Constructability and Productivity Analysis for Long Life Concrete Pavement Rehabilitation Strategies

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CALIFORNIA DEPARTMENT OF TRANSPORTATION

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16. Abstract

One of the main objectives of the Caltrans Long Life Pavement Rehabilitation Strategies for rigid pavements (LLPRS-Rigid) is to have a construction productivity of approximately 6 lane-kilometers within a 55-hour construction window. This productivity objective must not conflict with the other two main LLPRS-Rigid objectives: to provide 30 plus years of pavement service life and to minimize pavement maintenance. This report describes the processes and results of a constructability and productivity analysis for the Caltrans LLPRS-Rigid project, focusing on optimizing the maximum production capability within a 55-hour weekend closure. The analyses explored the effect of the following parameters on the concrete pavement construction productivity in California: pavement design profile, curing time, number and capacity of resources, number of lanes to pave, type of construction scheduling, and alternative lane closure tactics. The typical construction processes for concrete pavement rehabilitation were modeled with input from California concrete paving contractors, Caltrans, and academia.

The constructability analyses indicated that the current proposed strategy to rebuild 6 lane-kilometer with 55 hours of weekend closure would have a low probability of success. Concrete curing time was found out to be the most critical activity for the production capability of pavement rehabilitation. Material delivery resources were the major constraints limiting the production capability of the rehabilitation.

The tools developed in this study can be used by Caltrans for calculating concrete pavement construction productivities for various construction strategies and traffic management scenarios in order to optimize the rehabilitation process from both a production and user delay perspective.

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EXECUTIVE SUMMARY

One of the main objectives of the Caltrans Long Life Pavement Rehabilitation Strategies for rigid pavements (LLPRS-Rigid) is to have a construction productivity of approximately 6 lane-kilometers within a 55-hour construction window. This productivity objective must not conflict with the other two main LLPRS-Rigid objectives: to provide 30 plus years of pavement service life and to minimize pavement maintenance. This report describes the processes and results of a constructability and productivity analysis for the Caltrans LLPRS-Rigid project, focusing on optimizing the maximum production capability within a 55-hour weekend closure. The analyses explored the effect of the following parameters on the concrete pavement construction productivity in California: pavement design profile, curing time, number and capacity of resources, number of lanes to pave, type of construction scheduling, and alternative lane closure tactics. The typical construction processes for concrete pavement rehabilitation were modeled with input from California concrete paving contractors, Caltrans, and academia.

Typical Critical Path Method (CPM) schedules for each design profile (i.e., 203-mm, 254-mm, and 305-mm slabs), together with lead-lag relationships between activities involved in the rehabilitation were generated from the information gathered. Sensitivity analyses were conducted to find which parameters constrained the production capability of the rehabilitation. The constructability analysis was performed using spreadsheet software designed to link all factors involved in the rehabilitation processes interactively.

The constructability analyses indicated that the current proposed strategy to rebuild 6 lane-kilometer with 55 hours of weekend closure would have a low probability of success (<15 percent of the options investigated) even when use of fast-setting hydraulic cement concrete was considered. Concrete curing time was found not to be the most critical activity for the production capability of the pavement rehabilitation. Material delivery resources, especially dump trucks for demolition (removal) and end dump trucks for concrete supply, were the major constraints limiting the production capability of the rehabilitation. The design profiles of the pavement structures [i.e., different thicknesses of the concrete slab (203, 254, or 305 mm)] also proved to be a major element influencing the production capability. Increasing the required concrete slab thickness from 203 to 305 mm reduced the production capability by about 50 percent. Two different working methods—concurrent or sequential—were experimentally designed for the analysis. The constructability and productivity analysis verified that these different working methods affected the construction productivity. A concurrent working method, in which demolition and paving activities were allowed to proceed simultaneously in order to secure the maximum duration of operations, was more productive than a sequential working method, in which paving could only commence after demolition was completed in order to minimize the lane closures. The number of lanes to be paved simultaneously (i.e., single or double lane) impacted the production capability. Double lane paving was more productive at a cost of closing one additional traffic lane. Changing the concrete curing time from 4 to 12 hours reduced the productivity by less than 20 percent.

To compare alternative strategies with respect to time to completion, the concurrent working method with double lane paving was the most efficient strategy for all pavement thicknesses and curing times. However, this excludes the effect of the construction closure on the traveling public. An inconvenience factor was developed to measure the length of time a certain strategy would close a facility (lane-weekends closed). When the production capability was balanced with traffic inconvenience to the traveling public, it was determined that the sequential working method with double lane paving (closing 3 lanes) for thick pavements (254 and 305 mm) and the concurrent working method with double lane paving (closing 4 lanes) for thin pavements (203 mm) were the most optimal lane closure tactics. When comparing various construction windows, such as continuous closure with one, two, or three shifts operation per day and 55-hour weekend closure, it was found the continuous closure with two or three shifts operation was both the most productivity strategy and provided the least inconvenience to the public.

The tools developed in this study can be used by Caltrans for calculating concrete pavement construction productivities for various construction strategies and traffic management scenarios in order to optimize the rehabilitation process from both a production and user delay perspective.

1.0 INTRODUCTION

1.1 Problems of Aging Highway Systems

More than 90 percent of the total transportation volume in the United States relies on various highway systems (1). The highway systems in the United State include approximately 850,000 lane-kilometers of Portland Cement Concrete (PCC) pavements, with PCC pavements comprising over 50 percent of the Interstate System (2).

Unfortunately, a large portion of these highway systems has already carried much heavier traffic volumes and loads than their original designs permitted. Consequently, the serviceability of the transportation network has deteriorated significantly. The traffic overloading problem on the highway systems in the US has mainly resulted from "more demand than supply": the number of vehicles using the highway systems has increased by 75 percent while the highway systems have expanded by only 4 percent over last 20 years (1).

Highway agencies are facing another challenge that is not as glamorous as the initial construction of the highway system, but is of equal importance (3). Agencies are struggling with the problems of continuing to provide road users with reliable services in spite of ever increasing traffic volumes on the aged highway systems (4). Consequently, most federal, state, and local transportation agencies are turning their attention away from expansion of the highway systems to the maintenance and rehabilitation of the existing road network (5).

The deterioration of the highway systems has already started to adversely affect the safety of road users, ride quality, the operational cost of vehicles, and moreover, the cost of highway maintenance (2). As a part of efforts to cope with these aging and high traffic volume problems, many transportation agencies want to develop and implement rehabilitation and reconstruction strategies for the renewal of the freeway systems in a time of scarce resources by rationally selecting rehabilitation processes (5).

One of the difficulties of implementing rehabilitation or reconstruction of urban highway systems is working under heavy traffic volumes. Fast-track construction, a special type of construction in which construction methods and activities are planned so that the construction duration and the inconveniences to the traveling public are minimized, is normally adopted for major pavement rehabilitation projects (6).

1.2 Status of Pavement rehabilitation in California

In California, for example, the state highway system has over 24,000 centerline-kilometers of pavement with over 78,000 lane-kilometers. Approximately 75 percent of this system was built in the 15 years between 1959 and 1974. These pavements were designed for a 20-year service life based on traffic volumes and loads estimated at the time of design (7). Many highways in the state have been providing services for as much as twice their original design period.

The 1995 State of the Pavement Report indicated 22,500 lane-km (29 percent of the system) required corrective maintenance or rehabilitation, with 7,000 lane-km needing immediate rehabilitation. The 1995 report indicated that the number of lane-kilometers needing immediate rehabilitation had more than doubled from the 3,300 lane kilometers identified in the 1992 State of the Pavement Report. It has also been estimated that 80 percent of the rigid pavements needing rehabilitation are in urban areas in Southern California (7). Reducing the inventory of deteriorated pavement to about 7,000 lane kilometers and maintaining that level will allow Caltrans to maintain and rehabilitate the system at the lowest overall annual cost. As a part of the 10-Year SHOPP (State Highway Operation and Protection Program) Rehabilitation Plan, funding for construction of 3,000 lane-km of long-life pavement during the 10-year period (1998 through 2007) is planned (8).

Currently, faulting is the most prevalent distress occurring in Caltrans rigid pavements. Transverse cracking, corner cracking, and longitudinal cracking are also present in the Caltrans network. Axle loads and the number of trucks on the design lanes will undoubtedly increase over the next 30 years. Designs that may have worked in the past may not be sufficient in the future. Designs that did not provide adequate performance in the past will deteriorate even more quickly under the increased loading (9).

1.3 Caltrans Long-life Pavement Rehabilitation Strategies (LLPRS) Objectives

A need was identified to develop lane replacement strategies that would not require long-term closures associated with conventional PCC pavement construction. Furthermore, these strategies were intended to provide longer service lives than the currently assumed design life of 20 years. Initially, Caltrans required development of strategies for rehabilitation of concrete pavement that met the following objectives (10):

1. Provide 30+ years of service life,
2. Require minimal maintenance,
3. Have sufficient production capability to rehabilitate or reconstruct about 6 lane-km within a construction window of 55 hours (10 p.m. Friday to 5 a.m. Monday).

1.3.1 Questions to Be Answered

The selection of optimal rehabilitation procedures and strategies for deteriorating highway pavements requires knowledge of the type and cause of the distress, determination of candidate rehabilitation procedures, and selection of optimal strategy based on economic and other considerations (2).

A number of questions were formulated in developing Caltrans Long-Life Pavement Rehabilitation Strategies (LLPRS). The constructability analyses in this report were designed to address each of the following questions:

- Is 6 lane-km concrete pavement rehabilitation within a 55-hour weekend closure realistic given the constraints currently present in a typical urban freeway in California? If the analysis shows that 6 lane-km cannot be rebuilt within 55 hours, then what is the maximum production capability and what are the constraints? What is required in terms of construction duration and the number and capacity of major resources to rebuild 6 lane-kilometers?

- What are the major constraints limiting the production capability of the rehabilitation? These should be identified and evaluated in order to develop technical or political innovations as solutions to overcome these constraints. One of the subsequent concerns related to this is whether the curing time of concrete controls the production capability of the rehabilitation. What increase in project length does the contractor achieve with a fast-setting hydraulic cement concrete (decreased curing time)? How much does the resource availability influence the production capability?

- Finally, what are the most important innovations? The most important innovations, i.e., those that have the biggest payoff for more production capability, should be identified. The most efficient rehabilitation methods should be developed as the result of an economic analysis integrating scheduling, construction cost information, user delay costs, and the intended life of the pavement structures.

Ultimately, the rehabilitation approach should be selected on a project by project basis given the constraints involved. The development of this type of construction productivity analysis allows for simple evaluation of multiple variables in a reasonably short time frame. This will facilitate the final decision making process by the agency and reduce the probability of a less than optimal rehabilitation strategy.

1.4 Research Approach

The research for the constructability analysis of Caltrans LLPRS reflects the industry practices of concrete pavement rehabilitation in California. Figure 1 shows how the communications between parties involved for the analysis were developed with respect to the process of information. The following list outlines the major processes and methodologies required for the constructability analysis of the concrete pavement rehabilitation:

- Principles and guidelines for the constructability analysis, such as construction windows and paving materials, were supplied by Caltrans. Initial plans and strategies for the analysis were developed by the Pavement Research Center (PRC) at the University of California at Berkeley.

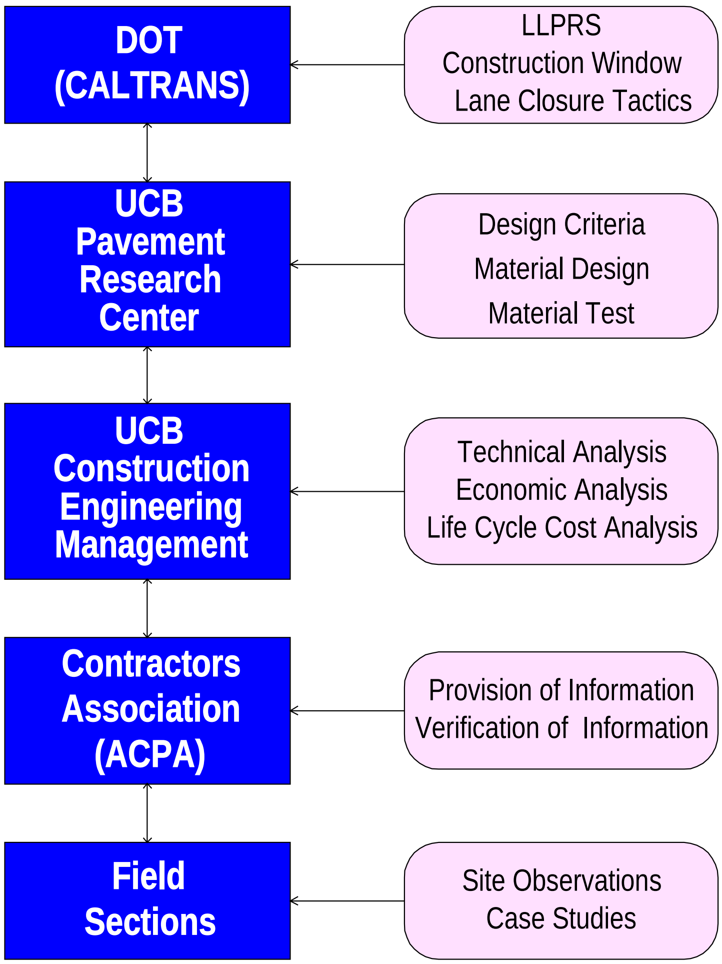


Figure 1. Information requirements for the construction analysis.

- Technical information for pavement structures, such as design profiles and concrete curing time, was provided by the PRC.
- In order to make the outcomes of the analysis more practical and realistic, a series of meetings were held between the research team and the Western States Chapter of American Concrete Pavement Association (WSCACPA), a concrete pavement industry group. The following information was sought through meetings with several California concrete paving contractors through WSCACPA:

  - typical processes of pavement rehabilitation
  - lead-lag relationships between activities
  - major constraints limiting the production capability of the rehabilitation
  - capacity of major resources needed for the rehabilitation
  - areas where innovations will pay off

- Generalized rehabilitation strategies would be selected based on the information collected from the construction analysis team and software developed to handle analysis and sensitivity studies of parameters involved in the construction process.

- A hierarchical structure of the constructability analysis was designed covering the level of categories of the analysis such as construction window, paving material, design profile, curing time, and working method, etc.

- Spreadsheet software was created to handle the constructability analysis by interactively and automatically linking all factors defined in the hierarchical structure of the analysis. Specifically, the software uses a linear scheduling technique as an analysis tool to deal with resource constraints for the rehabilitation. The software was designed to return 1) the maximum production capability of the rehabilitation in tables and graphs, 2) the sensitivity of the production capability to the input parameters, and 3) a comparison of different construction windows in terms of rehabilitation schedule.

1.5 Scope of Research

This report describes the details of the constructability analysis for Caltrans LLPRS. This report will look at how variables such as construction duration, construction methods, resources, number of paving lanes, pavement structure, etc. will affect the concrete paving production. The analysis described in this report is limited to the rehabilitation of concrete pavement structures. The constructability analysis is deterministic, i.e., the number and capacity of resources involved in the rehabilitation processes are fixed. An initial deterministic approach quickly indicates the major constraints and the maximum production capability. The future plan is to develop stochastic approaches by treating information about the resources as random variables.

2.0 EXPERIMENT DESIGN

2.1 Assumptions

In order to simplify the analysis of typical rehabilitation strategies, the following assumptions were made by the construction team to decrease the number of independent variables:

a) Construction window is 55 hours (10:00 p.m. Fri. to 5:00 a.m. Mon.).

b) Traffic barriers are installed prior to the weekend construction window: K-rails or rubber cones.

c) A centralized batch plant is available for use in the construction.

d) Slab is pre-cut and ready for removal by the contractor.

e) No subgrade preparation is required.

f) Replacement of truck lanes (most cases 2 lanes) only.

g) Truck lane adjacent to the shoulder shall be widened to 14 feet.

h) The new base shall be cemented treated (CTB).

i) Dowel bars installed in transverse joints do not affect construction productivity, i.e., dowel baskets or dowel bar inserters result in same paving production.

j) Rehabilitated truck lanes will be tied to existing adjacent slab at longitudinal joints, but will not affect the overall paving production.

k) The concrete opening strength to traffic shall be 400 psi (flexural).

l) Access to the construction site shall not be influenced by any external activities, (e.g., traffic congestion, accidents, haul time), won't affect productivity of the paver.

m) Concrete material selection, for example fast-setting hydraulic cement concrete, will not have an adverse effect on paving production.

n) Nighttime work operations have the same productivity as daytime operations as well as weekday versus weekend operations.

2.2 Hierarchical Structure of the Analysis

After comprehensive literature reviews and communications with the Concrete Pavement Association in California, the research team identified the potential elements most likely to affect the production capability of the pavement rehabilitation, shown in Table 1. Based on these elements, an experiment design for the constructability analysis of LLPRS was schematically developed, as shown in Figure 2. This diagram presents a hierarchical structure of the analysis, where each element is compared with other options available in the factorial design. The layout of the experimental design consists of two main parts:

i) upper part of Figure 2, as shown in Figure 3, details the options analyzed from the design point of view,

ii) lower part, as shown in Figure 4, indicates options analyzed for each design profile from construction point of view.

A more detailed description of the available options along with comparisons between the various elements is summarized in Section 2.3.

Table 1 Major elements affecting the production capability of the rehabilitation

<table>
<tr><th>Category</th><th colspan="2">Options</th></tr>
<tr><td rowspan="3">Construction Window</td><td colspan="2">Weekend Closure (Continuous Operation (3 shifts))</td></tr>
<tr><td rowspan="2">Continuous Closure</td><td>Continuous Operation(3 shifts)</td></tr>
<tr><td>Daytime Operation (1 or 2 Shifts)</td></tr>
<tr><td rowspan="2">Paving Material</td><td colspan="2">Concrete (Fast Setting or Ordinary PCC)</td></tr>
<tr><td colspan="2">Asphalt Concrete</td></tr>
<tr><td rowspan="5">Design Profiles</td><td rowspan="3">Concrete</td><td>203-mm Slab</td></tr>
<tr><td>254-mm Slab</td></tr>
<tr><td>305-mm Slab</td></tr>
<tr><td rowspan="2">Asphalt Concrete</td><td>CSOL (Crack Seat and Overlay)</td></tr>
<tr><td>Full Depth A/C Replacement</td></tr>
<tr><td rowspan="4">Curing (or Cooling) Time</td><td rowspan="3">Curing Time
(Concrete)</td><td>4 hours (Fast Setting Cement)</td></tr>
<tr><td>8 hours (Intermediate)</td></tr>
<tr><td>12 hours (Ordinary PCC)</td></tr>
<tr><td>Cooling Time (A/C)</td><td>Depends on thickness of lift</td></tr>
<tr><td rowspan="2">Working Method
(Concrete and Full depth AC)</td><td colspan="2">Concurrent Working Method</td></tr>
<tr><td colspan="2">Sequential Working Method</td></tr>
<tr><td rowspan="2">Number of Paving Lane
(Concrete only)</td><td colspan="2">Single Lane Paving</td></tr>
<tr><td colspan="2">Double Lane Paving</td></tr>
</table>

2.3 Construction Window

Three typical options for the construction window are developed and compared from a scheduling point of view.

i) Weekend closure

ii) Continuous closure/continuous operation with three 8-hour shifts

iii) Continuous closure/daytime only operation with one 10-hour shift or two 8-hour shifts

The analysis is mainly focused on the weekend closure construction window as a baseline. The other construction window options enable direct comparisons of time required to

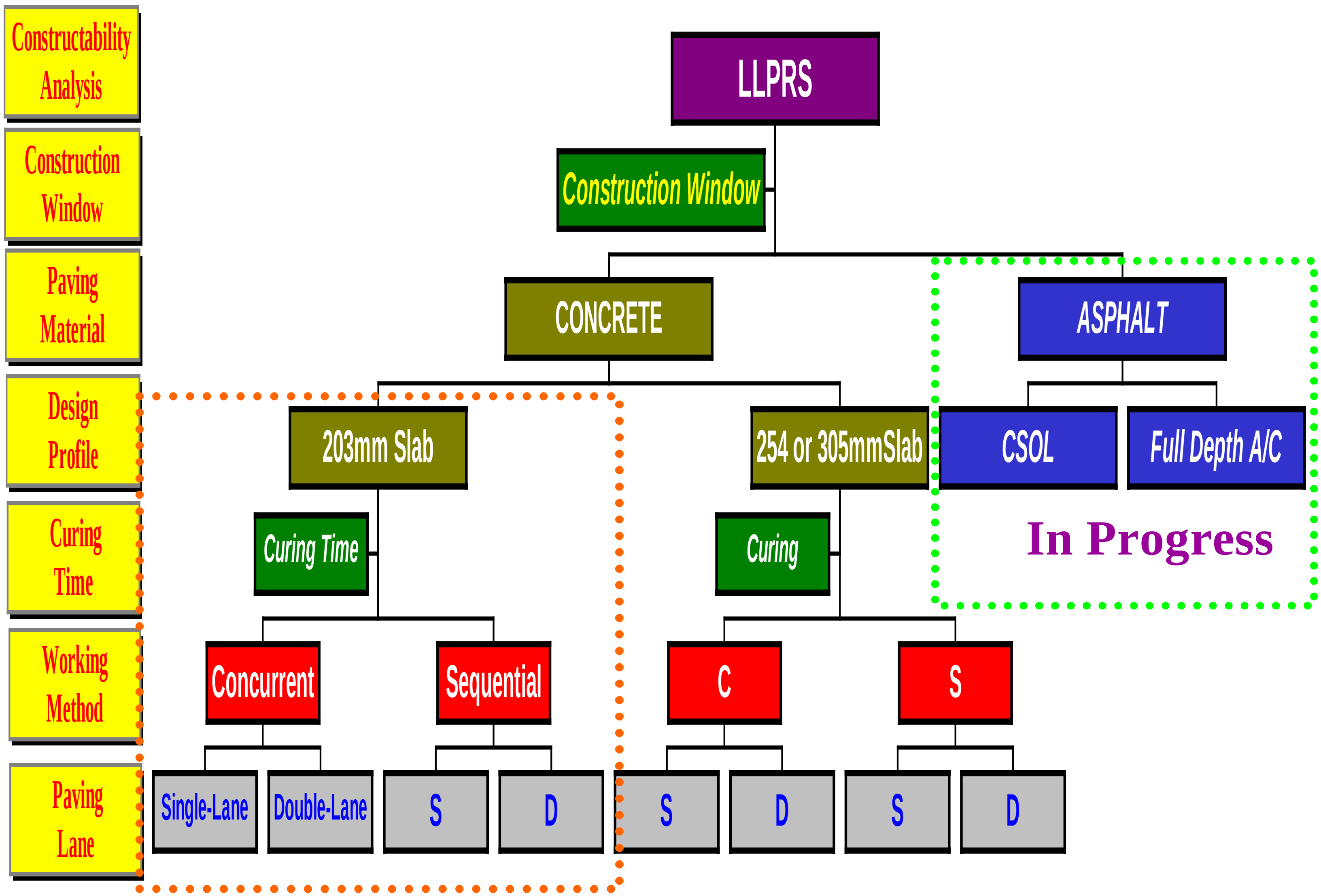


Figure 2. Hierarchical structure of the constructability analysis.

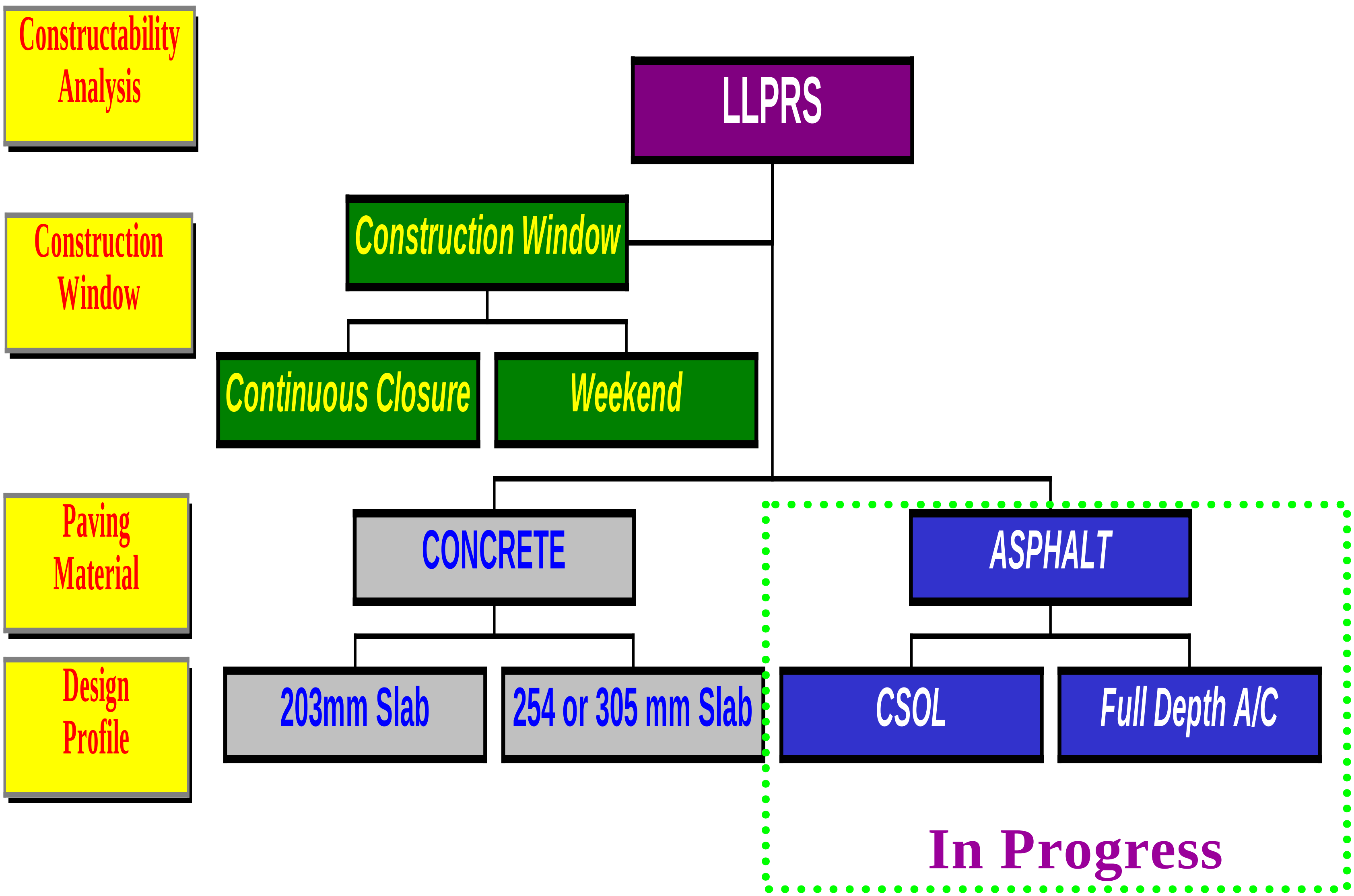


Figure 3. Criteria of the analysis from design point of view.

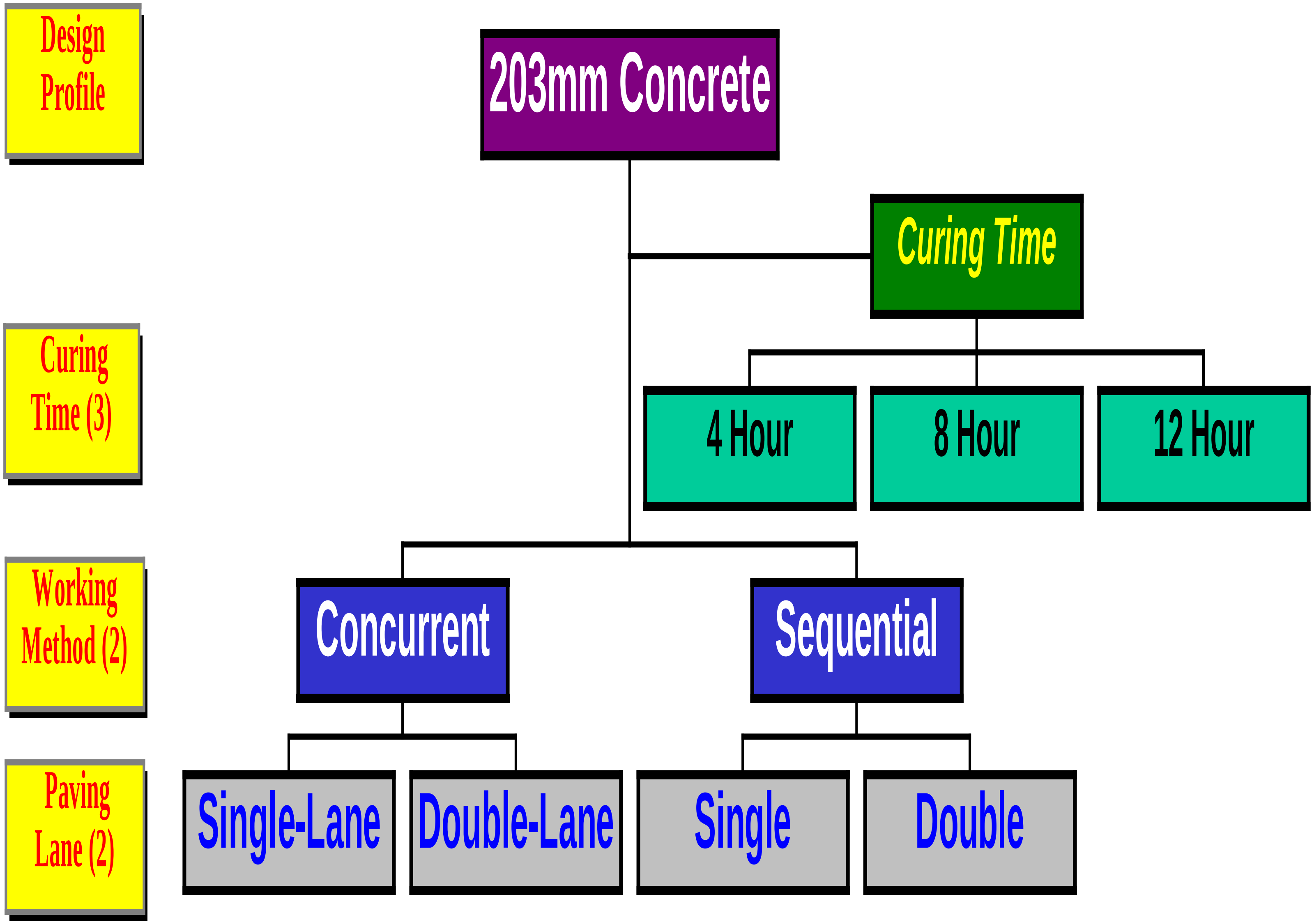


Figure 4. Options analyzed for each design profile for concrete rehabilitation.

complete a particular length of pavement rehabilitation project, i.e., continuous versus weekend only closures. The terms "weekend closure," "continuous closure," and others are defined in the Glossary included in this report.

2.3.1 Weekend Closure

The primary goal of the weekend closure is to minimize traffic interruption during the work week by implementing a rehabilitation project on the weekend. Caltrans initially set the weekend closure time of 55 hours (Friday 10:00 p.m. to the following Monday 5:00 a.m.) in order to avoid construction delays during weekday hours. However, a weekend closure strategy has some disadvantages from a scheduling viewpoint:

- *Repeated mobilization and demobilization.* A significant amount of time is wasted for repetitive mobilization and demobilization during weekend closures.
- *Curing time requirements.* At the end of the construction window, curing time is required for concrete strength gain before opening the freeway to traffic. Curing time does not become an issue in a continuous closure except at the end of the construction. However, during weekend closures, curing time is lost at the end of every weekend construction window to allow for concrete strength gain before opening to traffic.
- *Securing resources on the weekend only.* The weekend closure requires mobilizing resources such as labor, demolition, and paving trains including hauling and delivery trucks. To secure these resources only on the weekend is much more expensive and inefficient from the contractor's point of view. Labor costs on the weekend are

approximately 50 percent greater than regular weekday costs and will most likely not be as productive. A tradeoff between less traffic interruption and a more expensive operation will be optimized in the future.

- *Less overall productivity during nighttime operations* (11)

2.3.2 Continuous Closures (Continuous or Daytime Only Operation)

A continuous lane closure keeps traffic off the newly constructed lanes until the paving has been finished by the contractor. Although weekend closures may appear to reduce overall traffic interruptions, continuous closures could serve as an alternative strategy for reconstruction and will reduce the total time required to finish the required project.

The major advantage of a continuous closure is the ability to maximize working hours without the time loss of repeated mobilization/demobilization and delay for concrete strength gain on weekend closures. Two options for the continuous closure are considered:

- Continuous lane closure/Continuous construction operation (3 shifts).
- Continuous lane closure/Daytime only construction operation (1 or 2 shifts).

Although the continuous closure/continuous construction operation has benefits mentioned above, this scheme has some disadvantages from contractor’s point view such as:

1. reduced production for nighttime operation can be as much as 35 percent (11)
2. increased safety hazards for workers during nighttime operation because of visibility, and

3. 3 shift per day work is a more costly operation and requires that labor and equipment be available in sufficient quantities to keep it going.

In order to minimize these concerns, a continuous closure/daytime only operation with one 10-hour shift or two 8-hour shifts is considered as an alternative option. In the continuous construction window, the rehabilitated lanes are closed until the project is completed.

2.4 Concrete Pavement System

2.4.1 Material Selection

There are two major paving materials that can be used for pavement rehabilitation: concrete and asphalt concrete. Each material has its advantages and disadvantages for use in highway construction. Both materials can give adequate long-term pavement performance if the pavement structure is designed, constructed, and maintained correctly. Caltrans long-life pavement rehabilitation strategies (LLPRS) include both concrete and asphalt concrete strategies. For this analysis, the construction productivity of urban pavement rehabilitation using concrete will be explored.

2.4.2 Concrete Type

Concrete pavements have traditionally used Portland cement concrete (PCC). Two of the Caltrans LLPRS objectives were to minimize lane closures and construct 6 lane-km of pavement over a 55-hour weekend closure. Given that most of the long-life pavements are located in urban environments, Caltrans began exploring alternative materials to meet their LLPRS objectives.

Fast-setting hydraulic cement concrete (FSHCC) products were available that could achieve traffic opening strengths in 4 hours. Caltrans proposed using FSHCC to allow for extra paving time that could not be attained when using normal PCC due to its slower setting time and strength gain. Caltrans started experimenting with FSHCC to complete concrete pavement repairs during night closures in southern California. FSHCC had also been employed to accelerate bridge retrofitting after the Northridge earthquake.

2.4.3 Concrete Curing Times

As part of the University of California at Berkeley laboratory testing plan, concrete materials with different curing times are being evaluated. The three main categories of concrete are those that can be opened to traffic at 4 hours, 8 hours, and 12 hours after final finishing. Typically, the opening strength requirement has been 400 psi flexural strength using Caltrans Test Method 523. In general, Portland cements will not be able to consistently achieve opening strength at curing times less than 8 hours. For curing times less than 8 hours, FSHCC will most likely be the material of choice. For curing times greater than 12 hours, Portland cement concrete will be a better economic choice.

2.4.4 Concrete Pavement Design

A recent report submitted to Caltrans by Harvey et al. concluded most new concrete pavements in California would require thicknesses between 203 to 305 mm (8 to 12 inches), based on a mechanistic-empirical design procedure (9). The reasons for the wide range in pavement thicknesses were mainly the range of truck traffic levels, the different climatic zones in

California, slab lengths, design concrete strength, and proposed design features. For example, if a widened lane (4.3 m) or tied concrete shoulder can be used, then the pavement thickness can be reduced. However, corridor constraints may require conventional plain jointed concrete without these design features resulting in slightly thicker pavements.

Results from non-destructive evaluation of the underlying base and subgrade materials may also impact the final pavement structure. Changes in the pavement structure such as removal of the existing base and replacement with new treated base or stabilization of the subgrade will increase the time required to rehabilitate the freeway. Selection of the appropriate design features will be a project by project decision, therefore construction strategies have to be selected on a project by project basis. However, a constructability analysis must be completed on a range of design options to determine the sensitivity of parameters to concrete pavement productivity.

Although it was assumed for this study that replacement bases would be CTB, it is likely that UCB will recommend other base types to improve pavement performance. The constructability analysis and conclusions presented in this report should not be significantly impacted by this change of assumptions.

2.4.5 Change of Design Profiles

Three different slab thicknesses (203, 254, and 305 mm) were selected for the constructability analysis as typical design profiles for proposed LLPRS projects. Figure 5

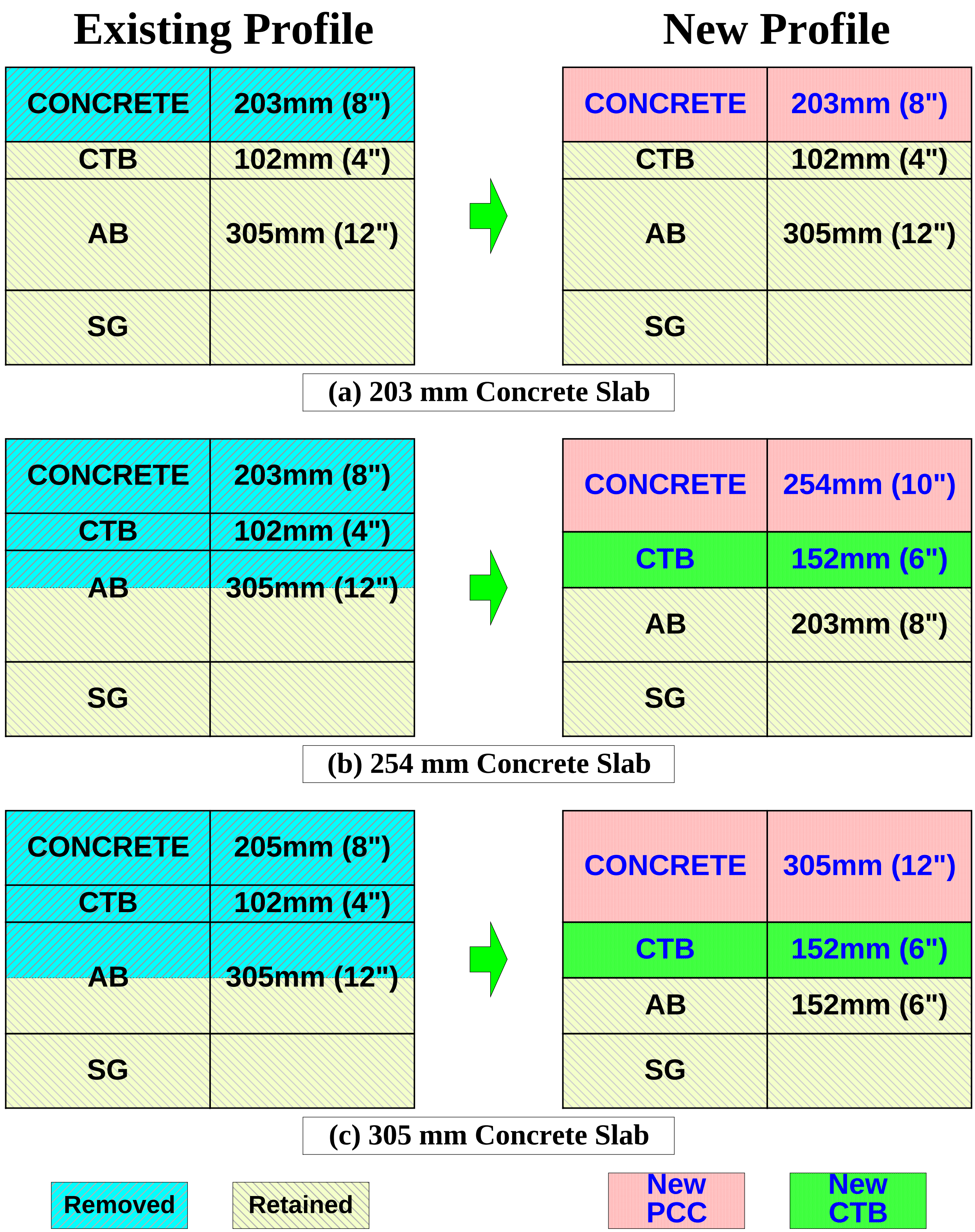


Figure 5. Change of design profiles for different slab thickness.

illustrates the change of section (design) profiles between the existing and new pavement structures for each slab thickness. The rehabilitation process for each design profile is as follows:

1. For new 203-mm slabs, only the existing slab will be replaced with the same thickness of new slab. This assumes the base, subbase, and subgrade are in satisfactory condition.
2. For new 254-mm slabs, the existing 203-mm slab and 102-mm CTB layer will be replaced with a new 254-mm slab over a 152-mm CTB layer. One third of the aggregate subbase (ASB) will be removed to accommodate the new, thicker slab and CTB.
3. For new 305-mm slabs, the existing 203-mm slab and 102-mm CTB layer will be replaced with a new 305-mm slab over a 152-mm CTB layer. Similar to the 254-mm slab case, the entire existing slab and CTB together with half of the aggregate subbase (ASB) will be removed to introduce a thicker slab and CTB.

2.5 Working Method and Number of Paving Lanes

To simplify the analysis, the number of lanes in one direction on a typical California urban freeway was assumed to be four. As shown in Figures 6 and 7, each lane is named P1 for passenger lane 1, T1 for truck lane 1, and S1 for shoulder 1, etc. Two out of the four lanes were assumed to be truck lanes. These existing two truck lanes will be replaced with the same thickness of concrete slab (203 mm) or a thicker slab (254 or 305 mm) depending on the design traffic volumes and desired design features (dowels, widened lane, tied concrete shoulder, etc.).

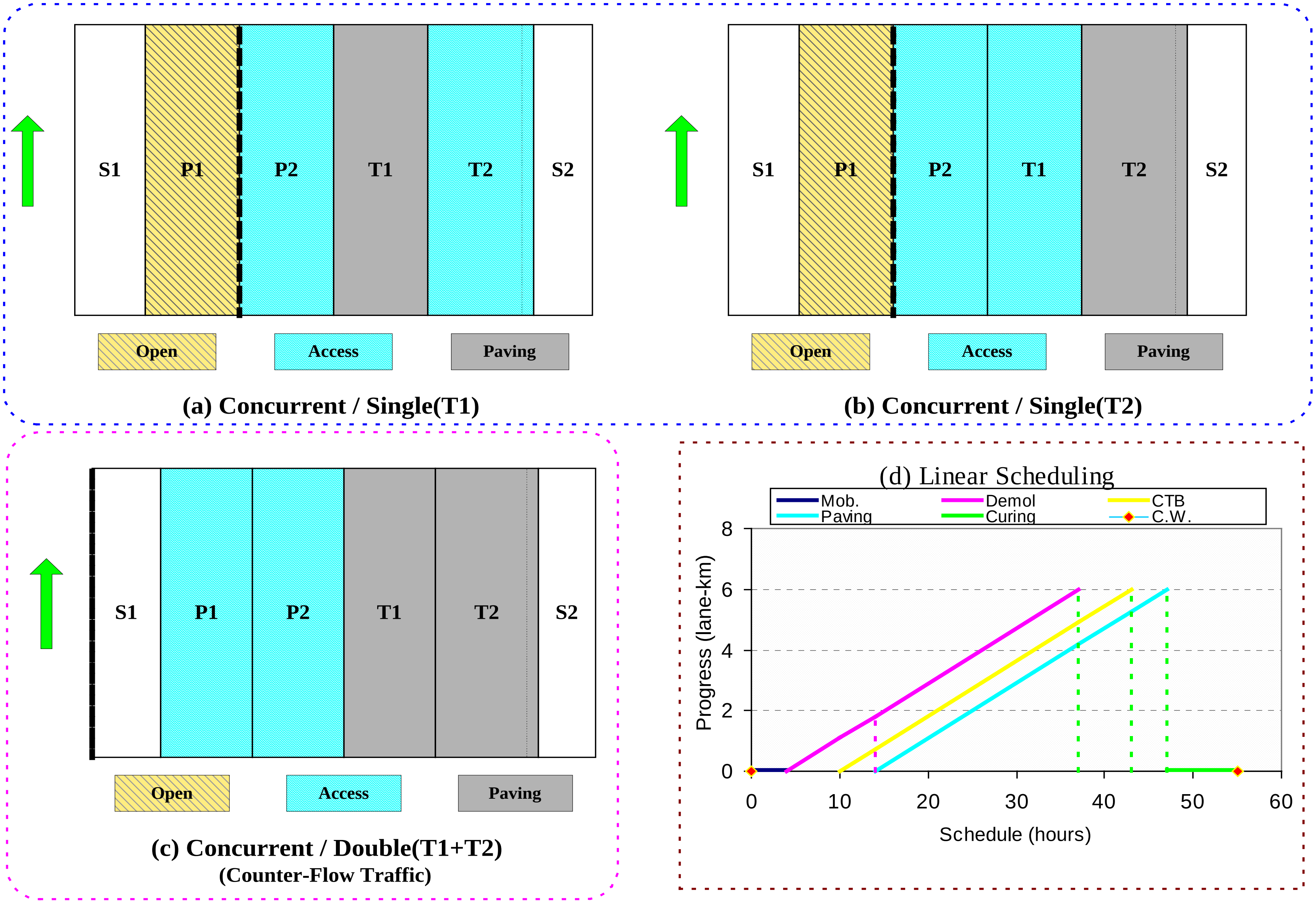
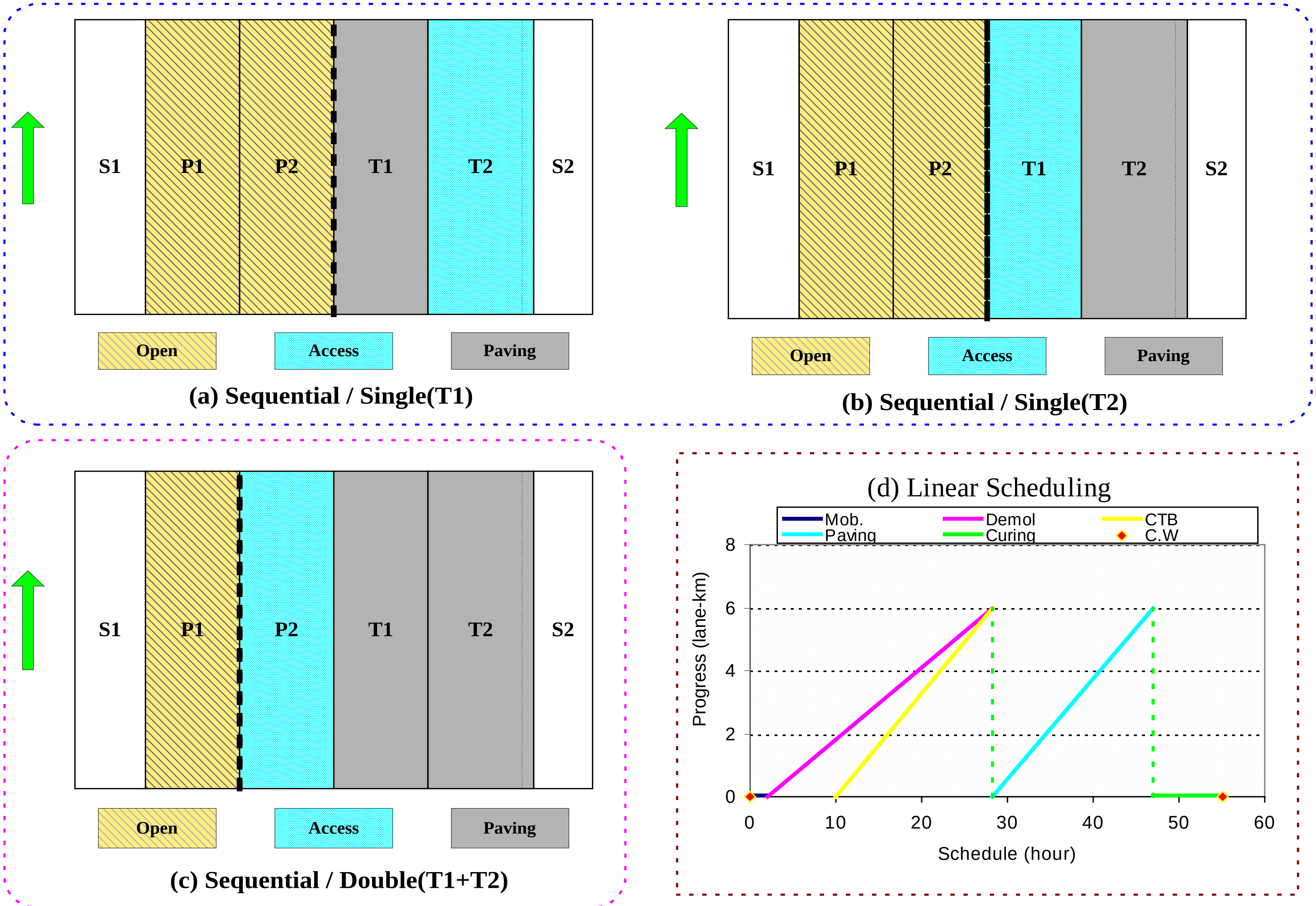


Figure 6. Work plan for concurrent working method.



(a) Sequential / Single(T1)

(b) Sequential / Single(T2)

(c) Sequential / Double(T1+T2)

Figure 7. Work plan for sequential working method.

Based on several communications and discussions with concrete paving contractors in California, two basic alternatives are defined to carry out the concrete pavement rehabilitation:

- **Concurrent working method**, as shown in Figure 6 and
- **Sequential working method**, as shown in Figure 7.

The basic distinction between the two schemes is whether demolition of the existing slab and paving of the new slab pavement can proceed simultaneously (concurrent) or the paving cannot begin until the demolition is completed (sequential).

2.5.1 Concurrent Working Method

In the concurrent working method case, two major activities, demolition and paving, can be performed in parallel with each activity having its own construction access, i.e., their own access lanes. As shown in the "Linear Scheduling" chart in Figure 6d, paving activity can start a certain number of hours after demolition activity began in order to minimize potential interruption between two activities. Although the demolition and paving activities have their own lane of access, the paving operation can catch up with the demolition operation because paving is more productive if only one demolition crew is operating. For a 203-mm slab, an 8-hour time lag time should be allotted between demolition and paving. For a 254- or 305-mm slab, a 10-hour lag time should be allowed between demolition and concrete paving. This time lag provides a 6-hour gap between demolition and CTB installation and a 4-hour lag between CTB installation and the concrete paving train.

Due to the concurrent construction operation, the interruptions between construction equipment, (e.g., loader, hauling trucks, paving machine, and delivery trucks), can be avoided or minimized by providing the demolition and paving activities with their own access. Hauling trucks for demolitions should run through their assigned lane, for example passenger lane 2 (P2) in Figure 6a, while concrete delivery trucks should drive through the other assigned lane, for example truck lane 2 (T2). Two sub-options for the concurrent working method, in terms of the number of lanes paved simultaneously, were analyzed as follows:

- Single lane paving
- Double lane paving

Rehabilitation (demolition and paving) can be carried out lane by lane (single lane paving) or both truck lanes together (double lane paving). Single lane and double lane paving are applicable for both the concurrent and sequential working method, as explained in more detail in the following sections.

2.5.1.1 Single Lane Paving

As shown in Figures 6a and 6b, blocking three lanes is required for concurrent paving with single lane replacement. On the first weekend, truck lane 1 (T1) is rebuilt concurrently for the planned length of segment, for example 6 lane-km, with lanes P2 and T2 serving as access for demolition and paving, respectively (Figure 6a). As the concrete gains specified flexural strength, typically 400 psi, the freeway is opened to traffic at the end of a 55-hour of weekend closure. On the second weekend, three lanes are closed again to rebuild truck lane 2 (T2) with lane P2 used for demolition and T1 (newly rebuilt last weekend) for paving train access (Figure 6b).

2.5.1.2 Double lane paving

The other option is double lane paving, as shown in Figure 6c, in which both truck lanes (T1+T2) are rebuilt together instead of one lane at a time. Demolition and paving of both truck lanes (T1+T2) can proceed concurrently by assigning P1 and P2 for demolition and paving access, respectively. A major disadvantage of the double lane paving option is that one direction of the freeway has to be closed.

The Washington Department of Transportation found that more production was achieved on the rehabilitation of I-405 when one direction of the freeway was fully closed (full rather than partial closure) (12). Furthermore, a recent study done in the Seattle, WA area found that the public overwhelmingly preferred total closures versus partial closures as long as the work was completed faster (13). Some of the advantages of double lane paving over single lane paving are listed below:

1. *Higher paver production.* If the speed of the paving machine is a major constraint limiting the production capability of the rehabilitation for single lane paving, double lane paving can achieve more production until the next constraining resource governs construction. In double lane paving, the paver needs to run only half of the distance of a single lane operation to achieve equivalent lane-km production.
2. *Simpler installation of tie bars.* As two truck lanes are constructed simultaneously, the installation of tie bars between the longitudinal contraction joint of the two lanes can be done during the paving operation. For single lane paving, tie bars have to be drilled and grouted into the newly paved truck lane 1 prior to re-constructing truck lane 2. Consequently, double lane paving can save a significant amount of time and cost over single lane paving due to the effort required for the installation of tie bars.

3. *Better quality control of longitudinal joint.* The quality of the longitudinal contraction joint between the two truck lanes is likely much higher if the two truck lanes are constructed simultaneously. In addition, the potential for damaging the newly built truck lane during demolition of the adjacent truck lane disappears for double lane paving. Furthermore, the risk of damaging the newly rebuilt truck lane by drilling and grouting tie bars during single lane paving is much higher than for double lane paving in which the tie bars are installed during the slip-form paving operation. Lastly, a longitudinal contraction joint should perform better than a longitudinal construction joint due to the added aggregate interlock between the two lanes.

2.5.2 Sequential Working Method

For the sequential working method, demolition and paving activities cannot take place simultaneously as only limited construction access is assigned in order to minimize interruptions in the regular traffic lanes. Unlike the concurrent working method, paving can only start after demolition and CTB installation are completed, as indicated in the “Linear Scheduling” chart in Figure 7d. Therefore, the demolition and paving activities must share one lane of construction access sequentially, i.e., first demolition and then paving. One positive aspect of sequential construction is that one more lane is open for freeway traffic as compared to the concurrent working method.

Similar to the concurrent method, the sequential method has two sub-options in terms of the number of paving lanes, i.e., single lane and double lane paving.

2.5.2.1 Single lane paving

As shown in Figure 7a, closure of only two lanes is required to rebuild truck lane 1 (T1). Because demolition and paving activities use truck lane 2 (T2) for access, the hauling trucks utilized for demolition must be complete their work before the concrete delivery trucks can begin supplying the paver. The closed lanes are open to the traffic as soon as the planned project length for truck lane 1 (T1) is completed. Truck lane 2 (T2) is rebuilt on the following weekend closure after truck lane 1 (T1) is completed. Truck lane 2 (T2) is reconstructed by using the newly rebuilt truck lane 1 (T1) as the construction access (Figure 7b).

2.5.2.2 Double lane paving

Similar to the "Concurrent/Double" method, truck lane 1 and 2 (T1+T2) can be rebuilt simultaneously with double lane paving (Figure 7c). Lanes T1 and T2 are reconstructed at the same time by using lane P2 as the access lane, first for demolition and then for paving.

Compared with single lane paving, double lane paving using the sequential working method has the same benefits as described above for concurrent method, i.e., more production capability, simpler installation of tie bars, and better quality control of longitudinal joint.

2.6 Construction Resource Constraints

The following resources are the major constraints limiting the production capability of pavement rehabilitation from the equipment point of view.

- Capacity of batch plant for concrete production

- Capacity and number of hauling trucks for demolition
- Capacity and number of concrete delivery trucks for concrete supply
- Speed of paving machine for concrete paving
- Capacity and number of concrete delivery trucks for CTB installation (254- and 305-mm options)

Table 2 shows the capacity and maximum number of resources used in the constructability analysis in order to calculate the maximum production capability of rehabilitation within a 55-hour weekend closure. Based on the information gathered from contractors, the capacity and number of resources listed in Table 2 are fully maximized relative to current construction practices in California. Due to the minimum loading and unloading time of 20 dump trucks per hour (demolition) per demolition crew and 20 end dump trucks per hour (concrete delivery) per paver, more truck resources currently cannot be increased. It is very difficult to add more trucks (>20) arriving every hour to this analysis unless further innovations are developed to shorten the 3-minute cycle time per truck.

Table 2 Number and capacity of resources used in the analysis

				Resource Constraints	
Resources	**Unit**	**Capacity**		**Concurrent**	**Sequential**
Batch Plant	m^3/hour	1	Each	200	200
Dump Truck (Demo)	per hour	25	Ton	20	20
End Dump Truck (PCC)	per hour	9	m^3	20	20
Paver Speed	m/min.	1	Each	3	3
End Dump Truck (CTB)	per hour	9	m^3	13	13

The following two constraints need to be further evaluated in the future to obtain a more realistic productivity analysis:

- *Turn-around time of trucks.* In this analysis, a certain number of dump trucks and end dump trucks per hour are assumed to be constantly available to the rehabilitation project. The actual turnaround time from batch plant to site for concrete delivery and from site to disposal area for demolition are not considered in this analysis. In reality, the turnaround time should be treated as a variable depending on the traffic condition. This will greatly affect the number of trucks arriving per hour onto the construction site. This impact will be evaluated as a stochastic (probabilistic) analysis by treating turnaround time as a random variable and will be compared with the result of the current analysis, i.e., a deterministic analysis.

- *Maximum number of trucks that can be mobilized.* The total number of trucks mobilized for a rehabilitation project should be determined by the required number of trucks per hour and their turnaround time. For 3-shift operation, potential limiting factor is the maximum number of trucks that can be mobilized in a weekend for a given region. In many cases, delivery and demolition trucks are owner-operators and three times as many trucks may be needed to meet the required truck demands on the construction site for 3-shift operation. For example, 20 trucks per hour is assumed in this analysis as a maximum number of resources, but if the turnaround time is predicted as two hours, then 40 trucks (20×2) should be mobilized to maintain 20 trucks per hour on site. Furthermore, if all trucks in the 3 shifts are owner-operators, then the total number of trucks becomes 120 (40×3). Consequently, when the total number of trucks mobilized is limited by locations or situational constraints, then the production capability of the rehabilitation is likely reduced.

2.7 Productivity Analysis Process

The process of the constructability analysis is summarized in Figure 8, and is described below in more detail. The input parameters set below can be easily changed depending on the objectives and constraints of a given project. The parameters selected below reflect the proposed rehabilitation process Caltrans is exploring for long-life concrete pavements in urban corridors.

1. **Set the rehabilitation project length as a production objective: 6 lane-km**

2. **Set up a construction window: 55 hours**

3. **Select paving material: Concrete versus asphalt concrete**

4. **Choose design profile: 203, 254, or 305 mm**

5. **Determine curing time: 4, 8, or 12 hours**

6. **Compare working method: Concurrent versus sequential working method**

7. **Consider number of lanes to be paved: Single versus double lane paving**

8. **Carry out CPM (Critical Path Method) scheduling.** One of the main purposes of CPM scheduling is to generate relationships between activities involved in the rehabilitation, especially demolition, paving, and curing time. CPM scheduling provides the maximum available working hours for the main activities, i.e., demolition and paving activities for a given concrete curing time.

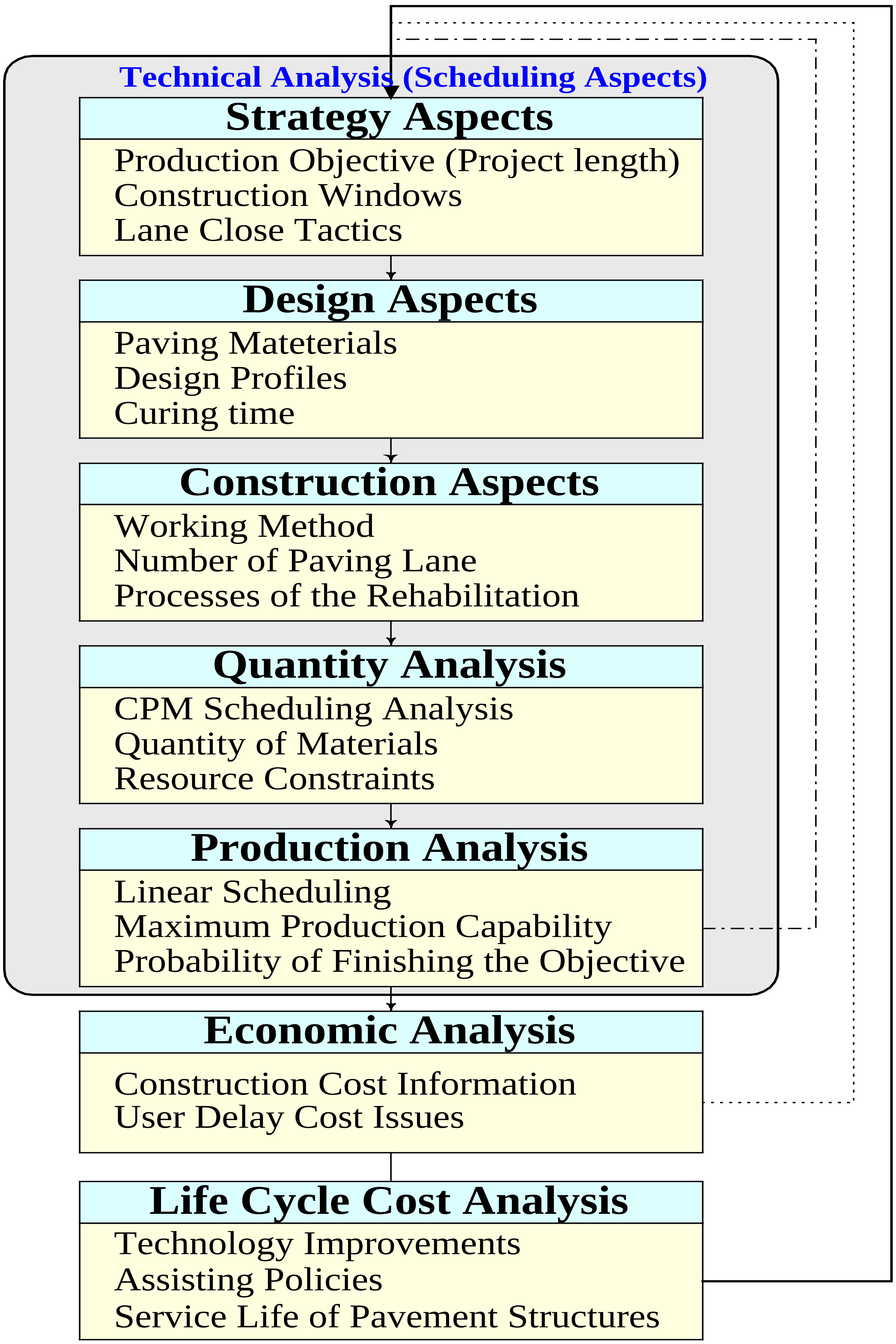


Figure 8. Process of the constructability analysis.

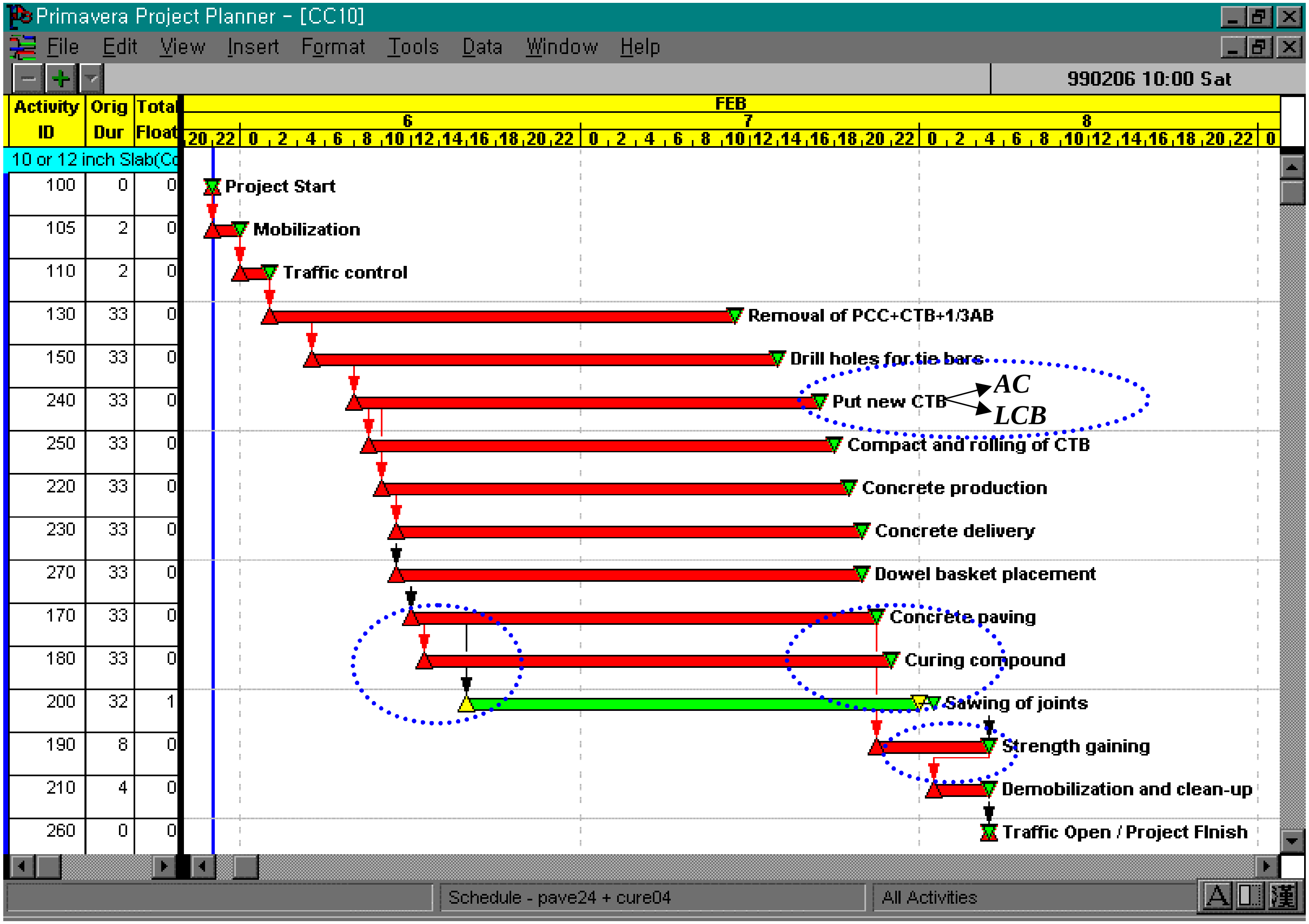


Figure 9. Typical CPM schedule for concurrent working method (254-mm or 305-mm slab).

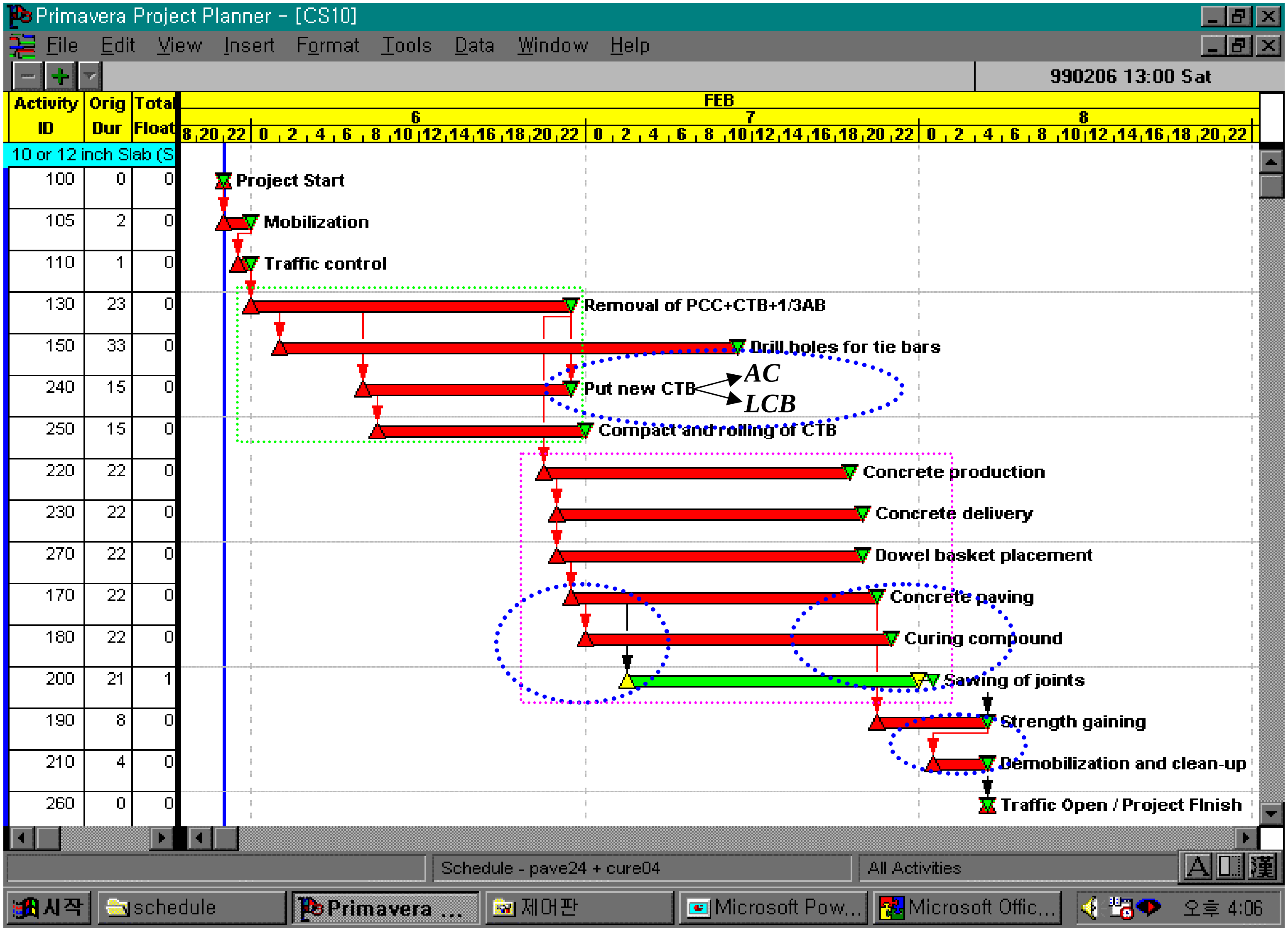


Figure 10. Typical CPM schedule for sequential working method (254-mm or 305-mm concrete slab).

Figures 9 and 10 show typical examples of CPM scheduling for the concurrent and sequential working methods, respectively.

Some of the following assumptions were made in the CPM scheduling:

a. Four hours of overlap were assumed between concrete strength gain and demobilization/clean up in order to maximize the working hours of the rehabilitation.

b. The sawing of the transverse and longitudinal joints in the new concrete slab should initiate as soon as a certain level of strength is reached in order to maximize the duration of the sawing activity.

c. Although CTB is the most commonly used base material in California, the CTB can be replaced with other alternatives such as AC (asphalt concrete), LCB (lean concrete base), or RCC (roller compacted concrete). One benefit of AC over CTB is that AC paving requires its own resources (plant and trucks) which would not conflict with the production and delivery of concrete to the construction site. One disadvantage of LCB versus CTB or RCC is that LCB needs a significant amount of curing time (minimum 8 hours) before the contractor can drive delivery trucks on it. This will slow down the production capability of the rehabilitation because it reduces working time available for the concrete paving.

9. **Calculate quantity of materials.** Table 3 shows the quantity of main materials required to complete 6 lane-km of concrete pavement rehabilitation for different slab thicknesses and working methods, i.e., demolition and concrete and CTB paving.

Table 3 also shows the total working hours required for each major activity and the quantity of materials that need to be handled per hour.

10. **Determine resource number and capacity.** The number and capacity of the major resources needed to complete 6 lane-km, i.e., batch plant capacity, number of dump trucks for demolition, number of end dump trucks for concrete delivery, and speed of the paver, are shown in Tables 4 and 5 for single and double lane paving, respectively.

Table 3 Quantity of major materials to be handled for 6 lane-km of the rehabilitation (single lane paving)

Slab Thickness		203 mm Concrete		254 mm Concrete		305 mm Concrete	
Materials		Concurrent	Sequential	Concurrent	Sequential	Concurrent	Sequential
Demo-lition	Quantity (m^3)	5,203		10,405		11,706	
	Hour	35	19	33	26	33	26
	Qty./Hour	149	268	315	396	355	458
Concrete	Quantity (m^3)	5,203		6,503		7,804	
	Hour	35	26	33	19	33	19
	Qty./Hour	149	204	197	347	236	401
CTB	Quantity (m^3)	0		3,902		3,902	
	Hour	0	0	33	18	33	18
	Qty./Hour	0	0	118	214	118	214

Table 4 Resources needed to rebuild 6 lane-km within 55-hour weekend closure (single lane paving)

Slab Thick.	**203mm Concrete**		**254mm Concrete**		**305mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
B-P(m^3/hr)	148	203	197	347	236	400
D-Truck(per hr.)	14	26	30	38	34	44
E-D-T(per hr.)	16	22	22	38	26	44
Paver(m/min.)	2.7	4.0	3.0	5.5	3.0	5.2

Table 5 Resources needed to rebuild 6 lane-km within 55-hour weekend closure (double lane paving)

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
B-P (m^3/hr.)	138	201	183	322	220	373
D-Truck (per hr.)	13	22	28	35	32	41
E-D-T (per hr.)	15	22	20	35	24	41
Paver (m/min.)	1.5	2.17	1.5	2.7	1.5	2.4

11. **Apply resource constraints.** The number of resources per hour per operation is limited by the minimum time for loading and unloading of the materials. For example, the number of dump trucks per hour for demolition cannot be increased above 20 in practice because the excavator cannot on average load trucks in less than 3 minutes. Table 2 indicates the maximum number of resources and capacity used in this analysis. The total number of resources to be mobilized is a separate issue subject to other circumstances such as turnaround time of the trucks and the number of shifts per day to be worked during the rehabilitation operation, as explained in Section 2.6.

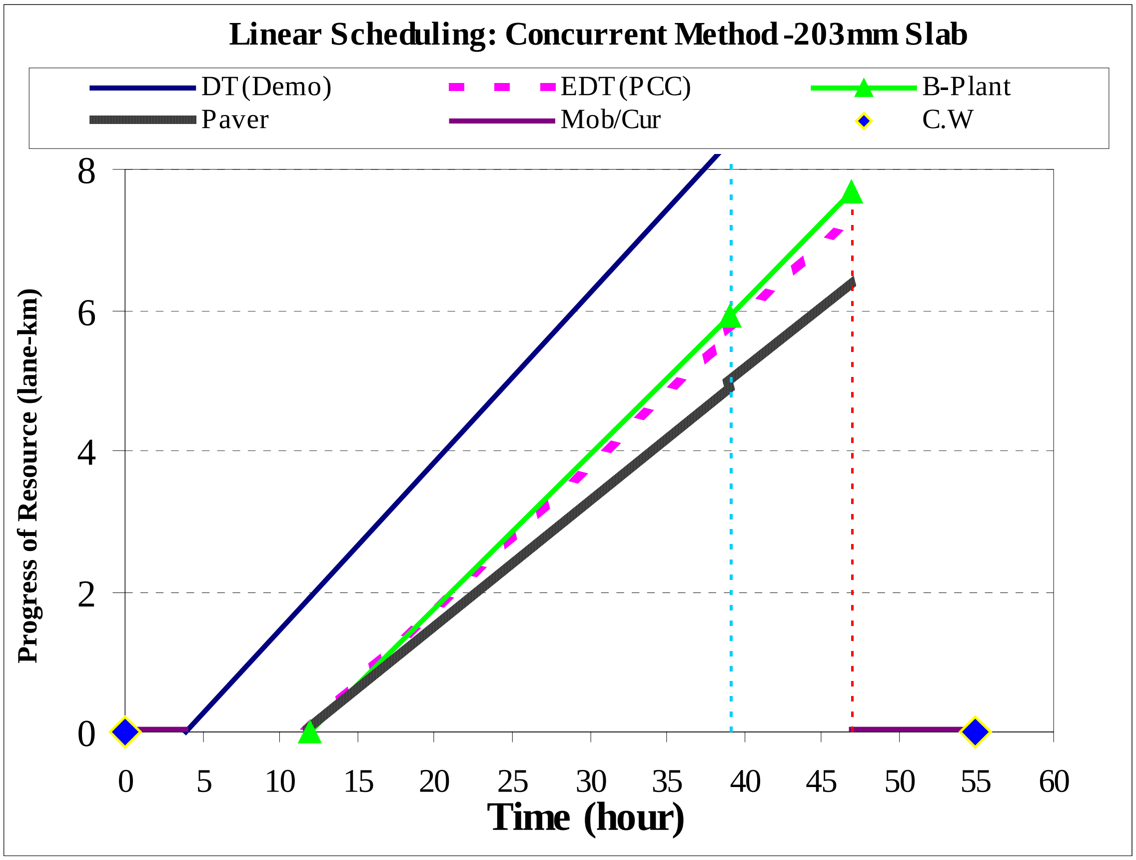
12. **Introduce linear scheduling.** Linear scheduling methods, described by Vorster et al. (14) and Johnston (15), are introduced into the analysis to obtain the maximum production capability of the rehabilitation given the resource constraints with different resource progress and to identify redundant resources:

> *"Linear construction projects are projects that involve repetitive operations. Projects that have these characteristics are highways, tunnels, pipelines, and high-rise buildings. In such projects it is important to plan*

and schedule the construction process to prevent the occurrence of 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 geographical linear nature, such as highways, the technique has been called the linear scheduling method (14). One axis of the scheduling diagram plots time, while the perpendicular axis plots location along the length of the project. When planned work activities are plotted, the result is a series of diagonal lines. The progress of each activity at any location along the length of the project is easily compared to one another. The location of work underway on a given date is defined in the schedule (15).”

Figures 11 and 12 show examples of linear scheduling plots for two options included in this study. The overall production capability of the rehabilitation is limited either by the production capability of the demolition or paving operation. In fact, the production capability of the demolition and paving is controlled by the individual resource involved (e.g., dump trucks, end dump trucks, batch plant, or paver) that makes the least progress. The concept of linear scheduling figures out the overall production capability of the rehabilitation controlled by the progress of the individual resources involved, as shown in Figures 11 and 12 for concurrent and sequential working methods, respectively.

The objective of linear scheduling is to obtain maximum production capability and to identify redundant resources, as shown in Figure 13. Linear scheduling allows the contractor to balance and optimize the progress of the individual resources to achieve an overall maximum production capability. Especially for the sequential working method, linear scheduling balances the allocation of time sharing between demolition and paving activities with the given number of the resources available per hour. Linear scheduling indicates the most constraining resource limiting the overall production capability. Once constraints are identified, then innovative strategies can be developed to increase the overall production capability.

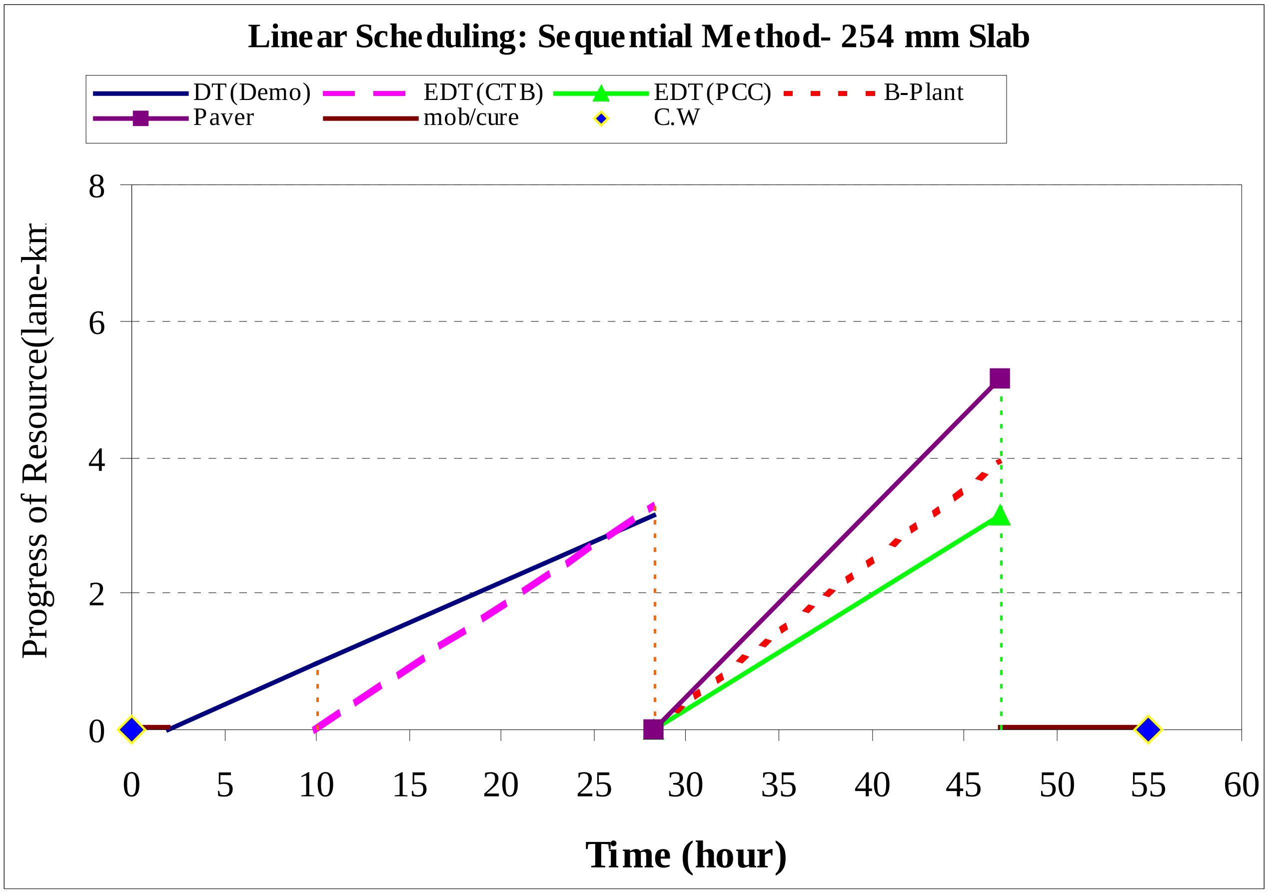


*. Resource Comparison Table

Resource	Plan	Needed
Dump Truck (Demo)	20	15
End Dump Truck (PCC)	20	17
Batch Plant (M^3)	200	160
Speed of Paver (M/min)	3.0	3.0
Demo, Pave(hours)	35	35

Maximum Production Capability = 6.4 lane-km

Figure 11. Linear scheduling for concurrent working method (single lane paving).



*. Resource Comparison

Resource	Plan	Needed
Dump Truck(Demo)	20	20
End Dump Truck(CTB)	13	12
End Dump Truck(PCC)	20	20
Batch Plant (M^3)	200.0	180.0
Speed of Paver (M/min.)	3.0	1.5
Demo, Pave (hours)	26.3	18.7
Demo:Pave Ratio	1	0.71

Maximum Production Capability = 6.4 lane-km

Figure 12. Linear scheduling for sequential working method (double lane paving).

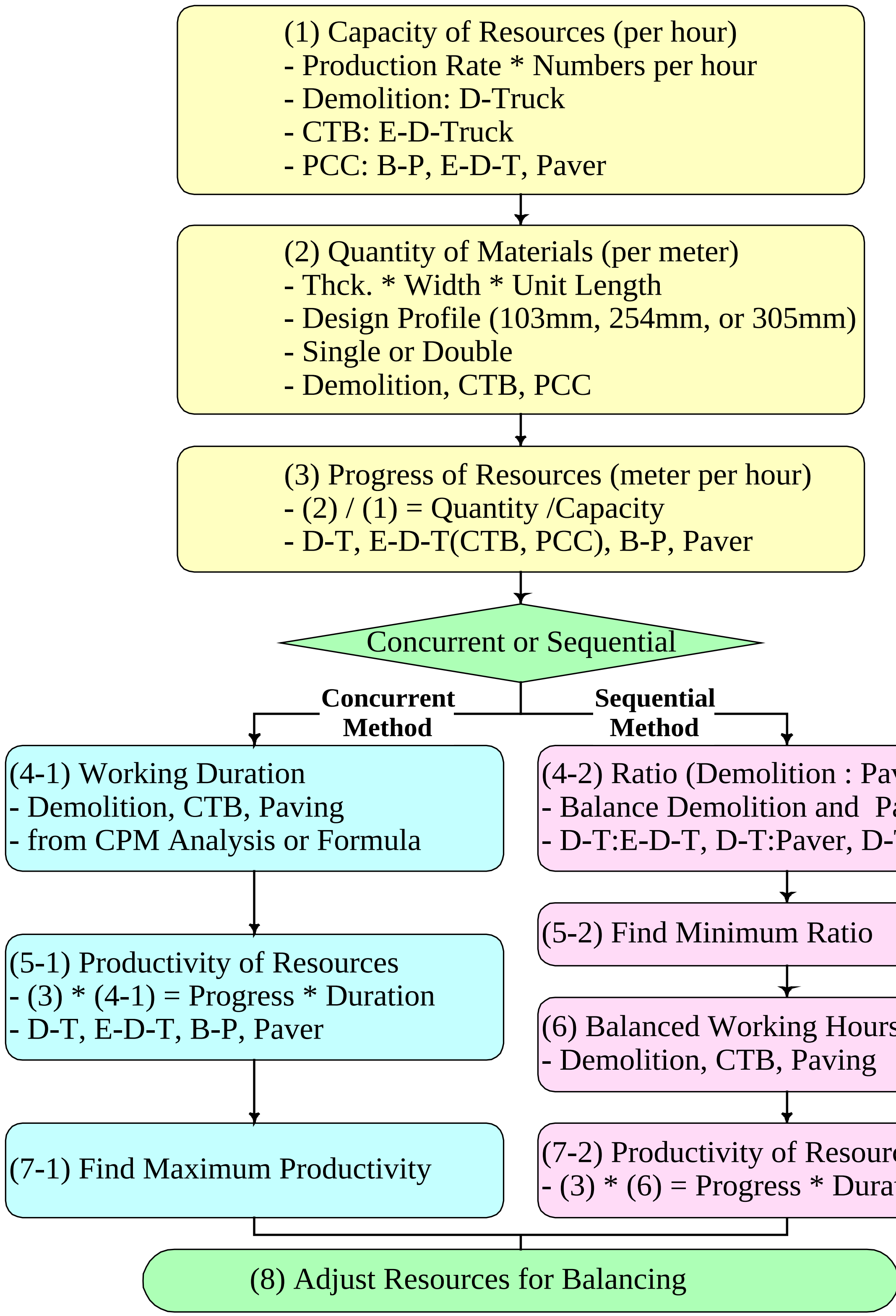


Figure 13. Processes of linear scheduling.

13. **Finalize maximum production capability.** Linear scheduling picks out the individual constraining resources at the maximum production capability for the rehabilitation for different design profiles, curing times, working methods, and paving lanes.

14. **Utilize the result of the analysis further for lane closure tactics and construction window options and for developing innovative construction strategies.**

3.0 STUDY RESULTS

3.1 Maximum Production Capability of the Rehabilitation

The primary question to be answered in the constructability analysis is "Can 6 lane-km be rebuilt within 55 hours?" Tables 6 and 7 provide the answer for the single and double lane paving methods, respectively, categorized by slab thickness, different curing time, and working method. Only 2 out of 18 options analyzed can meet the rehabilitation production objective of 6 lane-km for single lane paving and only 3 out of 18 options analyzed can meet the objective for double lane paving. Based on the results in Tables 6 and 7, the target of 6 lane-km rehabilitation within a 55-hour weekend closure has a low probability of success. Tables 8 and 9 are the maximum production capability of the rehabilitation for single and double lane paving, respectively, in terms of lane-km. These two tables were used to answer the question posed in Tables 6 and 7.

Table 6 Can 6 lane-km be rebuilt within 55 hours of weekend closure? (single lane paving)

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
4 hour	Yes	No	No	No	No	No
8 hour	Yes	No	No	No	No	No
12 hour	No	No	No	No	No	No
Total			***2 Yes, 16 No***			

3.1.1 Productivity Constraints

As shown in Tables 8 and 9, the major resource constraint limiting the overall production capability of the rehabilitation is identified for each option evaluated, (i.e., end dump trucks, dump trucks, or paver speed). The time allocation ratio between demolition and paving for the sequential working method is calculated in order to balance and optimize the overall production capability. The time allocation ratio for a 203-mm concrete section (single lane paving) is 1.31 hours of paving for every hour of demolition; the paver therefore controls the productivity. For a 305-mm concrete section, only 0.71 hours of paving was needed for every one hour of demolition because the demolition activity has a greater quantity of material to be handled than does the concrete paving activity. This indicates demolition dump trucks control the productivity on 254- and 305-mm concrete sections. When double lane paving is used, concrete delivery trucks control productivity on 203-mm slabs and demolition trucks control productivity on 254- and 305-mm slabs.

Table 7 Can 6 lane-km be rebuilt within 55 hours of weekend closure? (double lane paving)

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
4 hour	Yes	No	No	No	No	No
8 hour	Yes	No	No	No	No	No
12 hour	Yes	No	No	No	No	No
Total	***3 Yes, 15 No***					

Table 8 Single lane production capability (lane-km) within 55 hours of weekend closure

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
Average	5.5		3.6		3.1	
4 hour	7.1	5.1	4.4	3.4	4.0	3.0
8 hour	6.4	4.7	4.0	3.2	3.5	2.7
12 hour	5.7	4.3	3.5	2.9	3.1	2.5
Constraint	Paver Speed	Paver Speed	Demo Truck	Demo Truck	Demo Truck	Demo Truck
(Demo:Pave)	N/A	1:1.31	N/A	1:0.71	N/A	1:0.76

Table 9 Double lane production capability (lane-km) within 55 hours of weekend closure

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
Average	6.7		3.8		3.4	
4 hour	8.8	5.9	4.8	3.7	4.3	3.2
8 hour	7.9	5.4	4.3	3.4	3.8	2.9
12 hour	7.0	5.0	3.8	3.1	3.3	2.7
Constraint	Concrete Truck	Concrete Truck	Demo Truck	Demo Truck	Demo Truck	Demo Truck
(Demo:Pave)	N/A	1:1.14	N/A	1:0.71	N/A	1:0.76

3.1.2 Effect of Concrete Thickness

As the slab becomes thicker (203 to 305 mm), the production capability of the rehabilitation goes down significantly because the quantity of materials to be handled, especially the demolition quantity, increases significantly. This happens across the board for any strategy (e.g., different curing times, working methods, and paving lanes). When a 203-mm slab is increased to 254 mm, the production capability is reduced by about 40 percent. When the 203-mm slab is increased to 305 mm, the production capability decreases 47 percent. The main reason for the reduction in productivity is the need to remove the existing base and place a new thicker base (assumed to be CTB) as well as a new thicker slab. The reduction in production between the 254- and 305-mm concrete structures was approximately 10 percent. The overall reduction in productivity was similar when the concrete pavement thickness increased, regardless of whether the concurrent or sequential working method was utilized.

3.1.3 Effect of Construction Working Method

Different working methods played a significant role in production capability of the rehabilitation. When the sequential method was used instead of the concurrent method, the production capability was reduced by approximately 25 percent.

3.1.4 Effect of Number of Lanes to be Paved

The number of lanes to be paved simultaneously affected the production capability, especially for the 203-mm concrete slab. The paved length was reduced by 19 percent when single lane paving was used instead of double lane for a 203-mm slab thickness (concurrent work method). Sequential construction reduced the paved length by 14 percent when using single lane paving versus double lane paving for a 203-mm slab thickness. For 254- and 305-mm slabs, the reduction in the paved length is less than 10 percent when a single lane paving is used instead of a double lane, for both sequential and concurrent working methods.

3.1.5 Effect of Curing Time

Curing times influenced the production capability but not as significantly as pavement thickness, working method, or certain resource constraints. The analysis showed that the production capability was reduced by 10 percent when the 4-hour curing time was changed to 8 hours, or the 8-hour curing time was changed to 12 hours. This result was based on the assumption that the production capability with FSHCC (4- to 8-hour curing time) is the same as the production capability with PCC (12-hour curing time). In reality, the production capability with FSHCC is equal to, or more likely, less than conventional PCC based on current experience.

This discrepancy in production from using FSHCC instead of PCC was not considered in the current analysis due to lack of quality information on the productivity of FSHCC. Some of the potential reductions in productivity observed by Roesler et al. (16) when going from PCC to FSHCC are attributable to:

- FSHCC sticking to the drum
- The need to clean the delivery trucks more frequently
- Available transport time in the delivery truck decreased due to the quick set times of FSHCC
- Greater rate of slump loss and more difficulty in finishing
- Mixer trucks with agitators are required for FSHCC and therefore discharge rates will likely be slower.

3.1.6 Production Capability Graphs

To provide a better visual understanding, the rehabilitation production rates of the shown in Tables 8 and 9 were converted to production capability graphs for different design profiles, working methods, and paving lanes, as shown in Figures 14 and 15 for single lane and double lane paving, respectively. The vertical axes of the graphs represent the production capability in terms of lane-km; the horizontal axes indicate various curing times from 4 to 24 hours. The LLPRS production objective of 6 lane-km is represented as a horizontal dashed line. This allows a direct comparison between the actual production curves and the target production value.

These production capability graphs confirm that 1) the design profile is the most important factor, 2) the working method was the second most important factor, and 3) the number of paving lanes and curing times affected the production capability. However, the influence of the number of paving lanes and curing time variables are much less than selection of the design profile and working method. It can be seen in Figures 14 and 15 that the sequential method will never reach the production objective unless the number and/or capacity of the constraining resources are increased. This also holds true for the concurrent working method with 254- and 305-mm concrete slabs.

3.1.7 Effect of Weight Limits on Productivity Analysis

In the analysis, the capacity of an end dump truck (for concrete delivery) is assumed to be about 9 cubic meters per truck. This is equivalent to about a 22-ton payload. Existing regulations by the California Highway Patrol limit the payload of tandems to 15 tons (6.25 cubic meter). Figure 16 shows how the production capability of the rehabilitation changed when the capacity of the end dump trucks was reduced from 22 to 15 tons. The effect of this weight restriction was a 21 percent reduction in the productivity of the 203-mm slab rehabilitation with concurrent operations and 13 percent with sequential operations. This reduction in productivity was similar for single and double lane paving. The 254-mm and 305-mm rehabilitation strategies were not as sensitive because the major resource constraint was demolition dump trucks, not concrete delivery trucks (end dump trucks). Communications with the paving industry indicate that the end dump truck problem could be resolved by using semi-bottom dump trucks which carry up to about 9 cubic meter of fresh concrete. Semi-bottom dump trucks with

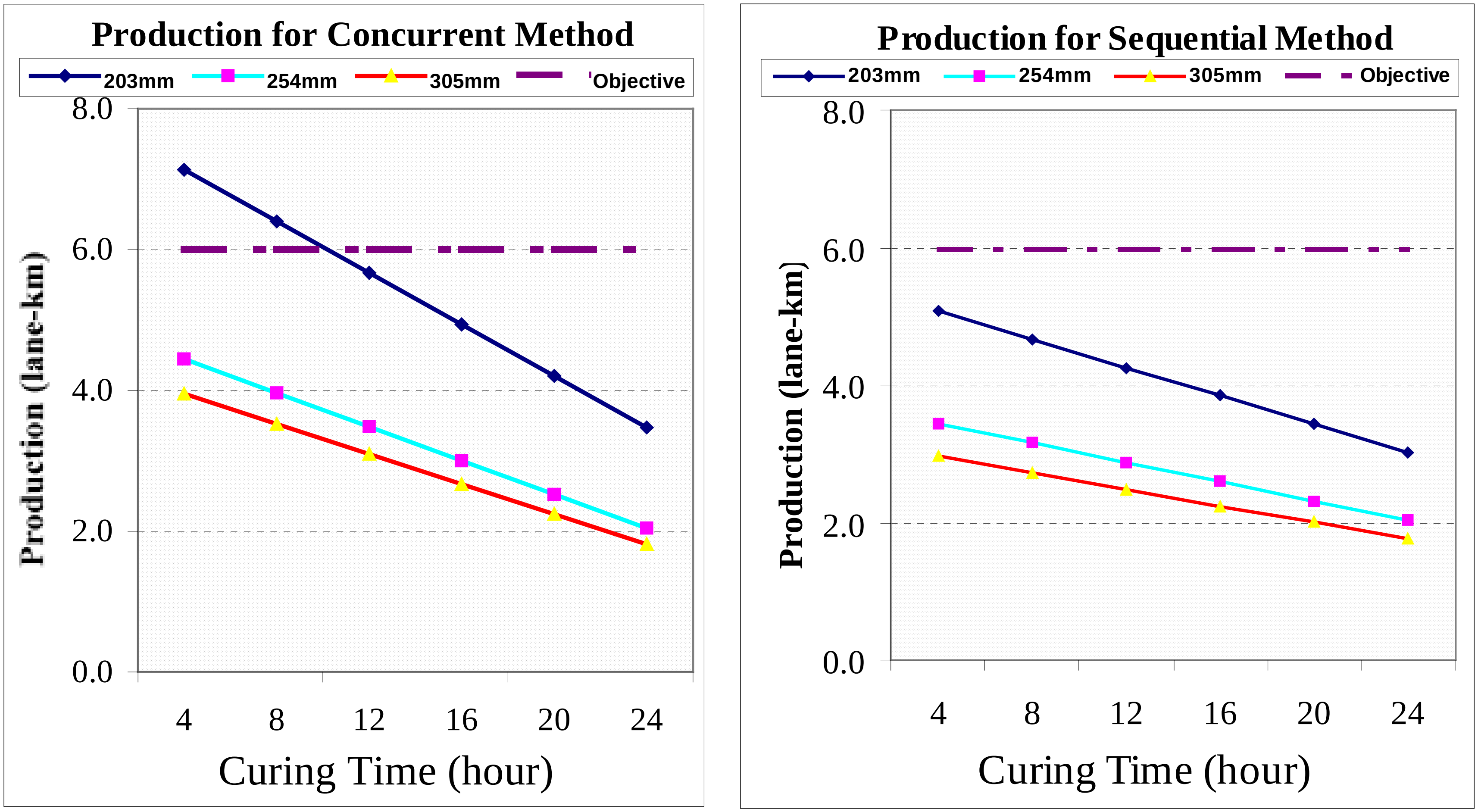


Figure 14. Single-lane production capability (lane-km) graphs.

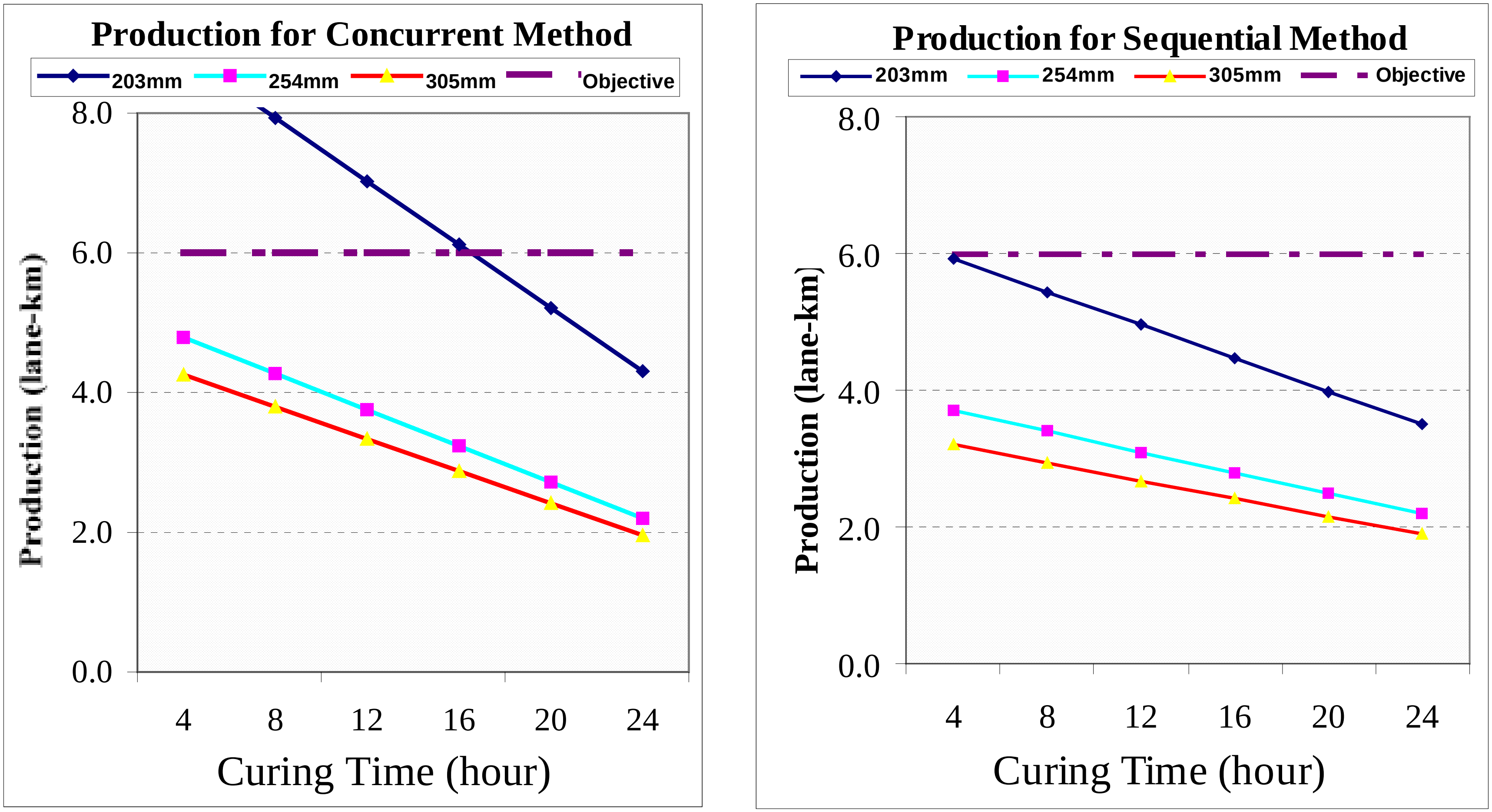


Figure 15. Double-lane production capability (lane-km) graphs.

The current assumption of 20 dump trucks for demolition and 20 end dump trucks for concrete delivery per hour may be too optimistic. Figure 17 shows the reduction in productivity when 15 trucks (demolition and concrete delivery) were used instead of 20 as a resource constraint. With 15 trucks per hour, the loading or unloading time is increased to four minutes rather than three minutes. In all cases, the productivity was reduced approximately 24 percent from the case when 20 demolition and 20 concrete delivery trucks per hour were used as the resource constraint. Figure 17 shows none of the current options will meet the Caltrans productivity objective given only 15 demolition and concrete delivery trucks per hour availability.

3.2 Sensitivity of the Productivity Analysis

The major factors affecting the production capability of the rehabilitation have been found to be the following: 1) design profile, 2) curing time, 3) working method, 4) number of paving lanes, and 5) number and capacity of delivery resources. Table 10 lists the average percent reduction in productivity for changes in these factors. This table summarizes the results presented in the previous sections.

As Table 10 indicates, the design profile was the most influential element for the production capability especially when the slab thickness was increased from 203 mm to 254 and 305 mm, given the resource constraint listed in Table 2. Changing the construction working method was the second most influential factor in reducing the overall productivity followed by

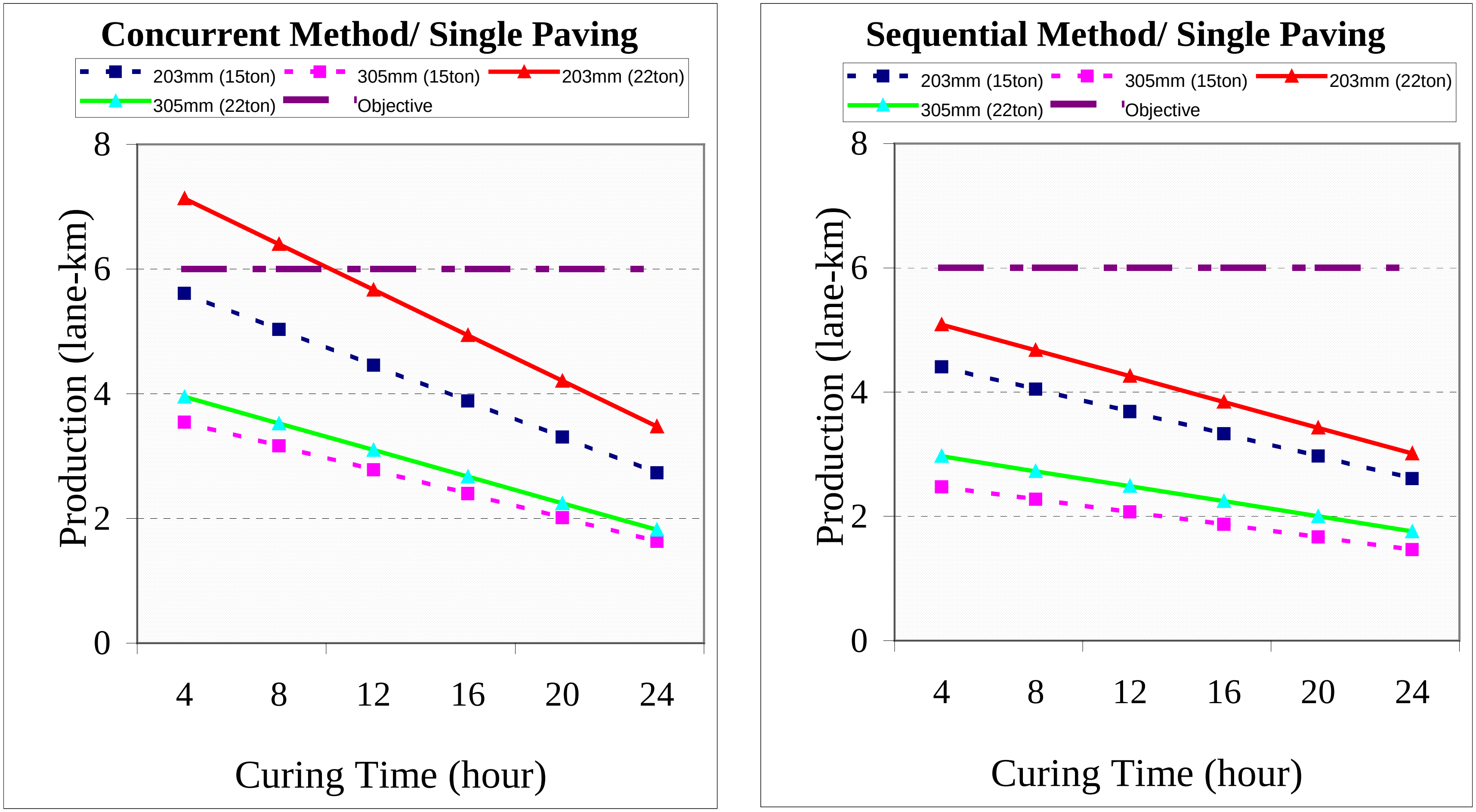


Figure 16. Reduction of production capability (lane-km) by changing the capacity of end dump trucks from 22 tons to 15 tons.

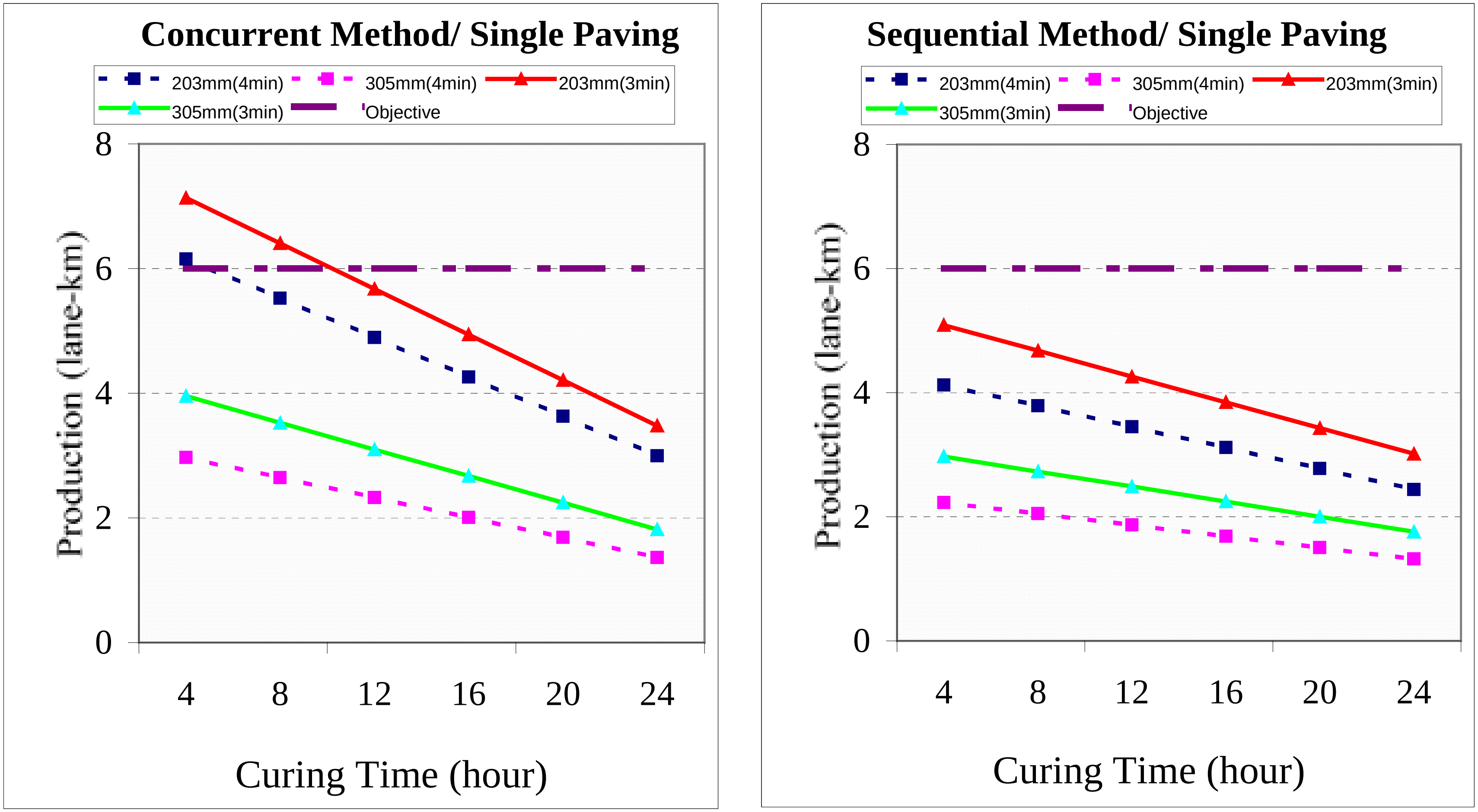


Figure 17. Reduction of production capability (lane-km) by changing the number of trucks from 20 (Cycle=3 min.) to 15 (Cycle=4 min.) per hour.

Table 10 Percentage of reduction in production capability (under optimistic conditions)

Options	**Comparison**	**Reduction**
Design Profile	203 254 mm 203 305 mm 254 305 mm	40% 47% 12%
Curing Time	4 hr 8 hr 8 hr 12 hr 4 hr 12 hr	10% 11% 19%
Working Method (Concurrent Sequential)	203 mm 254 or 305mm	29% 21%
Paving Lane (Double Single)	203 mm 254 or 305mm	17% 7%
EDT Capacity	22 15 ton	15%
Cycle Time	3 4 min	24%

curing time and number of paving lanes. The most sensitive resource to overall productivity was the number and capacity of the end dump trucks for concrete delivery.

3.3 Percent of Options Analyzed Achieving LLPRS Production Objective

As shown in Figure 4, the analysis dealt with the total of 12 options to be analyzed for each design profile (each slab thickness) consisting of the following components:

1. Curing time (4, 8, 12 hour): 3 options
2. Working method (concurrent, sequential method): 2 options
3. Number of paving lane (single, double lane): 2 options
4. Total number of cases to be analyzed = 3×2×2 = 12 options

One way to define the percentage of options analyzed meeting any production objective within a 55-hour closure time is the following:

$$\text{Percent analyzed finishing production objective} = \frac{\text{Number of options meeting the objective (lane - km)}}{\text{Total number of options analyzed}}$$

For each design profile for the cases analyzed, the average percentage of cases finishing a production objective is plotted in Figure 18. For example, for the cases analyzed, the percentage of cases completing 6 lane-km within 55 hours of weekend closure is 42 percent (5 out of 12 options) for a 203-mm slab. This concept is not a probability because it does not treat the input parameters as random variables. It can be used in the decision making process to measure the level of confidence when dealing with a number of rehabilitation processes and objectives.

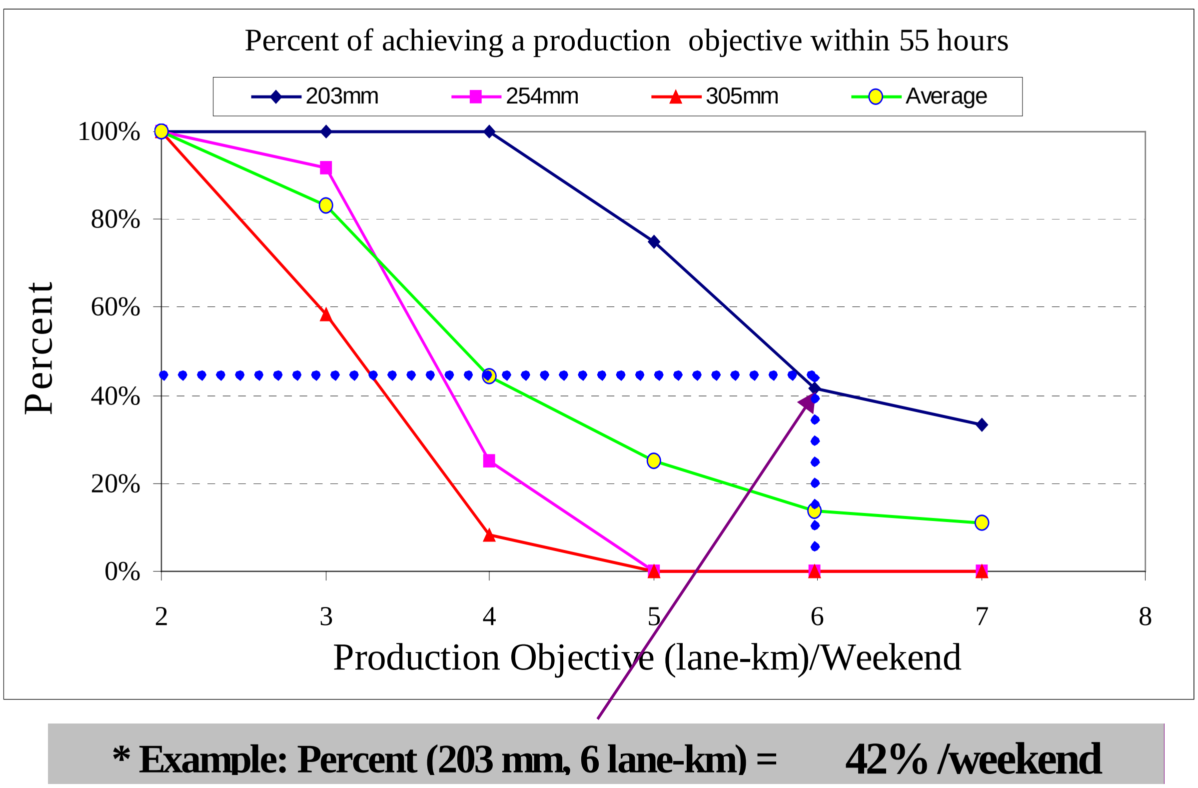


Figure 18. Percent of cases analyzed achieving a production objective within 55 hours.

For example, when 6 lane-km is selected as a production objective for a rehabilitation project, the average percentage of options analyzed successfully completing the project length is only about 15 percent. This 15 percent can be found in Figure 18 using the average curve for all project, the average percentage of options analyzed successfully completing the project length is design profiles. Of the cases analyzed, Figure 18 indicates successful completion of the LLPRS objective of 6 lane-km is unlikely, given the assumptions made in this analysis.

3.4 Number of lane-weekends closed

The main focus of this analysis has been determining the maximum production capability of the rehabilitation. From a traffic management and road user point of view, the number of lanes closed and how long the rehabilitation project will take are more important issues. The term “lane-weekends closed” has been developed to define the most important factor from the road user and traffic management point of view. Lane-weekends closed defines the time required to finish a certain project length during weekend-only construction. A weekend is defined as a 55-hour construction closure.

Table 11 shows how many lane-weekends closed were required to rebuild a 20 lane-km segment of the freeway, depending on working method and design profile. For example, the “Sequential/Single” method for 203-mm slabs needed to close two lanes for a 20 lane-km rehabilitation project, and it took 4.3 weekends (20 lane-km/4.7 lane-km/weekend) to rebuild. Consequently, the number of lane-weekends closed is 8.6 (2 lanes×4.3 weekends). As shown in Table 5, if four lanes were closed using the “Concurrent/Double” method and compared to the “Sequential/Single” method, the increase in productivity was 70 percent (7.9 lane-km versus 4.7 lane-km). The lane-weekends closed for the “Concurrent/Double” method was 10.1 (4 lanes×2.5

weekends). The increase in lane-weekends closed was 18 percent (10.1 lane-weekend/8.6 lane-weekend) when going from "Sequential/Single" to "Concurrent/Double" method. In other words, the "Concurrent/Double" work method will finish the project faster (2.5 weekends versus 4.3 weekends), but will inconvenience the public in terms of lane-weekends

Table 11 Number of lane-weekends closed for different working methods assuming 55 hours of weekend closure and 8 hours of concrete curing

Thickness	**Lanes Closed**	**2 Lanes**	**3 Lanes**		**4 Lanes**
	Working Method	**Sequential/ Single Lane**	**Sequential/ Double Lane**	**Concurrent/ Single Lane**	**Concurrent/ Double Lane**
203mm	Production (lane-km)	4.7	5.4	6.4	7.9
	Number of weekend	4.3	3.7	3.1	2.5
	Lane-weekends closed	8.6	11.0	9.4	10.1
254 mm	Production (lane-km)	3.2	3.4	4.0	4.3
	Number of weekend	6.3	5.9	5.0	4.7
	Lane-weekends closed	12.7	17.7	15.1	18.7
305 mm	Production (lane-km)	2.7	2.9	3.5	3.8
	Number of weekends	7.3	6.8	5.7	5.3
	Lane-weekends closed	14.7	20.4	17.0	21.1

closed (10.1 versus 8.6). The increased productivity (70 percent) achieved by using the "Concurrent/Double" method may be worth the 18 percent increase in inconvenience to the road users. A policy decision can now be made by Caltrans based on quantitative estimates of construction duration and inconvenience to the road users.

When the slab thickness is increased (254 to 305 mm), the number of lane-weekends closed for the "Concurrent/Double" method increases while the actual productivity difference between "Concurrent/Double" and "Sequential/Single" is approximately 40 percent. For 254- to 305-mm slabs using the "Concurrent/Double" method over the "Sequential/Single", the increased inconvenience to the public (~45 percent) is not offset by increased construction productivity (40 percent). For thicker slabs (254 to 305 mm), the “Concurrent/Single” strategy has the best balance between higher construction productivity (27 percent) and increased inconvenience to the public (17 percent) relative to the “Sequential/Single” strategy.

Figure 19 shows a summary of the comparisons of lane closure tactics for different options. The preliminary recommendation, as indicated by Figure 19, for lane closure tactics is that the optimal work plan for 203-mm slabs is “Concurrent/Double” method blocking 4 lanes, and for 254- and 305-mm slabs is “Sequential/Double”" method blocking 3 lanes, considering the increased inconvenience of public traffic offset by more increase of construction productivity. In the future, construction and traffic management strategies can be selected by optimizing the ratio between increased construction productivity and inconvenience to the road user, relative to the least intrusive construction and traffic management strategy, as demonstrated in Figure 19.

3.5 Effects of Changing Construction Window on Productivity

The baseline construction window for the initial constructability analysis was 55 hours during a weekend closure in order to minimize the traffic interruptions. Other types of construction windows can be explored for LLPRS projects. Table 12 shows how many actual hours are needed to rebuild 6 lane-km for the different design profiles, curing times, and working methods. On average, the 254- and 305-mm slabs will require 79 to 88 hours on the weekend to complete the 6 lane-km, a time period which is not available. Two disadvantages of weekend closures are the time lost mobilizing/demobilizing and waiting for the concrete to gain strength, which are not issues with continuous closures.

Table 12 Construction window of weekend closure (hours) needed to rebuild 6 lane-km (double lane paving)

Slab Thickness	**203 mm Concrete**		**254 mm Concrete**		**305 mm Concrete**	
Curing Time	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**	**Concurrent**	**Sequential**
Average	53.1		78.9		88	
4 hour	42	56	64	85	70	98
8 hour	46	60	68	89	74	102
12 hour	50	64	72	93	78	106

As an extension to this analysis, two additional construction windows, continuous closure/continuous operation and continuous closure/daytime only operation with one 10-hour shift, were analyzed and compared with a 55-hour weekend closure only strategy. For all three of these construction windows, time required to rebuild 2 out of 4 lanes on a 20-km segment of freeway was analyzed using the productivity process developed above. The total length of the project was 40 lane-km. It was assumed for the continuous closure with one daytime shift that the workday was 10 hours long and work was done 6 days per week. For all three construction windows, the concurrent working method with single lane paving was utilized, (i.e., three out four lanes were closed).

Figure 20 shows and compares how many weeks or weekends are needed to handle this 20-km hypothetical rehabilitation project for each 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. For 203-mm slabs with 8-hour curing time, “continuous closure/continuous operation” can finish the project within 1.4 weeks (10 days), while weekend closures require 6.2 weekends to complete the same project. For thicker slabs (254 and 305 mm), the time it takes to complete the project length on the weekends increases even more than if a continuous closure were selected. The continuous closure/daytime only

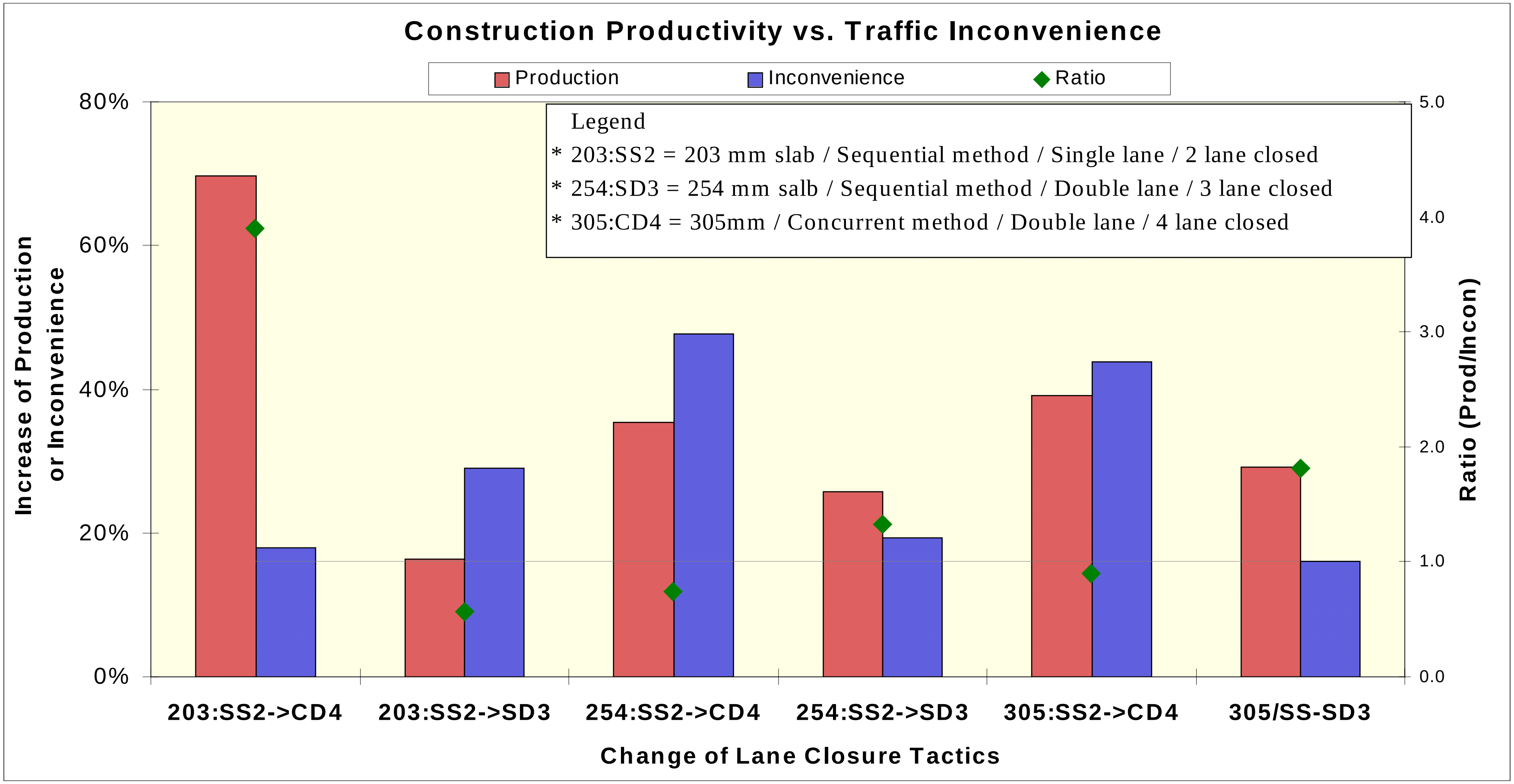


Figure 19. Comparison of increase between production and inconvenience.

operation with one shift took 50 percent longer than the continuous closure/continuous operation with three shifts. Figure 20 reinforces the idea that there are tradeoffs between the most productive construction solution in terms of duration and the degree the agency wants to inconvenience the traveling public, as reported in the previous section.

With continuous closure, the work is completed more quickly and the inconvenience to the public in terms of lane-weeks closed is less than weekend-only closures. For 203-mm slabs and weekend-only closures, the construction presence on the highway project was 342 percent longer and increased the inconvenience to the public by 45 percent as compared to a continuous closure (3 shifts). The argument for continuous closure is even more justified for thicker slabs for which this relationship shows that continuous closures are 375 percent faster (in terms of construction presence on the freeway) and still 36 percent less inconvenient to the public as compared to weekend-only closures. This strategy only holds true for a three-shift continuous closure operation. A one-shift continuous closure will increase the inconvenience to the public by 100 percent as compared to the weekend-only closure for 203-mm slabs. It was assumed that the continuous closure with one-shift operation had construction activities for only 60 hours per week. From a road user's point of view, it is an inefficient construction window compared with a continuous three-shift operation and a 55-hour weekend closure.

For better visual understanding and clear comparisons between the construction windows, each window is plotted on a calendar, as shown in Figure 21. This figure can give Caltrans traffic management and the public an indication of various construction window options and their time consequences. This concept of comparison between different construction windows can be extended to cover any range of rehabilitation projects, as shown in Figure 22.

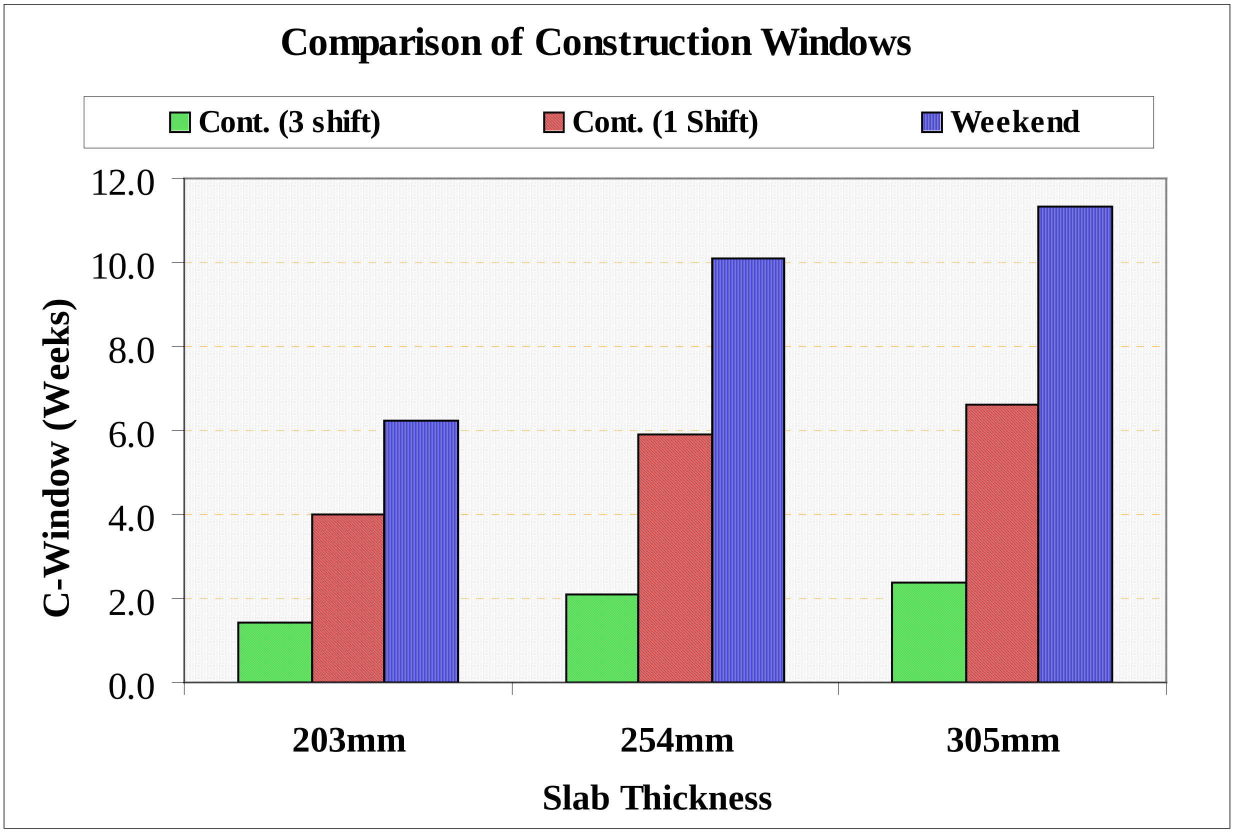
This comparison chart can be used in network level decision making to communicate the potential times required to finish rehabilitation projects to local authorities.

Figure 23 shows the shortening of the project duration for “continuous closure/daytime operation” if a two-shift (two 10-hour shifts) continuous operation is used instead of a one-shift operation. The two-shift continuous operation takes longer than the three-shift operation, but the two-shift operation is much more realistic. In terms of inconvenience to the public (lane-weeks closed), the two-shift continuous operation is more productive (220 percent) and 4.7 percent less inconvenient than a weekend-only closure for 254- and 305-mm slabs, and the same for 203-mm slabs. In the future, this comparative analysis for different construction windows needs to be integrated with the construction costs for each scenario, along with the user delay costs.

Contractors have found that the overall productivity during nighttime construction operations can be reduced by as much as 35 percent compared to daytime construction activities (11). Based on this information, a 55-hour weekend closure may further decrease productivity relative to a continuous closure operation with two shifts per day.

It is a contractor’s decision how many resources should be allocated to deal with a certain size of rehabilitation project, although the principles for the type of the construction windows are primarily controlled by the state Department of Transportation (DOT) policies. Although the selection of the different construction windows is the DOT’s prerogative, the contractor has flexibility to decide what type of operation to employ inside of the predetermined construction window. For example, the contractor can choose one, two, or three shifts within a continuous closure and whether to use concurrent or sequential working methods and single or double lane paving, depending on the availability of resources and constraints.

Distance of Project =	20.0	km
Number of Truck Lanes =	2.0	lanes
Length of Rehabilitation =	40.0	lane-km
Working Conditions =	10.0	hours/day
(for Cont. Closure / 1 shift Only)	6.0	days/week



Const. Window	203 mm	254 mm	254 mm	Duration
Cont. (3 shift)	1.4 (235 hours)	2.1 (352 hours)	2.4 (403 hours)	Weeks
Cont. (1 Shift)	4.0 (672 hours)	5.9 (991 hours)	6.6 (1,109 hours)	Weeks
Weekend	6.2 (341 hours)	10.1 (556 hour)	11.4 (627 hours)	No. of Weekend

(Note: numbers in the parentheses represent how long lanes are closed for the rehabilitation)

Figure 20. Comparison of construction windows to rebuild 20 km of a hypothetical project (8-hour curing time/concurrent working method/single lane paving).

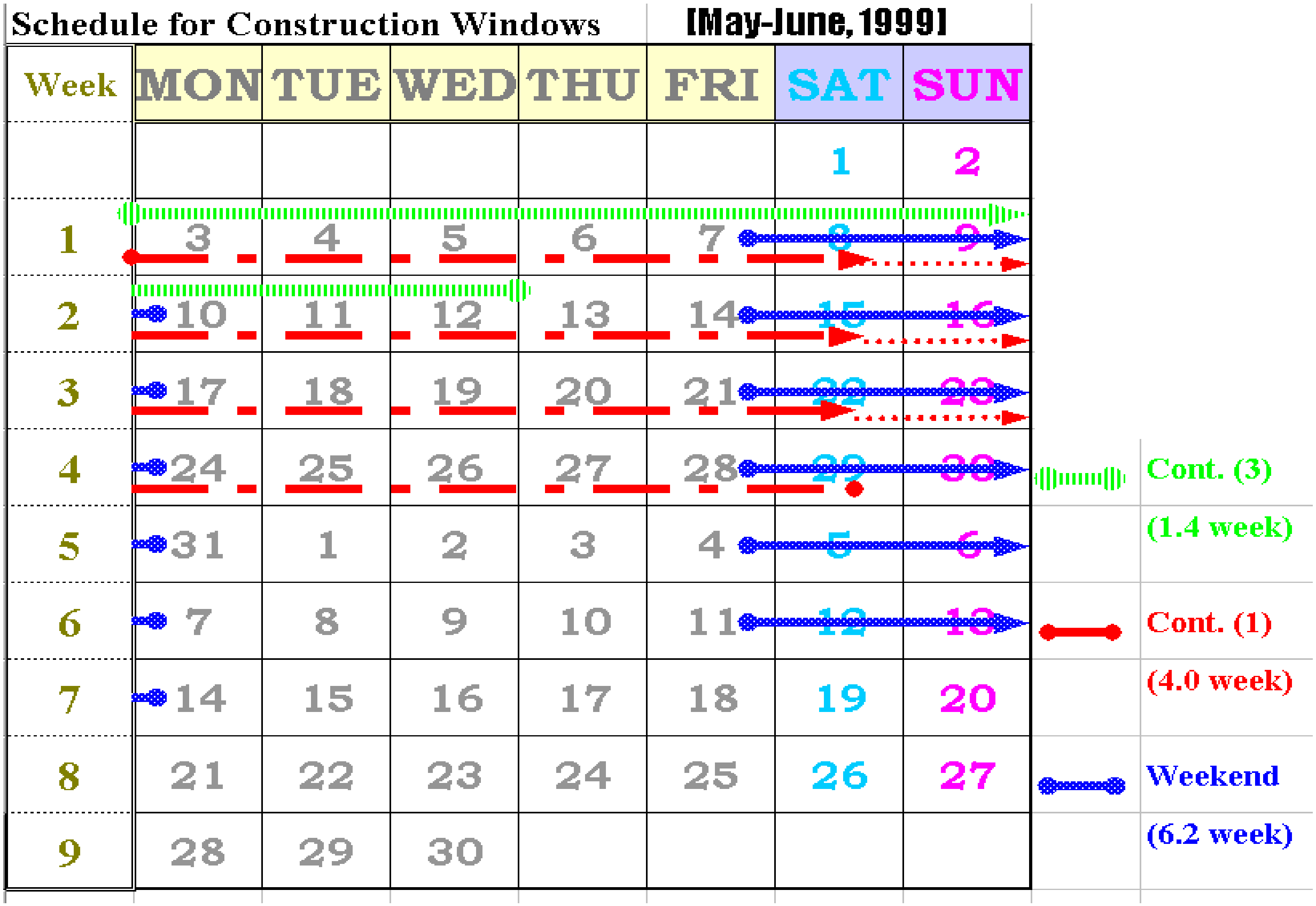


Figure 21. Example of scheduling for different construction windows.

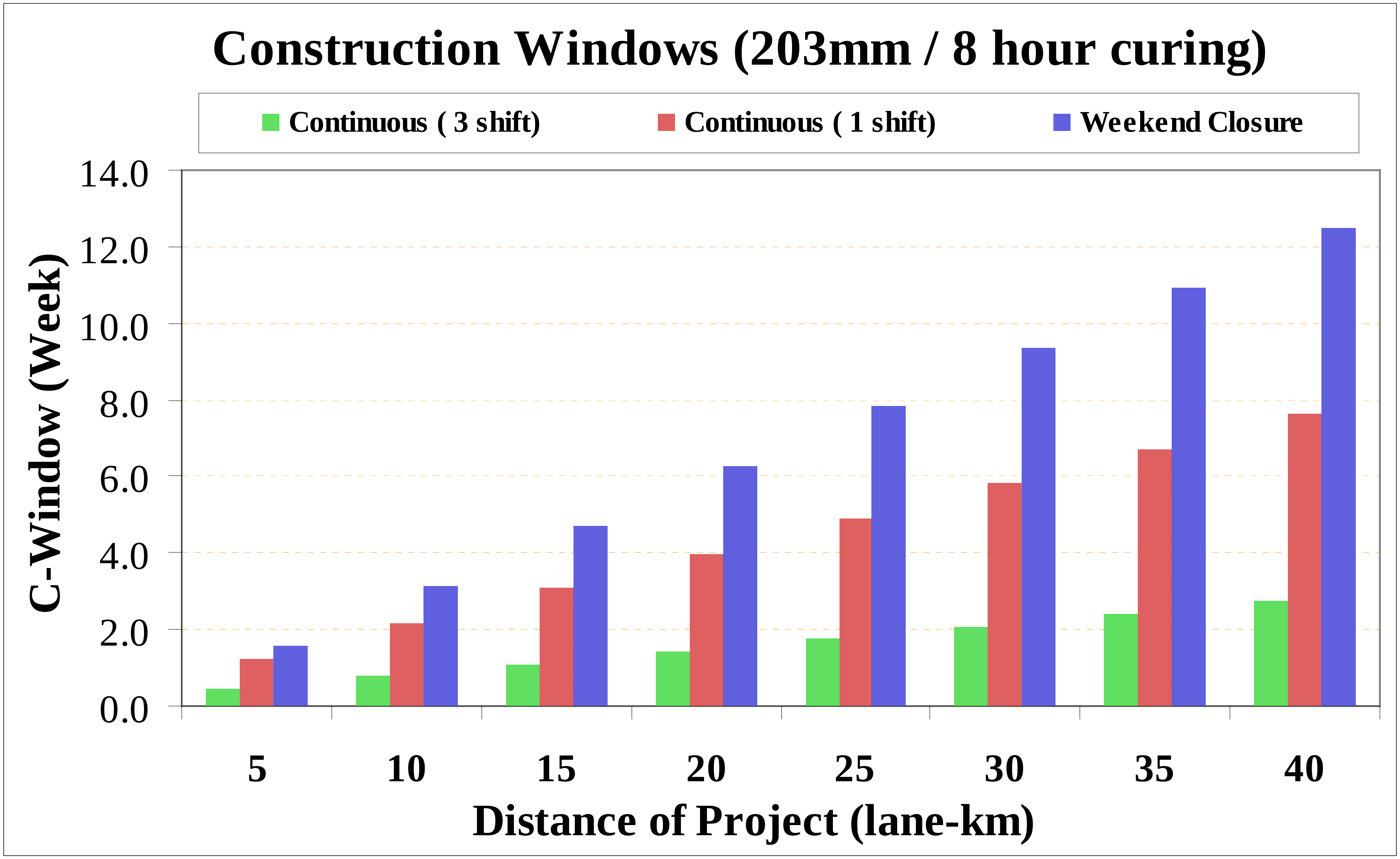
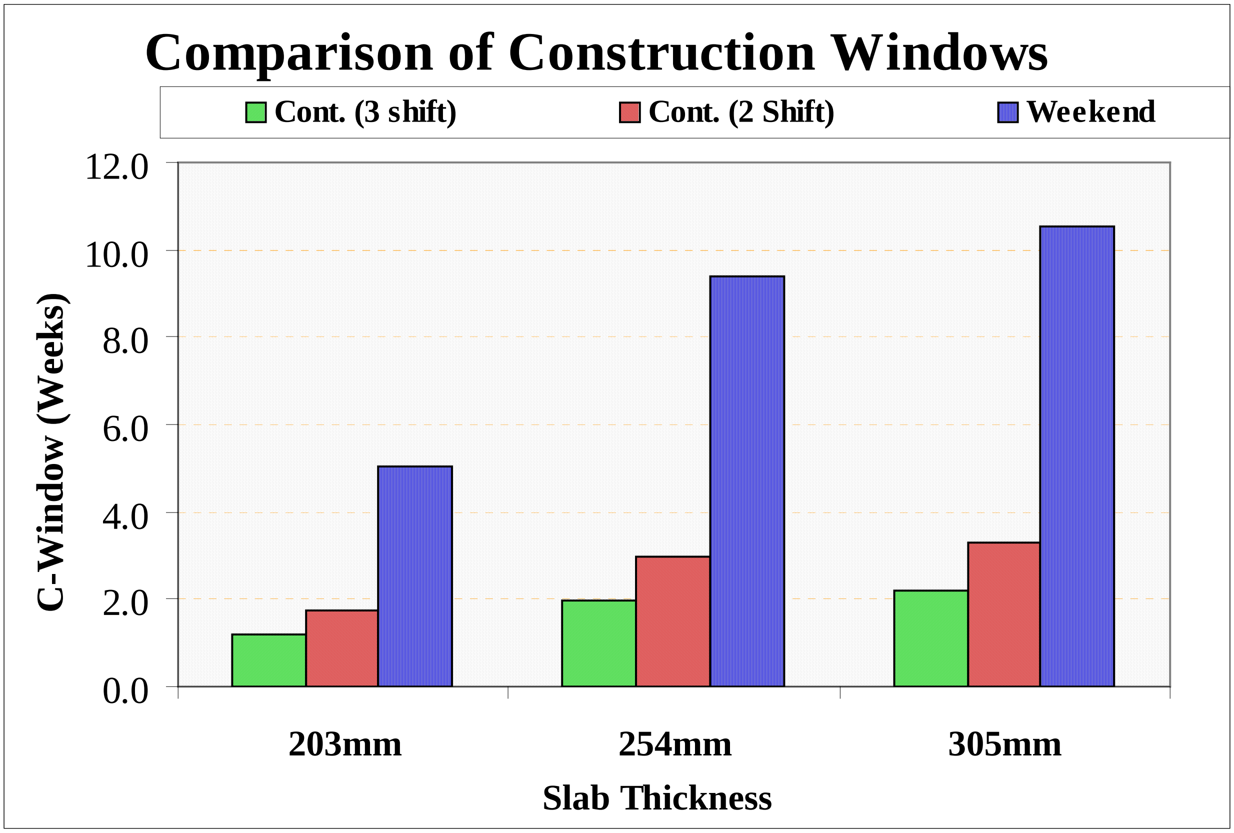


Figure 22. Construction windows covering any range of rehabilitation projects (203-mm slab/8-hour curing time/concurrent working method/single lane paving).

Distance of Project =	20.0	km
Number of Truck Lanes =	2.0	lanes
Length of Rehabilitation =	40.0	lane-km
Working Conditions =	16	hours/day
(for Cont. Closure / 2 shift Only)	7	days/week



Const. Window	203 mm	254 mm	254 mm	Duration
Cont. (3 shift)	1.4 (235 hours)	2.1 (352 hours)	2.4 (403 hours)	Weeks
Cont. (2 Shift)	2.1 (353 hours)	3.2 (538 hours)	3.5 (588 hours)	Weeks
Weekend	6.2 (341 hours)	10.1 (556 hour)	11.4 (627 hours)	No. of Weekend

(Note: numbers in the parentheses represent how long lanes are closed for the rehabilitation)

Figure 23. Comparison of construction windows to rebuild 20 km of a hypothetical project (8-hour curing time/concurrent working method/single lane paving.

Finally, the comparison of the construction windows and the cost analysis for the construction and user delay should be linked to different types of contractual strategies such as cost plus schedule, incentive/disincentive, and lane rental methods, as suggested by Herbsman et al. (3).

3.6 Implementation Challenges

The following implementation challenges are presented to help identify areas that may decrease the production capability results presented in this report, but which were initially assumed not to affect the results:

- **On-site concrete production facilities.** In order to handle the massive amount of the concrete production required to cover 6 lane-km (5,000 m^3 concrete for 203-mm slabs and 7,800 m^3 concrete for 305-mm slabs), construction space for the concrete batch plant and aggregate stockpiles is essential. One possible solution to meet this challenge is for Caltrans to rent space to the contractor near the job site.
- **Number of delivery trucks and operators.** The number of trucks operating every hour for demolition and concrete delivery is very sensitive to the production capability of the rehabilitation. Moreover, the total number of trucks to be mobilized is another challenge, especially when considering multi-shift operations with turnaround times of one hour or greater. Furthermore, according to the concrete paving industry, most truck drivers are owner-operators. A scenario could exist in which the total number of delivery trucks and demolition trucks to be mobilized may be 2 to 6 times the trucks needed per hour, assuming a 1 to 2 hour turnaround and a 2

to 3-shift operation. In some locations and depending on the number of ongoing construction projects, the number of trucks to be mobilized for full production may not be possible.

- **Installation of safety barriers.** In this analysis, the installation of safety barriers was assumed to be complete prior to the start of the rehabilitation project. If k-rails are required instead of rubber cones or movable barriers, installation of k-rails should be added as an independent activity in the CPM schedule. Consequently, the installation of k-rails could possibly take away valuable time from other major activities like demolition and paving. Such a constraint will ultimately reduce the overall productivity of the rehabilitation, especially on a weekend-only construction project.

3.7 Potential Areas of Innovation

Areas of innovation that will have the largest payoff in terms of productivity while minimizing inconvenience to the public were also targeted. Areas in which the contractor and Caltrans can innovate to achieve higher construction productivity include:

- Faster demolition and removal
- Faster delivery and discharging of concrete for paving
- More dump trucks and end dump trucks to be mobilized
- Centralized space for batch plant and aggregate stockpiles
- Speed up dowel and tie-bar placement

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This report describes the processes and results of a construction productivity analysis performed to evaluate the Caltrans Long Life Pavement Rehabilitation Strategies. Listed below are the conclusions of the analyses discussed in this report followed by recommendations.

1. **Caltrans initial objective of 6 lane-kilometers within a 55-hour weekend is very unlikely (15 percent possible based on the options analyzed).** The most optimistic target is to rebuild 4 lane-km, assuming no access, mobilization, and resource availability problems.

2. **Concrete curing time is found not to be the most critical activity.** For the majority of time, demolition and concrete delivery trucks are found to be the constraints limiting the production capability of a rehabilitation project. The analysis showed that less than 20 percent production capability is lost when curing time was changed from 4 to 12 hours. This conclusion specifically applies to the lane replacement scenario evaluated and assumes different strength gain concrete will not adversely affect the paving productivity.

3. **Selection of the design profile (thickness of reconstructed pavement) has the largest impact on the productivity of the rehabilitation assuming resource availability.** Constructing 254- or 305-mm slabs is about 50 percent less productive than removal and replacement of the 203-mm thick concrete slabs only.

4. **The construction working method for the rehabilitation process is the second most sensitive factor in the constructability analysis.** The concurrent working method is 25 percent more productive than the sequential working method because the paving can start before the demolition has been completed. However, with the concurrent work method, an extra lane is required to maintain a simultaneous operation of demolition and concrete paving.

5. **The number of paving lanes to be reconstructed at one time also affects the production capability of the rehabilitation.** Double lane paving is more productive than single lane paving, especially when the paver speed is found to be the major constraint.

6. **The most productive strategy in terms of time to completion is found to be the concurrent working method with double lane paving while sequential/single lane is the most advantageous from the road user's perspective.** Based on the number of "lane-weekends" closed, the sequential working method with single lane paving is the most advantageous from a traffic management and road user perspective. An optimal balance between productivity and inconvenience to the road users finds the "Concurrent/Double" method (4 lanes closed) the preferred strategy for 203-mm slabs, and the "Sequential/Double" method (3 lanes closed) for 254- and 305-mm slabs most desired.

7. **Although weekend closures initially seemed better from a road user perspective, continuous closures with two or three shifts per day are less onerous to the traveling public because the total "lane-days" closed is less than weekend only closures.**

4.2 Recommendations from the current research

This research modeled the typical processes of pavement rehabilitation from a constructability point of view to identify the major constraints limiting the production capability of rehabilitation and to calculate the maximum production capability for a given number of constraints. Through communications with the California concrete paving industry, Caltrans, and the extensive construction productivity analysis, the following are preliminary recommendations concerning the constructability of Caltrans LLPRS for rigid pavements:

1. **55-hour weekend closures are not the most efficient means of increasing productivity and decreasing inconvenience to the traveling public.** Based on the results of these analyses, continuous closures are both the most productive operation in terms of time to finish the project and least bothersome to the road user in terms of total lane-days of closure in most situations.

2. **The use of fast-setting hydraulic cement concrete (FSHCC) for LLPRS projects to increase productivity for lane replacement is not the most efficient means to increase the overall productivity of the construction activities.** Work should be focused on areas that will significantly increase overall construction productivity such as increased demolition and concrete delivery productivity and increased capacities and number of resources.

3. **The combinations of different construction working methods and the number of lanes to be paved result in different production rates, as the number of lanes to be closed varies.** Detailed lane closure tactics for rehabilitation should be developed based on the result of the analyses presented herein, especially tradeoffs between more production and the increased number of construction lanes required.

4. **In order to better understand and validate the processes of the constructability analysis, these analyses should be applied to several rehabilitation projects as case studies.** Throughout the case studies, calibrations should be made to adjust the factors and parameters in the analysis to reflect more realistic and accurate numbers.

5. **The selection of design and construction strategies will need to done on a project by project basis because of differing site conditions affecting the pavement design (e.g., existing structure, subgrade, climate, and truck traffic) and construction window availability (e.g., traffic management constraints on when and how many of lanes can be closed, neighborhood constraints on work hours).** These factors need to be dealt with and integrated during design for each project, not after construction has started. Tools such as those used for this analysis should be used.

5.0 GLOSSARY AND NOMENCLATURE

Terms

Concurrent working method. The demolition and paving activities of the rehabilitation proceed concurrently in parallel, each with its own construction access lane. The concurrent working method has single or double lane paving method as sub-options.

Construction window. A time frame 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 the 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.

Double lane paving. In double lane paving, both truck lanes (T1+T2) are rebuilt together simultaneously instead of splitting into two separate construction windows for each lane.

Fast-Setting Hydraulic Cement Concrete (FSHCC). Rapid strength gain concrete which achieves flexural strengths of 400 psi within 4 to 8 hours after placement.

Linear scheduling method. Linear scheduling is the planning and scheduling technique of the construction process with no 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.

LLPRS. The abbreviation of the Caltrans project, "Long Life Pavement Rehabilitation Strategies," the objectives of which are to 1) provide 30+ years of service life, 2) require minimal maintenance, 3) have sufficient production capability of 6 lane-km rehabilitation over a 55-hour weekend closure.

Sequential working method. A construction 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.

Single lane paving. In single lane paving, two truck lanes are rebuilt separately lane by lane over two separate weekend closures. In other words, one segment of truck lane one is rebuilt during the first weekend closure. On the second weekend closure, truck lane two is rebuilt for the same segment of the freeway.

Weekend closure. The traffic lanes needing rehabilitation are closed for a 55-hour period over the weekend, i.e., from 10 p.m. Friday to 5 a.m. the following Monday.

Abbreviations

AC. Asphalt Concrete

B-P. Batch Plant

CTB. Cement Treated Base

CPM. Critical Path Method

DOT. Department of Transportation

D-T. Dump Trucks

E-D-T. End Dump Truck

LCB. Lean Concrete Base

PCC. Portland Cement Concrete

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7.1 Meetings with the concrete associations (ACPA)

First Meeting

Date: Feb. 18, 1999 (Thursday)
Location: Marriott Hotel in Sacramento, CA
Participants:
From ACPA: Tom Salata, James Woodstrum
From UCB: EB Lee, J. Harvey, J. Roesler

Agenda:
- Detail explanation about the research to ACPA
- Discuss about the cooperation of the association
- Set up preliminary schedule of communications

Second meeting

Date: April 2, 1999 (Friday)
Location : Chumo Construction Co. in Baldwin Park, CA
Participants:
From ACPA: Tom Salata, James Woodstrum, Chumo Construction, Sapper Construction, etc.
From UCB: EB Lee, C. W. Ibbs, J. Harvey, J. Roesler

Citations:

With its own construction access for demolition and paving activities, the concurrent working method allows two activities to proceed concurrently with a 750-meter (800-yard) gap in order for these two activities to avoid any possible interruptions. However, for sequential working method, the demolition and paving activity can only proceed sequentially with a start-to-finish relationship by sharing lanes for construction equipment in order to minimize the number of lanes closed for the rehabilitation.

If lean concrete base (LCB) is used instead of CTB as a subbase, the production capability of the rehabilitation is reduced due to the 8-hour of curing time for the LCB. The curing time for CTB is insignificant, so the slab concrete can be paved on the top of CTB immediately after the compaction of CTB.

Third meeting

Date: June 1, 1999 (Tuesday)
Location : Chumo Construction Co. in Baldwin Park, CA
Participants:
From ACPA: Tom Salata, James Woodstrum, Chumo Construction, Sapper Construction, etc.
From PCA (Portland Cement Association): California Cement Promotion Council
From UCB: EB Lee

Citations:

Unless the on-site batch plant is not used, 15 tons is the maximum capacity for end dump trucks for concrete delivery. End dump trucks with 22-ton capacity can not be used because of safety limitations from the highway patrol. However, semi-bottom trucks with specially installed mechanisms to control discharge of the concrete can overcome these capacity limitations.

Approximately a 35-percent reduction in production capability for nighttime work as part of a 3-shift operation compared with 1- or 2-shifts daytime operation should be considered in the future analysis.

Additional labor costs on the order of 50 percent are normal practice for weekend overtime to carry a rehabilitation project with weekend closure base.

In practice, it is estimated that there is a more than 10 percent reduction in the workability of Fast Set Hydraulic Concrete Cement (FSHCC) (i.e., ease of production, delivery, paving, and finishing) because of its higher viscosity compared with standard Portland Cement Concrete. This negative aspect of the 4-hour curing time cement should be measured along with the expense of FSHCC against the benefit of increased production capability with respect to Portland Cement Concrete.