lift is placed immediately after the compaction of the first lift and therefore the first lift must cool to the maximum allowable AC temperature before the next lift is placed.

A computer simulation program was used to predict the temperature profiles in multi-lift AC Rehabilitation. The maximum production capability of the project within a weekend closure is determined by subtracting waiting time for AC cooling from the total number of available working hours in the CPM schedule. By optimizing the lift thickness and length of paving, the number of hours of waiting for AC lifts to cool can be minimized.

A software program called *PaveCool* was developed and implemented in Minnesota to estimate the allowable compaction time for single lift paving in cold weather.(*13*, *14*) The limitation of *PaveCool* was that it did not cover multi-lift asphalt concrete and was not designed for warm weather paving conditions. In 1999, a research team at the University of Minnesota was contracted by the Pavement Research Center of UCB to develop a new analysis software (CalCool) to predict the cooling time of multi-lift asphalt concrete pavements.(*12*) The numerical simulation software was developed utilizing Fourier's Second Law to deal with heat transfer in a pavement structure and the finite difference methods to solve a series of heat flux equations. More details about the basic theory of CalCool are described by Timm.(*12*) The cooling time output from CalCool is an estimated solution with some calibration to field test sections. In reality, the asphalt concrete cooling is very sensitive to the following variables: cloud cover, wind speed, ambient temperature, material composition, time of placement, and layer thickness.

3.1 Program Inputs and Outputs

As shown in Figure 13, the CalCool main input window consists of four categories as following:

- Paving starting time
- Environmental conditions
- Existing surface conditions
- Mix specifications

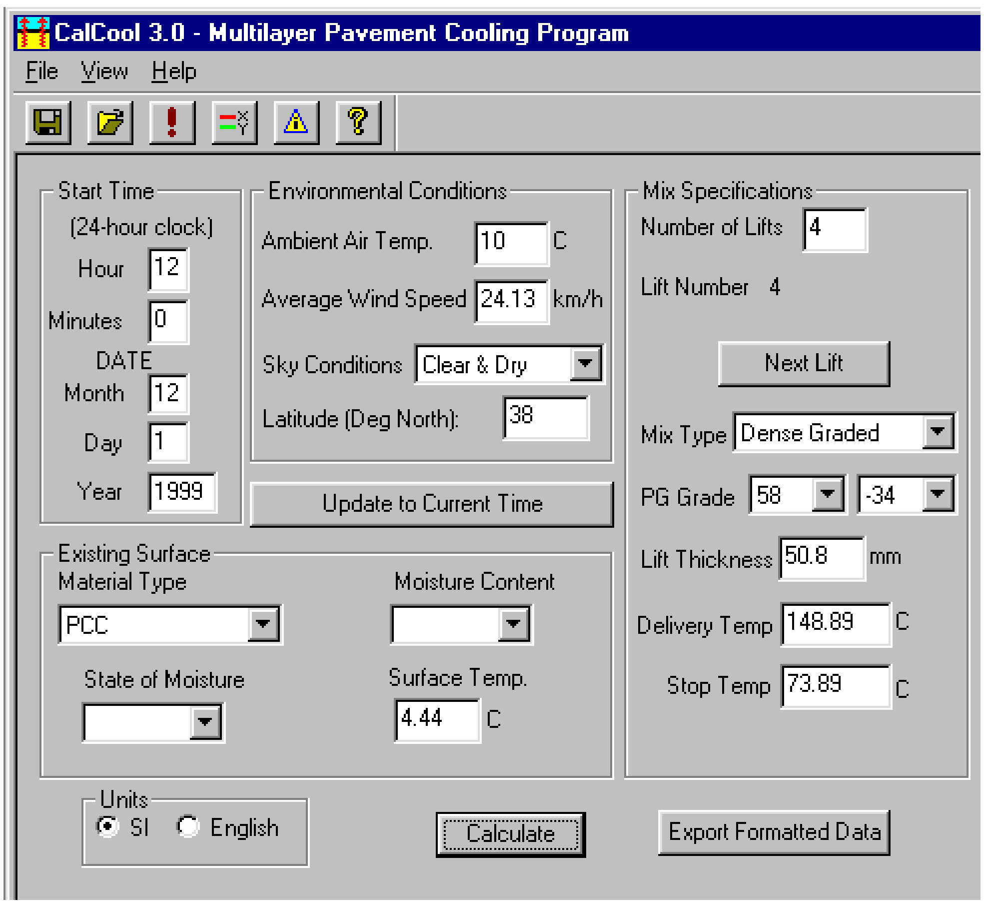


Figure 13. CalCool main input window.

The cooling time from CalCool is the average lift temperature for the individual lifts. The results of cooling time simulation are plotted graphically as cooling time curves or alternatively can be tabulated to show the predicted cooling time of individual lift to a specified temperature, as shown in Figure 14. The input and output data can be exported to a text file or a spreadsheet.

3.2 Experimental Validation of CalCool

CalCool needed to be validated with actual field data before used as a part of the asphalt constructability analysis model. A validation study of CalCool using experimental data collected by Pavement Research Center Staff from several AC paving projects in California was performed.(*15*) Both single and multi-lift comparisons were made between CalCool and the field data. Comparisons were also made with AC cooling data available in the literature from other field projects.

Table 3 compares the cooling time from CalCool with experimental data where the delivered temperature of the hot mix asphalt was 149°C (300°F) and the stop temperature was 79°C (175°F) for two different ambient temperatures.(*16, 17*) The predicted cooling time by CalCool was similar to the test results for both thin and thick asphalt pavement layers except for one data point. Cooling curves from two experiments were in good agreement with the predicted cooling curves from CalCool for a single AC lift, as shown in Figure 15.(*17*)

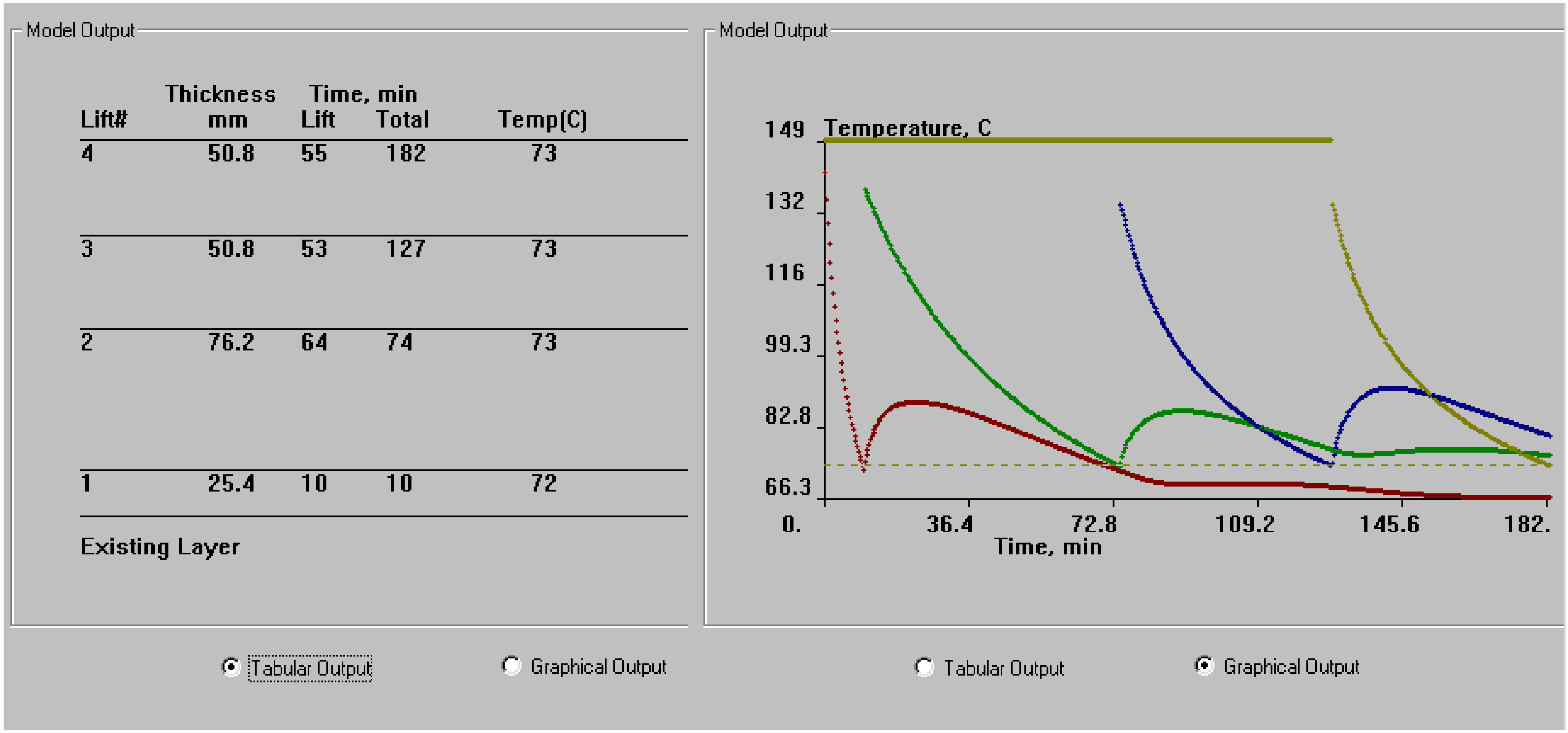


Figure 14. CalCool tabular and graphical output window.

Table 3 Comparison of Predicted Cooling Time using CalCool and Observed Cooling Time

Single Lift Layer Thickness	Ambient Temperature	Cooling Time* (min.)	
		Asphalt Institute Observation	CalCool Prediction
25 mm (1 in.)	32°C (90°F)	9	10
51 mm (2.4 in.)	32°C (90°F)	23	28
76 mm (3 in.)	32°C (90°F)	45	52
61 mm (2.4 in.)	21°C (70°F)	78	40
89 mm (3.5 in.)	21°C (70°F)	77	78
119 mm (4.7 in.)	21°C (70°F)	110	119
178 mm (7 in.)	21°C (70°F)	220	237

*Cooling time from 149°C (300°F) to 79°C (175°F)

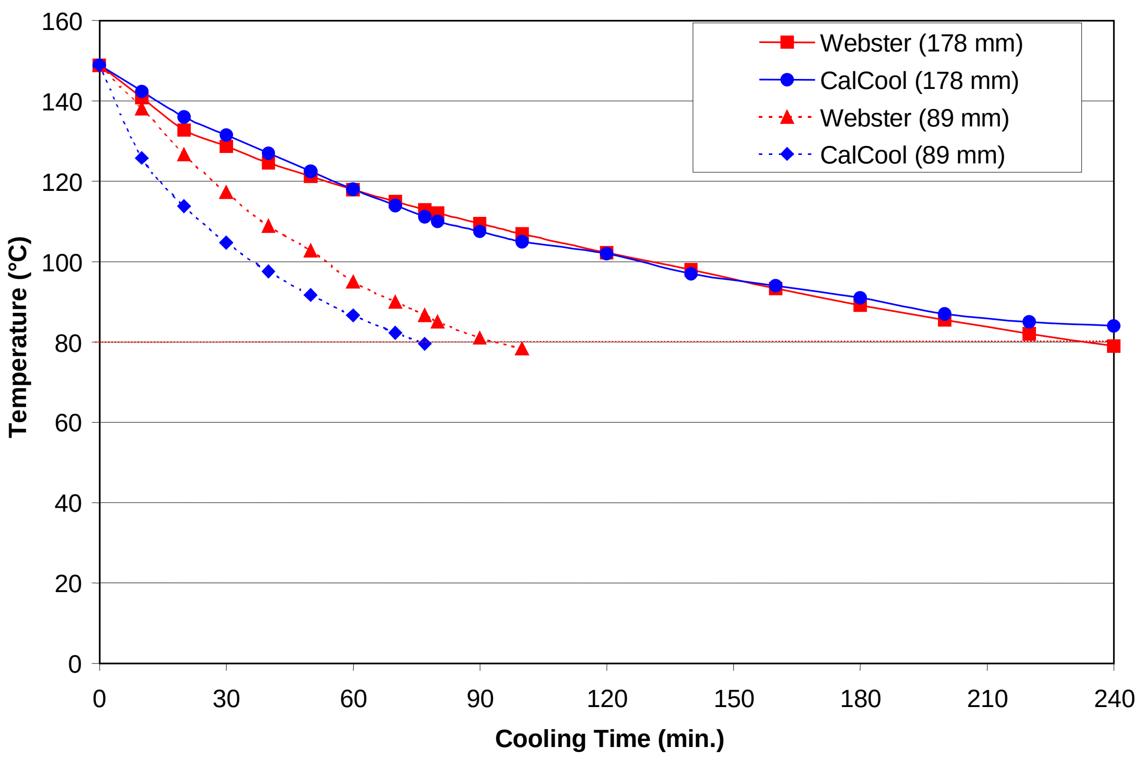


Figure 15. Comparison of Webster experimentally observed and CalCool predicted cooling times.

3.3 Validation of CalCool with Field Data

CalCool was compared with field data from two construction projects.(*15*) The first site involved daytime construction on a 2.4-km length of Route 1 in Lompoc, CA (near Santa Barbara, CA). The second site involved a nighttime construction on a main road in San Leandro, CA.

3.3.1 Temperature Data Collection for CalCool Validation and Calibration in Lompoc, CA

The Lompoc construction site involved removal of the existing asphalt concrete and placement of approximately 270 mm of new asphalt concrete in three lifts over the existing granular base. The first lift of material on the existing granular base was a rich bottom (5.8 percent asphalt content, AR-8000) asphalt mixture with 19-mm maximum size coarse aggregate. The asphalt content for the subsequent lifts was 5.3 percent. The hot mix asphalt concrete was placed in windrows by semi bottom dump trucks. For much of the time, the AC paver was waiting for the delivery of the hot mix asphalt and as a result, delivery temperatures measured in the windrow were on average 155°C.

An "anteater" was used to pick up the windrow and transfer it to the paver. The delivery temperature of the asphalt concrete was taken with a digital thermometer once the bottom dump truck placed the windrow. AC temperatures were monitored over time at the same locations. At each location, temperatures were recorded at three spots: near the edge, 1 m from the edge, and mid-depth in the lift. The air temperature and wind speed were also recorded at each location. The number and frequency of the measurements varied depending on the number of locations being monitored. Sampling of temperatures and wind speed continued until the AC temperature reached 50 or 60°C. At this construction site, the second lift was placed a day after the first lift, while the third lift was placed immediately after the second lift when its temperature reached 60°C.

3.3.2 Temperature Data Collection for CalCool Validation and Calibration in San Leandro, CA

The second site used to calibrate CalCool was on Marina Boulevard in San Leandro, CA. Unlike the Lompoc site, this project was constructed at night due to its use as a main corridor for heavy truck traffic off of Interstate 880. Construction involved removing 318 mm of existing asphalt concrete and replacing it with a 19-mm maximum size coarse aggregate mix with 5.2 percent asphalt (AR-8000). The first lift of asphalt concrete was placed over the existing granular base near the edge and over portland cement concrete on the adjacent lanes. The existing layers were wet due to heavy mist and rain. Three lifts of asphalt concrete were placed nearest the edge and four lifts on the adjacent lanes.

This construction can be considered a true multi-lift construction. The lifts were placed one after the other in the same night similar to the scenarios analyzed in this research and discussed in Section 2.0. End dump trucks were used to deliver the hot mix asphalt concrete. Unlike the Lompoc construction, delivery trucks were waiting in line to feed the AC paver. The project was much shorter than the Lompoc project (about 245 m on the first day) and the paver needed to maneuver around corners and backup to the start point after it reached the end.

Delivery temperatures of the asphalt mix were more variable and generally lower than the Lompoc construction. The average initial temperature of the hot mix asphalt was 144°C. Initial temperature measurements were also a bit lower for this project because they were taken behind the paver rather than from the truck or the windrow, as was done in Lompoc. Recording of asphalt cooling temperatures were performed in a similar manner to the Lompoc construction.

Measurements shown for the San Leandro project were the average of the three locations (edge, surface, mid-depth).

3.3.3 Comparison of CalCool and Field Measurements

One of the goals of recording cooling temperatures of field construction of asphalt concrete is to validate and calibrate CalCool. The two construction projects used for calibration were selected to include different values for most of the variables included in CalCool. The two projects included day and night construction, extremes in cloud cover (clear and dry to overcast), different existing surface materials (except subgrade), wet and dry conditions in the granular base, and single and multi-lift construction.

As shown in Figures 16 and 17, the field data correlated very closely with CalCool for single and double lift construction. With three lifts, CalCool overestimated how fast the lift would cool down and underestimated how much the lift heats back up when a new lift is placed on top of it, as shown in Figure 18. As shown in Figure 19, CalCool underestimated the time required to reach the stop temperature for AC placed over a PCC surface.

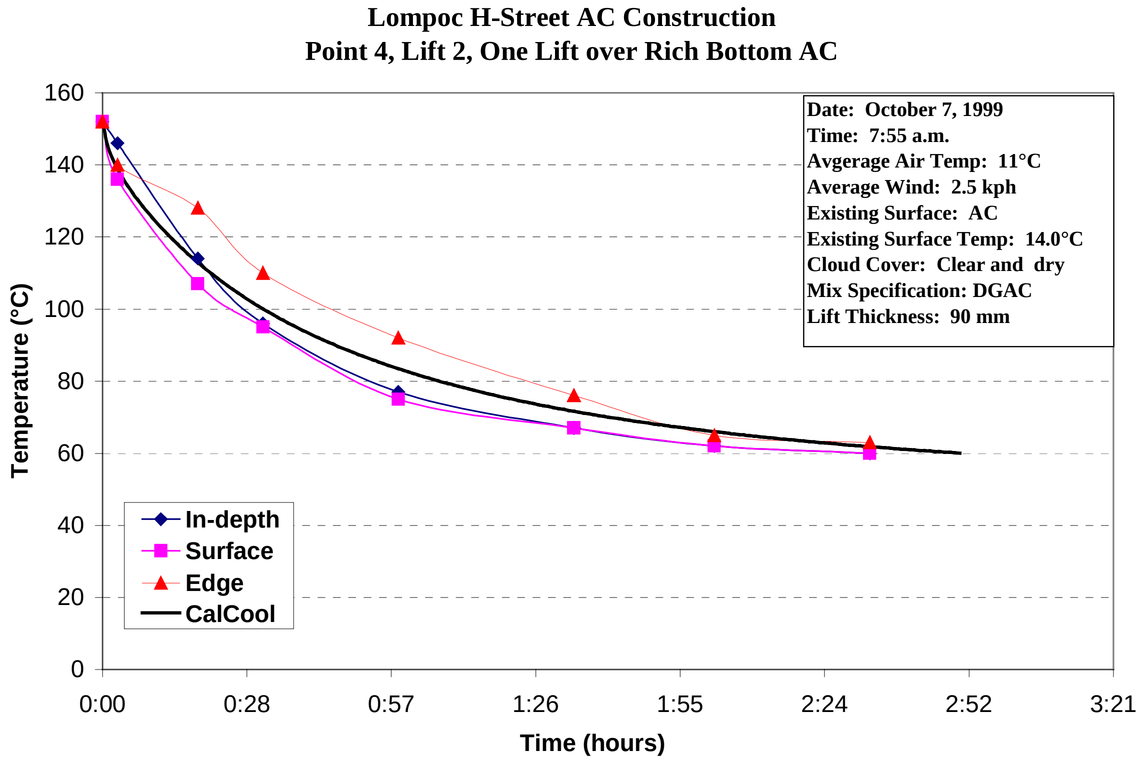


Figure 16. Cooling curve for a single lift of rich bottom AC placed on granular base (Lompoc project).

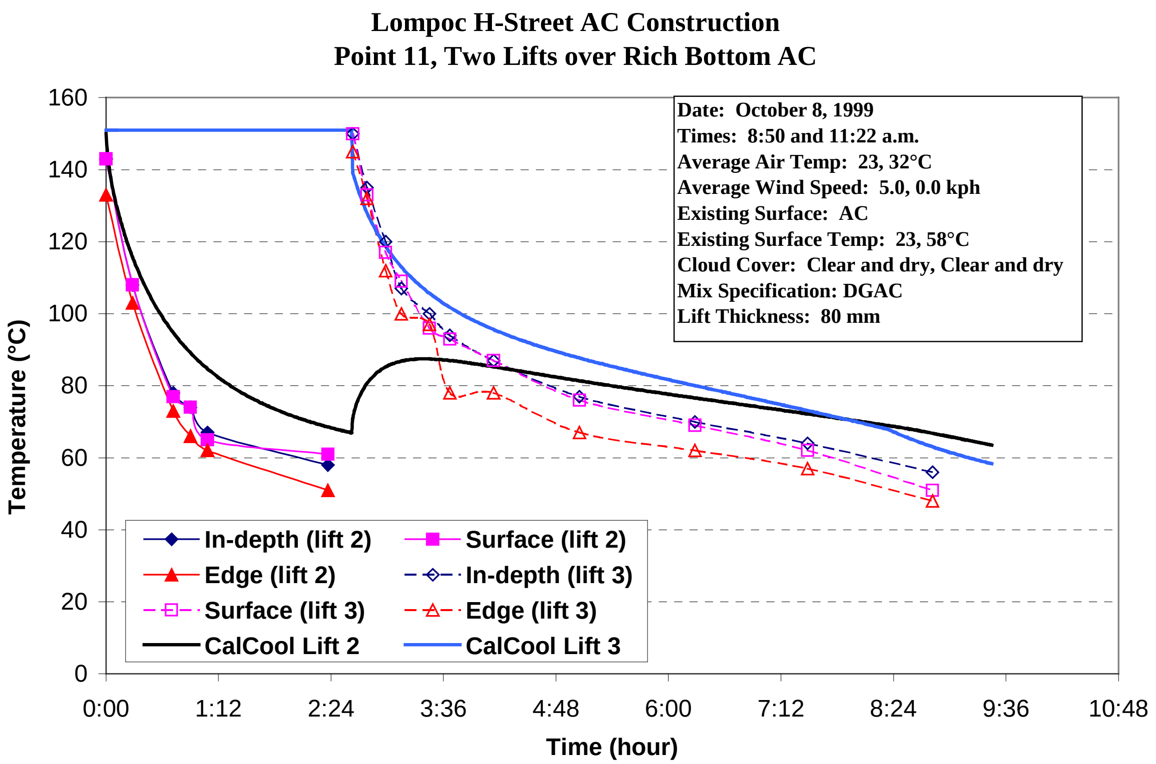


Figure 17. Cooling curve for a double lift of AC placed on rich bottom AC layer (Lompoc project).

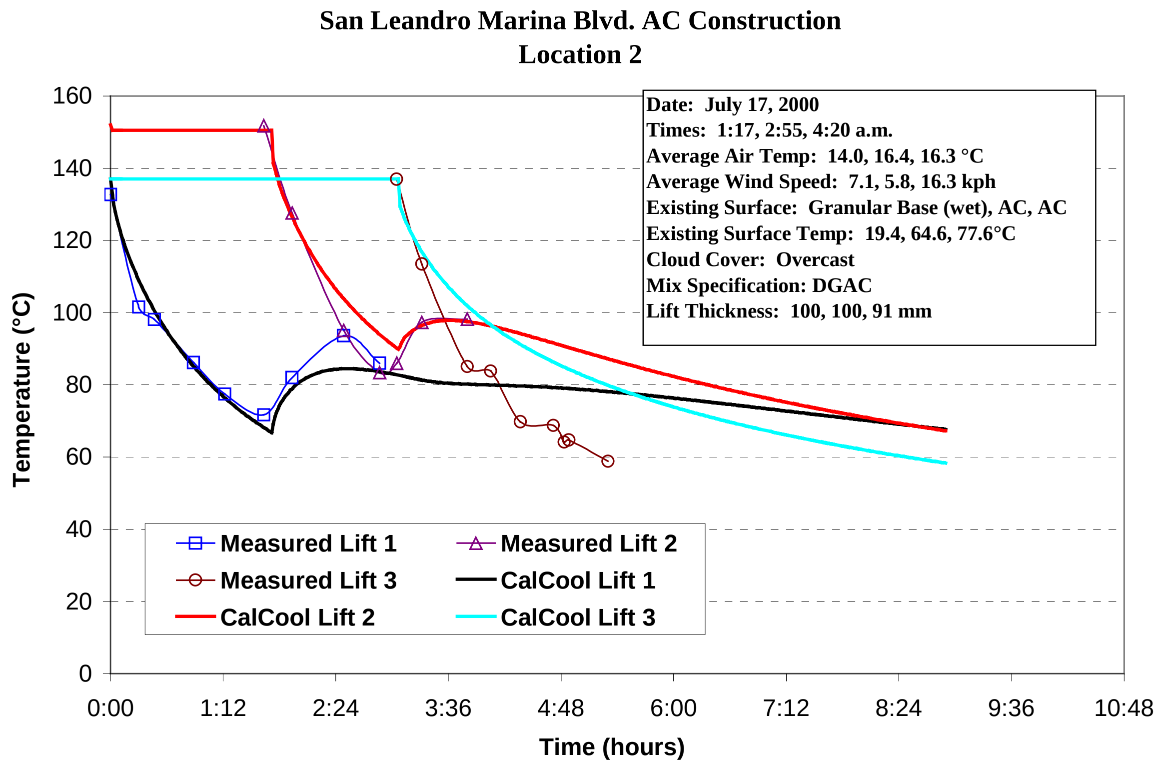


Figure 18. Cooling curves for a three lift AC layer placed on granular base (San Leandro project).

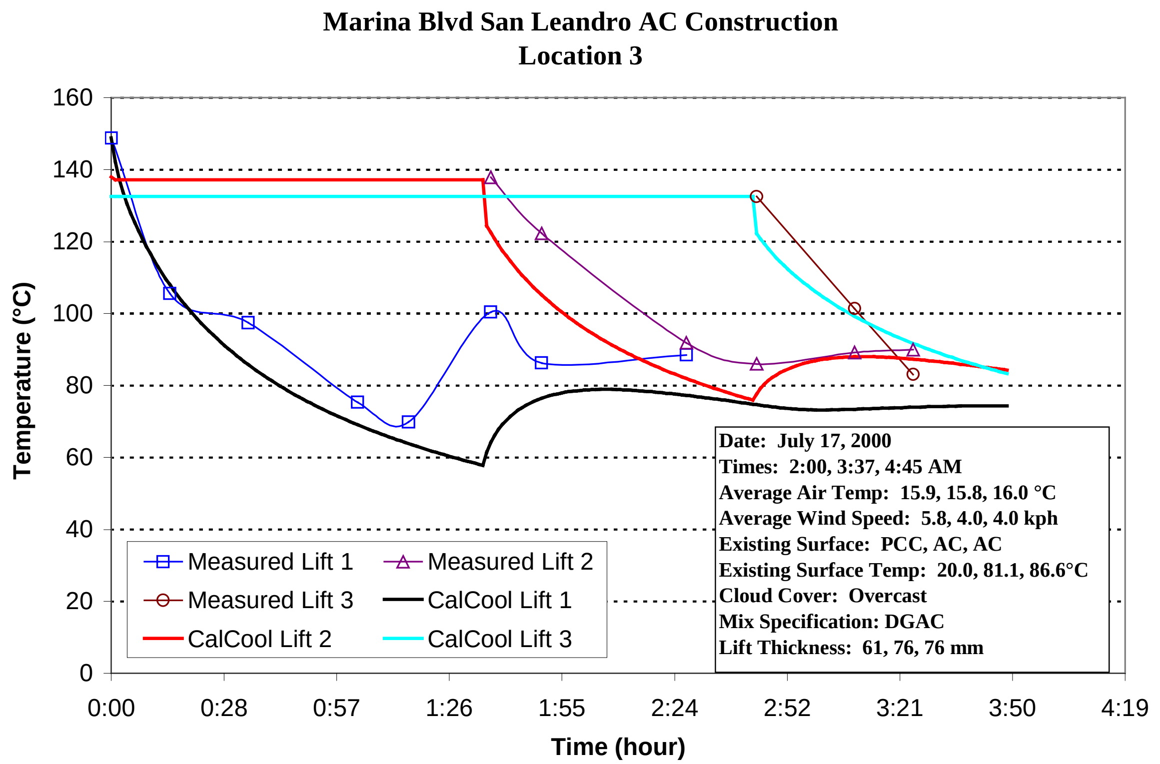


Figure 19. Cooling curve for a three lift AC layer placed on existing PCC (San Leandro project).

4.0 RESULTS OF THE AC CONSTRUCTABILITY ANALYSIS

Two types of calculation were implemented for the asphalt constructability analysis as follows:

- Deterministic analysis, in which major input parameters such as resource availability, scheduling factors, and delay for AC cooling time were treated as constants without variations, and
- Stochastic analysis, in which these parameters were treated as random variables with defined probability distributions. The stochastic engine used was called Crystal Ball from Decisioneering(*18*) along with the UCB prototype analysis spreadsheet for deterministic analysis.

The rehabilitation production capability analysis results are expressed in two different ways: centerline-meters and lane-meters. Lane-meters is the product of the number of rehabilitated lanes and centerline-meters.

4.1 CSOL Production Capability

4.1.1 Deterministic Analysis

The initial comparison between rehabilitation options was based on the deterministic analysis. The purpose of the deterministic analysis was to measure the sensitivity of the freeway rehabilitation production capability to all input parameters.

4.1.1.1 CSOL Production Capability in Centerline-meters

The result of the deterministic analysis of CSOL production capability (centerline-meters) for a 55-hour weekend closure is summarized in Table 4. For the partial lane closure options, the total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options. The Layer Profile "A" option for the CSOL Half Closure Partial Completion strategy was found to be similar to the CSOL Full Closure Full Completion option (Profile "A") and therefore was not included in Table 4.

Table 4 Deterministic Analysis Results for CSOL Production per 55-Hour Weekend Closure, Four-Lane Rehabilitation.

Semi Bottom Dump Truck Cycles		Production per Weekend Closure (Centerline-meters)				
		Full Closure		Half Closure		
		Full Completion		Full Completion		Partial Completion*
Cycle Time (min.)	Trucks per Hour	Profile "A"	Profile "B"	Profile "A"	Profile "B"	Profile "B"
7	9	859	988	708	806	930
6	10	1,002	1,153	825	940	1,085
5	12	1,202	1,384	991	1,128	1,302
4	15	1,503	1,729	1,238	1,410	1,628
3	20	1,552	1,750	1,253	1,427	1,647

*Total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options

The CSOL production table was converted into production graphs for better visual understanding and comparison between the rehabilitation options, as shown in Figures 20 and 21. In Figure 20, the rehabilitation production was presented as a function of the cycle time of the asphalt delivery trucks for each rehabilitation option (because the number of semi bottom

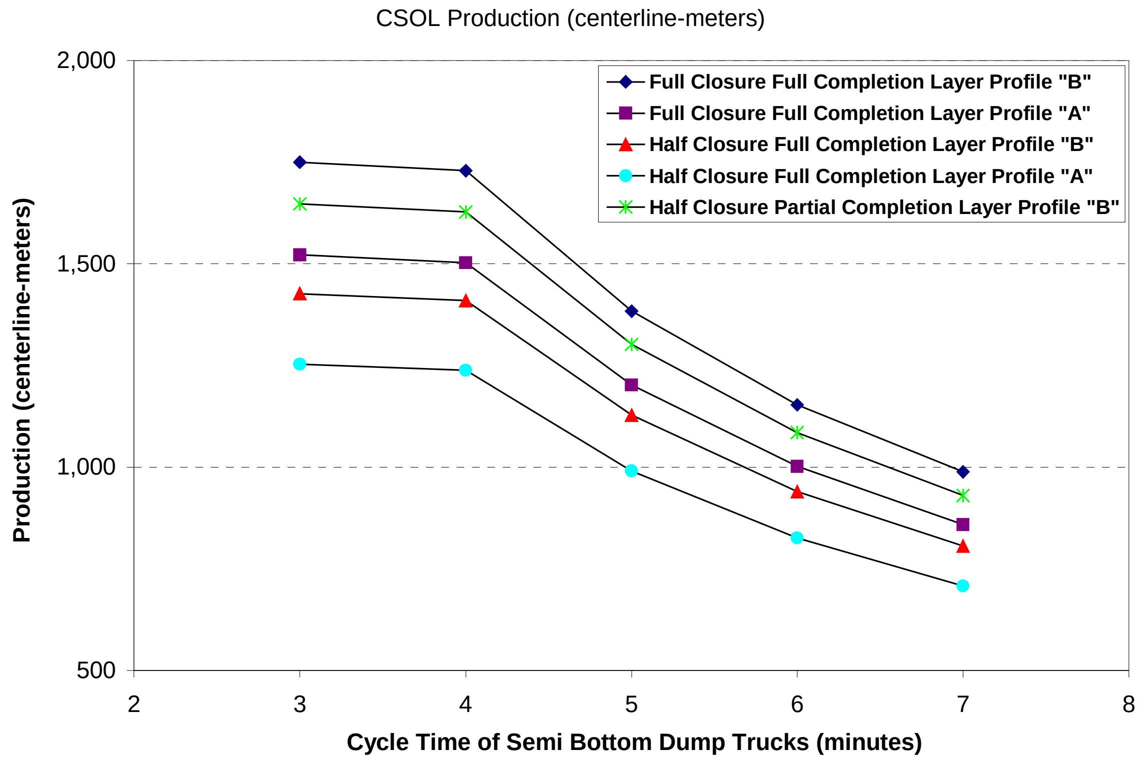


Figure 20. Deterministic analysis of CSOL production in centerline-meters as a function of semi bottom dump truck cycle time.

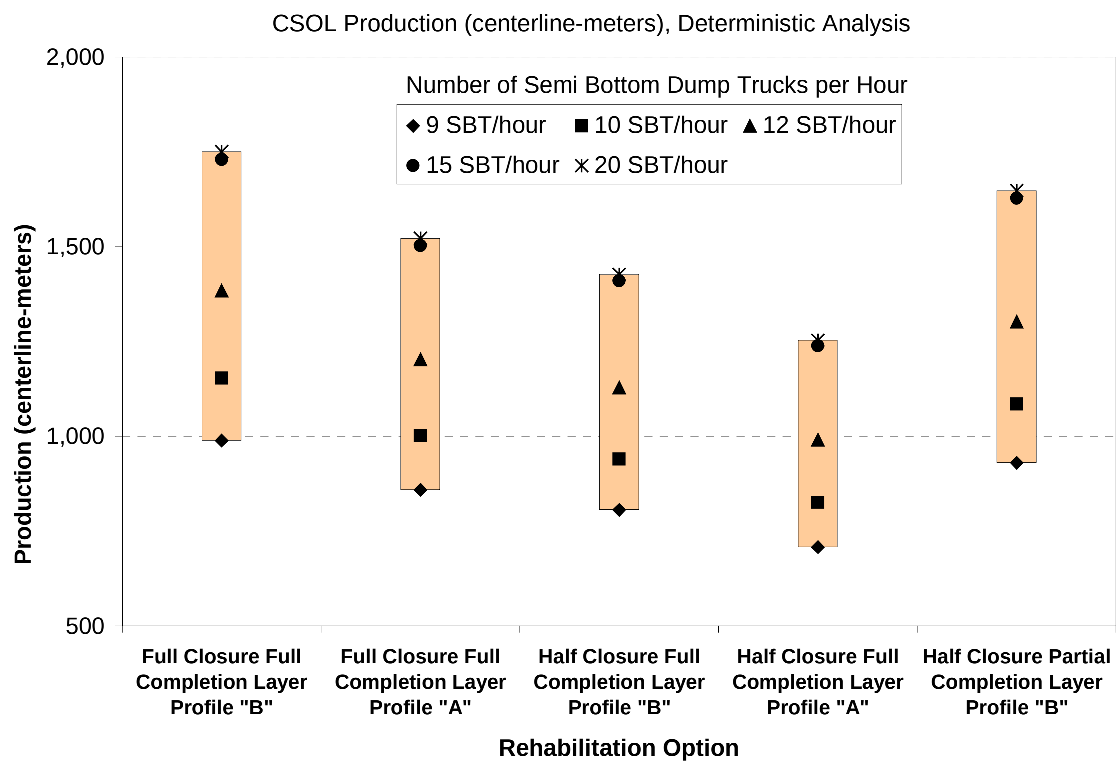


Figure 21. Deterministic analysis of CSOL production in centerline-meters as a function of rehabilitation option and number of semi bottom dump trucks/hour.

dump trucks is a primary constraint). In Figure 21, the production was plotted in comparison with various rehabilitation options with a range of delivery trucks per hour.

4.1.1.2 CSOL Production Capability in Lane-meters for Four-Lane Rehabilitation

Similarly, the result of the CSOL production capability in terms of total lane-meters for four-lanes rehabilitation is summarized in Table 5 for the various options. Figures 22 and 23 show a graphic display of the production capability results presented in Table 5 with respect to delivery truck cycle time and number of delivery trucks per hour, respectively.

Table 5 Deterministic Analysis Results for CSOL Production, Four-Lane Rehabilitation

Semi Bottom Dump Truck Cycles		Production per Weekend Closure (Lane-meters)				
		Full Closure		Half Closure		
		Full Completion		Full Completion		Partial Completion*
Cycle Time (min.)	Trucks per Hour	Profile “A”	Profile “B”	Profile “A”	Profile “B”	Profile “B”
7	9	3,435	3,953	2,830	3,222	3,720
6	10	4,007	4,612	3,302	3,759	4,340
5	12	4,808	5,534	3,962	4,511	5,208
4	15	6,010	6,918	4,953	5,639	6,510
3	20	6,088	7,001	5,014	5,707	6,589

*Total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options

The Layer Profile “B” with a full lane closure and full completion of the rehabilitation on all four lanes is the most productive strategy in terms of centerline-meters. The productivity of the rehabilitation increases for all options with an increase in AC delivery trucks per hour. The least productive option was the Layer Profile “A” with the CSOL Half Closure Full Completion strategy.

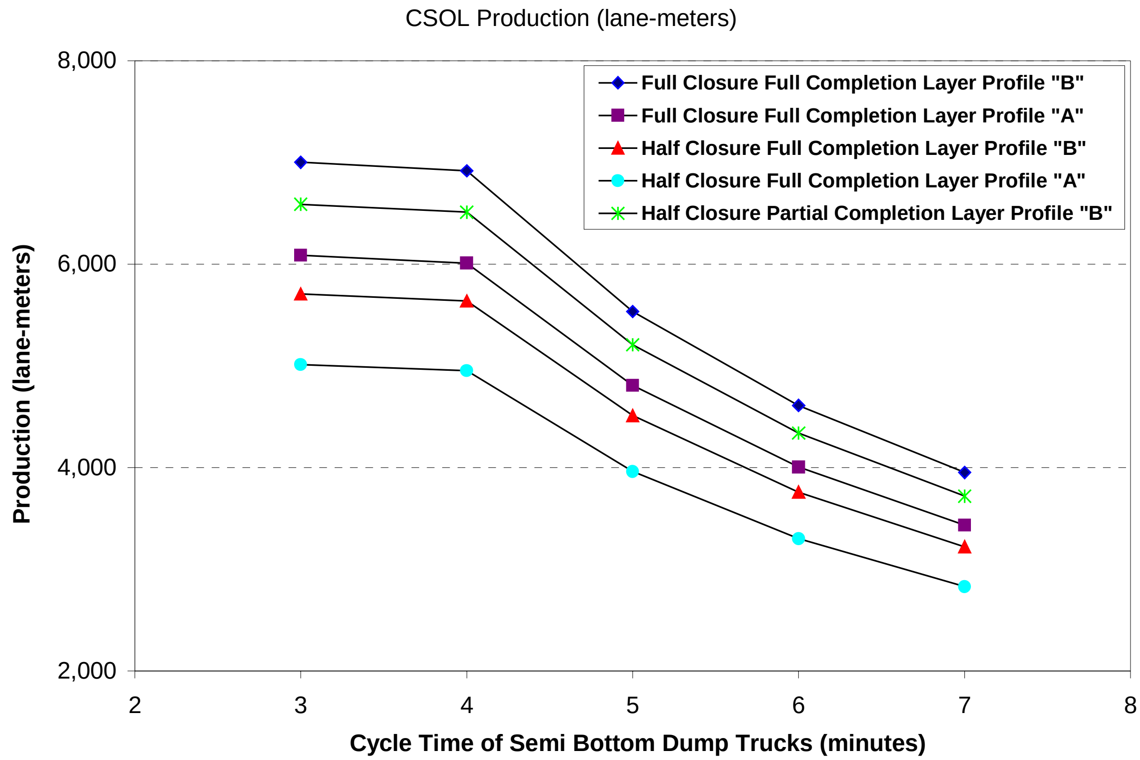


Figure 22. Deterministic analysis of CSOL production in lane-meters as a function of semi bottom dump truck cycle time.

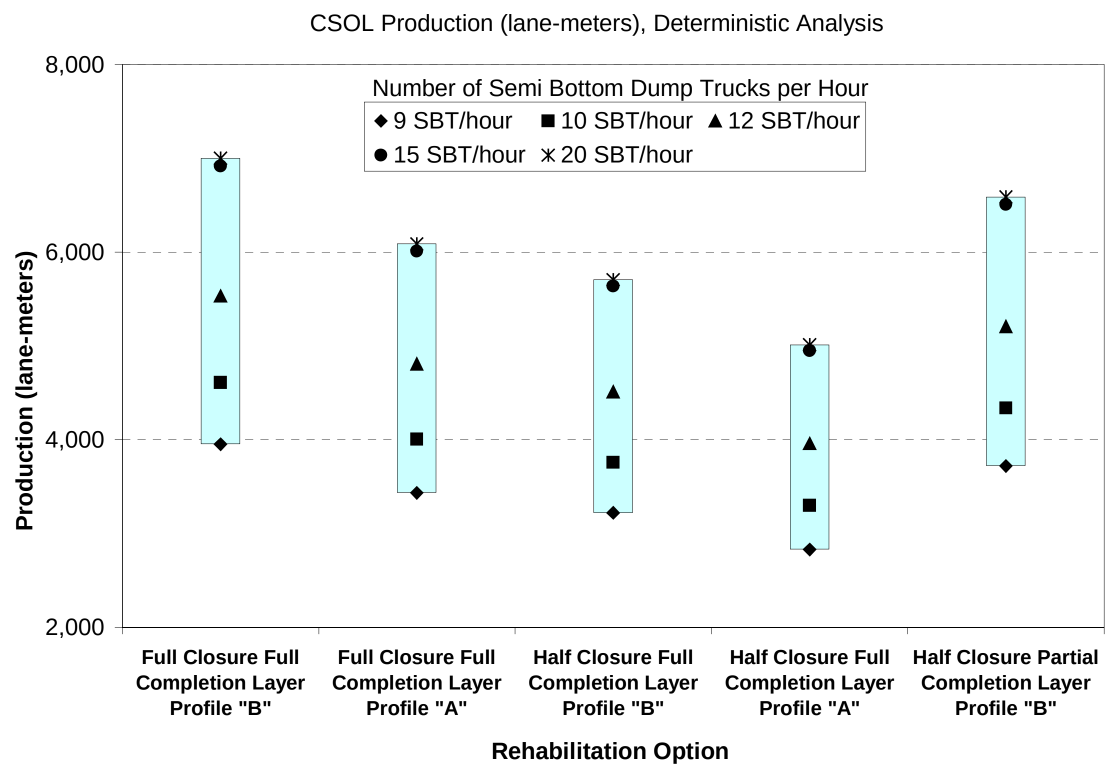


Figure 23. Deterministic analysis of CSOL production in lane-meters as a function of rehabilitation option and semi bottom dump trucks/hour.

4.1.2 Stochastic Analysis

In order to calculate a realistic range of production capabilities for the various rehabilitation options, a stochastic analysis was conducted by treating the parameters affecting production as random variables.

4.1.2.1 Random Variable Parameters for Stochastic Analysis.

Table 6 summarizes how major input parameters for the stochastic analysis were treated as random variables. The CSOL Half Closure Full Completion Layer Profile “A” option is used as an example.

Table 6 Example of Random Variables for the CSOL Half Closure Full Completion Layer Profile “A” Option, Stochastic Analysis

Variable (parameter)	Unit	Distribution Type	Probability Distribution Function
Mobilization time	hours	Triangular	min = 1, mean = 2, max = 3
De-mobilization time	hours	Triangular	min = 2, mean = 3, max = 4
Mix plant capacity	m^3/hour	Normal	mean = 150, standard deviation = 15
Cycle time of SBT	minutes	Normal	mean = 5, standard deviation = 0.5
Efficiency of SBT	n/a	Triangular	min = 0.85, mean = 0.95, max = 1.0
Traffic switch time	hours	Triangular	min = 0, mean = 1, max = 2
Delay for AC cooling	hours	Triangular	min = 3.5, mean = 5.5, max = 6.5

The type of distribution was assumed realistically with resource reference information from AC field data and the I-10 project concrete case study. The mean of the distribution is the same as the typical value for the deterministic analysis.(*6*)

The parameters were randomly generated and combined to complete 1,000 runs in the constructability analysis spreadsheet. The prediction of the production capability is shown in Figure 24 along with a “one-standard deviation” of confidence interval around the mean. As the sum of the independent input parameters of random variables, the production capability has an

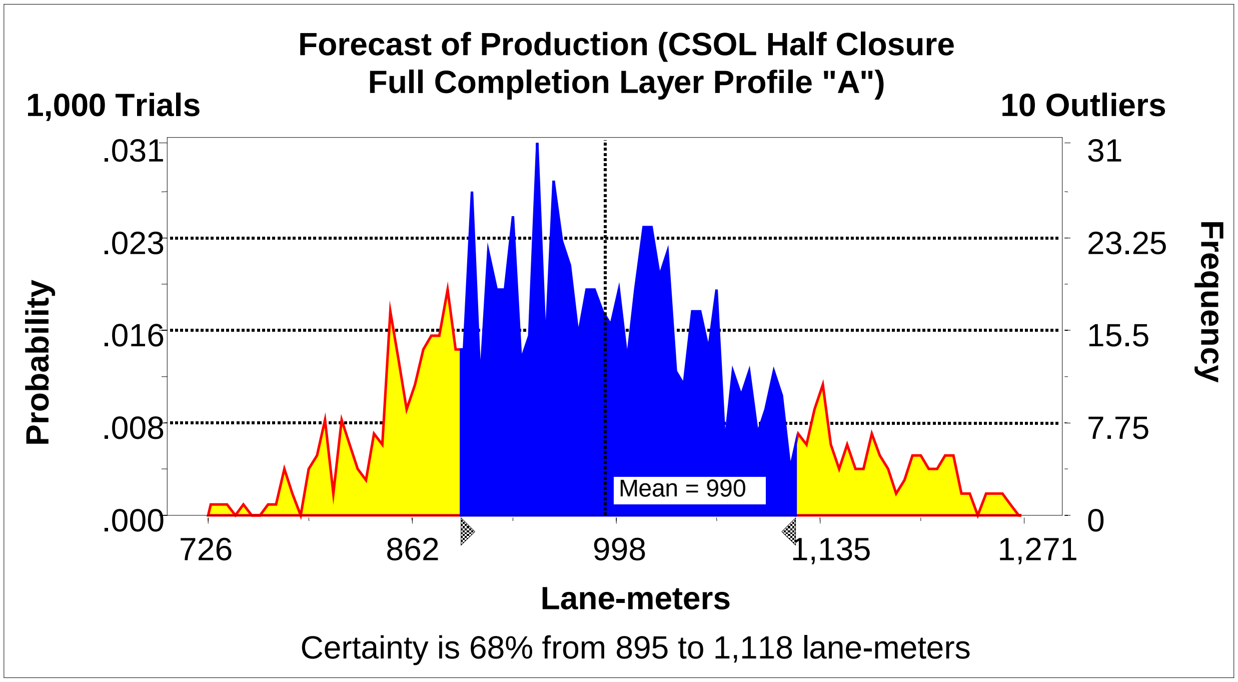


Figure 24. Forecast of production for CSOL from stochastic analysis (CSOL Half Closure Full Completion Layer Profile "A").

approximate normal distribution, based on the "Central Limit Theorem"(*19*), as shown in Figure 24. In Figure 24, one standard deviation for the confidence interval means there is a 68 percent likelihood the production capability of the rehabilitation will fall within the interval given the resource inputs and productions.

Another advantage of the stochastic analysis is to indicate the sensitivity of the results to the input parameters. Figure 25 shows that the cycle time of the asphalt delivery trucks (SBT) is the most influential variable in the rehabilitation production capability.

4.1.2.2 Result of the CSOL Stochastic Analysis

Table 7 summarizes the result of the CSOL stochastic analysis in terms of centerline-meters categorized into different intervals of likelihood, (i.e., lower bound, mean, and upper bound). The same results are plotted into a centerline-meters production graph (Figure 26)

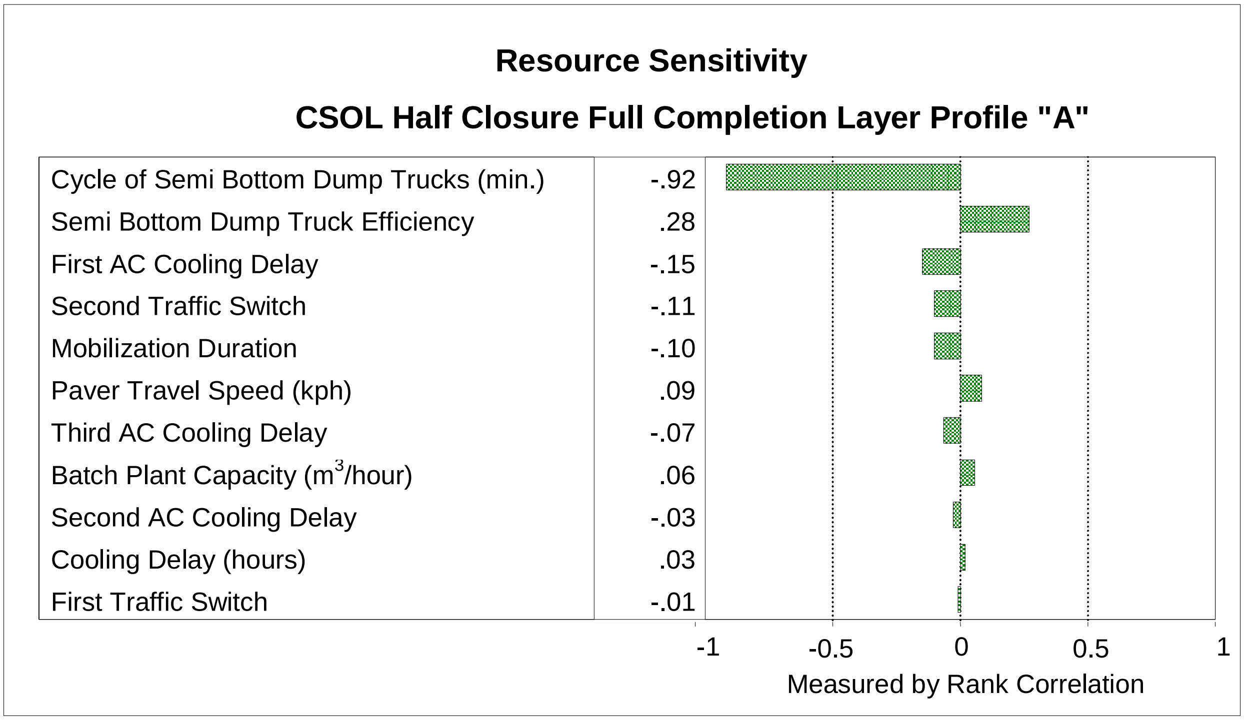


Figure 25. Resource sensitivity for CSOL stochastic analysis (CSOL Half Closure Full Completion Layer Profile "A").

Table 7 Stochastic Analysis Results for CSOL Production, Four-Lane Rehabilitation

	Production per Weekend Closure for Given Rehabilitation Option (Centerline-meters)				
Closure Option	**Full Closure**		**Half Closure**		
Completion Option	**Full Completion**		**Full Completion**		**Partial Completion[2]**
Layer Profile	**Profile "A"**	**Profile "B"**	**Profile "A"**	**Profile "B"**	**Profile "B"**
Lower Bound	1,080	1,231	894	1,003	1,193
Mean (average)	1,190	1,358	990	1,106	1,316
Deterministic[1]	1,202	1,384	991	1,128	1,302
Upper Bound	1,322	1,515	1,116	1,245	1,456

[1]12 semi bottom dump trucks per hour

[2]Total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options

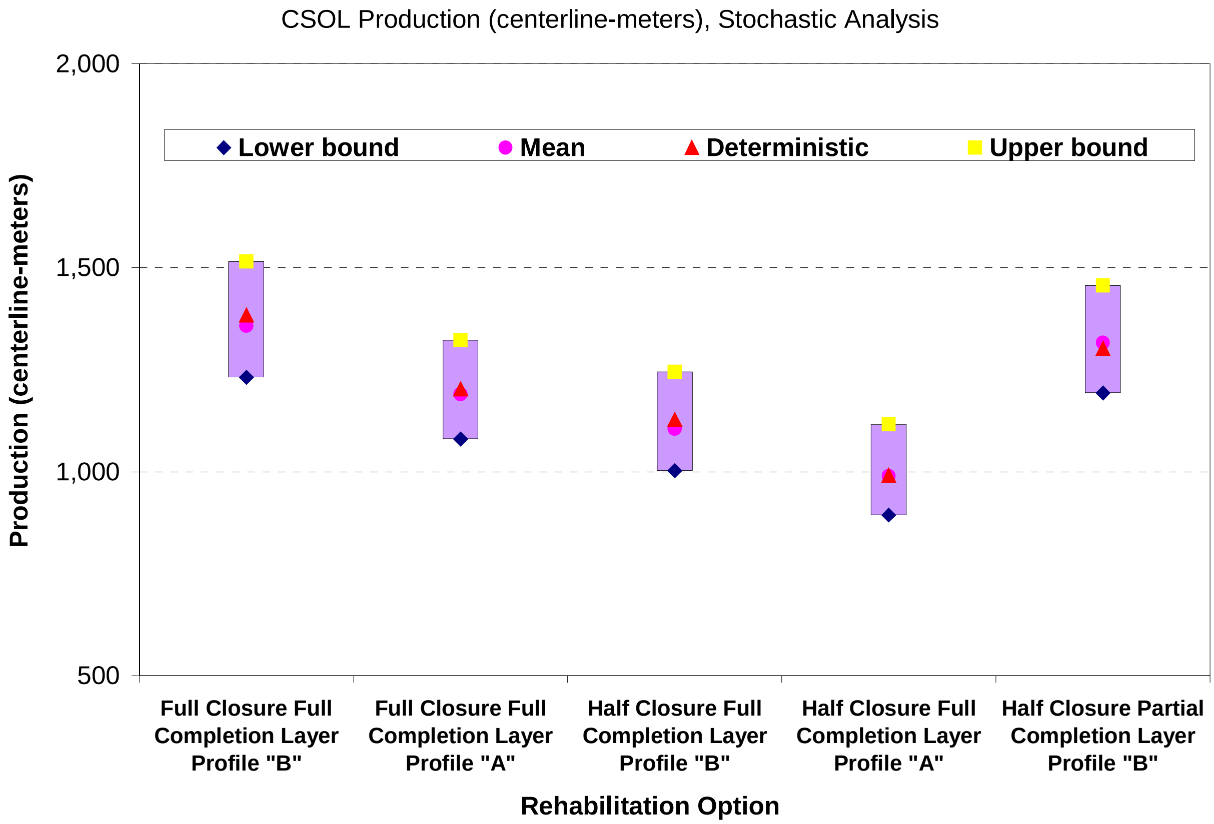


Figure 26. Stochastic analysis of CSOL production in centerline-meters as a function of rehabilitation option.

showing the likely production interval for the various analysis options. Similar to the centerline-meter production, the results of the stochastic analysis for CSOL in terms of total lane-meters for four lanes rehabilitated are summarized in Table 8 and Figure 27.

The mean production capability from the stochastic analysis is very close to the deterministic analysis when using an average of 12 asphalt delivery trucks (SBT cycle time of 5 minutes, as used for the stochastic analysis).

Table 8 Stochastic Analysis Results for CSOL Production, Four-Lane Rehabilitation

	Production per Weekend Closure for Given Rehabilitation Option (Lane-meters)				
Closure Option	**Full Closure**		**Half Closure**		
Completion Option	**Full Completion**		**Full Completion**		**Partial Completion[2]**
Layer Profile	**Profile "A"**	**Profile "B"**	**Profile "A"**	**Profile "B"**	**Profile "B"**
Lower Bound	4,321	4,925	3,575	4,010	4,773
Mean (average)	4,758	5,431	3,956	4,422	5,264
Deterministic[1]	4,808	5,534	3,962	4,511	5,208
Upper Bound	5,289	6,060	4,465	4,979	5,826

[1]12 semi bottom dump trucks per hour
[2]Total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options

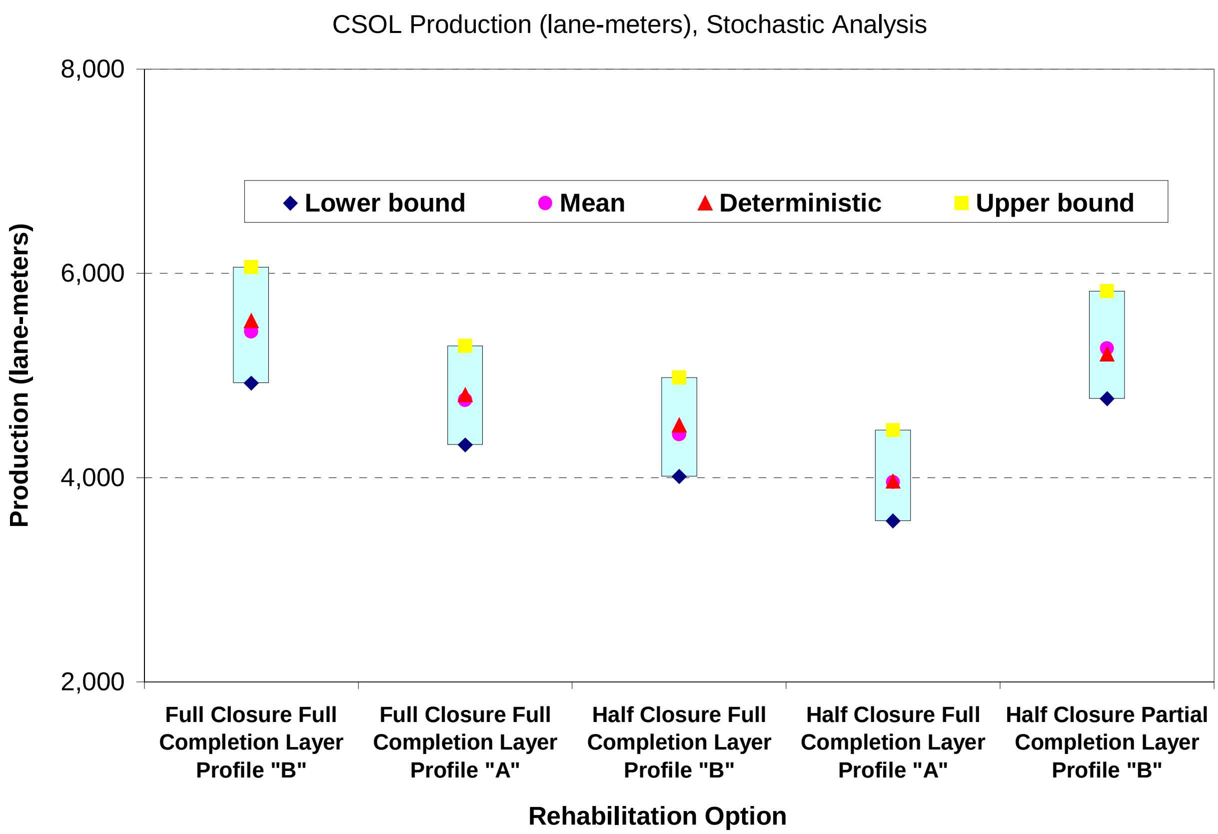


Figure 27. Stochastic analysis of CSOL production in lane-meters as a function of rehabilitation option.

4.1.3 Production Comparison of the Rehabilitation Options for CSOL

Table 9 compares the relative average production capability from the CSOL stochastic analysis between each rehabilitation option and the fastest option (i.e., CSOL Full Closure Full Completion Layer Profile “B”). Table 9 also includes the number of hours of delay due to waiting for hot AC to cool and switching of traffic between lanes. The results show that the amount of delay greatly affects the overall productivity of the rehabilitation.

Table 9 Production Comparison for CSOL Rehabilitation

<table>
<tr><th colspan="2"></th><th colspan="10">Comparison of Production per Weekend Closure for Given Rehabilitation Option (Lane-meters)</th></tr>
<tr><th colspan="2">Closure</th><th colspan="4">Full Closure</th><th colspan="6">Half Closure</th></tr>
<tr><th colspan="2">Completion Option</th><th colspan="4">Full Completion</th><th colspan="4">Full Completion</th><th colspan="2">Partial Completion[3]</th></tr>
<tr><th colspan="2">Layer Profile</th><th colspan="2">Profile “A”</th><th colspan="2">Profile “B”</th><th colspan="2">Profile “A”</th><th colspan="2">Profile “B”</th><th colspan="2">Profile “B”</th></tr>
<tr><td colspan="2">Average Production[1]</td><td colspan="2">4,758</td><td colspan="2">5,431</td><td colspan="2">3,956</td><td colspan="2">4,422</td><td colspan="2">5,264</td></tr>
<tr><td colspan="2">Comparison[2]</td><td colspan="2">88 %</td><td colspan="2">100%</td><td colspan="2">72%</td><td colspan="2">81%</td><td colspan="2">97%</td></tr>
<tr><td colspan="2">Delay (hours)</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">9</td><td colspan="2">8.5</td><td colspan="2">3</td></tr>
<tr><td>AC Cooling</td><td>Traffic Switching</td><td>0</td><td>0</td><td>0</td><td>0</td><td>2</td><td>7</td><td>2</td><td>6.5</td><td>0</td><td>3</td></tr>
</table>

[1]Stochastic analysis in terms of total lane-meters for four-lane rehabilitation
[2]Compared with CSOL Full Closure Full Completion Layer Profile “B”
[3]Total productivity required for two weekends was determined and then divided by two to come up with the production capability for one weekend in order to facilitate easy comparison to the other rehabilitation options

The Layer Profile “B” (200-mm overlay) has approximately 12 percent more production capability than the Layer Profile “A” (230-mm overlay) for full- and half-lane closure strategies. This production capability ratio is almost the same as the ratio of the overlay thicknesses of the two pavement profiles, (i.e., 88 percent = Profile “B”/Profile “A” thickness = 200 mm/230 mm).

On average, the Half Closure Full Completion case is approximately 20 percent less productive than the Full Closure Full Completion option for both pavement profiles. The 20 percent decrease in productivity must be compared with the reduced traffic delay caused by leaving two lanes open to traffic in the Half Closure option instead of having all four lanes closed as in the Full Closure option.

The Half Closure Full Completion option is less productive than the Full Closure Full Completion option because of delays for AC cooling and traffic switches. However, the road user is less inconvenienced with the Half Closure Full Completion option relative to the Full Closure Full Completion option.

In the Half Closure Partial Completion option, the delay caused by AC cooling is negligible and therefore the production capability was found to be almost the same as the Full Closure Full Completion case. With the Half Closure Partial Completion option, two out of four lanes are always open to traffic with only a 3 percent loss in productivity compared to the Full Closure Full Completion option. The only issue to resolve is the impact on pavement life of opening two out of the four lifts of AC for one week to normal urban freeway traffic.

4.2 Full-Depth AC Replacement Production Capability

The results of deterministic and stochastic analyses for Full-Depth AC Replacement with Single- and Double-Lane Rehabilitation are described in this section.

4.2.1 Deterministic Analysis

4.2.1.1 Production Capability of Full-Depth Single-Lane Rehabilitation

The linear scheduling technique descried in detail for the concrete constructability analysis in Reference (*4*) was used again in the analysis for Full-Depth AC Replacement. This technique was used to determine the optimum time allocation between the demolition and paving activities for a given set of resource constraints. For example, in a 55-hour weekend closure there were 24 hours for paving (including 3 hours AC cooling) and 28 hours for demolition assuming 12 demolition trucks and 10 asphalt delivery trucks per hour (Full-Depth Single-Lane Layer Profile "B" case).

Table 10 shows the constructability analysis results for the Single Lane Rehabilitation using the Full-Depth AC Replacement strategy. The constraints on production capability were the pavement profile (Profile "A" or "B") and the number of demolition teams. The number of demolition and asphalt delivery trucks also plays a key role in the production of this strategy. In the case of two demolition teams, more than one construction access lane needs to be provided during the demolition work. If the shoulder width is more than 3 meters, then it can be used as one of the access lanes. If only one access lane is available for two demolition teams, then the resultant productivity will be equivalent to 1.5 demolition crews.(*6*) The poor productivity of two teams with one access lane is caused by construction traffic congestion.

Table 10 Deterministic Analysis Results for Production of Full-Depth AC Replacement, Single-Lane Rehabilitation

Trucks per hour		Production (Lane-meters)					
		Profile "A"	Profile "B"	Profile "A"	Profile "B"	Profile "A"	Profile "B"
Semi Bottom Dump Truck	Dump Truck	1 Demolition Team	1 Demolition Team	1.5 Demolition Teams	1.5 Demolition Teams	2 Demolition Teams	2 Demolition Teams
10	10	1,544	1,216	2,028	1,600	2,356	1,879
10	12	1,723	1,357	2,222	1,753	2,548	2,032
12	10	1,648	1,298	2,203	1,738	2,593	2,068
12	12	1,853	1,460	2,433	1,920	2,827	2,255
15	10	1,766	1,391	2,411	1,902	2,883	2,299
15	12	1,943	1,530	2,597	2,049	3,057	2,438

4.2.1.2 Production Capability of Double-Lane Rehabilitation

The productivity results of Double-Lane Rehabilitation using Full-Depth AC Replacement are summarized in Table 11 for both pavement profiles and as a function of the number of demolition and asphalt delivery trucks per hour. Two demolition teams work simultaneously in the model, but because of the availability of only a single access lane, the calculation assumed 1.5 demolition teams (the net effect of 2 demolition teams with a single access lane).

The production capability of the Single-Lane Rehabilitation option in Table 10 and Double-Lane option in Table 11 were combined and the results shown in Figure 28 and Table 12. The Single-Lane Rehabilitation strategy was more productive than the Double-Lane Rehabilitation strategy because fewer working hours were spent waiting for AC cooling compared with the double-lane option.

Table 11 Deterministic Analysis Results for Production of Full-Depth AC Replacement, Double-Lane Rehabilitation

Trucks per hour		**Production**			
		Centerline-meters		**Lane-meters**	
Semi Bottom Dump Trucks	**Dump Trucks**	Profile “A”	Profile “B”	Profile “A”	Profile “B”
10	10	890	714	1,781	1,427
10	12	976	782	1,951	1,564
12	10	967	775	1,935	1,551
12	12	1,069	856	2,137	1,713
15	10	1,059	848	2,117	1,697
15	12	1,181	947	2,362	1,893

Table 12 Deterministic Analysis Results for Full-Depth AC Replacement Production, Single- versus Double-Lane Rehabilitation

Trucks per hour		Production (Lane-meters)			
		Single Lane		Double Lane	
Semi Bottom Dump Truck	Dump Truck	Profile "A"	Profile "B"	Profile "A"	Profile "B"
10	12	2,222	1,753	1,951	1,564
12	10	2,203	1,738	1,935	1,551
12	12	2,433	1,920	2,137	1,713

[1]1.5 demolition teams for both Single- and Double-Lane Rehabilitation

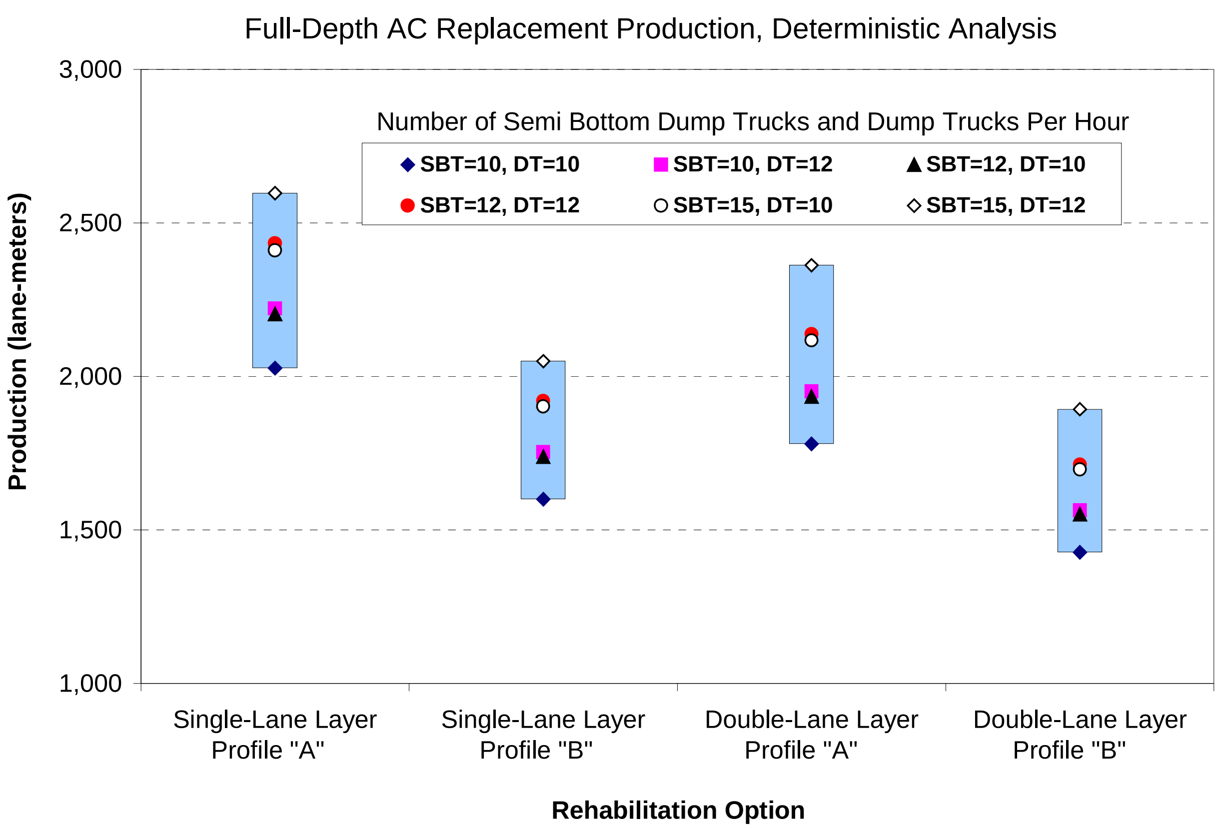


Figure 28. Deterministic analysis of Full-Depth AC Replacement production as a function of Single- or Double-Lane Rehabilitation, and type and number of trucks per hour.

4.2.2 Stochastic Analysis

For the Full-Depth AC Replacement strategy, a stochastic analysis was completed and the results were compared with the results of the deterministic analysis. Table 13 shows an example of the random variables used for the Full-Depth Double-Lane Layer Profile “B” case and their corresponding distribution types and probability distribution functions (PDF). Similar to the stochastic analysis for the CSOL case, the distribution types were realistically assumed using reference information from AC field data and the concrete case study with the I-10 project.(*6*) The typical value of the deterministic analysis was used as the mean of the distribution.

Table 13 Example of Random Variables for the Full-Depth AC Replacement, Double-Lane, Layer Profile “B,” Stochastic Analysis

Variable (Parameter)	Unit	Distribution Type	Probability Distribution Function
Mobilization time	hours	Triangular	min = 0.5, mean = 1, max = 1.5
Demobilization time	hours	Triangular	min = 2, mean = 3, max = 4
Mixing plant capacity	m^3/hour	Normal	mean = 150, standard deviation = 15
Demolition team*	number	Discrete	min = 1, mean = 1.5, max = 2
Dump truck frequency*	trucks/hour	Normal	mean = 10, standard deviation = 0.1
Dump truck efficiency*	-	Triangular	min = 0.45, mean = 0.6, max = 0.75
Semi bottom dump truck frequency	trucks/hour	Normal	mean = 12, standard deviation = 1.2
Efficiency of semi bottom dump truck	-	Triangular	min = 0.85, mean = 0.95, max = 1.0
Delay for AC cooling	hour	Triangular	min = 4, mean = 7, max = 9

*New variables in addition to the CSOL stochastic analysis (refer to Table 6)

An example of the Full-Depth AC Replacement stochastic analysis is shown in Figure 29 for the Full-Depth Double-Lane Layer Profile “B” case. For this rehabilitation case, the stochastic analysis forecasted an AC production capability with a range of 1.2 to 1.8 lane-km with a mean of 1.5 lane-km during a 55-hour weekend closure. As shown in Figure 30, the overall production of the AC Rehabilitation was most sensitive to the number of demolition

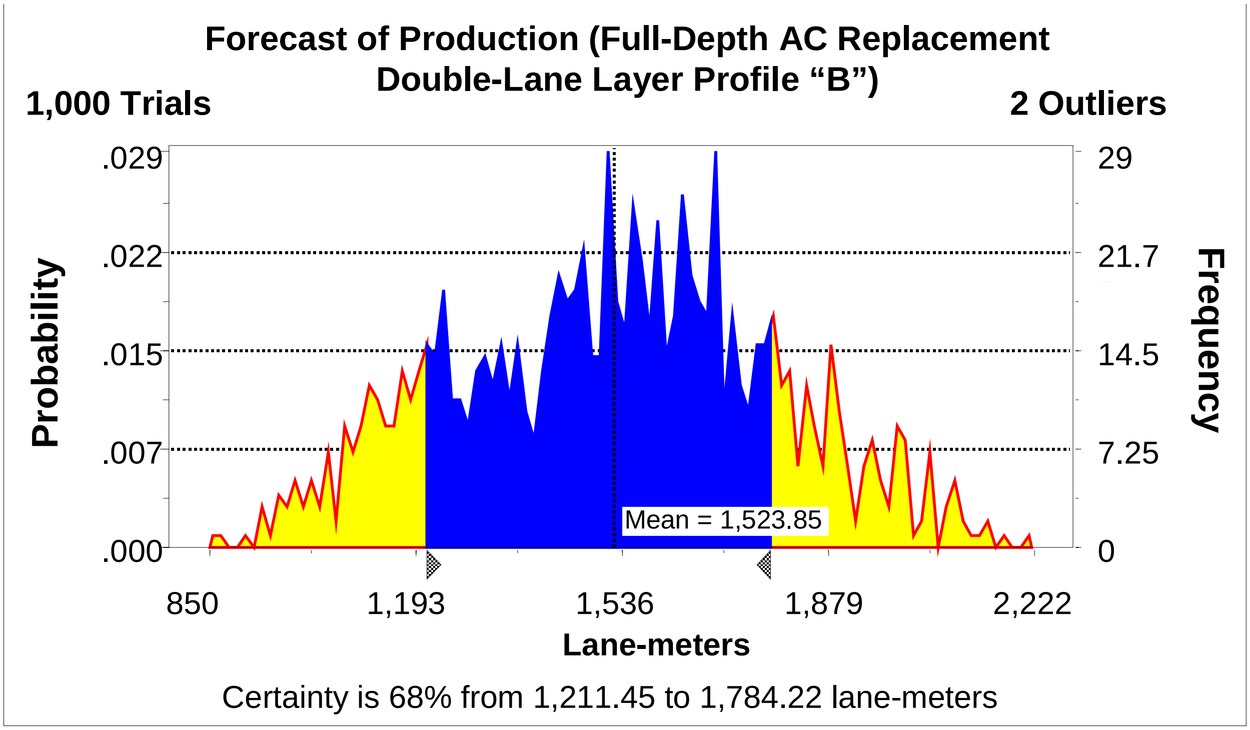


Figure 29. Forecast of production for Full-Depth AC Replacement from stochastic analysis (Full-Depth Double-Lane Layer Profile "B").

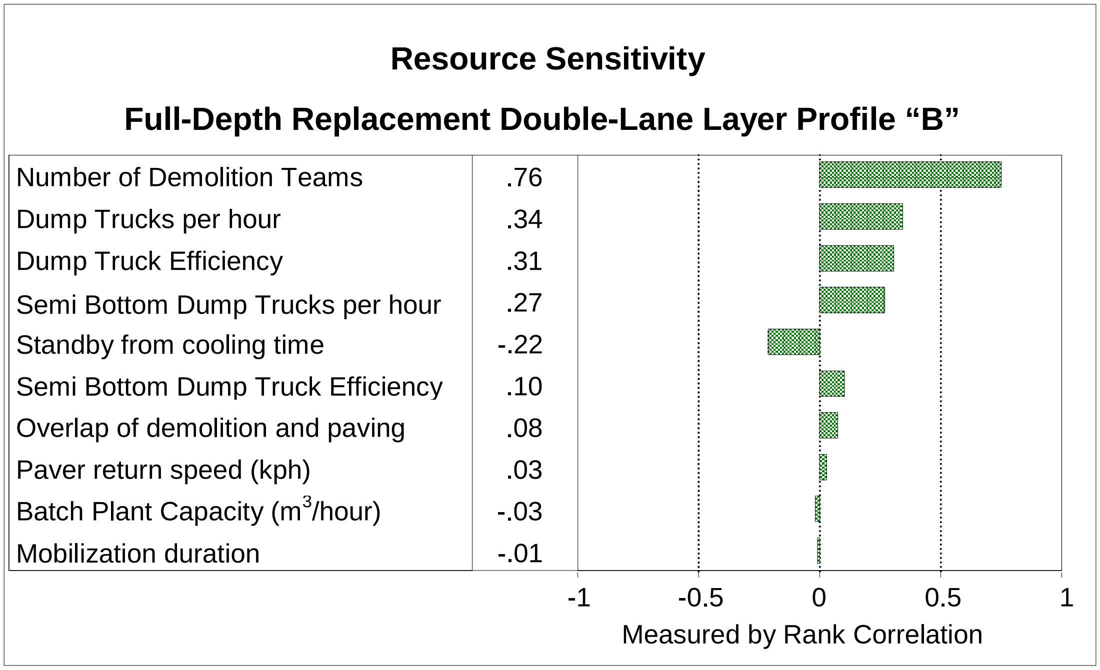


Figure 30. Resource sensitivity for Full-Depth AC Replacement stochastic analysis (Full-Depth Double-Lane Layer Profile "B").

teams, the number of dump trucks per hour, the efficiency of the dump trucks, the number of asphalt delivery trucks per hour, and the efficiency of the AC delivery trucks.

The results of the stochastic analysis for Full-Depth AC Replacement are summarized in Table 14 for the Single- and Double-Lane cases for each layer profile. The data from Table 14 was plotted to show the potential range of rehabilitation productivity, (i.e., lower and upper bounds with mean), as shown in Figure 31. Using stochastic analysis, the Single-Lane Rehabilitation case was found to be more productive than the Double-Lane Rehabilitation case. The mean productivity for each strategy was close to what was calculated using deterministic analysis because the mean of random variable distributions is same as the typical value of the deterministic analysis.

Table 14 Stochastic Analysis Results for Full-Depth AC Replacement Production.

	Production (Lane-meters)			
Lanes Rebuilt	**Single Lane**		**Double Lane**	
Layer Profile	**Profile "A"**	**Profile "B"**	**Profile "A"**	**Profile "B"**
Lower bound	1,647	1,330	1,512	1,211
Mean	2,103	1,694	1,914	1,524
Deterministic*	2,203	1,738	1,935	1,551
Upper bound	2,429	1,958	2,232	1,784

*Semi bottom dump trucks: 12/hr.; dump trucks: 10/hr.

4.2.3 Productivity Comparison of Full-Depth AC Replacement

Table 15 compares the production capability of Single- and Double-Lane Rehabilitation strategies for both pavement profiles ("A" and "B") along with the number of hours the paving operation was delayed due to AC cooling. The production for each option is compared to the most productive option (Single-Lane Layer Profile "A").

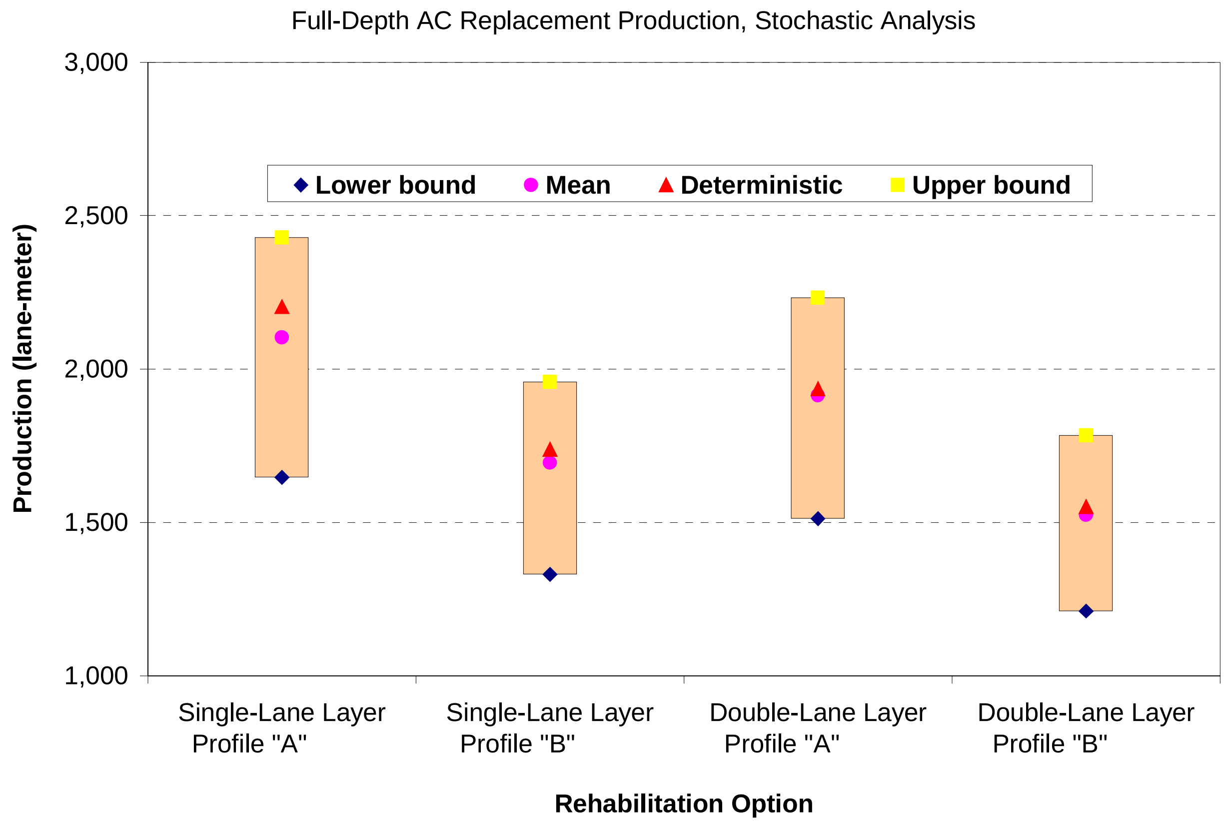


Figure 31. Stochastic analysis for Full-Depth AC Replacement production, Single- versus Double-Lane Rehabilitation.

Table 15 Production Comparison for Full-Depth AC Replacement, Four-Lane Rehabilitation

Lanes Rebuilt	**Single Lane**		**Double Lane**	
Layer Profile	**Profile "A"**	**Profile "B"**	**Profile "A"**	**Profile "B"**
Avg. production[1]	2,103 lane-meters	1,694 lane-meters	1,914 lane-meters	1,524 lane-meters
Comparison[2]	100%	80%	91%	72%
Suspension (hours)[3]	1 hrs.	3 hrs.	6 hrs.	7 hrs.

[1]Stochastic analysis results
[2]Compared with Full-Depth AC Replacement Single-Lane Layer Profile "A"
[3]Delay for AC cooling

The production capability for the Layer Profile “B” (406-mm thickness) was about 80 percent of the Layer Profile “A” (330-mm thickness) case. This reduction is similar to the extra amount of asphalt thickness that is required for the Layer Profile “B” (81 percent =Profile “A”/Profile “B” = 330 mm/406 mm). This suggests that the production difference was mainly the result of the amount of existing pavement to be removed and the quantity of asphalt material to be delivered.

Double-Lane Rehabilitation was about 10 percent less productive than Single-Lane Rehabilitation for both Layer Profile “A” and “B.” In the concrete constructability analysis, Double-Lane paving was more productive than Single-Lane paving because both lanes were paved simultaneously and the constraints for Single- and Double-Lane paving were different.(*4*) The AC cooling time for Full-Depth AC Replacement for Double-Lane rehabilitation is much longer than Singe-Lane rehabilitation (See Table 15). For Double-Lane construction during the 55-hour weekend closure, the paving time required for each lift is much shorter than the Single-Lane case, which results in more hours waiting for the previous AC lift to cool.

5.0 VALIDATION OF THE AC CONSTRUCTABILITY ANALYSIS MODEL (I-710 PROJECT)

5.1 Background of the I-710 Project

Caltrans is in the process of constructing a demonstration project for the Long Life Asphalt Concrete Pavement Rehabilitation Strategy (LLACPRS) on Interstate 710 (Long Beach Freeway). The project construction was started in spring of 2001. The I-710 project will be a good case study for the validation and calibration of the asphalt constructability analysis model described in this report, similar to the role the I-10 project played for the concrete constructability analysis, as described in References (*6*) and (*7*).

Given that the main reconstruction has not started yet, the asphalt constructability analysis model will be used to predict the most probable production capability of the I-710 project based on the preliminary design and planning information developed by Caltrans engineers. The predicted production capability from the analysis model will be compared with the production estimate developed by a committee of AC construction engineers from the Southern California Asphalt Pavement Association (SCAPA) and Caltrans.

As shown in Figure 32, the objective of the I-710 project is to rebuild about 4.8 km (3 miles) of existing PCC pavement with asphalt concrete during a series of 55-hour weekend closures (approximately 12 consecutive weekends). The site, located on I-710 between the Pacific Coast Highway (State Route 1) and Interstate 405, the freeway has three lanes in each direction.

Crack Seat and Overlay (CSOL) is the main rehabilitation strategy to be employed. The site also includes four bridge structure underpasses under which AC (Full-Depth AC

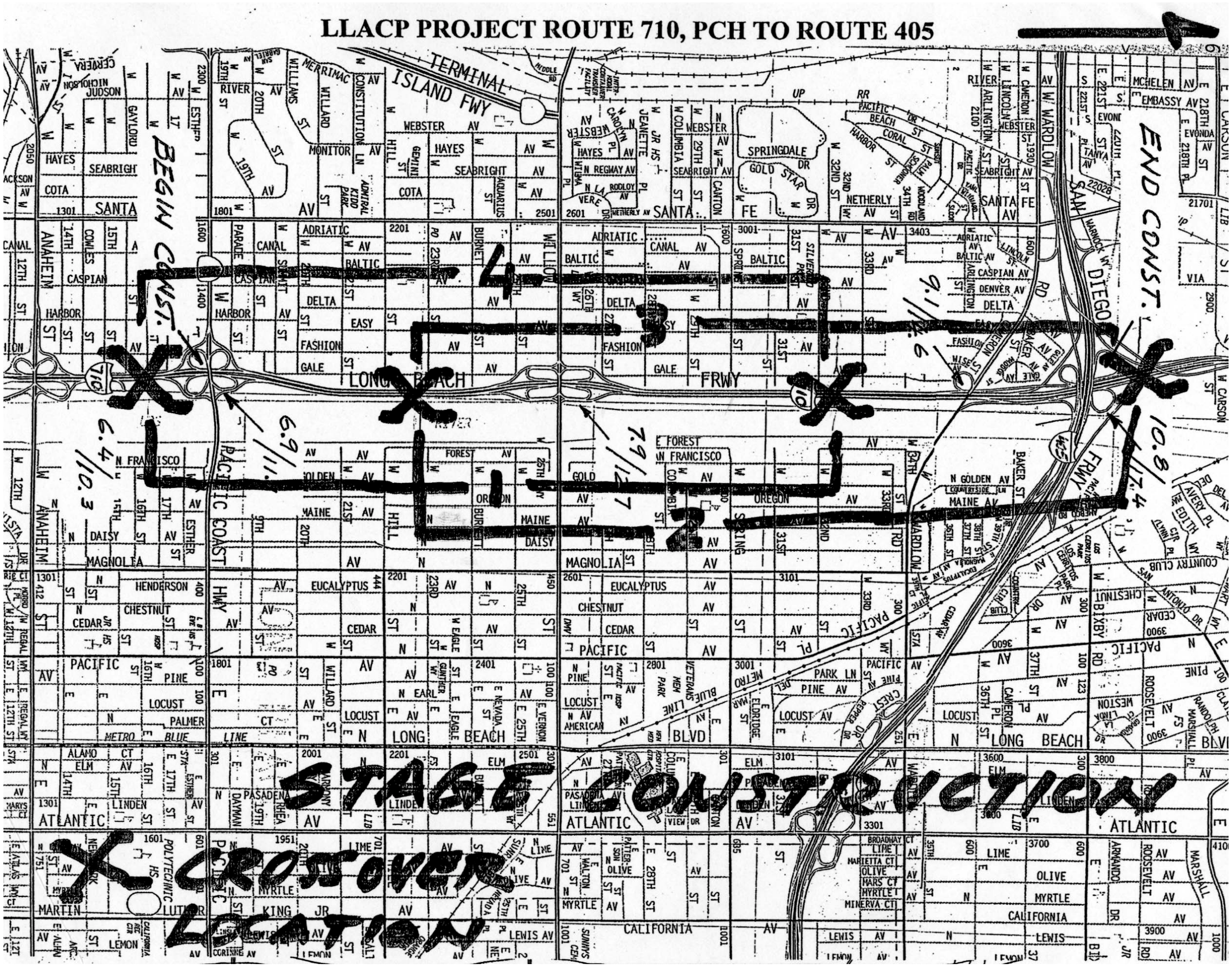
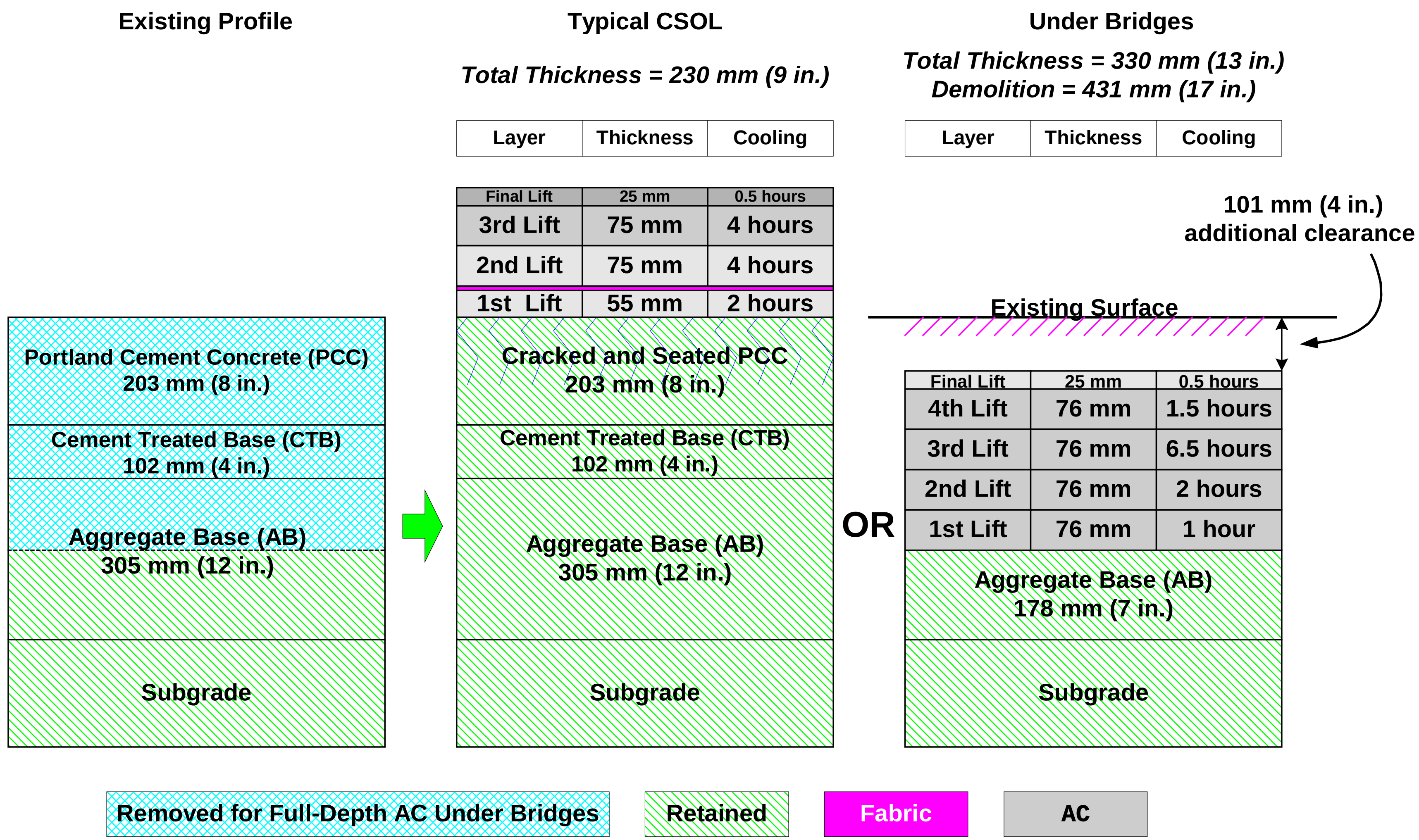


Figure 32. Site layout of the LLACPRS demonstration project on I-710.(*11*)

Replacement) will be placed to provide adequate clearance. Figure 33 shows the design profile of the CSOL and Full-Depth AC Replacement portions of the project. The CSOL portion will use the CSOL Layer Profile "A" (total AC thickness of 230 mm in four lifts), and the Full-Depth AC section will excavate 430 mm of the existing pavement and replace it with 330 mm of AC in five lifts (Layer Profile "A") with 100 mm additional clearance for the new pavement system under the bridge underpasses. The 4.8-km project length consists of a total of 2.8 km of CSOL and 2.0 km of Full-Depth AC. Most of the rehabilitation work is planned to be completed during 3 months of weekend closures; the project schedule is shown in Figure 34.



Note: Longer cooling time may be required for some lifts due to paving at around noon. The difference in layer cooling times between Figure 33 and Figure 10 (showing typical cooling times) is due to the scheduling unique to the I-710 project.

Figure 33. Proposed pavement profiles for I-710 project.

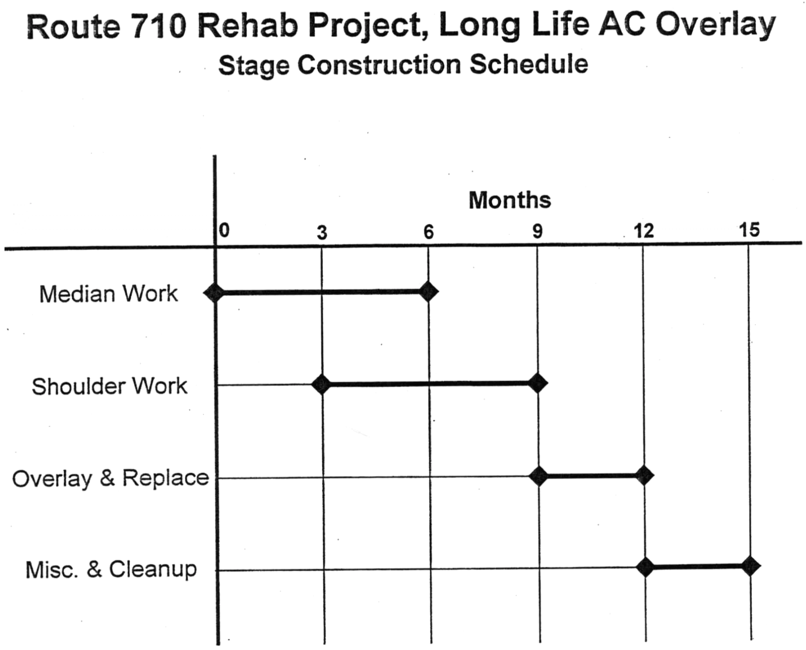


Figure 34. I-710 rehabilitation stage construction schedule.(*11*)

All three lanes in one direction of the freeway will be closed and traffic will be switched to the other side (counter-flow traffic). Shoulder and median work for the traffic switch will occur during a series of nighttime closures over the first 6 months of the project, as the project schedule shows in Figure 34. Shoulders on both sides of the CSOL segments will be overlaid simultaneously with the main traffic lanes. Caltrans will use a “stage construction” concept for the pavement rehabilitation; the 4.8-km project will be split into two equally divided segments in each direction for a total of four segments, as shown in Figures 32 and 35. According to the initial Caltrans plan (Figure 35), two or three 55-hour weekend closures will be assigned for each segment. During each closure, the entire segment being rehabilitated will receive the 230-mm CSOL pavement and the 330-mm Full-Depth AC pavement underneath the two bridge structures contained therein.

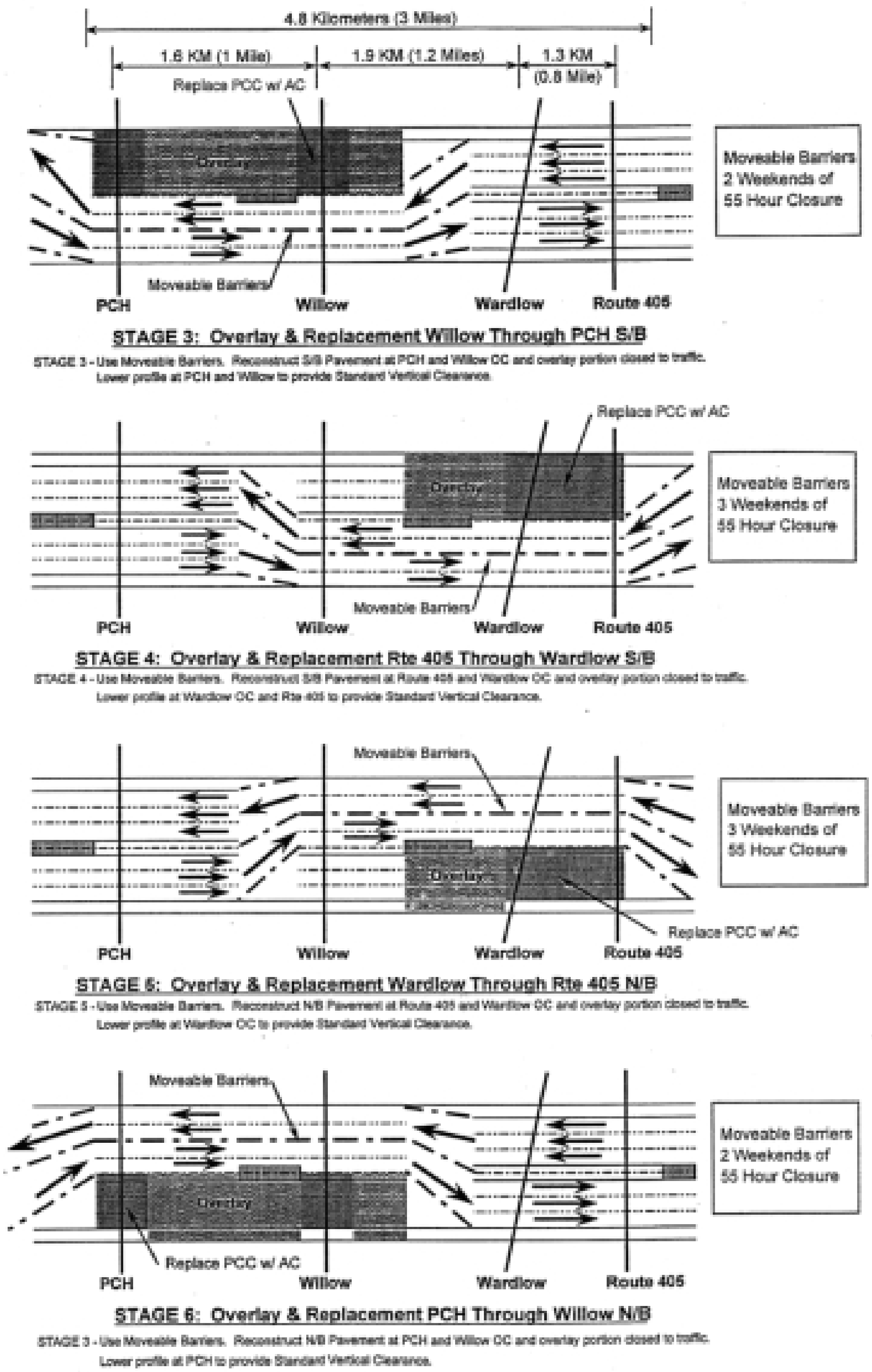


Figure 35. Schematic of the stage construction for the I-710 project.(*11*)

5.2 Predicted Production Capability for the 710 Project

The results of the stochastic analysis to predict the production capability on the I-710 project for both the CSOL and the Full-Depth AC Replacement sections are summarized in Table 16 and plotted in Figure 36. The predicted production capability for the CSOL portion (6.8 lane-km, 3 lanes overlaid) is similar to the typical production for the CSOL Full Closure Layer Profile "A" (6.8 lane-km, 4 lanes overlaid) shown in Table 8. For three lanes of CSOL rehabilitation, there is negligible time lost to AC cooling delay.

Table 16 Stochastic Analysis for Proposed I-710 Case Study

Design Profile	CSOL Production[1]		Full-Depth AC Production[2]	
Mileage	**Centerline-meters**	**3 Lanes (lane-meters)**	**Centerline-meters**	**3 Lanes (lane-meters)**
Lower bound	1,408	4,230	390	1,180
Mean (Average)	1,544	4,638	500	1,490
Deterministic[3]	1,537	4,624	510	1,520
Upper bound	1,720	5,202	590	1,780

[1] 1 paving team
[2] 1.5 demolition teams
[3] 12 semi bottom dump trucks per hour; 10 dump trucks per hour

The predicted production capability of the Full-Depth AC Replacement option for the I-710 project (1.5 lane-km, 3 lanes rehabilitated, 430 mm demolition depth, and 330 mm AC) is less than the Full-Depth AC Replacement Layer Profile "A" option shown in Table 14 (1.9 lane-km, 2 lanes rehabilitated, 330 mm demolition, and 330 mm AC). The main reasons for the reduced production capability were 1) more material had to be demolished on the I-710 project (430 versus 330 mm) to obtain additional bridge clearance, and 2) because of the short paving distance, there was more delay due to AC cooling.

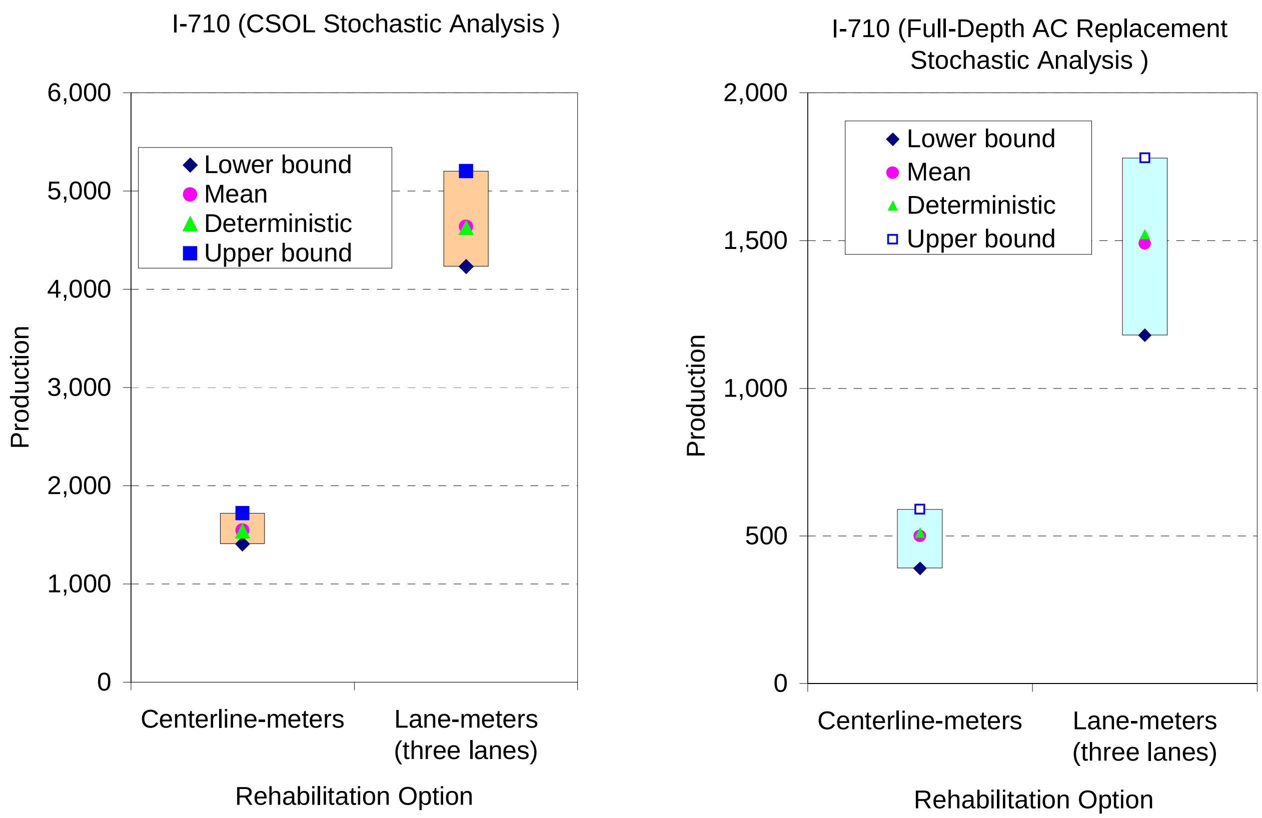


Figure 36. Stochastic analysis for the I-710 project.

The results of the predicted production capability from the asphalt analysis model for the CSOL and Full-Depth AC Replacement sections were compared with the production performance plan developed by the SCAPA/Caltrans committee. The comparison between the predicted production capability and the Caltrans planned production capability indicates that the current performance target of the I-710 project looks reasonable, but is somewhat "tight" or optimistic and doesn't have any contingency margin, as summarized below:

- Prediction from the asphalt analysis model (Table 16):
    - Two weekend closures: one weekend for CSOL and the other weekend for Full-Depth AC

- CSOL: 1.54 centerline-km (4.63 lane-km) per weekend closure
- Full-Depth AC: 0.5 centerline-km (1.5 lane-km) per weekend closure

- Caltrans planned production needed for the stage rehabilitation (Figure 35)

· For Stage 3 and Stage 6 (two weekend closures, total)

  - CSOL: one 1.6 centerline-km (4.8 lane-km) section per weekend closure
  - Full-Depth AC: two 0.4 km (1.2 lane-km) sections per weekend closure

  If the rehabilitation plan calls for the first weekend to produce 4.8 lane-km CSOL and the second weekend to produce 2.4 lane-km Full-Depth AC, then the production ratio (planned production/predicted maximum production) is:

  - CSOL (1st weekend) = 4.8 lane-km/4.6 lane-km = 104 percent
  - Full-Depth AC (2nd weekend) = 2 × 1.2 lane-km/1.5 lane-km = 160 percent

· For Stage 4 and Stage 5 (three weekend closures, total)

  - CSOL: one 1.1 centerline-km (3.3 lane-km) per weekend closure
  - Full-Depth AC: 0.65 km (1.95 lane-km) per weekend closure for two weekend closures (total of 3.9 lane-km rehabilitated)

  If the rehabilitation plan calls for the first weekend to produce 3.3 lane-km CSOL, the second weekend to produce 1.95 lane-km Full-Depth AC, and the third weekend to produce 1.95 lane-km Full-Depth AC, then the production ratio (planned production/predicted maximum production) is:

· CSOL (1st weekend) = 3.3 lane-km/4.6 lane-km = 72 percent

· Full-Depth AC (2nd and 3rd weekends) = 1.95 lane-km/1.5 lane-km = 130 percent

The comparison concludes that the production plan for CSOL is reasonable, but that the production plan for Full-Depth AC looks 30 to 60 percent overestimated. The final construction plans recently developed by the contractor indicate that this predicted production deficit will be overcome by leaving the last 75 to 100 mm of the structure off of the structure that must be paved in the 55-hour closure. The final 75- to 100-mm portion of the structure will be paved in another 55-hour closure, when the final lifts of the CSOL and Full-Depth AC Replacement sections are paved together. This paving plan will also result in a smoother riding surface for the entire project length.

6.0 EFFECTS OF CONSTRUCTION WINDOWS AND COMPARISON OF PAVING MATERIALS (CONCRETE AND AC)

6.1 Effects of Changing Construction Window

The basic construction window (55-hour weekend closure) was compared with two additional construction windows, “continuous closure/continuous operation (three shifts, 24 hours per day)” and “continuous closure/daytime operation (two shifts, 16 hours per day)” to see the effect of different construction windows on production capability. For all three of these construction windows, the time required to rebuild a 5-km segment of the freeway (one direction) was analyzed. As the freeway was assumed to have 4 lanes, the rehabilitation scope would be 20 lane-km if the CSOL option were applied, (i.e., the four main traffic lanes and shoulders on both sides are rehabilitated), or 10 lane-km if the Full-Depth AC Replacement option were applied (i.e., only the two truck lanes are replaced). For the continuous closure/daytime operation, it was assumed that the work progressed 7 days per week for 16 hours per day (two shifts). Lane closure tactics were assumed to be CSOL Full Closure Full Completion for the CSOL option and Full-Depth Single-Lane for the Full-Depth AC Replacement option.

Table 17 and Figure 37 show how many weeks or weekends were needed to accomplish this 5-km hypothetical rehabilitation project for each proposed construction window. The duration of the continuous closures is in weeks, while the unit of the weekend closure is number of 55-hour weekends required to complete the project length. In the case of the CSOL option, using Profile “A” as an example, continuous closure/continuous operation can finish the project within 1.2 weeks (8 days), while using only weekend closures requires 4.2 weekends to complete the same project. In case of the Full-Depth AC Replacement option, using Profile “A” as an

Table 17 Comparison of the Effect of Different Construction Windows

	Number of Weeks or Weekends Required to Complete Rehabilitation			
Design Profile	**CSOL**		**Full-Depth AC**	
Layer Profile	**Profile "A"**	**Profile "B"**	**Profile "A"**	**Profile "B"**
Thickness	**230 mm (9 in.)**	**200 mm (8 in.)**	**330 mm (13 in.)**	**406 mm (16 in.)**
Weekend Closure	4.2	3.7	4.8	5.9
Continuous Closure (16 hrs./day, 2 shifts)	1.8	1.6	2.1	2.6
Continuous Closure (24 hrs./day, 3 shifts)	1.2	1.1	1.4	1.8

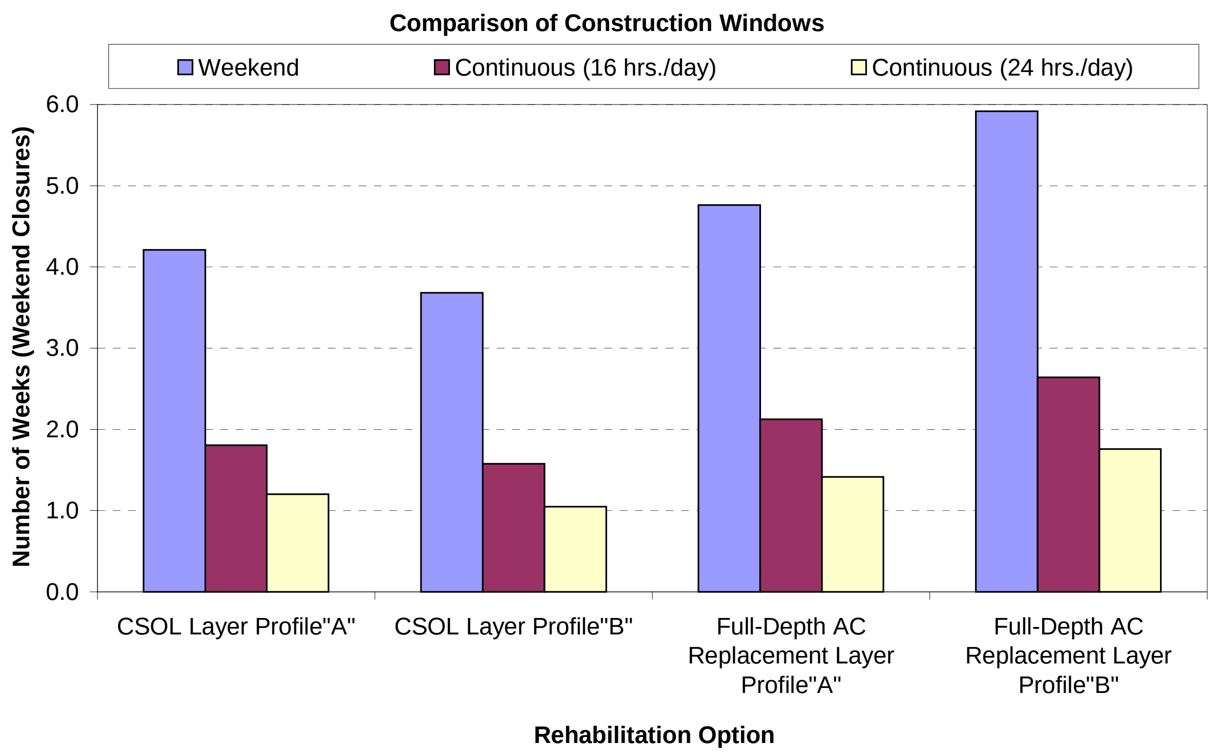


Figure 37. Comparison of the effect of different construction windows.

example, continuous closure/continuous operation can finish the project within 1.4 weeks (10 days), while using only weekend closures requires 4.8 weekends to complete the same project.

The continuous closure/daytime operation (two shifts, 16 hours per day) took about 50 percent longer than the continuous closure/continuous operation for both CSOL and Full-Depth options. The Full-Depth AC Replacement option took slightly longer than the CSOL option for all the construction windows because the scope of the Full-Depth AC Replacement rehabilitation is greater than that of CSOL. Full-Depth AC Replacement includes demolition, paving, and a new thicker pavement whereas CSOL doesn't include the demolition and removal of material nor does it have as thick a pavement profile. On the other hand, for Full-Depth AC Replacement, there are fewer lanes to be rehabilitated, usually only the two truck lanes, while for CSOL four lanes plus two shoulders must be paved.

Continuous closure/continuous operation enables the CSOL project to be finished 15 percent faster and the Full-Depth AC Replacement project to be finished 12 percent faster compared to weekend-only closures. However, continuous closure/continuous operation may not be realistic for many projects due to weekday traffic interruptions as well as additional costs, noise problems for nearby residents, and logistics. With continuous closure/daytime operation (two shifts), the net project duration was still shorter than weekend-only closure, but more inconvenient to the public because the total closure duration of the freeway for continuous closure/daytime operation was longer than that for the weekend closure, as presented in Figure 37.

6.2 Effect of Paving Shoulders for CSOL

As mentioned in Section 2.3.2, CSOL has two options for paving the shoulders on both sides, (i.e., pre- or simultaneous paving option). The comparison of production capability for both options during a 55-hour weekend closure is summarized in Table 18. For comparison, CSOL Full Closure Full Completion was assumed for both options.

Table 18 Comparison of Production Capability of CSOL Rehabilitation Option During a 55-hour Weekend Closure, Effect of Paving Shoulders

	Production During 55-hour Weekend Closure (Lane-km)		
Shoulder Paving Option	**Simultaneous paving option**		**Pre-paving option**
Paved shoulder width	**3.0 meters**	**2.0 meters**	**N/A**
CSOL Profile “A”	4.8	5.3	6.7
CSOL Profile “B”	5.4	6.0	7.7

For both layer profiles (Profile “A” and “B”), the simultaneous paving option with the 3.0-meter shoulder width is about 40 percent less productive than the pre-paving option. The simultaneous paving option with 3.0-meter shoulder width is about 10 percent less productive than the 2.0-meter shoulder width case.

As there is no delay due to AC cooling for either option, the production difference between the options is basically proportional to the width of the shoulders to be overlaid. A tradeoff exists between the increased safety risk to road users and the greater production capability of rehabilitation because the accident risk of the pre-paving option, even with K-rails or MCB in place, is much greater than that of the simultaneous paving option.

6.3 Comparison of Concrete and Asphalt Concrete Rehabilitation

As the constructability evaluations and analyses for both paving materials, [i.e., hydraulic cement concrete (LLCPRS) and asphalt concrete (LLACPRS)], are completed, the issue of the production capability of LLPRS that remains is how much more productive one rehabilitation (paving) material is than the other for a given freeway configuration and design profile. Road agencies are struggling with this fundamental question in developing the strategies for urban pavement rehabilitation.

Comparing AC and concrete production capability directly is difficult because too many different variables are involved in the analysis for each rehabilitation material. Furthermore, each analysis model has different aspects of rehabilitation such as: design criteria, rehabilitation methodology, traffic delay with respect to lane closure tactics, and initial and life cycle cost for rehabilitation. Therefore, a systematic approach is required to select the optimized design and construction strategy for the given location and traffic situation.

More detailed reasons why a direct comparison of production capability for the two rehabilitation materials is neither practical nor realistic except on a project-by-project base are:

1. The pavement structures for each strategy depend on the location of the project. It is therefore not adequate to simply compare the two rehabilitation materials using two equivalent thicknesses. The pavement structures required for a given location depend on expected truck traffic, climate, existing pavement structure, and subgrade. The ratio of thicknesses between concrete and AC strategies is therefore not constant. The cross-sections for both AC and concrete options have to be designed using the same assumptions to determine the required thicknesses.
2. Lane closure tactics vary from project to project. Each rehabilitation strategy requires different lane closure tactics. In addition, the flexibility of the lane closure tactics depends on the number of available lanes and local traffic delay restrictions.
3. The construction window utilized (for example, 7- or 10-hour nighttime closure, 55-hour weekend closure, or continuous closure) also plays a role in determining which strategy is the best for a particular location.

Road agencies must reconcile all these aspects in strategy selection. Therefore, a direct comparison of the production capability for AC and concrete should be implemented on a project by project based on the actual rehabilitation scheme and constraints of the project in question. Because of the above reasons, a production comparison between the two rehabilitation materials with a hypothetical assumption of resource constraints and lane closure tactics is unrealistic and serves no useful purpose.

7.0 CONCLUSIONS AND RECOMMENDATIONS OF THE AC CONSTRUCTABILITY ANALYSIS

This report describes the processes and results of a constructability and productivity analysis performed to evaluate the Caltrans Long Life Asphalt Concrete Pavement Rehabilitation Strategies (LLACPRS). Two pavement design profile options are considered in this constructability analysis: a Crack, Seat and AC overlay (CSOL) and Full-Depth AC Replacement of the existing PCC pavement. Listed below are the conclusions of the analyses described in this report followed by recommendations.

7.1 Conclusions

Various rehabilitation methods were selected for this constructability analysis based on extensive consultation with the asphalt paving industry and Caltrans. These methods were then organized into a hierarchical structure of analysis options. Two different layer profiles, Layer Profile “A” the Layer Profile “B”, were selected as spanning a typical range of layer profiles by the UCB Pavement Research Center (PRC) for the purpose of checking the impact of different layer profiles. These layer profiles were compared for both CSOL and Full-Depth AC Replacement. Different lane closure tactics such as Full Closure versus Half Closure for CSOL and Double-Lane versus Single-Lane Rehabilitation for Full-Depth AC Replacement were also compared.

1. **Caltrans production capability objective.** The objective of the Caltrans LLACPRS to rehabilitate 6 lane-kilometers of truck lanes (3 centerline-kilometers) within a 55-hour weekend closure has a low probability of success. Only 30 percent of this objective could be met with the Full-Depth AC Replacement design profile, and 50 percent (counting two truck lanes rehabilitated) with the CSOL design profile.

However, the negative aspect of the CSOL option is that the net centerline-meters of freeway rehabilitated within one weekend closure is less than half of the total rehabilitation work that could be completed for the truck lanes only because all of the traffic lanes (truck and passenger lanes) as well as the shoulders should be overlaid.

2. **Impact of pavement profiles to the production capability.** In the case of the CSOL production capability, an extra AC lift reduced the production capability by 12 percent (Layer Profile “B” of 200 mm versus the Layer Profile “A” of 230 mm). This production capability difference was proportional to the two profiles’ total overlay thickness.

   For the Full-Depth AC Replacement case, the production capability for the Layer Profile “B” (406-mm thickness) was about 80 percent of the Layer Profile “A” (330-mm thickness) case, and this ratio was almost the same as the ratio of total replacement asphalt pavement between the two pavement profiles.

3. **Impact of lane closure tactics on production capability.** For CSOL, the Half Closure case enabled two more traffic lanes to be open than the Full Closure option, but was about 20 percent less productive than the Full Closure option due to time lost to AC cooling and traffic switching operations. This loss of paving operation hours could be avoided by adopting the CSOL Half Closure Partial Completion option, in which the paving suspension time for AC cooling is negligible. The performance of the pavement with only two AC lifts under a week of traffic should be considered before implementing this recommendation.

   For Full-Depth AC Replacement, Double-Lane Rehabilitation was about 10 percent less productive than Single-Lane Rehabilitation because of delays caused by AC cooling time.

4. **Impact of cooling time on production capability.** If multiple lifts (4 to 6) are scheduled to be placed on multiple lanes (2 to 4 lanes) within a weekend closure, the paving operation would have to be stopped if the AC cooling time was longer than the time it took to complete the AC lift.

   The results of the asphalt concrete constructability analysis showed that the AC cooling time depended on the lane closure tactics and pavement profile. It will also depend on the climate region of the project, and the time of year when paving is performed. In the case of CSOL, Full Closure did not have any time loss due to AC cooling, while the Half Closure had from 2 to 7 hours of delay for AC cooling. In the case of Full-Depth Replacement, 1 to 3 hours for Single-Lane and 6 to 7 hours for Double-Lane paving operation were lost to delay because of AC cooling. Efficient lane closure tactics along with adjustment of pavement profile will minimize non-working time and increase the production capability of the project. Flexibility in lift thicknesses within the limit of the total thickness permitted by the agency will aid in the development of efficient paving plans.

5. **Validation of CalCool program.** CalCool is a numerical AC cooling time simulation program developed to predict the temperature profiles in multiple lifts of an AC rehabilitation project. Several case studies conducted in California verified the creditability of this program for use in predicting the cooling rates of AC lifts.

7.2 Recommendations from the AC Constructability Research

This research developed an asphalt constructability analysis model with the purpose of: a) defining the typical processes of asphalt pavement rehabilitation, b) identifying the major constraints limiting the production capability of rehabilitation, and c) calculating the maximum production capability for a given number of resources. The following recommendations are based on the AC constructability analysis results and conclusions for LLACPRS:

1. **Recommendation of the most efficient lane closure tactics.** The most efficient lane closure tactic for CSOL is Half Closure Partial Completion, assuming that the impact on pavement performance of having two out of the four lifts of AC open to normal urban freeway traffic for one week is acceptable. The CSOL Half Closure case needs two fewer traffic lanes closed than the CSOL Full Closure option, but was only 20 percent less productive than the CSOL Full Closure case. Especially for the CSOL Half Closure Partial Completion option, almost the same amount of production capability as to CSOL Full Closure can be achieved.

   For Full-Depth AC Replacement, Single-Lane Rehabilitation is much more efficient than Double-Lane Rehabilitation. The negative aspect is that good interlock of the longitudinal joint between the two lanes will be difficult to obtain.
2. **Further case studies for the validation of the analysis model.** Case studies of several AC Rehabilitation projects, such as I-710 Project, should be conducted to validate the constructability analysis system described in this report. The case studies can aid in calibration of the analysis model so that it provides more realistic and accurate estimation of rehabilitation capability and comparison of strategies.
3. **Integration of the constructability analysis with a lifecycle cost analysis model.** The constructability analysis model described in this report is limited to the

consideration of the scheduling aspects of pavement rehabilitation to determine the maximum production capability. A more broad analysis model to cover cost aspects (i.e., direct construction cost for each of rehabilitation options and indirect cost from user delay cost) should be developed. This model should also permit evaluation of the tradeoffs between fast construction and the durability of the pavement structure to provide more comprehensive and systematic comparison of rehabilitation options.

4. **"Tight" production performance (planned) for the I-710 Project.** The predicted production capability from the asphalt analysis model for both CSOL and Full-Depth AC Replacement were compared with planned production performance for the I-710 Project. The comparison indicates that the current performance target of the I-710 Project looks feasible as long as no contingencies arise.

8.0 GLOSSARY AND NOMENCLATURE

The following sections define the terms and abbreviations used in this report.

8.1 Terms

CalCool:
A numerical AC cooling time simulation program developed to predict the temperature profiles in multiple lifts of asphalt concrete.

concurrent working method (concrete):
A concrete pavement rehabilitation method in which the demolition and paving activities of the rehabilitation proceed simultaneously, each with its own construction access lane. The concurrent working method has single- or double-lane paving methods as sub-options.

construction window:
A timeframe to carry out a rehabilitation project covering a segment of the freeway from mobilization of the project until opening the rehabilitated section to traffic. Three types of construction windows are explored in this analysis: weekend closure, continuous closure with continuous operation, and continuous closure with daytime operation.

continuous closure:
Continuous closure blocks several traffic lanes from the beginning to the end of the rehabilitation project. Two options are defined for the continuous closure: continuous closure/continuous operation in which the operation of the rehabilitation continues 24 hours with 3 shifts per day, and continuous closure/daytime operation in which work occurs over 1 or 2 shifts per day in order to save operation cost from nighttime operations.

AC cooling time:
The time to cool the asphalt concrete layer from delivery temperature (149°C = 300°F) to the specified stop temperature (74°C = 165°F).

CSOL (Crack, Seat and Overlay):
Crack, Seat and Overlay is a typical asphalt concrete pavement rehabilitation method. With this method, approximately 200 mm of hot mix asphalt concrete, typically in 4 lifts, is placed on an existing cracked and seated PCC pavement.

deterministic analysis:
Constructability analysis with input parameters treated as fixed numbers. *See also* ***stochastic analysis.***

Double-Lane Rehabilitation:
The Double-Lane Rehabilitation option (AC Rehabilitation) specifies that both truck lanes (T1+T2) are rebuilt in the same construction window instead of separating them into two separate weekend construction windows.

Full Closure:
A CSOL rehabilitation working method in which all lanes in one direction of the freeway (four lanes) are closed for rehabilitation at the same time.

Full Completion:
A **Half Closure** scenario for **CSOL** rehabilitation in which multiple lifts (four lifts) are placed on all lanes during the weekend closure.

Full-Depth AC Replacement:
A type of AC pavement rehabilitation in which the existing pavement structure, the PCC slab, CTB, and part of the aggregate base are completely replaced with AC (typically in six lifts).

Half Closure:
A type of **CSOL** rehabilitation working method in which half of the lanes in one freeway direction (typically two lanes) are closed while the other lanes are open to traffic. As soon as two lifts of AC paving are completed, traffic is switched to those lanes, and the other lanes may be paved.

linear scheduling method:
Linear scheduling is the planning and scheduling technique of the construction process with more than one activity in the same location at the same time (in some cases, to ensure work continuity of crews). When applied to a project with a geographically linear nature, such as highways, the technique has been called the linear scheduling method.

Layer Profile "A":
A pavement profile for **LLACPRS** proposed by the Pavement Research Center at the University of California at Berkeley. For **CSOL,** Layer Profile "A" is 230 mm (9 in.) AC in four lifts, while for **Full-Depth AC Replacement** the profile is 330 mm (13 in.) AC in five lifts. *See also **Layer Profile "B."***

Layer Profile "B":
A pavement profile for **LLACPRS** proposed by the Pavement Research Center at the University of California at Berkeley. For **CSOL,** Layer Profile "B" is 200 mm (8 in.) AC in four lifts, while for **Full-Depth AC Replacement**, the profile is 406 mm (16 in.) AC in six lifts. *See also **Layer Profile "A."***

LLACPRS
*see **LLPRS***

LLCPRS
*see **LLPRS***

LLPRS:
The abbreviation for Caltrans Long Life Pavement Rehabilitation Strategies, of which the objectives are to 1) provide 30+ years of service life, 2) require minimal maintenance, and 3) have sufficient production capability for 6 lane-km rehabilitation over a 55-hour weekend closure. LLPRS consists of two categories of rehabilitation in terms of paving materials: **LLCPRS** is LLPRS with Concrete and **LLACPRS** is LLPRS with Asphalt Concrete.

Partial Completion:
A **Half Closure** working method for **CSOL** rehabilitation in which only a part (typically the first two lifts) of the AC pavement profile (typically four lifts) is placed in all lanes during the first weekend closure. The remaining two lifts are placed during the second weekend closure.

sequential working method:
A concrete pavement rehabilitation method in which the demolition and paving activities of the rehabilitation cannot proceed simultaneously. Instead, the paving activity can start only after the demolition activity is finished. This scheme has single- or double-lane paving as sub-options. *See also* ***concurrent working method***.

Single-Lane Rehabilitation:
Single-Lane Rehabilitation is an AC Rehabilitation option in which paving is completed in one of the two truck lanes on the first weekend and the adjacent lane is paved during the following weekend closure.

stochastic analysis:
Constructability analysis with input parameters as random variables generated from a predefined PDF for each input parameter. *See also* ***deterministic analysis***.

weekend closure:
A freeway closure in which the traffic lanes needing rehabilitation or needed for construction access are closed for a 55-hour period over the weekend, i.e., from 10 p.m. Friday to 5 a.m. the following Monday.

8.2 Abbreviations

AB: Aggregate Base

AC: Asphalt Concrete

ADT Average Daily Traffic

Caltrans: California Department of Transportation

CSOL: Crack Seat and Overlay (Asphalt overlay)

CPM: Critical Path Method

CTB: Cement Treated Base

DOT: Department of Transportation

DT: Dump Trucks

EDT: End Dump Truck

HMA: Hot Mixed Asphalt

LLPRS: Long Life Pavement Rehabilitation Strategies

LLCPRS: Long Life Concrete Pavement Rehabilitation Strategies

LLACPRS: Long Life Asphalt Concrete Pavement Rehabilitation Strategies

MCB: Movable Concrete Barrier

PCC: Portland Cement Concrete

PDF: Probability Distribution Function

PRC: Pavement Research Center

QA/QC: Quality Assurance/Quality Control

SBT: Semi Bottom Dump Truck

SG: Subgrade

UCB: University of California at Berkeley

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