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Case Study of Urban Concrete Pavement Reconstruction and Traffic Management for the I-10 (Pomona, CA) Project

Report prepared by:
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REPORT CONTENTS AND ACKNOWLEDGMENT

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LIST OF ABBREVIATIONS

FSHCC	Fast Setting Hydraulic Cement Concrete
FSHCTB	Fast Setting Hydraulic Cement Treated Base
PCC	Portland Cement Concrete
E-D-T	End Dump Truck (Demolition)
M-T	Concrete Mixer Truck
UCB	University of California, Berkeley
Caltrans	California Department of Transportation
CPM	Critical Path Method
LLPRS	Long Life Pavement Rehabilitation Strategies
MCB	Movable Concrete Barrier
MK	Morrison Knudsen Corporation
CTB	Cement Treated Base
QA/QC	Quality Assurance/Quality Control

EXECUTIVE SUMMARY

A case study was performed on a Caltrans concrete rehabilitation project near Los Angeles on Interstate 10. The project was unique in that the contractor had to remove and replace 2.8 lane-km of concrete pavement in a 55-hour weekend closure. The existing cement treated base was not removed except in places where it had deteriorated, and a fast setting hydraulic cement concrete with a 4-hour opening strength was used for the surface concrete. The contractor used a concurrent working method in which demolition and concrete paving occurred simultaneously and only a single lane was removed and replaced. The contractor had only one standard width construction access lane (3.7 m) and a shoulder width of less than 3.0 m.

The contractor successfully completed this 2.8 lane-km objective in 55 hours and was eligible for a $500,000 bonus per the contract. The demolition operation took 76 percent longer than planned, but it did not delay the overall progress of the project. The concrete paving activities, especially the concrete delivery and discharge, controlled the overall progress of the 55-hour weekend project. In terms of the number of slabs replaced per hour, the 55-hour weekend closure was 54 percent faster than the average nighttime closure conducted by the same contractor. The amount of the rehabilitation work performed over the 55-hour extended closure would have normally taken 2.5 weeks (16.4 days) of nighttime lane closures. If no work stoppages in the concrete paving had occurred, the maximum amount of rehabilitated road would have been 3.5 lane-km. In 10-hour nighttime closures, the contractor was able to remove and replace 50 slabs on average compared with 15 slabs for 7-hour nighttime closures.

During weekend daylight hours, traffic through the construction zone was reduced by 30 to 60 percent compared with normal weekend traffic volume. During construction, the percentage of traffic diverting to other routes doubled over normal diversion in the daylight hours, but was only approximately 5 percent more than normal during the nighttime hours. The reduced traffic volumes passing the construction site indicated driver awareness of the weekend construction window and traffic lane closures. Caltrans did an excellent job of informing the public of the project through local media outlets (radio, newspapers, and television), signage, and brochures.

The construction productivity data from the demolition and paving operation was used to validate a constructability and productivity analysis software coded by the University of California Berkeley (UCB). The average results from a deterministic and stochastic analysis were in agreement with the actual project productivity. The stochastic analysis showed that the expected range for the project productivity was between 2.2 and 3.4 lane-km for a 68-percent confidence interval with the average productivity being 2.8 lane-km.

Case Study of Urban Concrete Pavement Reconstruction and Traffic Management for the I-10 (Pomona, CA) Project

Report prepared for Innovative Pavement Research Foundation (IPRF)

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CHAPTER 1

1.0 INTRODUCTION

1.1 CALTRANS LONG LIFE PAVEMENT REHABILITATION STRATEGIES (LLPRS)

Many of the urban concrete pavements in California have exceeded their design lives and are close to the end of their service lives. The reconstruction and rehabilitation of these urban concrete pavements provides many challenges to the California Department of Transportation (Caltrans) and pavement contractors. Caltrans wants a long-life concrete pavement that requires minimal maintenance over its design life. Furthermore, Caltrans expects the concrete pavement to be constructed efficiently and with minimal user disruption. Caltrans has initially assumed fast-track construction of long-life urban concrete pavements should result in a reduced life cycle cost, increased safety for users and agency personnel, and reduced user delay costs. In order to properly assist Caltrans in completing this work, contractors want to be reasonably confident that the project can be completed within the tight guidelines of fast-track construction with the added long-life pavement features specified by Caltrans and still make a profit.

Given that very little urban reconstruction has been completed to date, information is needed to determine which methodologies for pavement design, materials selection, traffic management, and reconstruction strategies are most suitable to achieve Caltrans objectives for long-life pavement and minimum traffic delays. There is a need to investigate and document construction projects and techniques to better inform Caltrans, other road agencies, contractors, and policy-makers as to which strategies are most advantageous for concrete pavement reconstruction in an urban area. This report seeks to provide some of that information.

Caltrans has undertaken a demonstration project on I-10 in Pomona, CA (Los Angeles County). A contractor was awarded the I-10 project to determine how many lane-kilometers could be reconstructed on an urban freeway during repeated nighttime closures and one 55-hour weekend lane closure.

1.2 RESEARCH OBJECTIVES

The objective of the University of California at Berkeley (UCB) research was to complete a case study of the I-10 Pomona project focusing on documentation of the traffic management plan and construction process for both nighttime and weekend closures. The emphasis of this research project was to document the techniques the contractor used to construct the urban concrete pavement and identify which construction areas were constraining the overall project productivity (e.g., concrete curing time, concrete delivery, concrete pavement demolition, etc.).

Identification of the constraining activities is required in order to efficiently improve future construction productivity by allowing contractors and agencies to apply innovations where they are most needed. Interaction between UCB, Caltrans, and the prime contractor was key to the success of the research. Figure 1 shows the major parties involved in completing and documenting this project.

To best disseminate construction and traffic management information from this reconstruction project, UCB was present to record and document the reconstruction process. The documentation of the I-10 project includes an overview of the project, traffic management strategies utilized, the contractor's scheduling of the project, construction constraints, actual construction productivity and procedures, and a comparison of estimated productivities versus actual productivities. This information can be used by Caltrans, other agencies, contractors, and elected officials to make decisions on future urban reconstruction projects.

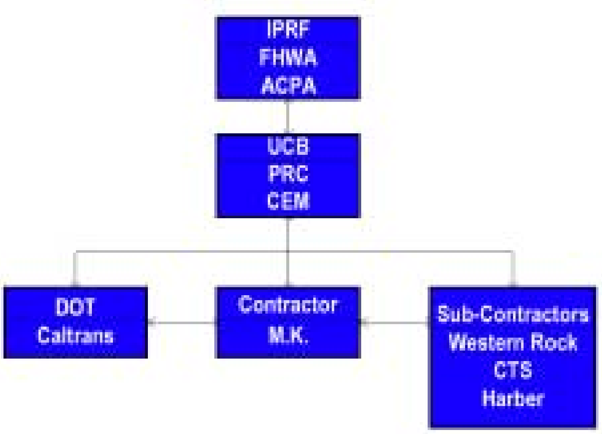


Figure 1. Information process chart for the case study.

1.3 RESEARCH APPROACH

1.3.1 Preparations before Construction

Several meetings were held with the contractor and Caltrans prior to the 55-hour construction window on the I-10 Pomona project. These meetings focused on gathering background information on the project, the contractor's proposed work plan, the availability of resources, the proposed traffic management strategies, and the contractor's critical path method (CPM) schedule. Caltrans and the contractor were individually interviewed to determine why certain construction methodologies and traffic management strategies were selected. Photographic documentation was made of the site prior to construction. The information collected from Caltrans and the contractor (the work plan, CPM schedule, and resource availability) was put into a constructability analysis program previously developed by the UCB research team for Caltrans to estimate the most probable productivity (lane-km) within the 55-hour weekend closure (1, 2). This analysis is covered in Section 4.0.

1.3.2 Data Collection during Construction

During the I-10 55-hour weekend construction phase, UCB had five people in Pomona with 2 or 3 people always at the construction site. UCB made photographic documentation of all activities surrounding the construction process, including the traffic management activities, demolition, material placement, equipment, and personnel. Detailed record keeping and documentation were performed in conjunction with the photography.

The on-site record keeping and documentation focused on evaluating the construction methodology and pavement rehabilitation processes, and on observation of freeway traffic behavior adjacent to the construction area. The construction methodology evaluation included resource productivity data, required number of resources, actual construction process, and critical resources. The activities that constrained the construction productivity were identified, and to the extent possible, quantified from these observations. Traffic behavior around the construction site was recorded by Caltrans and UCB to provide data on impact of construction activity on traffic, and on the effect of traffic management strategies on delays.

1.3.3 Data Analysis after Construction

After completion of the 55-hour weekend construction, the final product delivered to Caltrans by the contractor was photographically documented. The actual constraints for the project were identified. The actual CPM schedule versus the planned CPM schedule were plotted and compared. UCB interviewed Caltrans and the contractor after the project was completed to discuss why certain changes occurred during construction and what could be done in the future to improve productivity. Based on the information collected, Caltrans' and the contractor's initial planning were compared and contrasted to determine which assumptions were the most realistic for this urban reconstruction project.

The rehabilitation information for the 55-hour weekend closure was compared with the performance data from nighttime closures gathered from the contractor to determine negative and positive aspects of both options. The construction data gathered by UCB was also input into the UCB constructability model (1) for further calibration and validation.

Caltrans shared traffic volume data measured during the 55-hour weekend closure from their inductive loop sensor system. This data was analyzed and compared with the traffic volume data of a typical (historical) weekend. By comparing the traffic volume of the 55-hour weekend with that of a typical weekend, the impact of the rehabilitation over a weekend to the road users could be determined.

CHAPTER 2

2.0 MAJOR FEATURES OF THE PILOT PROJECT

2.1 Project Background

Interstate 10, one of the most important arterial roads connecting the east and west coasts, begins in Jacksonville, Florida and extends throughout the southern United States and terminates in Santa Monica, California. The segment of the I-10 running through Southern California, commonly called the "San Bernardino Freeway," was built in the early 1960s with a 20-year design life. I-10 has a high concentration of deteriorated concrete pavement with extensive concrete slab failures due to transverse and longitudinal cracks and faulting, as illustrated in Figure 2. Traffic volumes in this stretch of freeway are as high as 240,000 Average Daily Traffic (ADT), as illustrated in Figure 3.

In 1998, Caltrans launched the long-life pavement rehabilitation strategies (LLPRS) program to rebuild 3,000 lane-km of concrete pavement on the state highway network over the 10 proceeding years. One of the main objectives of the LLPRS is to minimize user delays and rehabilitate 6 lane-km over a weekend.

Caltrans selected a 5-kilometer (3.3 mile) stretch of the I-10 from Route 57/210 to Garey Avenue (km post 68.2/73.5) in Pomona (Los Angeles County), shown in Figure 4. The section of freeway was rehabilitated using Fast-Setting Hydraulic Cement Concrete (FSHCC) over a series of repeated nighttime closures and one 55-hour weekend closure. The project was a pilot for use of FSHCC and long-life pavement techniques for full-scale lane replacement. The main purposes of the pilot project were to evaluate constructability of new rehabilitation techniques that can be used to replace aged and deteriorated concrete pavements throughout California, and to evaluate the advantages of using FSHCC for state highway concrete rehabilitation projects to minimize traffic delays.

Figure 2. Typical failure of concrete pavement on U.S. Interstate 10.

Figure 3. Typical traffic volume on U.S. Interstate 10.

Figure 4. Location of project in Pomona, CA.

In early 1999, Caltrans awarded a $15.9 million contract (Contract No. 07-181304 (07-LA-10-68.2/ 73.5)) to Morrison Knudsen Corporation (MK) of Highland, CA to complete the pilot project. Four other contractors participated in the bidding of the project, and the second lowest bid was about $150,000 more than the MK bid estimate. The winning proposal from MK was approximately 10 percent more than the engineer's preliminary estimate.

The total volume of FSHCC was estimated at 14,000 m^3 to rehabilitate about 20 lane-km of concrete pavement. This 20 lane-km consisted of a 5-km centerline stretch of freeway for eastbound and westbound I-10 for lanes three and four only (Caltrans numbers lanes starting from the median and moving towards the outer shoulder). The rehabilitation contract began in April 1999 and was completed in February 2000.

2.2 Scope of the Rehabilitation

The I-10 freeway has four lanes in each direction in the area of the project. Only minor work took place on the two inner passenger lanes and outer auxiliary or connector lanes. Caltrans required two of the four lanes to remain open while rehabilitation work was underway. Lane Number 3 was assigned for the construction access to rehabilitate Lane Number 4 and vice versa. The inner and outer shoulders were already rehabilitated with asphalt concrete prior to the rehabilitation of the concrete pavement lanes. The inner shoulder was used as part of Lane Number 1 when Lane Numbers 3 and 4 were closed because 1.2m of Lane Number 2 was required to secure space to install safety barriers (Mobile Concrete Barrier (MCB) or cones) between the open and closed lanes during the rehabilitation, and for the concrete screed.

The outer shoulder could not be used as a full access lane because of a sound wall adjacent to the shoulder which limited the shoulder width to 2 to 3 m in some locations. The outer shoulder was used as a full access lane in areas where its width was 3 m. Where the width of the outer shoulder was limited to less than three meters, the number of access lanes for construction was reduced to one lane. Consequently, when only one full lane was available for construction access during the rehabilitation, vehicles could not pass by one another in the only through lane. This constraint of a single access lane for construction delayed parts of the rehabilitation process because the demolition and paving operation interfered with each other.

For most of the 55-hour weekend, Caltrans did

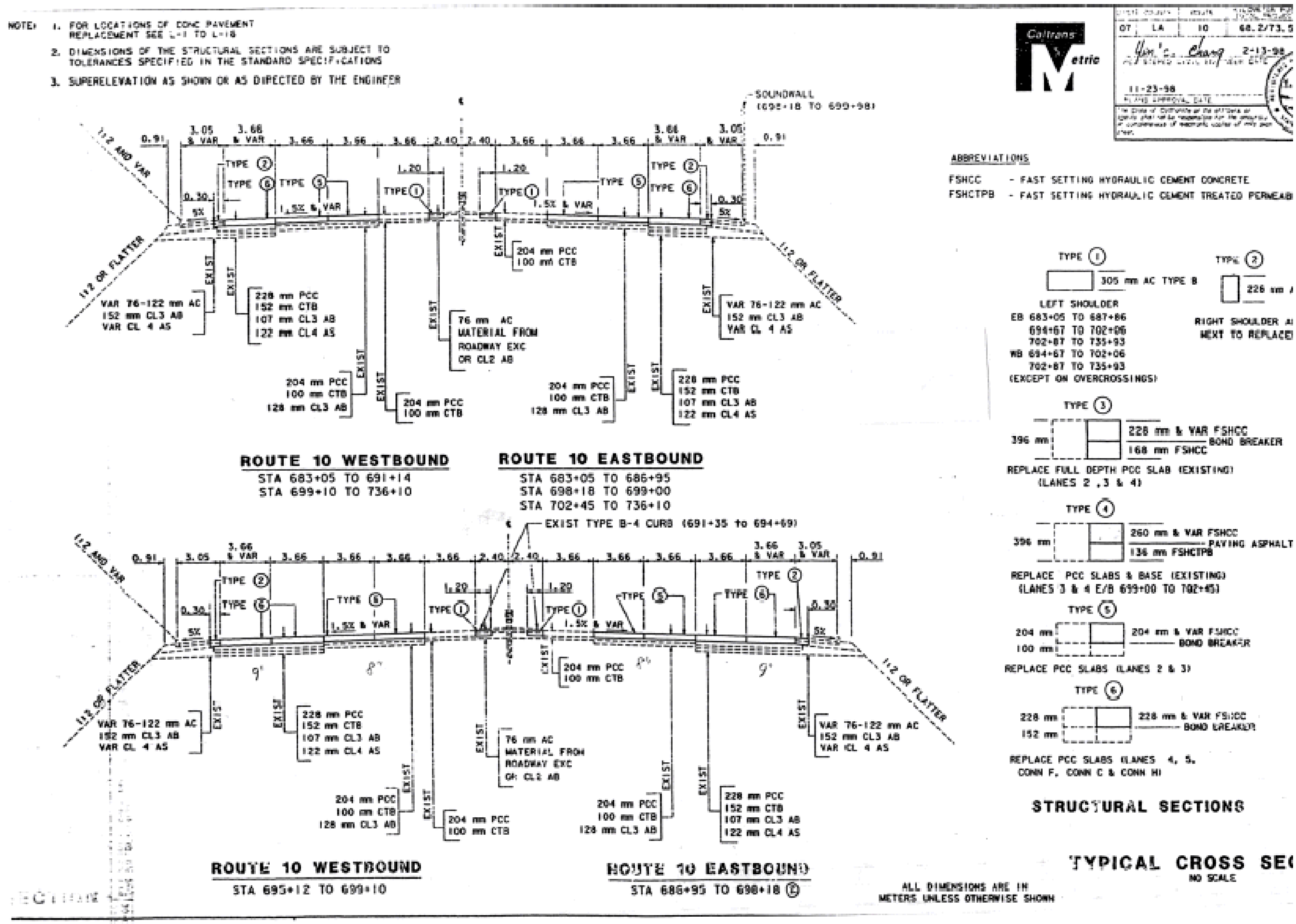


Figure 5. Typical cross section of the rehabilitation for the I-10 project.

not require the contractor to remove and replace the cement treated base (CTB) or aggregate subbase. In several locations where the CTB was badly deteriorated, the slab and CTB were removed and replaced.

Figure 5 shows examples of cross sections designed by Caltrans for the I-10 rehabilitation project. Six different types of structural sections were designed (Figure 5). They can be categorized into three groups:

- shoulder rehabilitation: asphalt concrete used to rehabilitate shoulder
- slab replacement: 204 mm (8 in.) concrete, re place slab only
- full depth replacement: (concrete slab and CTB): 228 mm (9 in.) and 260 mm (10 in.) slab with variable new CTB thickness

Although it appears that many different pavement cross-sections were implemented for the I-10 project, the majority of the rehabilitation was slab replacement. This report mainly focuses on the slab replacement process with a limited description of the full depth replacement option. In the case of slab replacement, the existing 204-mm PCC slab was replaced with the same thickness of FSHCC. In the case of full depth replacement, the existing 100 mm (4-inch) CTB was replaced with a thicker fast setting hydraulic cement treated base (FSHCTB) (136 to 168 mm), and the existing 204-mm (8-inch) PCC slab was replaced with a thicker 228-mm (9-in.) or 260-mm (10-in.) FSHCC slab.

During the 55-hour weekend closure, the major task of the rehabilitation was slab replacement. The occasional occurrence of full depth replacement during the 55-hour weekend closure did not slow down the overall rehabilitation process because it occurred in several isolated locations. Figure 6 shows a typical design profile change for slab replacement option. In a previous report to Caltrans by UCB, full depth replacement was found to be 50 percent less productive than a slab replacement only strategy (1).

2.3 Summary of the Unique Features of the Project

The I-10 rehabilitation project has several unique features:

- Caltrans decided to implement one 55-hour weekend closure versus nighttime-only closures in order to check how many lane-km of existing PCC slab could be replaced with new FSHCC and how a weekend closure would impact traffic conditions in the area.
- The amount of FSHCC used on the I-10 project as the slab replacement material was the largest volume of material used to date for pavement rehabilitation by Caltrans on one project.
- The contractor used a "slab lift-out" method as a type of "non-impact demolition" for the concrete slab demolition operation. The slab lift-out method was intended to protect the underlying CTB from damage. In this technique, concrete slabs are cut into 3 pieces by sawing prior to the 55-hour project, and the segments are dug out by an excavator and loaded into a 22-ton capacity end dump truck. Caltrans hoped this "non-impact" method of demolition would expedite the demolition process and release the slab demolition activity from the potential constraints of the rehabilitation process.
- A Movable Concrete Barrier (MCB) was used as a safety barrier system between traffic and construction zone instead of rubber cones or K-rail. Although it is quite expensive, it allows for quick installation, dismantling, and moving of the barrier system in short construction windows.
- Finally, Caltrans used incentive/disincentive clauses and QA/QC for quality in the contract for the first time on a concrete pavement project. The purpose of the incentive/disincentive clauses were to encourage as much rehabilitation during the 55-hour weekend closure as possible while maintaining ad equate quality. QA/QC construction places responsibility for the final product quality on the contractor because the contractor is allowed to select the concrete mix design as long as the final product meets Caltrans specifications.

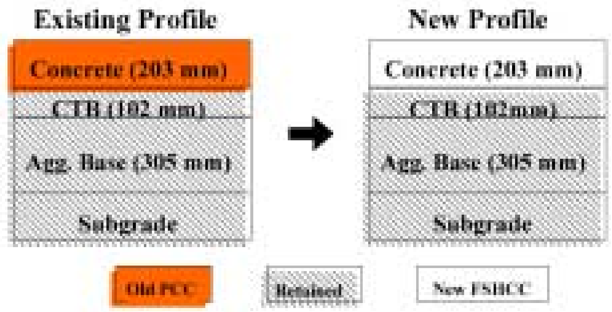


Figure 6. Typical change of design profile for slab replacement option.

2.4 Contract Incentives/disincentives

Over last several years, a number of road agencies have introduced alternative contracting and bidding methods to the traditional "lowest bidder" principle in which only the cost aspects of the contractor's proposal are considered for highway rehabilitation projects. For the purpose of minimizing road user inconvenience during rehabilitation projects, road agencies have sought to reduce highway reconstruction times and the number of lanes to be closed by including scheduling aspects in addition to the cost aspects. For example, Herbsman compared the advantages and disadvantages of a) bidding on cost/time, b) incentive/disincentive for time delay, c) bidding on cost/time combined with incentive/disincentive, and d) lane rental (3).

The traditional low bid concept was used for the I-10 project overall, but incentive and disincentive conditions were applied to the segment to be built in the 55-hour extended weekend closure to encourage the contractor to achieve the rehabilitation production objective. The following paragraph from the of the I-10 project contract demonstrates how the incentives/disincentives worked (4):

> "Incentive payment will be made to the Contractor in the amount of $600 per lane meter, for each lane meter replaced, which is in excess of 2,000 lane meters, and which is replaced during the 55 hour extended weekend closure. Disincentive deduction will be assessed the Contractor in the amount of $250 per lane meter for each lane meter less than 2,000 lane meters that the Contractor replaces during the 55 hour extended weekend closure. One lane meter is defined as one meter long of the full width of one slab within longitudinal joint. The total of all incentive payments that the Contractor may receive from the designated portion of work will not exceed $500,000."

In addition to the incentives/disincentives clauses, a relatively severe liquidated damages clause was provided in the contract to make sure the 55-hour weekend closure would be completed as scheduled:

> "Should the Contractor fail to provide all lanes ready for use by public traffic at the end of the 55 hour extended weekend closure, liquidated damages will be assessed by the Department as follow: For each 10 minute period, or fraction there of, that all lanes are not available for use by public traffic, the amount of liquidated damages assessed will be $10,000."

2.5 7- and 10-Hour Nighttime Closures

Most of the 20 lane-km segment to be rehabilitated was planned to be rebuilt with 7-hour or 10-hour nighttime closures except for the 2.8 lane-km stretch that was to be replaced during the 55-hour weekend closure pilot project. Work completed in 7- and 10-hour nighttime closures consisted of replacing individual and multiple slabs in a row.

As indicated in Table 1, two types of nighttime closure were implemented as basic construction windows. Ten-hour nighttime closures took place from 10 p.m. to 8 a.m., while 7-hour nighttime closures went from 9 p.m. to 4 a.m. For the eastbound freeway (out of downtown Los Angeles), 10-hour closures were used during the whole week (weekday and weekend nights). For the westbound lanes, 7-hour closures were applied during weekday nights because of greater traffic volumes heading to downtown Los Angeles, and 10-hour closures were used during weekend nights. Overall, 10-hour closures covered approximately 64 percent of the nighttime closures and 7-hour closure covered the remaining 36 percent.

2.5.1 Nighttime Closure Productivity

In terms of nighttime closure productivity, the contractor rebuilt on average 50 slabs, and at best 60 slabs per 10-hour nighttime closure. The 7-hour closure productivity was much less than 10-hour closure. MK could only replace about 15 slabs on average with a maximum of 20 slabs and 6 slabs in the worst case. The slow productivity of 6 slabs during a 7-hour closure resulted from having to skip and jump around slabs in some areas, which wasted time for mobilization/demobilization and the alignment of equipment such as the self-propelled gang drill units for the drilling of tie bars. The comparison of productivity between these two different nighttime closures is covered in more detail in Section 2.7.

The summary of the typical scheduling of the nighttime closure:

- Auxiliary work: 5 hours
  - mobilization & traffic setup: 1/2 hour
  - curing: 4 hours
  - clean & demobilization: 1/2 hour
- Main work (demolition, concrete delivery, and paving)
  - 7-hour closure: 2 hours
  - 10-hour closure: 5 hours

2.5.2 Resources Involved in Nighttime Closures

The details of the major resources involved in the nighttime closures are summarized in Table 2. Based

Table 1. Comparison of nighttime closures

	7-hour Closure	10-hour Closure
Closed Time	9 p.m. – 4 a.m.	10 p.m. – 8 a.m.
Direction	Westbound (weekday)	Eastbound (whole week) Westbound (weekend)
Percent of Nighttime Hours	40%	60%
Productivity (slabs* per hour)	7.5	10
Typical Production (Slabs per Closure)	15	50

(* Note: typical panel size is 0.2m thick x 3.6 m width x 4.5 m length)

Table 2. Details of major resources involved in the nighttime closure

Resource	Capacity	Number mobilized
Dump truck	22 ton	7 trucks with one excavator
Mixer truck	8 cubic yard	4 – 8 mixers
Batch plant	220 cubic yard per hour	1
Paving machine	Hand operated screed	1 plus 1 standby

on experience, the contractor used the number of resources listed in Table 2. The number of resources mobilized for nighttime closures was less than half of that required for the 55-hour weakened closure because of a higher number of limiting constraints, such as shorter available work duration, construction access, and space limitation.

Originally, a Moveable Concrete Barrier (MCB) was going to be used as the safety barrier between the open and closed lanes for both types of nighttime closure and the one weekend closure. However, a storage area for the MCB along the freeway outer shoulder was not made available in most cases, so rubber cones were used during nighttime closures. Using rubber cones on nighttime closures was inexpensive, simpler to install, and took less time, however, cones could not provide the same level of safety as the MCB. During the 55-hour weekend closure, the MCB was used as the safety barrier between live traffic and the construction zone. The MCB was required in the specifications because road users and construction workers were going to be exposed to potential hazards during the 55-hour continuous closure.

2.6 55-hour Extended Weekend Closure

The 55-hour weekend closure began at 10 p.m. on Friday, October 22, 1999 and the rehabilitated lanes were opened to live traffic again at 5 a.m. Monday, October 25, 1999. During the 55-hour weekend closure, 2.8 lane-km of deteriorated concrete slabs were to be removed and replaced in Lane Number 3. The location of the project was on eastbound I-10 between Fairplex Drive exit (station 704+80) and Garey Avenue exit (station 736+05), as shown in Figure 7. The purpose of the first 51 hours of the 55-hour weekend closure was to replace existing 204-mm concrete pavement slabs (PCC) in Lane Number 3 with the same thickness of new FSHCC. In areas where the base was seriously damaged from moisture and erosion, Fast Setting Hydraulic Cement Treated Base (FSHCTB) was used to replace the existing base (full depth replacement option). The same mix was used for concrete base and slab. For this 2.8 lane-km stretch, Lane Number 4 had previously been rehabilitated through nighttime closures.

Figure 8 shows a plan view of the freeway and

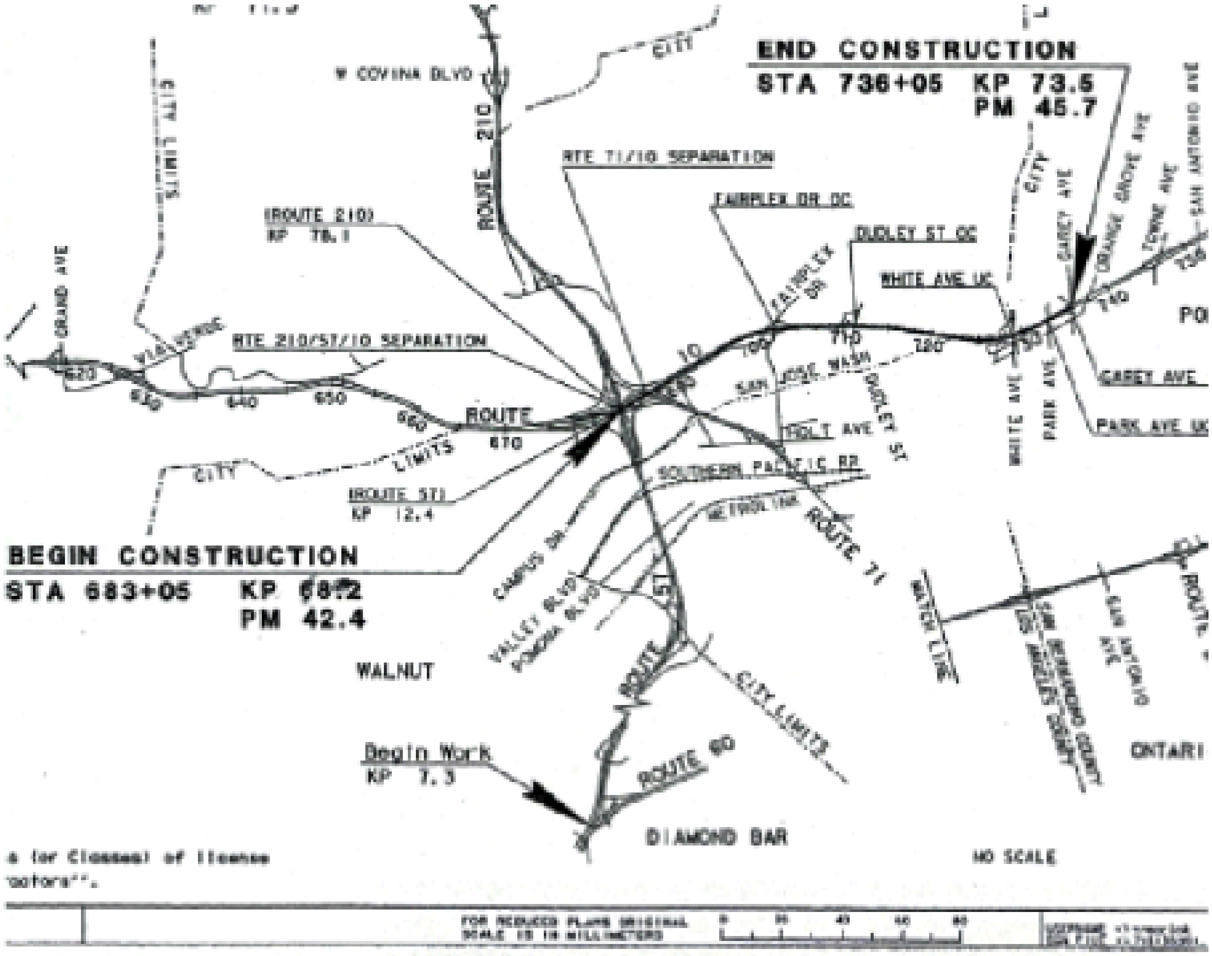


Figure 7. Detailed layout of the I-10 project.

the lane closure tactics utilized during the pavement rehabilitation.

Two out of the four lanes remained open while rehabilitation work was underway. In the first kilometer of the project, two lanes were assigned for construction access, Lane Number 4 as a main access lane and the shoulder as an auxiliary access.

For the remaining two-thirds of the project, only Lane Number 4 was assigned as the construction access. The width of the outer shoulder varied from 2 to 3 meters with an adjacent sound wall. The reduction in the number of access lanes significantly impacted the demolition operation because trucks entering or exiting the demolition area were blocked by other trucks being loaded with the removed concrete slabs.

In the design stage, Caltrans surveyed the existing pavement structure to assess the condition of the pavement and especially to check the CTB. Based on the survey results, the Caltrans design team produced drawings that laid out the rehabilitation for each section of freeway as shown in the example

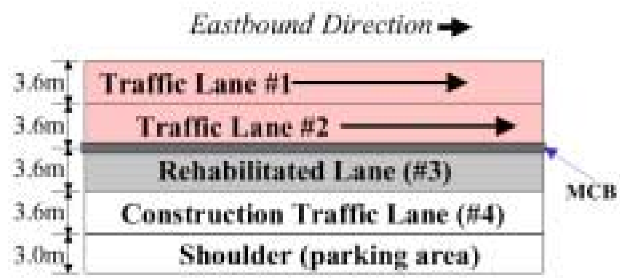


Figure 8. Plan view of lane closure tactics.

drawing in Figure 9. When read in conjunction with the pavement cross-sections (Figure 5), the drawings are clearly marked as to which slabs should receive which type of rehabilitation. With the drawings of proposed rehabilitated slabs, the contractor knew where to apply the two main types of rehabilitation processes (full depth replacement or slab replacement only).

For the pilot project, which specified either Lane Number 3 or Lane Number 4, the contractor preferred to rehabilitate Lane Number 3 because of the

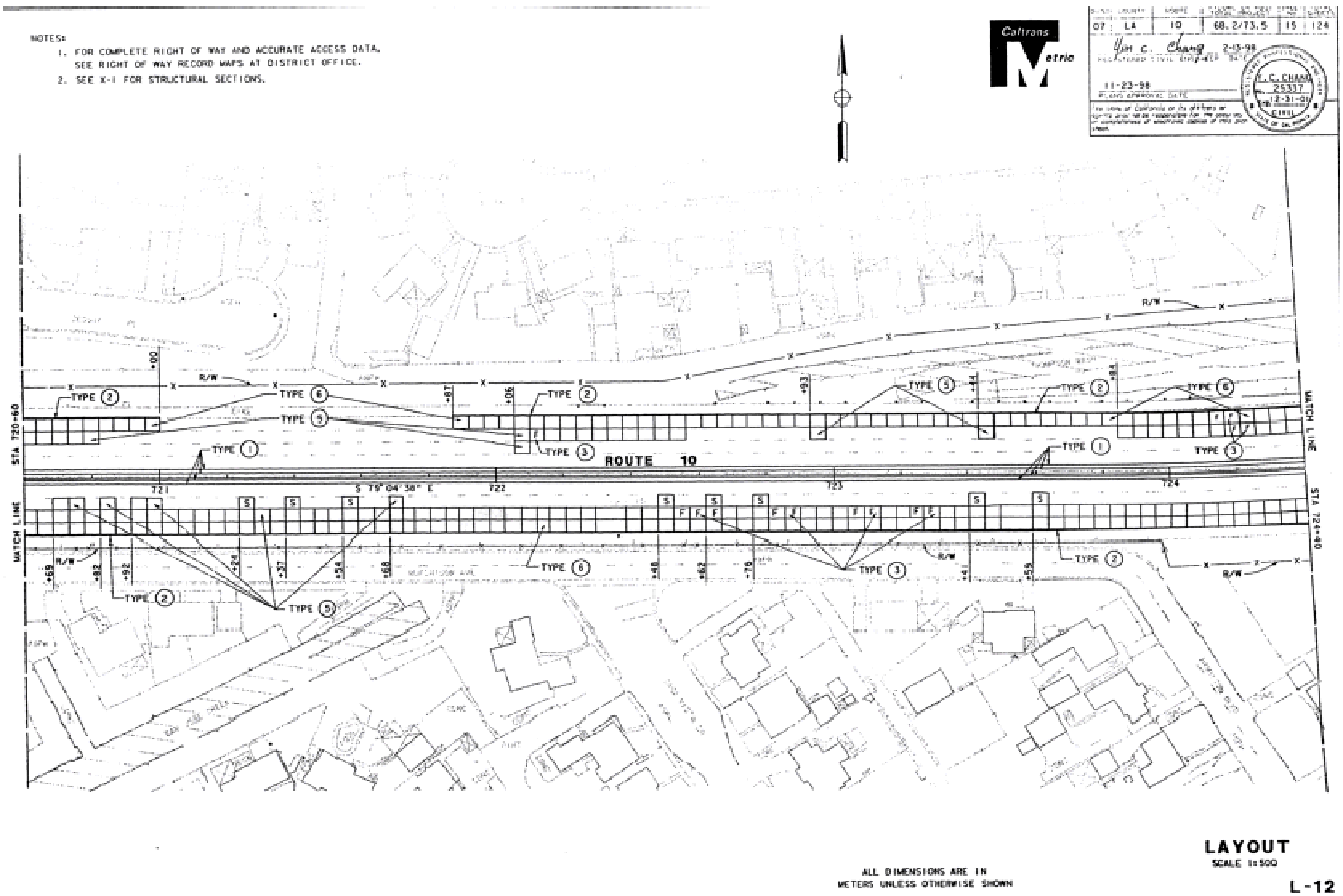


Figure 9. Layout drawing for categorization of rehabilitation.

Table 3. Comparison of productivity for different construction windows

	Nighttime Closure		Weekend Closure
	7-hour Closure	10-hour Closure	55-hour Closure
Net working hours (concrete pouring)	2 hours	5 hours	43 hours
Auxiliary hours (mobilization/curing/ demobilization)	5 hours	5 hours	8 hours
Number of slabs replaced	15	50	615
Productivity (slabs per hour)	7.5	10	14
Major resources	7 dump trucks 4 mixer trucks	7 dump trucks 8 mixer trucks	21 dump trucks 12 mixer trucks

more efficient construction access. In the rehabilitation of Lane Number 3, two full access lanes are available except for areas where the sound wall exists adjacent to shoulder. When the two access lanes are located all on one side, more mobility is afforded to the contractor in manipulating demolition and delivery trucks. If the contractor decided to rehabilitate Lane Number 4 instead of Lane Number 3, the productivity of the rehabilitation would be less because the two access lanes, Lane Number 3 and the shoulder, would have to be split apart.

After the 55-hour weekend closure, project engineers for the contractor commented that if the contractor had been provided with two full construction access lanes from the beginning to the end of the project, significantly more production could have been achieved. In a UCB study delivered to Caltrans, one of the major constraints limiting the rehabilitation production was found to be the number of access lanes available to the contractor (1).

2.7 Production Comparison of Weekend Closure with Nighttime Closures

Nighttime and weekend closures have both positive and negative aspects from a production and traffic inconvenience point of view. A detailed comparison for the two nighttime closures (7 and 10 hours) and the 55-hour weekend closure is summarized in Table 3, especially focusing on the productivity, i.e., how many slabs could be replaced per hour during each different construction windows. The definition of productivity used in Table 3 is based on the average number of slabs replaced per hour without consideration of the number of resources involved in the specific rehabilitation process.

Table 3 shows that the additional three hours of work in the 10-hour closure versus 7-hour closure greatly enhance the productivity of the nightly operation (50 slabs versus 15 slabs replaced). This can be further extrapolated to 55-hour weekend closures where mobilization, demobilization, and curing times become a smaller percentage of the total project length and thus more production can be achieved. In terms of the number of slabs replaced per hour, the 55-hour weekend closure was 54 percent more productive than the average nighttime closure.

Approximately 2,300 m^3 of FSHCC was used for the rehabilitation during the 55-hour weekend closure, which was about 16 percent of the total concrete volume of 14,000 m^3 for the entire rehabilitation project.

The entire rehabilitation project took 10 months to complete. Yet, in one 55-hour weekend closure, 16 percent of the total material used in the rehabilitation project was placed. The high productivity of the weekend closure demonstrated it to be an efficient alternative to nighttime only closures for both the road users and Caltrans.

The amount of the rehabilitation work done over the 55-hour extended closure would have normally taken approximately 16 days of nighttime lane closures to complete based on the average nighttime closure window, as shown on the next page.

Productivity of the weekend closure compared to nighttime closures

- Eastbound Nighttime Closures = 7 days of 10-hour closures per week
- Westbound Nighttime Closures = 2 days of 10-hour closures and 5 days of 7-hour closures per week
  - Average nighttime closure time (eastbound & westbound):

$$\frac{9\ days \times 10\text{ - }hour\ closure + 5\ days \times 7\text{ - }hour\ nighttime\ closure}{14\ days} =$$

$$8.9\ hours\ per\ nighttime\ closure,\ average$$

- Average performance 7-hour nighttime closure = 15 slabs
- Average performance 10-hour nighttime closure = 50 slabs
- Average number of slabs per 8.9-hour closure = 37.5 slabs
- The performance of the 55-hour weekend closure = 615 slabs
- Productivity of a 55-hour weekend closure compared to nighttime closures:

$$\frac{\#\ of\ slabs\ for\ 55\text{ - }hour\ weekend\ closure}{Avg.\#\ of\ slabs\ for\ nighttime\ closure} = \frac{615}{37.5} = 16.4\ times\ as\ many\ slabs$$

which means that 16.4 nighttime closure are required to achieve the same number of replaced slabs on a 55-hour weekend.

Comparison of the duration of a weekend closure to 16.4 nighttime closures

- Average number of hours of a nighttime closure = 8.9 hours per nighttime
- Number of hours for 16.4 nighttime closures = 16.4 x 8.9 = 146 hours
- Number of hours for a weekend closure = 55 hours
- Ratio of lane closure duration = 55 / 146 = 38 %

From the road user's point view, when the total duraFrom the road user's point view, when the total duration of lane closures for 16 days of nighttime closure is compared to one weekend closure, the duration of the 55-hour weekend closure is only 38 percent of the 16 nighttime closure duration as shown above.

For either 7-hour or 10-hour nighttime closures, a 4-hour opening strength material is required to achieve the proper concrete strength to open the lane back to traffic in a relatively short construction window. This is one reason for the application of FSHCC in nighttime only closures. The benefits of FSHCC for a 55-hour weekend closure may not outweigh its costs, and it may not be the most efficient material to use for weekend closures.

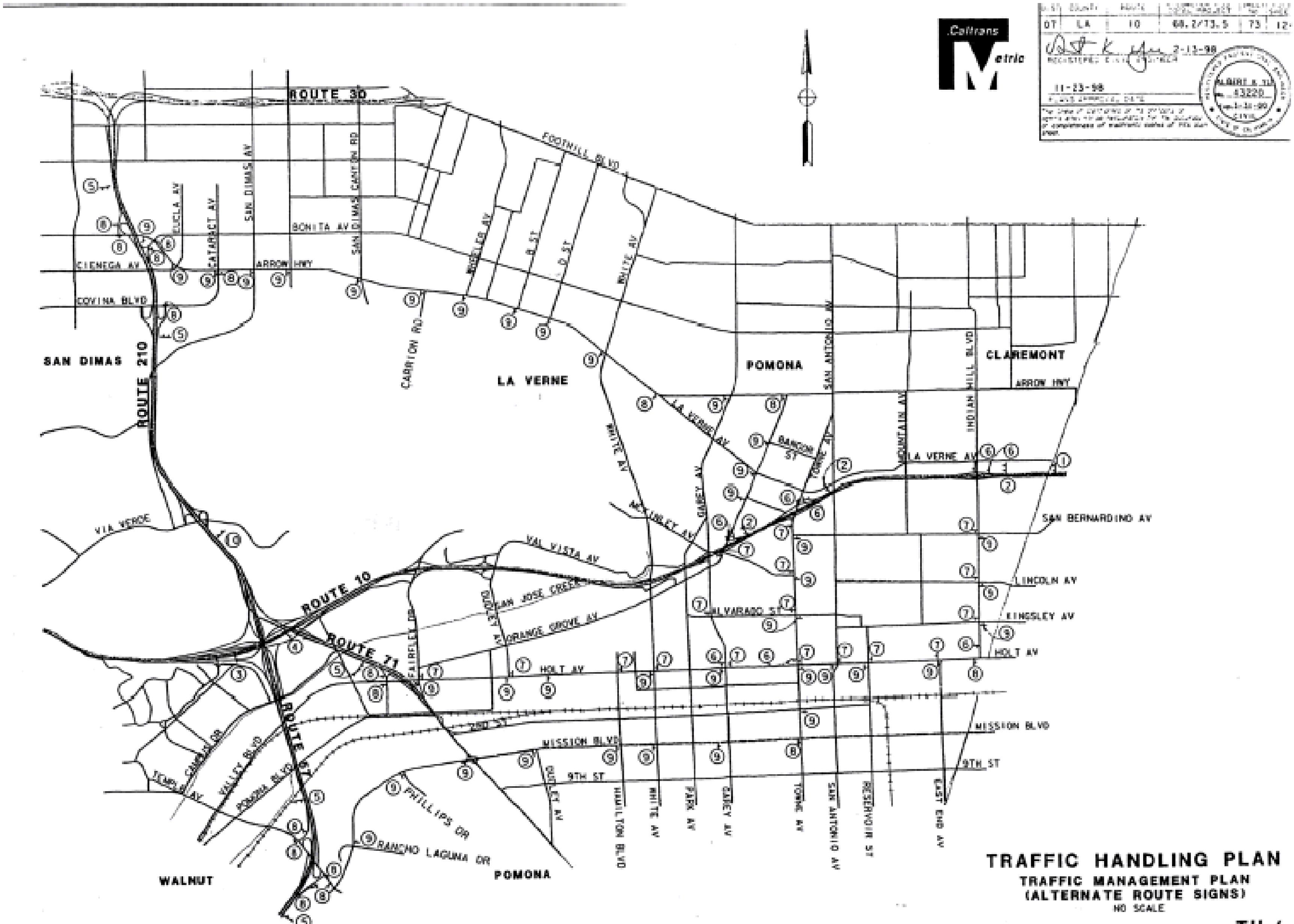


Figure 10. Example of comprehensive traffic manage

2.8 Traffic Management

2.8.1 Traffic Management Plan

Prior to the 55-hour weekend closure, Caltrans and the contractor made a large effort to disseminate information about the I-10 project through several media outlets. During the design stage, a comprehensive traffic management plan was developed with detailed detour plans for the 55-hour weekend closure. In order to control traffic and inform the public of detours during the 55-hour weekend closure, approximately one hundred message and signboards were installed through the neighboring freeways, highways, and main arterials in the vicinity of the I-10 corridor.

Figure 10 shows an example of a traffic management plan drawing for the I-10 project. The goal of Caltrans traffic plan was to divert as many road users from the I-10 corridor as possible onto alternative routes during the 55-hour weekend closure. Caltrans advertised the I-10 project plan through local media sources such as newspapers, TV, radio, and flyers for both nighttime closures and the 55-hour weekend closure. Caltrans also utilized the Internet for the advertisement of the 55-hours weekend closure by opening an exclusive web page for the project. (6)

In its traffic plan, Caltrans decided to close the connector route entrances to eastbound I-10 from the 210 and 57 freeway during the 55-hour weekend closure for two reasons: first, to minimize incoming traffic to eastbound I-10 by detouring the traffic to alternative routes; second, the location of the incoming connectors (210 and 57) was too close to the starting point of the weekend rehabilitation and there would not be sufficient capacity in the two open lanes on eastbound I-10 to accommodate the expected volume of traffic from through and connector routes. Figure 11 shows a photo of the beginning of the I-10 weekend rehabilitation project with two lanes and a shoulder closed and two lanes left open for traffic. Figure 12 shows the connector ramp to eastbound I-10 from the 210 freeway closed during the 55-hour weekend.

The ramps closed in the direct vicinity of the weekend closure included the entrance ramp at Fairplex, the entrance and exit ramp at Dudley, the exit ramp at White, and the exit ramp at Garey. All of these ramps were still open to construction vehicles, which helped expedite the demolition and concrete delivery operation and minimized construction site traffic jams. These ramp closures were posted to the public on signboards prior to the implementation of the weekend closure.

Caltrans cooperated with local transportation organizations such as the Auto Club of Southern California and the California Trucking Association to help distribute the information about the project. A team of officers from the California Highway Patrol was dispatched to the site during the weekend closure to help the project team control traffic and security of the site, particularly during the nighttime hours. The California Highway Patrol had the authority to suspend or stop the project independently of Caltrans if they felt the safety of the road users or construction workers would be compromised.

Figure 11. Beginning of closure of two right lanes with rubber cones.

Figure 12. Closure of eastbound entrance and exit ramps during the 55-hour weekend closure.

2.8.2 Impact of the Weekend Closure to Road Users

2.8.2.1 Traffic Measurement Plan. With the assistance of Caltrans traffic management in Distr the trends of road users during the 55-hour weekend closure. This traffic data was compared with historical weekend traffic data. Caltrans measured the eastbound traffic volume at two stations during the 55-hour weekend closure.

The first measuring location collected the total eastbound traffic volume at “Kellog” (near “Via Verde”) before any connector diversion. The measuring station was located west of the 210, 57, and 71 interchanges on I-10 eastbound. The traffic volume measured at Kellog represents the number of vehicles using the I-10 before the connector spilt at the 210, 57, and 71 freeway.

The second set of traffic data to measure was the net traffic volume through the project site (Fairplex Avenue to Garey Avenue). However, the traffic measuring detectors for this location were damaged during previous nighttime closures. The net traffic volume through the construction site was instead calculated by subtracting the diverted traffic volumes at the 210, 57, and 71 freeway from the measured traffic volume at Kellog. The connector ramps entering I-10 from these alternative routes were closed during the 55-hour weekend closure and therefore traffic volumes from these routes did not need to be included in the traffic analysis.

2.8.2.2 Comparison of 55-ho*u*r Weekend Traffic Data with Historical Data. The raw traffic volume data collected by Caltrans was analyzed for the 55-hour weekend closure and is shown in Figures 13 to 15. The key point of interest to Caltrans traffic management is how the traffic pattern of the traveling public changed during the 55-hour weekend closure relative to a typical weekend.

The findings from the information displayed in Figures 13 to 15 are:

- During the 55-hour weekend closure, the east bound traffic volume passing through the project site at the peak-hours (Saturday and Sunday 9 a.m. – 9 p.m.) was reduced by 30 to 60 percent compared with the peak traffic during typical weekends (Figures 13 and 14).
- The reduction in the hourly volumes through the construction zone during the day resulted from more road users taking alternate routes than on typical weekends (Figure 14). The Kellog traffic volume measurements indicate that 25 percent of the traffic diverted to Route 57, and 25 percent diverted to Route 210 and 71, leaving only 50 percent of the traffic to pass through the construction site on eastbound I-10.
- The total eastbound traffic volume at Kellog during the 55-hour closure was 5 to 35 percent less than typical weekends at peak hours (Figure 15). Off peak-hour vehicles were not discouraged or concerned about the weekend lane closures, so diversions during nighttime hours were only 5 percent different than historical volumes, as shown in Figure 14. The overall reduction in traffic volumes on I-10 during the peak-hours indicates that road users were well informed.

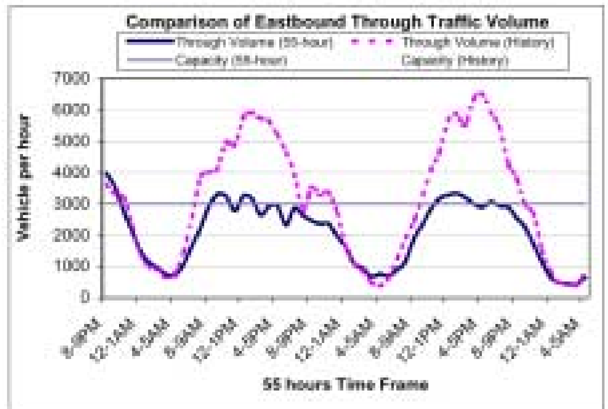


Figure 13. Through traffic volume during construction weekend compared with typical weekend.

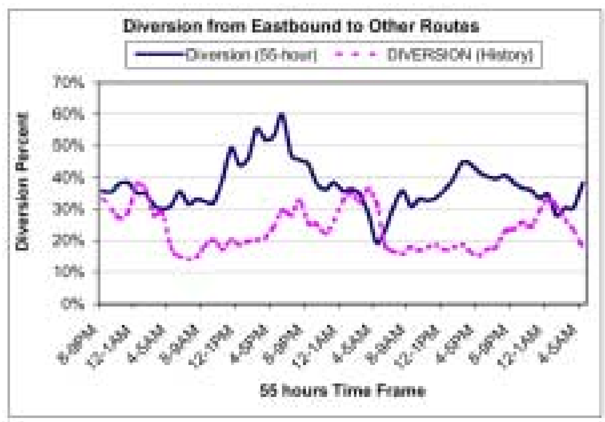


Figure 14. Diversion traffic during construction weekend compared with typical weekend.

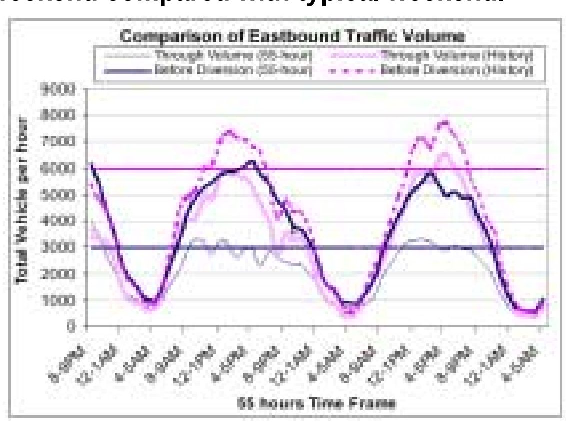


Figure 15. Net through traffic volume compared with total volume before diversion.

The demand by road users during the weekend construction was still under the capacity of the freeway (1500 vehicles per hour per lane). Overall, Caltrans traffic management efforts were successful without any significant delays on the freeway during the 55-hour weekend closure. The largest delay was 19 minutes on Sunday afternoon between 2 and 4 p.m.

2.9 Fast Setting Hydraulic Cement Concrete (FSHCC)

2.9.1 Mix Design

A Fast Setting Hydraulic Cement Concrete (FSHCC) was used for the I-10 project. Caltrans selected FSHCC to evaluate the effects of reducing the concrete curing time to a minimum. The cement utilized for this project was supplied by CTS Cement Manufacturing Company (CTS). Rapid Set, is a proprietary cement from CTS with its main component being calcium sulfo-aluminate. The final mix design the contractor used is shown in Table 4.

The main requirement in the specification was that the concrete flexural strength should be 2.8 MPa (400 psi) after 4 hours. This early strength specification essentially eliminates normal portland cement concrete from consideration in the mix design. The FSHCC was also required to reach 4.2 MPa (600 psi) within 28 days.

The target water to cement ratio (w/c) of the mix design was 0.46 with a desired slump of 15 ± 5 cm (6 ± 2 in.). Three aggregates were blended together: 25-mm stone, 9.5-mm pea gravel, and washed concrete sand.

A superplasticizer (Daracem ML-330) was used to improve the workability of the concrete. A retarder (Recover) was also added to delay the initial set time of the concrete. The FSHCC was found to be temperature sensitive, so the retarder and superplasticizer were adjusted for any 5∞C changes in ambient temperature to maintain a constant workability and set time of the mix.

FSHCC begins initial set after about one hour and final set occurs after about 80 minutes. This rapid set time helps achieve the required high early strength, but this characteristic also requires careful management of the concrete delivery trucks to avoid setup in the mixer drums. If the concrete is not discharged within approximately one hour after batching, then the FSHCC begins to build up on the mixer fins in the drum. Traffic congestion on the way to the site, construction traffic jams, or a backup in discharging of the preceding mixer trucks may result in rejection of a load, increased build up in the mixer drum, and the potential loss of the mixer truck from service until it can be chipped out.

To manage the risk of early setup the contractor had to balance the need to maximize the number of concrete delivery trucks arriving at the site per hour to provide the most efficient paving production and the risk of unwanted buildup in the mixer trucks or rejection of the concrete trucks due to unanticipated delays in transit or at the site.

2.9.2 Concrete Testing Plan

All fresh and hardened concrete property testing was contracted to Twining Laboratories of Southern California, Inc. Caltrans did not adopt non-destructive testing methods in their specification, although the Federal Highway Administration was independently conducting maturity testing. Third-point flexural strength beam tests were used to measure concrete strength as the basis for accepting and rejecting the in-place concrete. Cylinders were used to measure compressive strength, but results were only to be used as a reference in case of disputes. The contractor was required to sample 10 beams and 6 cylinders from every 15 mixer trucks [*once every 100 cubic meters or part there of in between* (4)]. The detailed testing schedule and strength requirements stated in the specification are summarized in Table 5.

Table 4. Major features of the FshCC mix design

Constituent	Quantity
Rapid Set Cement	390 kg/m^3
Concrete Sand	676 kg/m^3
9.5-mm Aggregate	215 kg/m^3
25-mm Aggregate	900 kg/m^3
Water	181 liters/m^3
Entrapped Air	1.5 percent
Water to Cement Ratio	0.46
Target Slump	150 ± 50 mm
Daracem ML 330 (21C)	25 oz./cwt.*
Recover (21C)	27 oz./cwt.*

(*oz./cwt. – ounces per hundred pounds weight of cement)

Table 5. Test schedule and strength requirements in the specification

Curing Time	Flexural Strength		Compressive Strength	
	Number of Specimens	Strength	Number of Specimens	Strength
3 hours	3 beams	N/A	1 cylinder	N/A
4 hours	3 beams	2.8 MPa	2 cylinders	N/A
28 days	3 beams	4.2 MPa	2 cylinders	N/A
Contingency	1 beam		1 cylinder	
Total Specimens	10 beams		6 cylinders	

Table 6. Criteria for strength requirement in connection with payment condition

Flexural strength requirement		Acceptance/Payment
4-hour curing	28-day curing	
2.8 MPa (400 psi)	4.2 MPa (600 psi)	Accepted/full pay
2.8 MPa (400 psi)	3.8–4.2 MPa (540–600 psi)	Accepted/95% pay
2.4-2.8 MPa (342-400 psi)	3.8 MPa (540 psi)	Accepted/90% pay
Less than 2.4 MPa (342 psi)	-	Rejected*

(*Note: rejection required concrete to be removed and replaced at the contractor's expenses)

Table 7. Result of concrete beam testing for nighttime and weekend closures (MPa)

Curing Time	Required Strength	Nighttime Average Strength	Weekend Average Strength	Total Average Strength
3 hours	N/A	2.9	3.0	2.9
4 hours	2.8	3.1	3.3	3.1
28 days	4.2	4.7	4.68	4.7

Table 8. Result of concrete cylinder testing for nighttime and weekend closures

Curing Time	Required Strength	Nighttime Average Strength	Weekend Average Strength	Total Average Strength
3 hours	N/A	23.6	22.6	23.5
4 hours	N/A	24.8	25	24.8
28 days	N/A	41.6	41.3	41.5

2.9.3 Flexural Strength Requirement Criteria

The strength criteria used for accepting and rejecting placed concrete is shown in Table 6 (4). If any disputes over the flexural strength results arose, the cylinder strengths could be used to resolve the strength discrepancies. Caltrans and the contractor agreed prior to the 55-hour window that the incentive/disincentive clause for paving production would not be tied to the concrete strength criteria. Therefore the contractor could receive 100 percent of the incentive ($500,000) for completing the 2.8 lane-km of paving even if some sample units did not meet the 4-hour or 28-day flexural strength criteria.

2.9.4 Results of the Concrete Testing

Tables 7 and 8 show the average results of the concrete beam and cylinder testing, respectively, for both the 55-hour weekend and nighttime closures. The 3- and 4-hour flexural tests met the Caltrans strength specification of 2.8 MPa at 4 hours for both nighttime and weekend construction. Likewise, the average 28-day strength results were 10 percent higher than the specification. The flexural strength results were approximately the same for nighttime and weekend work. The compressive strength data showed trends similar to those of the flexural strength results.

CHAPTER 3

3.0 Construction Productivity During the 55-hour Weekend Closure

3.1 Participation of Subcontractors

One principal contractor (Morrison Knudsen Corporation) managed the I-10 project. The principal contractor was in charge of drilling holes for tie bars, installing dowel bars, paving the concrete, controlling traffic, and handling the movable concrete barrier (MCB). All other activities were contracted out to specialty contractors or were the responsibility of the owner (Caltrans). Cellular telephones were used very efficiently as a communication tool for coordination among the contractor and subcontractors at the site.

3.2 Contractor's Internal CPM Schedule

The contractor developed and pursued two CPM schedules, an "internal" and a "formal" schedule, for the 55-hour work weekends. The internal CPM schedule was the most optimistic option, as shown in Table 9. The formal CPM schedule, shown in Table 10, was submitted to Caltrans.

Based on nighttime closure work, MK was confident they could achieve the rehabilitation goal of 2.8 lane-km during the weekend closure much earlier than the formal CPM schedule indicated. MK's original intent with the internal CPM schedule was to complete the target goal of 2.8 lane-km and then continue rehabilitating other parts of the contract work on I-10 during the remainder of the weekend. The main purpose for this strategy was to take advantage of the large traffic management effort and finish work that would otherwise have to be completed on nighttime closures. As shown in Section 2.6, weekend work was 66 percent more efficient than nighttime work. Furthermore, the faster the work was completed by the contractor, the less risk to the construction workers from construction zone exposure.

The contractor was not permitted to implement the internal CPM schedule as the formal plan because of a number of obstacles. Caltrans was not in favor of the contractor's internal CPM for two main reasons. The first reason was that the traffic management plan would have to be revised to allow the contractor access to other locations on I-10 not included in the 2.8 lane-km production run. Secondly, Caltrans would have had to adjust several contractual conditions to accommodate the proposed addi-

Work was split among the participants as follows:

- Caltrans (Owner): Inspection and traffic management
- Morrison Knudsen (principal contractor): Management and concrete paving activities
- Harber: Demolition (slab removal with excavators and hauling with dump trucks)
- Western Rock Inc.: Concrete Batch Plant and delivery with mixer trucks
  - CTS: Cement supply (Rapid Set cement)
  - Vulcan Materials: Aggregate supply
- Twining Laboratories: Concrete testing
- Barrier Systems Inc.: Moveable Concrete Barrier, including transfer and transport of machine

Table 9. Contractor's internal CPM schedule for the 55-hour weekend closure

Sequence	Work Activity	Start	Finish	Duration (hrs)
I	**Rehabilitation of 1st area (main rehabilitation work)**			
1	Set traffic control	-2	1.0	3.0
2	Install Mobile Concrete Barriers (MCB)	0	2.0	2.0
3	Slab demolition	0.5	16.0	15.5
4	Cleaning sub-base	1	16.5	15.5
5	Drill and tie bar install	1.5	20.0	18.5
6	Set polyethylene and dowel baskets	2.0	20.5	18.5
7	Concrete slab paving	2.0	40.5	38.5
8	Pavement marker	41.0		
II	**Rehabilitation 2nd Area (additional rehabilitation work)**			
9	Slab demolition	18.0	24.0	6.0
10	Cleaning sub-base	18.5	24.5	6.0
11	Drill and tie bar install	23.0	31.0	8.0
12	Set polyethylene and dowel baskets	23.5	31.0	7.5
13	Concrete slab paving	40.0	50.0	10.0
14	4 hour curing	50.0	54.0	4.0
15	Remove MCB	52.0	54.0	4.0
16	Open to traffic	55.0	55.0	

(Note: time 0 starts at 10 p.m. on Friday)

tional work. For example, payment and quality control factors for the extra work, which would not be connected with the original 55-hour project plan, would have had to be worked out. The internal CPM plan proposed by the contractor (Table 9) was realistic in terms of predicted progress of the rehabilitation, assuming no mishaps would have occurred to slow down the production rate.

3.3 Formal CPM Schedule Submitted to the Owner

Figure 16 shows the contractor's formal CPM schedule submitted to Caltrans. Table 10 is the summary of the CPM schedule showing the main activities of the rehabilitation with start times, finish times, and durations. The CPM schedule is straightforward, as most activities have "start-to-start" or "start-to-finish" relationships.

The activities on the critical paths are as follows:

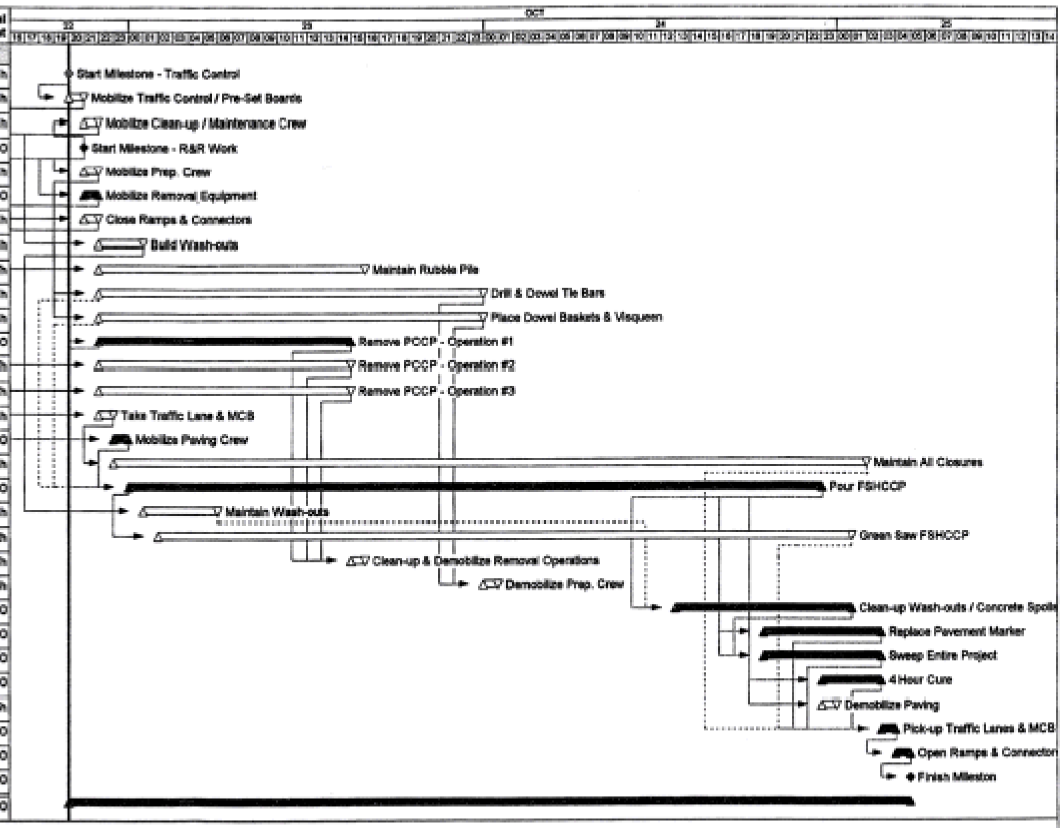
mobilization →
slab removal →
pour FSHCC →
clean up wash-outs →
pavement markers →
Cure FSHCC 4 hours →
pick-up MCB →
open ramps and connectors

The CPM schedule of the 55-hour weekend closure was very tight, with most of the main activities on the critical path without any alternative paths or floats for contingency.

The contractor reviewed and checked the plan very carefully due to the contractual pressures to finish the targeted 2.8 lane-km in 55 hours. The proposed CPM schedule submitted to Caltrans was more relaxed than the contractor's internal schedule. The contractor was very confident of the plan and schedule based on experience from a number of repeated nighttime closures. MK did realize that if one activity lagged in production or a breakdown occurred, then it could delay the whole rehabilitation process and jeopardize the targeted completion goal of 2.8 lane-km. For this reason, MK included redundancy in major equipment, including the batch plant, demolition trucks, excavators, paving screeds, and concrete delivery trucks.

A couple of points can be made about MK's proposed CPM schedule as compared to MK's internal CPM schedule:

Act ID	Activity Description	Rem Dur	Early Start	Early Finish	Total Float
55 Hour Extended Work Weekend					
MLS100	Start Milestone - Traffic Control	0	22OCT99 8:00PM		1h
TRF100	Mobilize Traffic Control / Pre-Set Boards	1	22OCT99 8:00PM	22OCT99 8:59PM	1h
CLN100	Mobilize Clean-up / Maintenance Crew	1	22OCT99 9:00PM	22OCT99 9:59PM	31h
MLS110	Start Milestone - R&R Work	0	22OCT99 9:00PM *		0
PRP100	Mobilize Prep. Crew	1	22OCT99 9:00PM	22OCT99 9:59PM	1h
RMV100	Mobilize Removal Equipment	1	22OCT99 9:00PM	22OCT99 9:59PM	0
TRF110	Close Ramps & Connectors	1	22OCT99 9:00PM	22OCT99 9:59PM	1h
CLN110	Build Wash-outs	3	22OCT99 10:00PM	23OCT99 12:59AM	31h
CLN210	Maintain Rubble Pile	18	22OCT99 10:00PM	23OCT99 3:59PM	37h
PRP200	Drill & Dowel Tie Bars	26	22OCT99 10:00PM	23OCT99 11:59PM	1h
PRP210	Place Dowel Baskets & Visqueen	26	22OCT99 10:00PM	23OCT99 11:59PM	1h
RMV200	Remove PCCP - Operation #1	17	22OCT99 10:00PM	23OCT99 2:59PM	0
RMV210	Remove PCCP - Operation #2	17	22OCT99 10:00PM	23OCT99 2:59PM	37h
RMV220	Remove PCCP - Operation #3	17	22OCT99 10:00PM	23OCT99 2:59PM	37h
TRF120	Take Traffic Lane & MCB	1	22OCT99 10:00PM	22OCT99 10:59PM	1h
PLC200	Mobilize Paving Crew	1	22OCT99 11:00PM	22OCT99 11:59PM	0
TRF200	Maintain All Closures	51	22OCT99 11:00PM	25OCT99 1:59AM	1h
PLC210	Pour FSHCCP	47	23OCT99 12:00AM	24OCT99 10:59PM	0
CLN200	Maintain Wash-outs	5	23OCT99 1:00AM	23OCT99 5:59AM	31h
PLC230	Green Saw FSHCCP	47	23OCT99 2:00AM	25OCT99 12:59AM	2h
RMV300	Clean-up & Demobilize Removal Operations	1	23OCT99 3:00PM	23OCT99 3:59PM	37h
PRP300	Demobilize Prep. Crew	1	24OCT99 12:00AM	24OCT99 12:59AM	28h
CLN300	Clean-up Wash-outs / Concrete Spoils	12	24OCT99 1:00PM	25OCT99 12:59AM	0
CLN220	Replace Pavement Marker	8	24OCT99 7:00PM	25OCT99 2:59AM	0
CLN310	Sweep Entire Project	8	24OCT99 7:00PM	25OCT99 2:59AM	0
PLC220	4 Hour Cure	4	24OCT99 11:00PM	25OCT99 2:59AM	0
PLC300	Demobilize Paving	1	24OCT99 11:00PM	24OCT99 11:59PM	5h
TRF300	Pick-up Traffic Lanes & MCB	1	25OCT99 3:00AM	25OCT99 3:59AM	0
TRF310	Open Ramps & Connectors	1	25OCT99 4:00AM	25OCT99 4:59AM	0
MLS200	Finish Mileston	0		25OCT99 4:59AM	0
		57	22OCT99 8:00PM	25OCT99 4:59AM	0



Start date	22OCT99 8:00PM
Finish date	25OCT99 4:59AM
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Morrison Knudsen Corporation
55 Hour Extended Work Weekend

- Early start point
- Early finish point
- Early bar
- Progress bar
- Critical bar
- Summary bar
- Progress point
- Critical point
- Summary point
- Start milestone point
- Finish milestone point

Figure 16. Contractor's formal CPM schedule.

Table 10. Formal CPM schedule submitted to Caltrans

Sequence	Major work activity	Start time	Finish time	*Duration (hours)*
1	Set traffic control	-2.0	-1.0	*1.0*
2	Install MCB	0	1.0	*1.0*
3	Slab demolition	0	17.0	*17.0*
4	Cleaning sub-base	0	17.0	*17.0*
5	Drill and tie bar install	0	26.0	*26.0*
6	Dowel baskets	0	26.0	*26.0*
7	Concrete slab paving	2.0	49.0	*47.0*
8	Saw cut	4.0	51.0	*47.0*
9	Pavement marker	45.0	53.0	*8.0*

Note: time 0 starts at 10 p.m. on Friday

- A lot of preparatory activities at the beginning of the project were scheduled to take place immediately upon closure of the project area (i.e., time zero [Friday, 10 p.m.]) in order to maximize the available time for the main activities, especially concrete paving. In MK's internal CPM schedule, these activities were scheduled to start with one- or two-hour lags sequentially.
- The duration of slab demolition (17 hours) was relatively short compared with the concrete paving duration, which was scheduled for 47 hours. The contractor believed demolition could be completed quickly with multiple crews, i.e., three excavator teams. This would be equivalent to one demolition crew working continuously for 51 hours.
- Finally, the duration of the paving activity (47 hours) in the proposed CPM schedule was stretched as much as possible as compared with the internal CPM schedule of 38.5 hours of paving time.

3.4 Initial Resource Planning

3.4.1 Manpower Organization

Due to the tight work schedule, workers on the job site were scheduled to work 12-hour shifts with two shifts per day. Although there were many activities involved in the rehabilitation project, MK mobilized approximately 35 people for coordination, paving, and traffic control. The breakdown in labor for the principal contractor was as follows:

- Project manager: 1
- Project engineers: 2
- Superintendents: 2
- Total number of laborers: about 30
- Paving operation: 21 per shift
- Traffic control: 6
- Dumping area: 3

3.4.2 Details of Resource Operation Plan

Table 11 shows the major resources schedule for usage by the contractor during the 55-hour weekend closure. Compared with the resource schedule for the nighttime closure shown in Table 2, the number of the resources increased significantly. For example, three times as many demolition and concrete delivery trucks were planned as compared to the nighttime only closures. Inclusion of many crews was possible because the entire construction zone was protected from traffic and crews could work in different locations on the site.

Because many parts of the rehabilitation work were contracted out to specialty contractors, the prime contractor did not have complete control of the resource planning. For example, the concrete batch plant, end dump trucks for demolition, and mixer trucks for concrete delivery were under the control and responsibility of subcontractors. The responsibility for mobilizing the total number of each resource needed was placed on the subcontractors.

In the demolition plan, multiple crews were to be mobilized to shorten the duration of the demolition. Three demolition teams working simultaneously were planned with a minimum gap between the teams. Each team would take care of a certain number of slabs and then leap forward in front of the other demolition crews until completion of the work.

In the demolition plan, seven end dump trucks were assigned to each excavator. Multiple

Table 11. Initial resource plan for 55-hour weekend closure

Resource	Quantity	Total Quantity of Resource
End Dump Truck, 22-ton Capacity	7 per team	21 trucks (3 teams)
Excavator, $1m^3$ Capacity	1 per team	3 (3 teams)
Mixer Truck, 8 cu. yd. Capacity	12 per hour	15 mixers (3 standby)
Batch plant, 220 cu. yd. per hour Capacity	1	2 (1 standby)
Hand Operated Screed	1	2 (1 standby)
Gang Drill for Tie Bar Holes	2	2 (for both longitudinal edges)
Concrete Saw for Transverse Joints	1	1

demolition crews were possible as two construction access lanes were available (Lane Number 4 and the shoulder). Shortly after construction began, demolition trucks could use closed exit and entrance ramps to the site to try and avoid any interruption between the demolition teams and undesired queuing of the trucks in one location.

In the concrete delivery plan, 12 mixer trucks per shift were slated for operation with 3 standby mixers in case of excess buildup of FSHCC in the mixer drum. A dry mix batch plant from Western Rock was exclusively used for the project during the weekend closure. A standby batch plant was arranged with the same stock of materials, as contingency for an emergency. Two rotating concrete screeds were mobilized for concrete paving with one screed being used for backup.

3.5 Sudden Change of the Contract from Traffic Control Requirement

One of Caltrans biggest concerns during the 55-hour weekend closure was the inconvenience to road users, especially since Caltrans did not have experience with this type of urban freeway closure. At the same time as the I-10 project, several other rehabilitation projects were underway on nearby freeways. These neighboring rehabilitation projects could aggravate the traffic congestion on the I-10 (Pomona) segment during the weekend closure.

A few days prior to the pilot project, Caltrans requested a contingency plan by the contractor to open the rehabilitated lane to traffic within two hours of notice by the Resident Engineer. Caltrans issued a letter to the contractor stating the demolition progress could not be more than 20 slabs from the paving operation. The reason for this action by Caltrans was to avoid large delays to the road users travelling through the I-10 Pomona corridor. The contractor would be required to open the rehabilitated lanes to traffic if traffic backup on eastbound I-10 was 30 minutes longer than that of a normal weekend. Another reason for this stipulation by Caltrans was to make sure the contractor could efficiently produce, deliver, and place the FSHCC before completely removing all the slabs in Lane Number 3.

This restriction on the number of slabs demolished ahead of the paving operation was lifted on Saturday morning at 10:30 a.m. Caltrans and the contractor could not afford to have the road still closed when rush hour traffic began on Monday at 5 a.m.

According to the contractor, enough time was not available to properly develop a contingency plan for this restriction, as they were only given this information several days prior to the 55-hour weekend closure. The contractor's solution was to slow down the progress of demolition after a certain time period to make sure the demolition crews did not outpace the paving operation. The contractor reduced the demolition operation from three teams to two teams approximately 5 hours after the demolition began.

The downsizing of the demolition from three to two crews was one reason why the actual duration of demolition was much longer than (almost twice) than the scheduled demolition in the proposed CPM. However, this demolition restriction did not hinder the contractor from achieving the production goal of 2.8 lane-km in 55-hours. The reason the contractor was able to complete the entire length of the project was that the demolition operation was far enough ahead of the paving. The concrete paving was on the critical path for the majority of the project, while the demolition work was only briefly on the critical path at the beginning of the project.

3.6 Typical Rehabilitation Processes

The typical process of the rehabilitation for the 55-hour weekend closure was planned as follows:

1. Saw cutting for demolition (completed during previous nighttime closure)

2. Install MCB and lane closures
3. Demolition of slab/hauling out demolished slab
4. Demolition an paving of CTB (for full depth replacement only)
5. Clean and sweep CTB
6. Drill holes and install tie bars
7. Install bond break (Polyethylene sheets)
8. Install dowel bar baskets
9. Concrete production and delivery
10. Concrete placement
11. Finishing and texturing
12. Spread curing compound
13. Cure concrete
14. Saw transverse joints
15. Install pavement reflectors
16. Clean up slab surface
17. Demobilize of MCB
18. Open lanes to traffic
19. Grind pavement surface (to occur during a subsequent nighttime closure)

The rehabilitation process over the 55-hour w end closure is a typical example of linear produc with an optimal distance between the activitie avoid interruptions while still minimizing the n ber of resources. A detailed description of the ab processes is in Sections 0 and 3.12.

3.7 Traffic Closure with Movable Concrete Barrier (MCB)

The first step of the rehabilitation process was t fic control. The major traffic control activities v setting up traffic signs, closing of entrance/exit ramps and connectors from other routes, and installing Moveable Concrete Barrier (MCB) for the lane closure. The contractor began to set up traffic signs two hours before the lane closure could be implemented, i.e., Friday at 8 p.m.

During the 55-hour weekend closure, the specification required installation of MCB between the traffic and rehabilitation lanes, i.e., Lane Numbers 2 and 3. The purpose of the MCB was to serve as a temporary safety barrier between road users and construction workers. For nighttime closures, rubber cones were used instead of MCB for prompt installation and removal. Figure 17 shows an isometric view of a MCB from the contract drawing with its typical dimensions. Figure 18 shows a picture of the MCB utilized as a safety barrier on the I-10 project.

The MCB is only available for lease from a specific manufacturer, namely Barrier Systems, Inc. This manufacturer also supplied the transfer and transport machine for the MCB. The price quoted by the manufacturer for any successful bidder was $125 per linear meter of concrete barrier and $133,000 per unit of transfer and transport machine based upon a year lease (4).

The MCB segments were already placed and lined up on the outside shoulder before the weekend closure and only needed to be shifted into place (between Lane Number 2 and 3) by the transfer and transport machine. In addition to the benefit of concrete barriers for worker safety, the high cost of using the MCB could be justified by the simplicity and quickness of the installation process. The installation of the MCB for the whole 3 lane-km segment was performed within 30 minutes. Figure 19 shows how the MCB was installed by the transfer and transport machine at the beginning of the project.

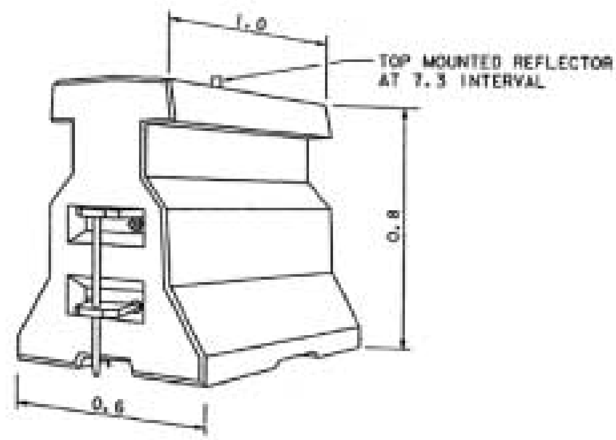

Figure 17. Isometric view of the MCB (unit: meter).

Figure 18. MCB installed as safety barrier during the weekend closure.

Figure 19. Installation MCB using transfer and transport machine.

3.8 Demolition of PCC Slab

Most contractors use two types of demolition methods for concrete pavement rehabilitation: impact and non-impact. In the case of impact demolition, the concrete slab is rubblized by a breaker, which repeatedly drops a heavy hammer mounted on the impact equipment. The rubblized slab can then be loaded onto a truck in small pieces. This impact demolition method is normally used for full-depth replacement options, as the drop hammer can rubblize the pavement down to the subbase level.

In the case of non-impact demolition, the concrete slab is cut into several pieces by longitudinally and transversely cutting the slabs, and then lifting out large slab segments with an excavator. In this case, the CTB remains undisturbed and only the concrete slab is removed. Figure 20 shows the saw cutting operation for the non-impact slab demolition. Figure 21 shows concrete slab cut into three pieces longitudinally for easy removal.

Both demolition methods were used for the I-10 project. Most areas required only slab replacement (non-impact demolition method), while a few areas needed the full-depth slab replacement (impact demolition). For the non-impact demolition process, slabs were already longitudinally saw cut into three parts, one meter from both longitudinal edges, during previous nighttime closures. There was some saw cutting during the weekend closure towards the end of the project because the contractor could not finish cutting all 615 slabs before the project began. The concrete slabs cut during nighttime closures prior to the 55-hour weekend closure were used as normal traffic lanes until the time of the weekend closure.

3.8.1 Slab Demolition Plan

The demolition contractor (Harber) mobilized three demolition teams at the beginning of the project. Each team worked simultaneously with a minimal separation and moved forward in a staging progress rather than spread out into three equally divided parts spanning the whole project length. After about one-third of the slabs had been demolished, only two demolition teams remained until the end of the demolition phase due to the physical constraints of the project.

One excavator with a 1 m^3 bucket capacity and seven end dump trucks were assigned for each team in the initial demolition plan. End dump trucks were owner-driver trucks and were mobilized throughout the Southern California area. At the start of the demolition, a hand held pneumatic hammer broke up the first slab to allow the blade of the excavator to lift out the first slab, as shown in Figure 22. With the non-impact demolition method, the excavator sat in Lane Number 3 in front of the slabs that it was removing. The excavator then loaded the old concrete into the end dump truck sitting in Lane Number 4, as shown in Figure 23. The loading rate of the cut slabs (non-impact demolition method) was quicker than that of the rubblized slabs (impact demolition method) because the excavator could more easily remove a few large pieces than many smaller pieces.

When two construction access lanes (i.e., Lane Number 4 and shoulder) were not provided, especially for the final two-thirds of the rehabilitation project, the excavator on Lane Number 3 and dump truck on Lane Number 4 blocked the passage of concrete mixer trucks, as shown in Figure 24. For a large part of the project, a soundwall was adjacent to the shoulder causing access lane restrictions. In Figure 25, an end dump truck for demolition was being

Figure 20. Slab cutting for non-impact demolition method.

loaded on the shoulder and part of Lane Number 4. As another demolition truck is trying to pass this crew, the excavator must halt its operation briefly. In many instances, a demolition truck or mixer truck could not pass the demolition crew, as shown in Figure 24. In this situation, the demolition truck had to move forward to allow for the waiting truck to pass and then back up to the excavator. Occasionally, the demolition truck would move forward to the next demolition crew especially if there were a significant number of demolition trucks queuing from behind.

The passage of an empty concrete mixer truck on the way back to the batch plant had first priority in most cases. The reason for this was that the concrete paving was the critical activity and the contractor wanted to avoid buildup of FSHCC in the mixer truck drums. Occasionally, the laborer assigned to the demolition crew would help direct traffic trying to pass the demolition crew, but this construction site traffic management was almost always left up to the demolition contractor superintendent or excavator operator.

Figure 21. Slab panels cut into three pieces longitudinally.

Figure 22. Breaking the starting point of the slab with a jackhammer.

Figure 23. Non-impact demolition.

Although the 22-ton capacity end dump trucks hauling out the old concrete slabs had a 9-m^3 capacity (12 cubic yard volume of concrete, or 2.7 slabs), the volume of concrete in each truck was between 1 and 1.5 slabs. For a typical slab size of 3.7 m by 4.5 m by 0.23 m thick, the weight of the concrete in an end dump ranged from 8 metric tons (3.3 m^3 volume) for one panel or 12 metric tons (4.9 m^3 volume) for 1.5 slabs. The main reason the actual loading volume was less than the capacity of a truck was that the slab pieces (> 1m) could not be packed efficiently into the truck bed.

The unpacked volume between the pieces of slab was too high and consequently when only half of truck's payload was utilized the volume of the truck bed was full. However, the contractor already knew about this 50 percent capacity reduction from their nighttime closure experience. The contractor needed to mobilize more trucks to compensate for reduced hauling volume per truck in order to finish the demolition in the minimum amount of time. According to the measured result of 466 demolition deliveries, the average efficiency of demolition trucks was found to be approximately 47 percent of their volume capacity, as discussed in detail in the next section.

One of the challenges for the agency and contractor was securing a large enough area located within a few miles of the rehabilitation site where the removed concrete slabs could be dumped. Luckily, the location of the dumping area for the I-10 project was about 8 km (5 miles) from the job site. The contractor rented a dump site from a private business in Los Angeles County. Figure 26 shows the view of the dumping area with an end dump truck and a breaker. The contractor's site office, subcontractor's batch plant, and dumping area were in the same area near the project site, which minimized haul distances.

The contractor commented that without the dumping area for the old concrete slabs close to the site, the project wouldn't work. The main reason for this is the turnaround time per truck was not long and therefore not as many end dump trucks were required to be mobilized. The contractor used a breaker mounted on a backhoe to rubblize slab pieces at the dumping site, as shown in Figure 26. Figure 27 shows the stockpile of rubblized concrete left at the dumping area for future use.

Under the freeway bridges, a small backhoe was used to excavate the concrete slabs instead of the large excavators used for the normal demolition. The reason for using the small backhoe versus the large excavator was the clearance underneath the bridges. The loading time underneath the bridges took about twenty to thirty minutes compared with approximately five minutes for the normal demolition operation.

For the slab replacement only case, cleaning up the base with a front-end loader followed right after the slab demolition, as shown in Figure 28. For most of the project, the existing CTB layer had loose debris on top of it from erosion of the base or materials washing underneath the slab. In many places, the CTB could be scraped away by the heel of a shoe. The overall condition of the existing base was not very good for a pavement section expected to last for 30 years.

Figure 24. Concrete mixer truck waiting for clearance to pass behind the demolition operation.

3.8.2 CTB Demolition and Replacement

Although most of the rehabilitation was limited to slab replacement, in some areas where the base was badly deteriorated, full-depth demolition took place. Figure 29 shows impact demolition through the use of a guillotine breaker. In order to accommodate a thicker CTB and slab in the full-depth option, part of the aggregate subbase had to be removed. After the guillotine hammer was finished, the whole section was taken out with an excavator, as shown in Figure 30. FSHCC was used for the placing the new CTB layer to quickly achieve early strength with the purpose of placing the slab as soon as the CTB achieved the minimum required strength. Placement of the fast-setting hydraulic cement treated base can be seen in Figure 31.

Figure 25. Excavator pausing operation to allow an end dump from other demolition team to pass.

Figure 26. View of the dumping area with end dump trucks and breaker for rubblization.

Figure 27. Stockpile of rubblized concrete.

Figure 28. Cleanup of base with a small loader for “slab replacement” case.

Figure 30. Removal of PCC slab, CTB, and part of aggregate base for full depth replacement.

Figure 29. Impact demolition with a breaker for full depth replacement.

Figure 31. Placement of FSHCC CTB.

3.8.3 As-built Progress of Slab Demolition

The following sections compare and contrast the actual progress with the proposed CPM for the concrete pavement demolition. There were 615 concrete slabs removed from Lane Number 3 for the 2.8 lane-km project.

3.8.3.1 Summary of End Dump Truck Operation. The UCB research team recorded a total of 466 loaded end dump trucks exiting the site to haul out the 615 slabs. On average, each end dump truck carried about 10.3 metric ton (4.3 m^3), which was equivalent to approximately 1.3 concrete slabs. The maximum carrying capacity of the end dump trucks was 22 tons. This meant that only 47 percent of the total carrying capacity of the end dump truck was being utilized, due to the inefficient packing of the large panel pieces.

The demolition progress can be summarized as follows:

- The first demolition truck was loaded at 22:30 Friday as planned.
- The demolition operation took 30 hours, from time 0.5 (Friday 22:30) to time 30.5 (Sunday 4:30 a.m.). (Note that the CPM schedule planned 17 hours for demolition.)
- For a period of time, three demolition teams operated simultaneously with a staging progress method, but for the majority of time only 2 demolition crews worked simulta neously. The reason for this was construction site access problems and the constraint on the contractor to not progress more than 20 slabs in front of the paving operation at the beginning of the project, as discussed in Section 3.5.
- A total of 466 trucks hauled out demolished concrete slabs. (Note that the contractor’s plan estimated a total of about 400 trucks.)
- Average number of slabs carried per end dump truck loading = 615 slabs / 466 truck

loads = 1.32 slabs per truck = 10.3 metric ton (4.3 m^3) of concrete per end dump truck.

- Efficiency of the end dump truck = 10.3 metric ton average divided by the 22 metric ton capacity of the end dump truck for an efficiency of the truck of approximately 47% of its capacity.
- The average number of panels demolished per hour = 615 slabs / (30 hours x 2 teams) = 10 slabs per hour per team. (Note that the contractor's plan was to demolish 12 slabs per hour per team with 1 to 1.5 panels loaded for each end dump truck.)
- Average loading time of an end dump truck = 30 hours x 60 min. / (466 /2 teams) = about 8 minutes per load.
- Average number of trucks showing up per hour = 466 / (30 x 2 teams) = about 8 trucks per hour per team.
- A total of 32 end dump trucks were mobilized —11 more than the 21 planned in the contractor's CPM schedule.
- Between 19 and 20 end dump trucks were in continuous operation, with the extra dump trucks reserved for shift changes and spares, if necessary.

There were two main reasons why the actual demolition duration was 30 hours instead of the proposed 17 hours. The first reason for demolition delay was that the contractor had to make sure the demolition crew did not outpace the paving operation per Caltrans' instruction to not to be more than 20 slabs in front of the paving operation and be able to open the section to traffic within two hours (see Section 3.6). Accordingly, several hours after beginning demolition, the contractor reduced the demolition operation to one crew to meet this requirement.

The second reason was that after the demolition restriction was lifted on Saturday morning, the contractor was not able to use three crews because the final two-thirds of the project had only one full access lane (Lane Number 4) for construction traffic instead of the initial two access lanes (Lane Number 4 and outer shoulder). This made it difficult to run multiple demolition crews along with the paving operation. As shown in Figures 24 and 25, it was very difficult for the demolition crew to pass in the area with the sound wall without interrupting the loading of a truck.

3.8.3.2 Statistics for Demolition Truck Operation. The UCB research team recorded arrival, departure, and loading time of almost all end dump trucks used in the demolition operation (466 trucks). The main purpose of recording the demolition trucks entering and exiting the site was so that the progress of the demolition process could be analyzed and related to the other construction operations and the total project production. The data would also be useful to help calibrate the UCB constructability and productivity analysis model discussed in Section 4.0 (1), especially for use in stochastic analysis given that a realistic shape of the distribution curve for the resource profiles (trucks, batch plant, screed) was required.

The demolition truck operation can be summarized as follows:

- Average loading time per end dump truck was 5.5 minutes with a 0.9-minute standard deviation, as shown in Figure 32.
- On average, approximately 9 end dump trucks showed up per hour per crew for demolition with a 2.3 truck standard deviation, as shown in Figure 33. For every demolition crew, an

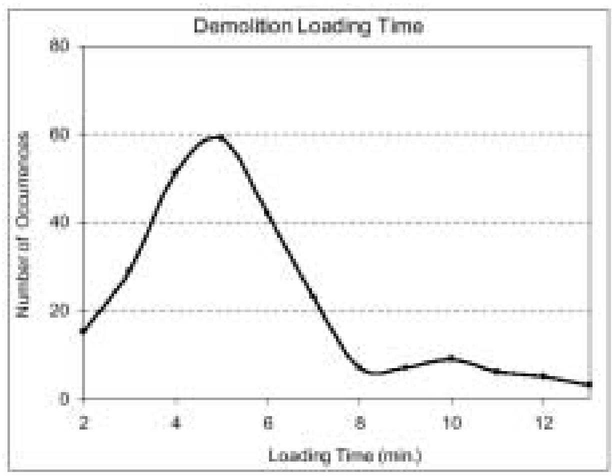

Figure 32. Distribution of the cycle time of demolition loading.

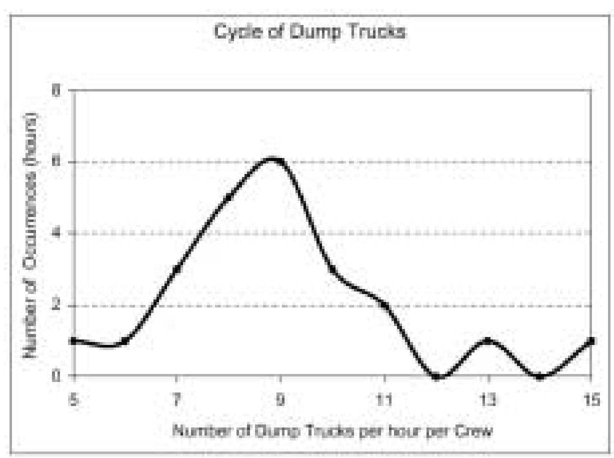

Figure 33. Distribution of the number of end dump trucks arriving at the site per hour.

end dump truck arrived at the demolition area every 7 minutes. There were several minutes of waiting for each dump truck along with the previously mentioned 5.5-minute average loading time. This meant that when three crews were operating simultaneously, a demolition truck was enter-ing or exiting the construction zone every 2.3 minutes.

- When construction access was reduced to one lane, a three-team operation was not feasible because interference between demolition truck crews would occur before one truck could be loaded in the average 5.5 minutes.
- As reported in Section 3.8.3.1, approximately 8 end dump trucks arrived at the site every hour per team instead of the nine planned. The main reason for the discrepancy is that on average, fewer than two demolition teams were operating simultaneously. This would increase the efficiency of each demolition operation to nine end dump trucks per hour.
- Although there were alternative entrances to the construction zone, two of the ramps (Fairplex and Dudley Avenue) did not reduce the congestion of demolition truck traffic be cause they were located at the beginning of the project. The White Avenue exit ramp was used as entering point for the demolition trucks, but it was located 2 km from the start of the project and therefore was not useful for most of the weekend. Furthermore, the dimensions of the White Avenue exit made it difficult for standard length tractor-trailers to make a U-turn in order to start heading east bound in the construction zone and thus demolition loading delays were encountered near this exit ramp.
- Based on the average loading time of the end dump trucks (5.5 minutes), the average maximum number of end dump trucks to load per hour was 11. The average efficiency of the end dump truck loading process was 82 percent (9 / 11).
- The average turnaround time of demolition trucks was measured as approximately one hour (64 minutes with a five-minute standard deviation), as shown in Figure 34. Due to the turnaround time averaging more than one hour and the average number of demolition trucks per crew of 9, the total required demolition trucks to be mobilized needed to be more than the 21 originally planned. The contractor had 32 demolition trucks available for the 55-hour weekend.

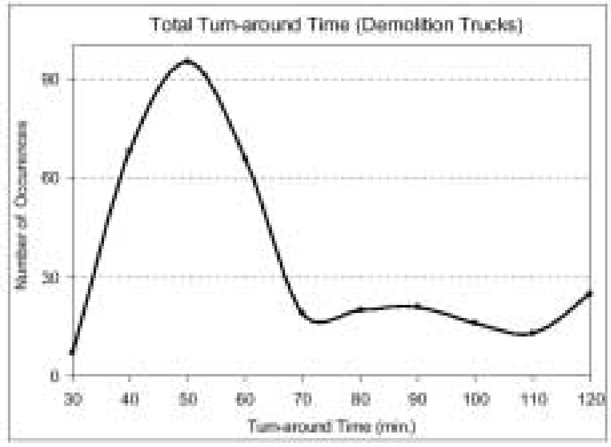

Figure 34. Distribution of turnaround time of demolition trucks.

3.9 Installation of Dowel bars and Tie bars

Historically, the typical concrete pavement in California was jointed plain concrete without tie or dowel bars. In the new design criteria for LLPRS projects, dowel bars at transverse joints and tie bars at longitudinal joints have to be installed in the new pavement structure. Figure 35 shows the implementation of the new design criteria on the I-10 project. The tie bars were installed on both sides of Lane Number 3 during the 55-hour weekend closure. Tie bar holes were bored by a self-propelled gang drill unit. The gang drill created 27-mm diameter holes at a depth of 0.38 m with 0.75-m spacing between bars, as shown in Figure 36. The epoxy coated deformed steel tie bar was 16 mm in diameter by 0.75 m in length and was placed at the middle of the slab thickness. The tie bar was inserted into the hole and secured there by a fast-setting epoxy as shown in Figure 37.

Each 4.5-m length panel had 5 holes for tie bars. A total of 6150 holes were drilled. With two self-propelled gang drill units, the operation took approximately 38 hours. In terms of drilling productivity, about 80 holes per hour per gang drill were completed. This translates into an average progress rate of 72 lane-meters per hour for the drilling operation. Other than an initial setup problem, which delayed the start of paving by approximately one hour, the performance of the gang drills was excellent.

3.10 Installation of Polyethylene Sheet

As soon as the tie bar holes were drilled, a 0.15-mm polyethylene sheet was spread out on the existing CTB to act as a bond breaker between the

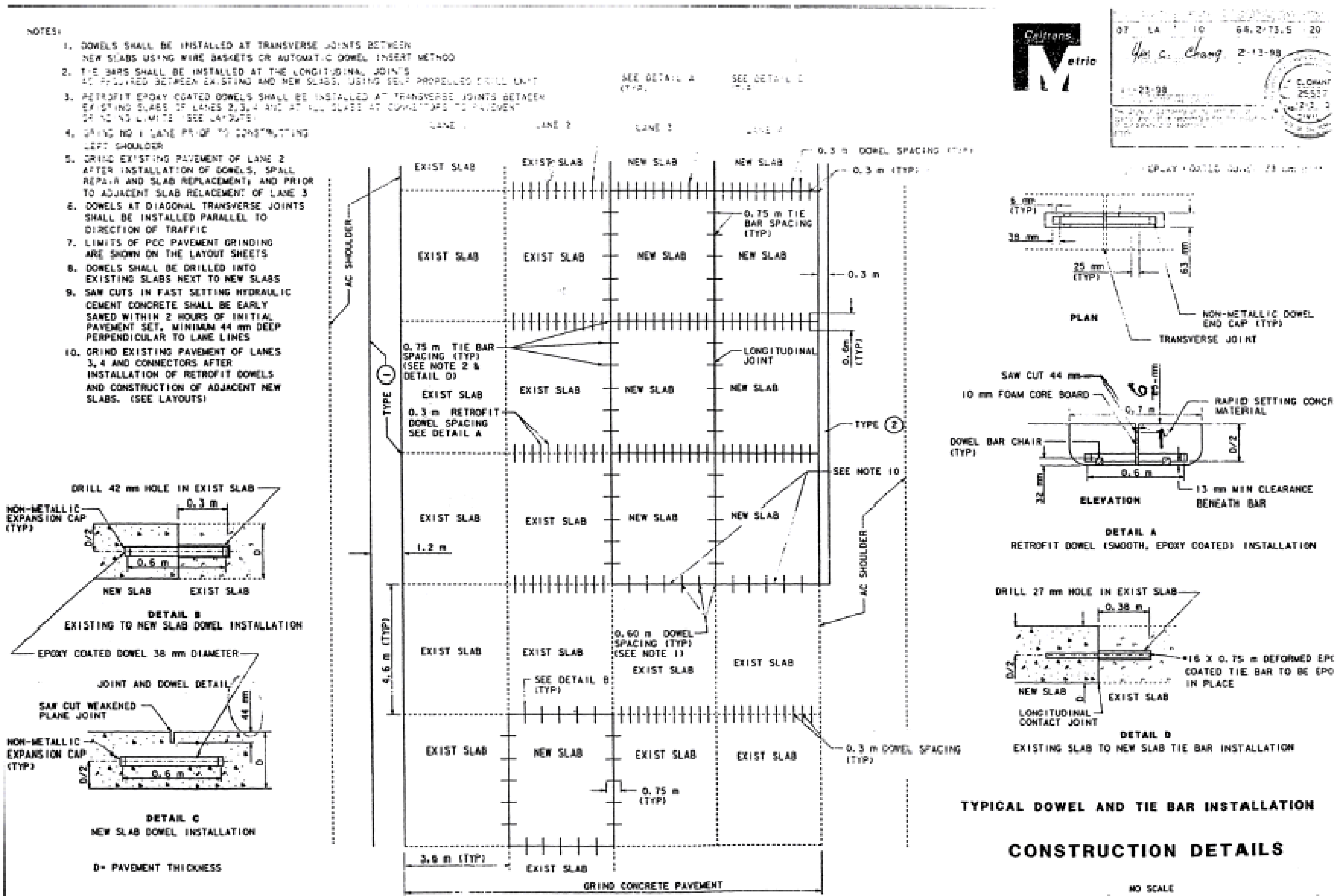

Figure 35. New design criteria for installation of tie bars and dowel bars for LLPRS.

Figure 36. Self-propelled gang drill unit for drilling the bar holes to the existing slab.

Figure 37. Injection of epoxy into the bar holes.

Figure 38. Placement of polyethylene sheet as a bond breaker between CTB and new slab.

CTB and new concrete slab, as shown in Figure 38. The bond breaker would reduce friction between the concrete slab and CTB, which would reduce the risk of shrinkage cracking. However, the condition of the existing CTB probably did not warrant use of a bond breaker. In certain areas, the existing CTB visually appeared to be a lightly cement treated base and in other areas appeared to be a granular base.

3.11 Placement of Dowel Baskets

Dowel baskets were pre-fabricated with ten epoxy coated dowel bars per joint with the steel dowel having a diameter of 38 mm and a length of 0.6 m. Dowel baskets were too heavy to be handled manually, so a small crane mounted on a delivery truck was used for unloading and positioning the baskets. The dowel baskets were fixed to the CTB at the proper transverse joint locations, as shown in Figure 39. The joint locations were chosen to match the sawed joint on the adjacent slabs. A chemical release agent was sprayed on the dowel bars to prevent bonding of the dowel bars to the concrete, as shown in Figure 40. At construction joints, the dowel bars were drilled into the existing slabs, as shown in Figure 41. In some instances during construction, the dowel baskets or drilled dowels were not completely parallel to the pavement surface as seen in Figure 41.

3.12 Concrete Production and Batch Plant Operation

The contractor believed the batch plant to be the most critical resource in this accelerated operation and included contingencies to make sure concrete could be produced continuously even if the main batch plant broke down. Western Rock was the subcontractor in charge of the production and delivery of concrete through the use of their own resources, i.e., batch plant and mixer trucks.

Figure 42 shows the dry mix batch plant that was used exclusively throughout the I-10 55-hour weekend project. The hourly capacity of the batch plant was 170 m^3, however, only half of the capacity was utilized for the I-10 project. The plant was located approximately 8 km from the construction site. A nearby batch plant was on standby in case the primary batch plant was not able to supply the job with sufficient concrete.

The constituents of the FSHCC were continuously supplied to the batch plant since only a limited storage space existed at the plant. The quantity of stock materials at the plant was enough to produce concrete for a couple of hours before new materials were required. The manufacturer of the cement had to continuously supply the cement silos to keep up with the concrete pavement production. Aggregates materials were supplied to Western Rock continuously during the concrete production from Vulcan Materials, an aggregate quarry and crushing plant, as shown in Figure 43. The aggregate source was located about 10 km from the batch plant.

The turnaround time for the aggregate delivery was about one hour using 22-ton capacity end dump trucks, shown in Figure 44.

Figure 39. Installation of dowel bar basket.

Figure 40. Application of release agent to the dowel bars..

Figure 41. Placement of dowel bars in existing slab.

Figure 42. Western Rock batch plant, 220 m^3 per hour capacity.

Figure 43. Vulcan Materials crusher plant (aggregate source).

Figure 44. Delivery of aggregate with 22-ton capacity end dump truck.

A dry mix concrete batch plant was used for the project instead of central ready mix drum since buildup on a central drum plant would occur and eventually slow down the overall production of FSHCC. With the dry mix plant, the concrete mixer trucks would mix the concrete ingredients at the batch plant and on the way to the construction site. If any trucks had excessive buildup in the mixer drums, then those mixers could be taken out of service and chipped out.

3.12.1 Breakdown of the Batch plant

On Saturday around 11:30 a.m., the main concrete batch plant suspended its operation because of a breakdown. The power transformer supplying electricity to the plant malfunctioned catastrophically. The standby batch plant production was reliable and some concrete was supplied from there until the primary plant was operational again. Approximately four hours after the transformer malfunction, a generator was rented to supply power to the primary batch plant and concrete delivery was begun once again. This temporary loss in concrete production prevented the contractor from finishing the project ahead of schedule. The rented generator was used for the remainder of the project to supply power to the primary batch facility.

3.12.2 Buildup of FSHCC

One of the handling issues with some FSHCC materials is buildup of concrete on metal surfaces, such as the mixer drum, due to the chemistry and viscosity of the cement. The contractor took special precautions to prevent buildup by washing out every mixer drum with a high-pressure water jet after the truck had discharged its load. Figure 45 shows a picture of one of the washout areas. The washout material had to be collected in a trough to prevent contamination of the ground and sewer lines with cement slurry. Although two temporary washout sites were in service during the rehabilitation, mixer trucks were usually queued in a line waiting to washout. The washout process typically took about 15 minutes per mixer truck. Even with the high-pressure water jet cleaning, concrete buildup still occurred in some mixer trucks.

At the batch plant, a large scale was used to measure the weight of an empty mixer truck as soon as the mixer arrived back to the plant from its delivery. The amount of concrete buildup in the ready mix truck drum was obtained by finding the difference between the measured weight of the returning mixer truck and the empty, clean mixer truck weight. During the 55-hour weekend project, one ton of FSHCC buildup in the mixer drum was acceptable and the mixer was left in service until the amount of buildup accrued to 4 tons. If the concrete buildup was more than the 4-ton criteria for a given mixer truck, it was taken out of service and moved to a chipping area.

As shown in Figure 46, a laborer had to climb into the mixer drum and chisel the FSHCC stuck to the mixer drum with a pneumatic hammer. The process of chipping out 4 tons of material from the drum took anywhere from one to four hours and resulted in significant costs.

Due to the buildup in the mixer trucks, spare mixer trucks were required in the event that some trucks had to be taken out of service for chipping. The contractor had originally planned to have 15 concrete mixer trucks – 12 running and 3 on call in the event of difficulties. In reality, the contractor had 20 mixer trucks in continuous operation and a total of 27 mixer trucks mobilized during the 55-hour weekend. This buildup in the mixer trucks was also why the average efficiency of each mixer truck turned out to be approximately 87 percent (discharging volume / charging volume).

Figure 45. Temporary washing area for concrete buildup in the mixer drum.

3.13 Concrete Delivery

Although the batch plant was regarded as the resource most critical to the rehabilitation process, the concrete mixer trucks proved to be the resource most constraining to the production rate of the rehabilitation project.

Because agitation was required to prevent the FSHCC from setting up, regular mixer trucks (rotating drum) had to be used rather than end dump trucks. Due to the potential for concrete buildup in the drums, only 6-m^3 loads were batched into the each mixer truck. This capacity was 20 percent less than the maximum capacity of the drum (7.5 m^3) typically used for PCC mixes.

The concrete delivery trucks and drivers were provided by the Western Rock along with the FSHCC. At the site, the mixer trucks were positioned on Lane Number 4 and discharged concrete into Lane Number 3 in front of the rotating concrete screed, as shown in Figure 47. On the majority of the site, no construction traffic (demolition trucks or contractor vehicles) could pass the paving operation until the concrete mixer truck had fully discharged its load. In most cases, empty demolition trucks returning from the dump area were not blocked by mixer trucks, since the demolition trucks took other entrance ramps to avoid the paving operation. However, the mixer trucks leaving the site were almost always interrupted by the demolition operations because they had to be washed out before returning to the batch plant.

The contractor had to optimize the concrete paving production with sufficient mixer trucks while avoiding discharge backups, which could cause loss of material and possibly loss of service for trucks in which the FSHCC set. Although the number of mixer trucks was optimized as a balance between more production and minimal risk of delay and setup during delivery, at one point seven mixers were rejected for having mix in the drum for more than one hour. The reason for this long wait to discharge was a breakdown of the rotating concrete screed. It took more than a half-hour to replace the broken screed with the backup screed.

Near the end of the paving operation, the screed broke down again. Approximately seven mixers were queued waiting for the replacement of the screed, as shown in Figure 48. Fortunately, none of the trucks were rejected since they were within one hour of being batched.

The contractor estimated each mixer truck could carry enough concrete to pave approximately 1.5 new concrete slabs (5.5 m^3) based on previous nighttime closure experience. For the 55-hour weekend, it took 440 concrete delivery trucks to complete 2.8 lane-km (615 slabs of 4.5-m length and 0.23-m thickness). Based on this data, the average efficiency of each mixer truck was 87 percent. This meant that on average, only 5.2 m^3 out of each 6-m^3 batch from the concrete plant was discharged at the site. It should be noted that this efficiency also includes any trucks rejected at the site.

Figure 46. Chipping area at the batch plant.

Figure 47. Concrete discharge and paving operation.

Figure 48. Queuing of mixer trucks waiting to discharge during screed breakdown.

The remaining 0.8 m^3 of material per truck can be attributed to concrete buildup in the truck, material washed out at the site, and trucks that did not discharge at the site due to other paving factors such as screed or plant breakdown. This efficiency of each mixer truck was similar to what MK had expected based on their previous nighttime work.

3.1.3.1 Summary of As-Built Mixer Truck Operation

As reported in the previous section, the efficiency of the mixer truck was found to be 87 percent during the weekend closure. According to the data recorded by the UCB research team, it took 440 mixer truck deliveries to pave 615 slabs during the weekend closure. This is equivalent to 1.4 concrete slabs (4.5 m by 3.66 m) per mixer truck volume compared with the target panel replacement per truck of 1.5. Due to the faster setup time and the buildup in the mixer trucks, FSHCC is probably not as efficient as PCC, and therefore would not be as productive if the same volume of PCC were batched, delivered, and discharged at the construction site.

Production rates on total mixer trucks at the site, duration of paving, and volume of concrete paved are summarized as follows:

- The first discharging of concrete started at 01:30 Saturday morning. Note that there was a 1.5-hour delay because the drilling of holes for tie bars took longer than planned at the beginning of the project.
- 47 hours of the paving operation from hour 3.5 (Saturday 01:30) to hour 50.5 (Monday 00:30) including a 4-hour suspension of the concrete delivery due to the main batch plant breaking down (net total hours of concrete paving was 43).
  (Note that 47 hours actual duration is same as proposed CPM schedule.)
- Total number of concrete delivery truck arrivals = 440
- Average number of slabs place by each mixer truck delivery = 615 slabs / 440 deliveries = 1.4 slabs per delivery = 5.2 m^3 per delivery of concrete mixer truck.
- Efficiency of the end dump truck = 5.2 m^3 out of total volume capacity of 6 m^3. The efficiency of the concrete mixer truck was about 87 percent of its capacity.
- When the entire concrete pavement volume is divided by the total volume of the all the mixer trucks arriving at the site, it is found that each mixer truck could have carried an additional 0.8 m^3. If the average truck were 100 percent efficient, then only 384 mixer truck loads would have been required to supply the entire project. With 100 percent efficient trucks, the paving would have been completed in seven fewer hours. This would be considered an ideal situation but not practically achievable.
- Average number of panels paved per hour = 615 slabs / 43 hours = 14 slabs per hour.
- The average discharge rate for a mixer truck = 43 net hours _ 60 min. / 440 trucks discharging = approximately 6 minutes per discharge.
- Average number of mixer trucks per hour = 440 / 43 hours = approximately 10 mixer trucks per hour.
- A total of 27 concrete mixer trucks were mobilized.
- Between 20 and 21 concrete mixer trucks were in continuous use during the paving operation with the extra trucks used for spares when the FSHCC buildup became excessive.

3.13.2 Concrete Mixer Truck Operation Statistics

The UCB research team recorded concrete mixer truck delivery data throughout the entire 55-hour weekend project and calculated the following statistics:

- Average concrete discharge time per mixer truck was measured at 3.5 minutes with 0.7-minute standard deviation, as shown in Figure 49. This time did not include waiting time and time to position the truck in the correct spot. The average time for waiting, positioning, and discharging concrete was found to be 6 minutes, as noted in the Section 3.13.1.
- On average, approximately 10 mixer trucks discharged concrete per hour with a 2.1-truck standard deviation, as shown in Figure 50. This means that about every 6 minutes, a concrete mixer truck arrived at the paving area. Each mixer truck typically discharged concrete for 3.5 minutes. Waiting and positioning of the truck took approximately 2.5 minutes. The contractor had planned on having 12 mixer trucks per hour making deliveries to the construction site. If one truck could be discharged every 3.5 minutes, then the maximum number of trucks per hour to discharge would be 17. However, the maximum output of the batch plant was 15 trucks per hour. The average efficiency of the mixer trucks to discharge per hour relative to the maximum possible was 67 percent (10 / 15).
- The average turnaround time for concrete mixer trucks was 74 minutes with a 4-minute standard deviation, as shown in Figure 51.

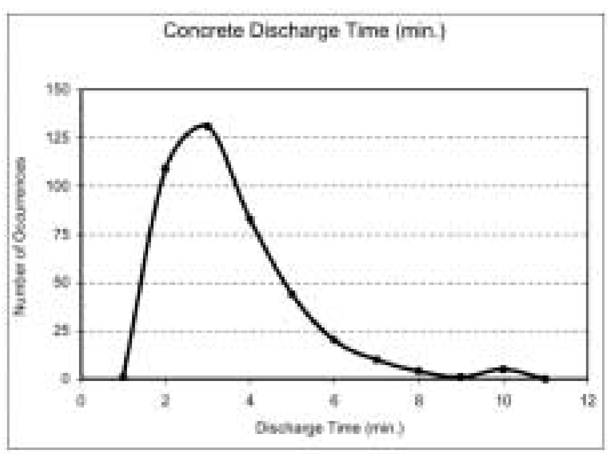

Figure 49. Distribution of cycle time of concrete discharging from mixer trucks.

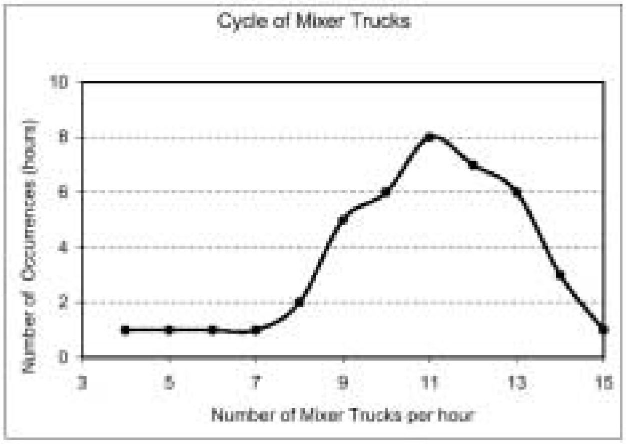

Figure 50. Distribution of the number of mixer trucks arriving to the construction site per hour.

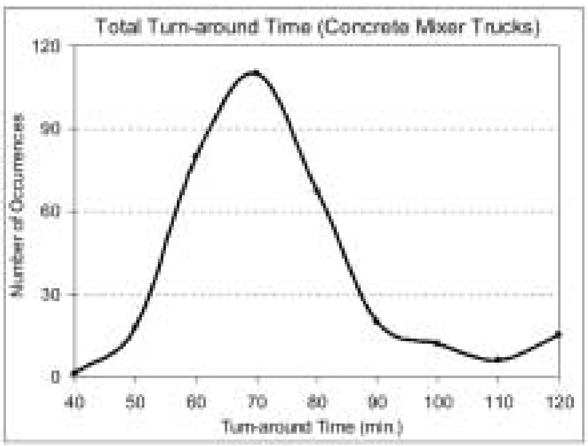

Figure 51. Distribution of turnaround time of mixer trucks.

The contractor had expected a mixer truck to show up to the paving area every 5 to 6 minutes, which the actual records indicated was nearly achieved. The contractor also expected the average turnaround time of the mixer trucks to be between 45 and 60 minutes. The average turnaround time for the mixer trucks was 74 minutes, which was approximately 40 percent more than the contractor had planned. Most likely, the contractor underestimated the time it took to washout the mixer drum, which consisted of waiting in line, removing concrete chutes, and washing with a high-pressure water jet. The power washing operation was delayed several times due to insufficient availability of water for rinsing. Traffic during the weekend, particularly during the day, also played a role in increasing the turnaround time.

3.13.3 Breakdown of the Concrete Mixer Truck Turnaround Cycle

The cycle of a typical concrete delivery truck is shown in Figure 52 and Table 12. Figure 52 indicates that 43 percent of the mixer truck's operational time is spent driving from the plant to the site and back to the plant. This transit time ends up costing the contractor and agency additional money because more trucks have to be mobilized in order to meet the concrete volume required at the screed. In order to increase productivity of the project and reduce costs, batch plant areas adjacent to the project site are necessary. In the future, agencies should explore rental of public right of way to the contractor near the site to help increase project productivity and decrease costs by minimizing the number of mixer trucks in the system.

3.13.4 Comparison of PCC versus FSHCC Productivity Related to Concrete Delivery

Figure 52 and Table 12 show that the concrete production and placement with FSHCC most likely increases the turnaround time for mixer trucks. Several processes would be reduced or eliminated if FSHCC had not been used in this project. For example, concrete batching would have been 50 percent faster with PCC because a central mixing drum could have been used to batch the concrete and charge the trucks. The five minutes in the batch plant area for initial mixing could also have been eliminated since a central drum plant would complete most or all of the mixing process. The washout process could have been reduced to five minutes, since PCC does not buildup as rapidly as FSHCC in the mixer drums and weighing the drum for buildup could be eliminated with PCC.

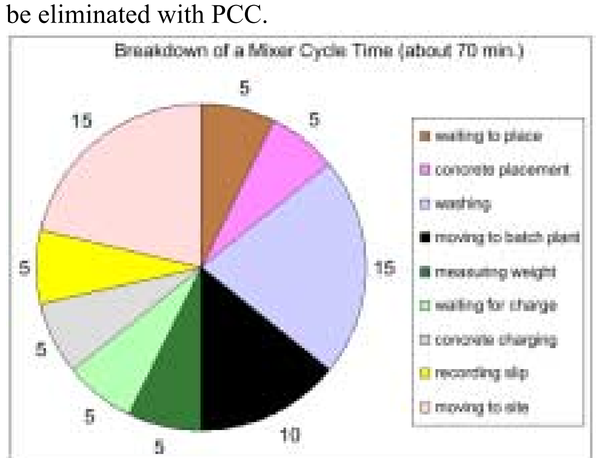

Figure 52. Components of typical turnaround time of mixer trucks.

Table 12. Breakdown of a full cycle for a concrete mixer truck

Activity	Duration (minutes)
Concrete charging from the batch plant	5
Receive record slip from the office	5
Drive to paving site	15
Waiting in the queue for pouring	5
Concrete discharging	5
Wash out the drum	15
Drive back to the batch plant	15
Measure weight and wait in the queue for loading	5
Typical total turnaround time of mixer trucks	70

Based on these estimates, PCC would have decreased the turnaround time for mixer trucks by about 30 percent. This means that an FSHCC operation probably requires 30 percent more mixer trucks to supply the same volume of concrete at the jobsite. If PCC were used on this project, only 19 mixer trucks would have needed to be mobilized.

It should be noted that this comparison does not take into account the early strength requirements of the concrete, which PCC would not have met. Furthermore, the overall project productivity would not have changed since the volume of concrete to the site was kept constant in this comparison and the number of resources were reduced for PCC construction.

If the early strength requirement in the specification were relaxed, then a higher volume of PCC could have been delivered to the site per hour.

End dump trucks could have been used to deliver the PCC. However, in California, most end dump trucks for PCC have a carrying capacity of 6 m^3. According to the contractor, the concrete mixer trucks could have carried 7.5-m^3 loads of PCC instead of the 6-m^3 loads of FSHCC. For the larger loads, the batch plant used by the contractor could not have been used since it only batched 6-m^3 loads. The efficiency of PCC would most likely be higher since buildup and regular chipping would not be an issue. Assuming mixer truck efficiency for FSHCC and PCC were the same and a large capacity batch plant were available, a PCC operation could have supplied 25 percent more concrete to the site per truck. For the I-10 project, this would have required only 352 mixer trucks of PCC versus 440 mixer trucks of FSHCC. The paving could also have been finished 25 percent sooner and required 35 hours for PCC versus 43 hours for FSHCC. This indicates the same distance of PCC with a 12-hour opening strength could have been paved as the 4-hour opening strength FSHCC.

This comparison suggests that there are ideal windows where FSHCC is the most efficient material to use for rehabilitation while slightly longer windows make PCC the preferred material. The construction window times for each material depends on many factors and should be determined on a project-by-project basis.

The discharge rate at the site can be 30 to 50 percent faster with PCC in end dump trucks compared with mixer trucks. If end dump trucks were utilized for PCC paving on this project, then a concrete spreader would have been required. If PCC mixer trucks are utilized, then the discharge rate will be the same as FSHCC mixer trucks. When the concrete volume increases to a certain level, a manual screed (clary) is not the most efficient way to pave, and consolidation and finish of the concrete become more cumbersome.

3.14 Concrete Paving and Finish Work

As mentioned previously, a rotating concrete screed was used instead of a slip-form paver. This was done for two reasons: first, FSHCC tends to build up on the paver, and second, the slip-form paver would have further reduced the construction access lanes. The slip-form paver would have required an additional 1 m of Lane Number 4 due to the track of the paver and the string line for grade and possibly 0.3 m of Lane Number 2. If the site offered more access lanes, then productivity would have been better and less labor intensive with a paver than with a rotating screed.

Two laborers operated the screed on either side of the machine, striking off the excess concrete and then smoothing out the surface of the concrete with a final pass, as shown in Figure 53. Two laborers consolidated the concrete with concrete vibrators in front of the screed. Approximately ten workers were continuously involved in the paving and finishing operations.

The FSHCC had a high slump since it was being placed by hand and Lane Number 3 had the adjacent slabs to act as forms. The overall workability of the fresh concrete supplied was good, as shown in Figure 54, but occasionally the consistency of the concrete was observed to be too wet, as shown in Figure 55.

One undesirable characteristic of the FSHCC on this project was formation of cement balls inside some of the mixer trucks. Some of the cement balls were as much as one foot in diameter. Figure 56 shows a laborer with a cement ball he found in the FSHCC. Similar cement balls were encountered during construction of the Palmdale test sections on State Route 14, which utilized FSHCC from a different cement supplier (7).

Figures 57 and 58 show the subcontractor (Twining Laboratories) sampling the concrete to make specimens for strength testing. Ten beam and six cylinder specimens were cast from every 15th mixer truck. The Kelly Ball penetration test was used to measure the consistency of the fresh concrete.

Finishing and texturing were completed manually by two laborers who floated, trowelled, and broomed the pavement surface behind the concrete screed, as shown in Figure 59. Curing compound was sprayed on the surface immediately after finishing and texturing, as shown in Figure 60. Approximately two hours after the concrete was finished, a 44-mm deep saw cut was made on each transverse joint with a single saw team, as shown in Figure 61. The condition of the finished surface was rough, but the contractor planned to diamond grind the surface during a nighttime closure as part of the contract with Caltrans. The Caltrans specification allowed for a maximum grinding depth of 6 mm (4).

Figure 53. Manual alignment of the screed.

Figure 54. Example of good quality, fresh concrete.

Figure 55. Example of poor quality, watery concrete.

Figure 56. Cement ball from the mixer truck; evidence of buildup.

Figure 57. Ten beam specimens were taken from every 15 mixer trucks for flexural testing.

Figure 58. Six cylinder specimens were taken from every 15 mixer trucks for comprehensive testing.

Figure 59. Manual finishing and texturing of the pavement.

Figure 60. Curing compound being applied manually.

Figure 61. Sawing transverse and joints after 2 hours of curing.

3.15 Comparison of Actual Progress with Proposed Progress

Table 13 presents a comparison between the planned CPM schedule and the as-built CPM schedule. As shown in Table 13, most of the activities progressed as planned in the CPM schedule except for the existing slab demolition activity. The demolition process took 30 hours instead of the planned 17 hours. As mentioned in Section 3.5, the main cause for the demolition slow down was the constraint placed on the contractor not to demolish more than 20 slabs in front of the concrete paver.

Consequently, the contractor slowed down the concrete slab demolition by operating only two demolition teams most of the time, instead of three teams. However, this increase in demolition time did not affect the overall productivity of the rehabilitation in terms of total lane-km as the demolition

Table 13. Proposed CPM schedule vs. actual schedule for the weekend closure

Sequence	Work Activity	Proposed CPM schedule			Actual schedule		
		Start	Finish	Duration (hr)	Start	Finish	Duration (hr)
1	Set traffic control	-2	-1.0	*1.0*	-2	-1.0	*1.0*
2	Install MCB	0	1.0	*1.0*	0	2.0	*2.0*
3	Slab demolition	0.0	17.0	*17.0*	0.5	30.5	*30.0*
4	Cleaning sub-base	0.0	17.0	*17.0*	1.0	31.0	*30.0*
5	Drill and Tie bar install	0.0	26.0	*26.0*	2.0	40.0	*38.0*
6	Dowel baskets	0.0	26.0	*26.0*	3.0	41.0	*38.0*
7	Concrete paving	2.0	49.0	*47.0*	3.5	50.5	*47.0*
8	Concrete curing (end)	49.0	53.0	*4.0*	50.5	55.0	*4.5*
9	Saw cut	4.0	51.0	*47.0*	6.0	52.5	*46.5*
10	Pavement marker	45.0	53.0	*8.0*	45.0	53.0	*8.0*

Note: time 0 starts at 10 p.m. on Friday

Table 14. Performance of slab demolition and concrete delivery

Description	Demolition (End dump truck)	Concrete (Mixer truck)
Performance data		
Total number of panels (1 panel = 3.6 m × 4.5 m × 0.23 m)	615	
Activity duration (hours)	30	47
Total number of deliveries	466	440
Average progression (slabs per hour)	20	14
Average volume of delivery	10 tons (4.2 m^3)	5.2 m^3
Capacity of truck	22 tons (9.0 m^3)	6.0 m^3
Efficiency of truck	47%	87%
Statistics of demo/delivery trucks		
Average cycle time (min.)	5.5	3.5
Average no. of trucks per hour	9	10
Average turnaround time (min.)	64	74
Efficiency of Operation (based on average cycle time)	82%	67%

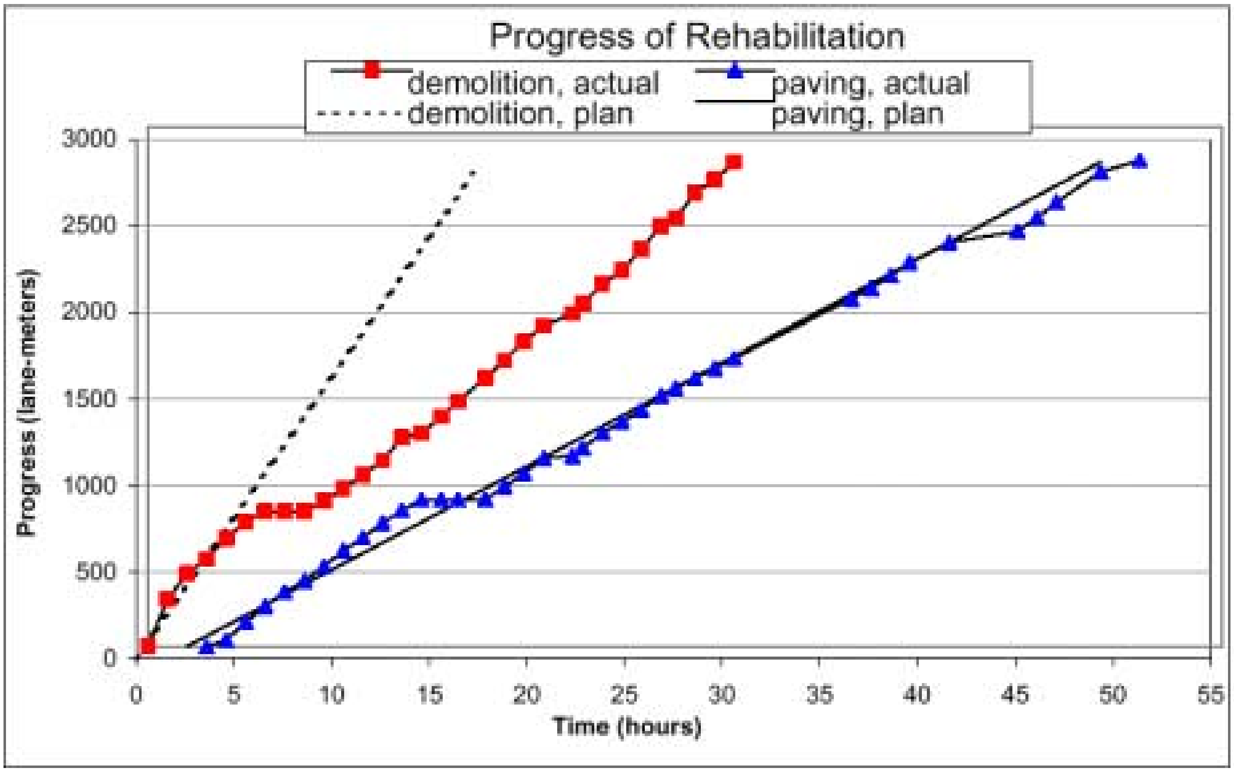

Figure 62. Actual progress of the rehabilitation compared with planned progress.

operation was not on the critical path for most of the project. There were conflicts between the concrete mixer trucks and the demolition teams, but it is difficult to determine from the data collected if the concrete paving productivity was significantly affected by the increased duration of demolition.

The actual duration of the paving operation was the same as the contractor's original schedule. Four of the total paving operation hours were due to the batch plant breakdown, which means the contractor actually had fewer net paving hours than originally planned.

3.15.1 Overall Progress of the Rehabilitation

Table 14 is the summary of the overall performance of slab demolition and concrete delivery operations, which are described in Sections 0 and 3.12, respectively.

The actual progression of slab demolition and concrete paving are plotted in Figure 62 with the original planned progress plotted with dashed lines. Figure 62 shows that the planned and actual demolition rate was similar, but changed five hours from the start. For the most part, Figure 62 shows that the planned and actual rate of concrete paving were the same. Figure 63 shows the events that slowed down the demolition and paving which occurred during the project. The actual progress of the activities was measured by determining the position of each activity along the project length. The research team recorded the panel number location for both demolition and paving approximately every hour and converted the data into lane-km for the overall progress.

3.15.1.1 Overall Progress of Slab Demolition.

The actual progress of slab demolition deviated from the original planned schedule by almost a factor of two. The demolition progress after five hours was much slower than the initial progress due to the constraint placed on the contractor on having to open the lane to traffic within two hours, as shown in Figure 62. The initial demolition up to five hours had three demolition crews, which closely resembled the proposed productivity rate, as shown in Figure 62. Between the fifth and eighth hour, very little demolition progress was made because only one demolition crew was working and the demolition operation had greatly outpaced the paving. The final two-thirds of the demolition had a constant productivity rate, which was a result of using two demolition crews. As shown in Figure 62, the final

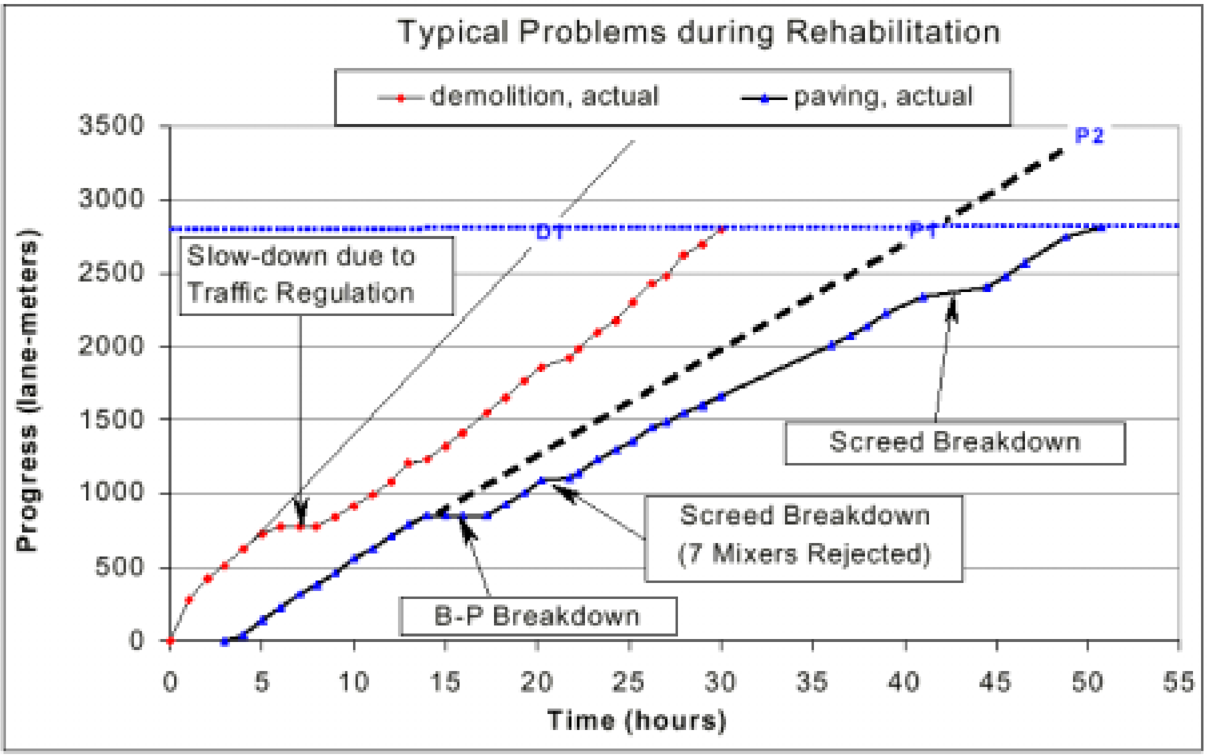

Figure 63. Major problems which delayed the overall rehabilitation progress.

demolition rates were slower than the initial rate due to the use of only two crews. The contractor was not able to use three demolition crews during Saturday afternoon and night because of the construction access constraints posed by a soundwall and reduced shoulder width.

3.15.1.2 Overall Progress of Concrete Delivery and Paving. The actual progress of the paving operation was directly controlled by the progress of concrete delivery. Since the actual concrete delivery progress was similar to the proposed schedule, it is no surprise that the actual paving duration time was similar to the planned CPM.

As shown in Figure 63, the paving operation experienced several delays. The batch plant broke down for four hours and in two instances the paving screed broke down, temporarily suspending the operation. However, the contractor still achieved the rehabilitation goal within the 55-hour weekend. Without the breakdown in the batch plant and the screeds, the contractor may have finished six hours earlier.

The slope of the paving progress in Figure 63 shows a gradual slowdown in the operation relative to the initial production rate due to construction fatigue of the paving crew. Figure 63 did not indicate any increase or decrease in paving when operations were occurring during the day or night.

3.15.1.3 "What if" Scenarios for Demolition and Paving Productivity. Additional information can be extracted from the overall progress of the slab demolition and concrete paving operations, shown in Figure 63, by asking "what if" questions about the rehabilitation progress. Several "what if" questions are listed below with a corresponding answer based on the collected data.

- What if the contractor could maintain the initial productivity of the demolition through out the project without having to intentionally slow down the demolition operation?

  i) Based on the initial progress rate shown in Figure 63, the fastest the concrete slab demolition could have been completed was 22 hours based on a maximum of three crews. This would have saved the contractor 8 hours of labor from the actual progress duration of 30 hours. The "D1" symbol in Figure 63 represents the duration potential if the contractor would have maintained a constant progress from the beginning, assuming the same resource availability. This projection also suggests that the contractor would probably not have been able to complete the demolition of the concrete within the planned 17 hours unless an additional demolition crew had been added.

ii) Based on the initial production rate for demolition, as much as 5 lane-km could have been completed within the 55-hour construction window. This ideal production of 5 lane-km can be read from the projection of the initial progress of the demolition plotted in Figure 63. This calculation gives an upper boundary on concrete demolition in an urban area using the same process and resources. This calculation assumes that concrete paving would not be on the critical path.

- What if the contractor could maintain the initial progress of the concrete paving and delivery without any breakdown in equipment or construction worker fatigue until the end of the project?

i. The paving operation could have been completed within approximately 41 hours instead of the actual duration of 47 hours as marked by "P1" in Figure 63. It is interesting to note that this paving duration of 41 hours is identical to the contractor's internal CPM plan. If paving could have progressed at this rate, then the rehabilitation project would have been completed in 46 hours rather than the planned 55 hours.
ii. The maximum amount of concrete paved based on the contractors process, paving rate, and resources would have been 3.5 lane-km compared to the as-built 2.8 lane-km, if the contractor had continued paving at full capacity within the 55-hour construction window. This ideal production of 3.5 lane-km can be read as point "P2" on Figure 63. Based on the maximum allowable amount of paving, the efficiency of the contractor's paving operation can be calculated as 80 percent (2.8 lane-km / 3.5 lane-km).

- What if the ideal scenario of 100 percent efficient paving production (an average discharge rate of 3.5 minutes and a maximum of 17 mixer trucks per hour) were achieved and neither the batch plant nor the paver were a constraint?

i. The paving would have been completed in 23 hours.
ii. If the concrete delivery had the efficiency that was measured, the number of hours to complete the paving would have been 26 hours.
iii. Since the dry mix batch plant had a maximum output of 15 trucks per hour the paving time would have been closer to 30 hours.
iv. Consequently, the minimum weekend closure to cover the 2.8 lane-km of the rehabilitation with the best assumptions is 38 hours.

- How fast would demolition be completed if 3 demolition crews could load 11 end dump trucks per hour, based on the average loading time of 5.5 minutes?

i. The demolition could be completed within 15 hours.

From the overall progress of the slab demolition and concrete delivery and paving, demolition was not the critical constraint for this project. Instead, concrete delivery and paving was the most critical constraint as it directly governed and decided the total amount of rehabilitation within the 55-hour weekend closure. In order to increase the rehabilitation productivity (lane-km) for weekend construction windows, strategies should be developed that focus on increasing the number of concrete delivery mixer trucks per hour arriving and discharging at the site. These strategies may involve increasing the capacity of each mixer truck, decreasing the discharging time, and/or using a different concrete material for the majority of the project.

CHAPTER 4

4.0 UCB Constructability Analysis model

The UCB research team has developed a constructability and productivity analysis program which determines the maximum length of a rehabilitation project that can be paved under certain time constraints, given the number and capacity of resources, construction methodology, and pavement design profile. Figure 64 shows the hierarchical structure of the UCB model representing the level of analysis and options available at each level. One of the main purposes of this constructability and productivity research was to determine how many lane-kilometers of pavement reconstruction could be achieved in a 55-hour weekend closure.

A technical report (1) has already been submitted to Caltrans presenting the findings of the

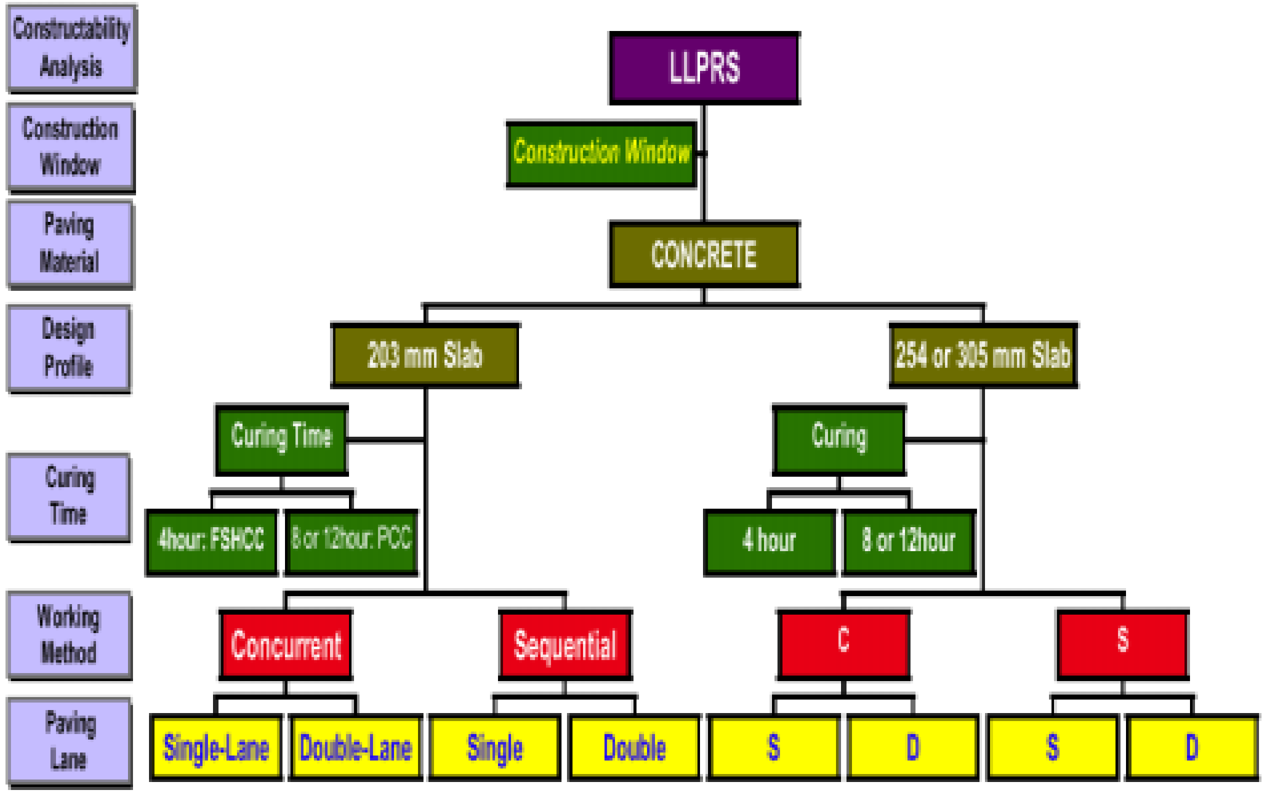

Figure 64. Hierarchical structure of UCB constructability and productivity analysis model for LLPRS.

constructability and productivity analysis. In the UCB analysis, two basic alternatives were defined to carry out the concrete pavement rehabilitation: "concurrent working method" and "sequential working method." The basic distinction between the two schemes is whether demolition of the old concrete slab and paving of the new slab pavement can proceed simultaneously ("concurrent"), or paving cannot begin until the demolition is completed ("sequential"). In the UCB analysis model, the rehabilitation can be staged for single lane or double lane paving. Single lane and double lane paving are applicable for both concurrent and sequential working methods.

The rehabilitation methodology adopted for I-10 project was the "concurrent working method" in terms of construction sequencing and the "single lane method" in terms of the number of lanes demolished and paved simultaneously. The scope of the work for the I-10 rehabilitation project was the same as the concrete rehabilitation scheme for a 203-mm (8-inch) concrete slab replacement defined in the UCB constructability model (1) and shown in Figure 6.

4.1 Results of UCB Analysis Model for the I-10 Project

Table 15 and 16 summarize the detailed construction information from the I-10 project, such as the construction window, design profile, material characteristics, proposed work plan, resource availability and constraints, and construction traffic patterns. This information was used as inputs to the UCB constructability analysis program to predict the most probable rehabilitation productivity before construction happened with the planned resource profiles and to verify the actual construction productivity with the actual resource profiles recorded during the project operation.

The resource availability and construction traffic patterns were treated as constants for a deterministic analysis (i.e., no variations) and as random variables for a stochastic analysis (i.e., resource number and productivity treated as a random variables with defined distributions).

Table 15. Input parameters of the I-10 project into UCB analysis model

Category	Input parameter
Construction Window	55-hour Weekend Closure
Paving Material	Concrete (Fast Setting Hydraulic Cement)
Design Profiles	203-mm Slab Replacement only
Curing Time	4 hours
Working Method	Concurrent Working Method
Number of Paving Lane	Single Lane Paving
Resource Condition	Refer to Table 16.

Table 16. Input resource details (planned versus actual)

Delivery Trucks	Planned Truck Resources		Actual Truck Resources	
	Max. Capacity	Trucks per hour	Actual Capacity	Trucks per hour
Demolition (End Dump Truck)	22 ton	7 per crew × 3 crews	10 ton	9 per crew × 2 crews
Concrete (Mixer Truck)	6 m^3	12	5.2 m^3	10

4.1.1 Deterministic Analysis

The I-10 project parameters in Table 15 and resource profiles in Table 16 were put into a prototype program developed for constructability and productivity analysis for Long Life Pavement Rehabilitation Strategies by Lin et al. (5) for deterministic analysis. Figure 65 shows one of the input screens with the actual resource profiles. Figure 66 is an output screen of the analysis.

The result of the UCB constructability analysis model with the contractor's planned resource profile and formal CPM schedule described in 6479770 Table 10 was 3.7 lane-km. The 3.7 lane-km of rehabilitated concrete pavement over a 55-hour weekend closure predicted by the UCB model was too optimistic compared with the actual performance of the rehabilitation (2.8 lane-km).

The contractor's internal CPM schedule shown in Table 9 was similar to the results of the UCB's deterministic analysis. The contractor had planned to finish paving the 2.8 lane-km rehabilitation target in 38.5 hours and cover additional work outside the 55-hour weekend closure. Extrapolating the contractors planned production to 55-hours of work would have resulted in 3.5 lane-km of rehabilitated concrete pavement.

The major discrepancy between the predicted productivity and actual performance resulted from a deviation between the actual resource profile and the planned resource profile. For example, the planned average number of mixer trucks per hour was 12 with an average capacity of 6 m^3, while the actual average number of mixer trucks was 10 per hour with an average capacity of 5.2 m^3 per mixer truck.

After completion of the 55-hour weekend closure, the actual resource profiles recorded by the research team (average number of end dump trucks and mixer trucks per hour and their corresponding average capacities) and the actual CPM schedule (Table 13) were input into the UCB analysis model to verify its applicability to a real rehabilitation project.

The result of the analysis shown in Figure 66 is exactly same as the actual performance of the project of 2.8 lane-km. This result validates the UCB model for predicting concrete pavement rehabilitation productivity given the project constraints and actual resource profiles.

However, for a deterministic analysis, in order to predict the correct rehabilitation length accurately, the actual resource profiles must be predicted accurately before construction begins or a substantial error may result. This can be seen by comparing the results of the analysis for the predicted and actual resource profiles demonstrated above. The predicted rehabilitation length based on the contractors internal CPM and resource profile was 3.7 lane-km versus the actual completed length of 2.8 lane-km. The errors in the number and capacity of resources caused a 32 percent deviation in the completed project length. Thus a deterministic analysis may introduce large errors in the predicted project productivity if the variability in the number and capacity of resources are not accurately taken into account in the model.

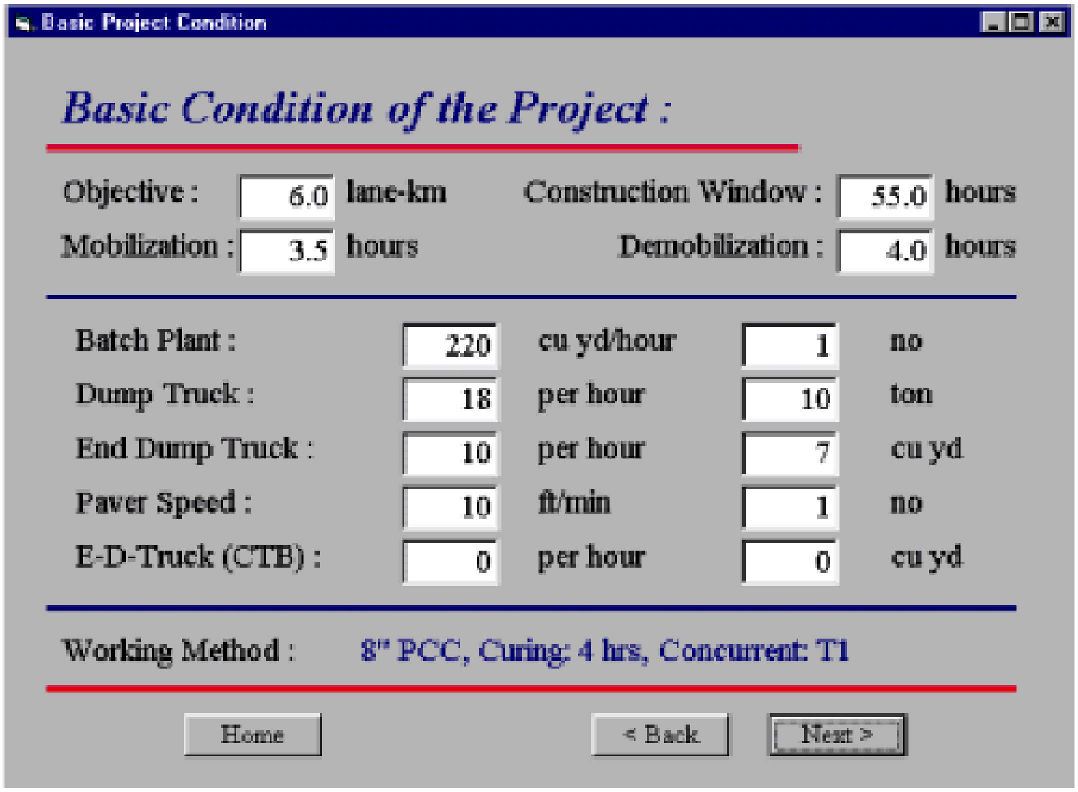

Figure 65. Sample input screen of the UCB analysis model.

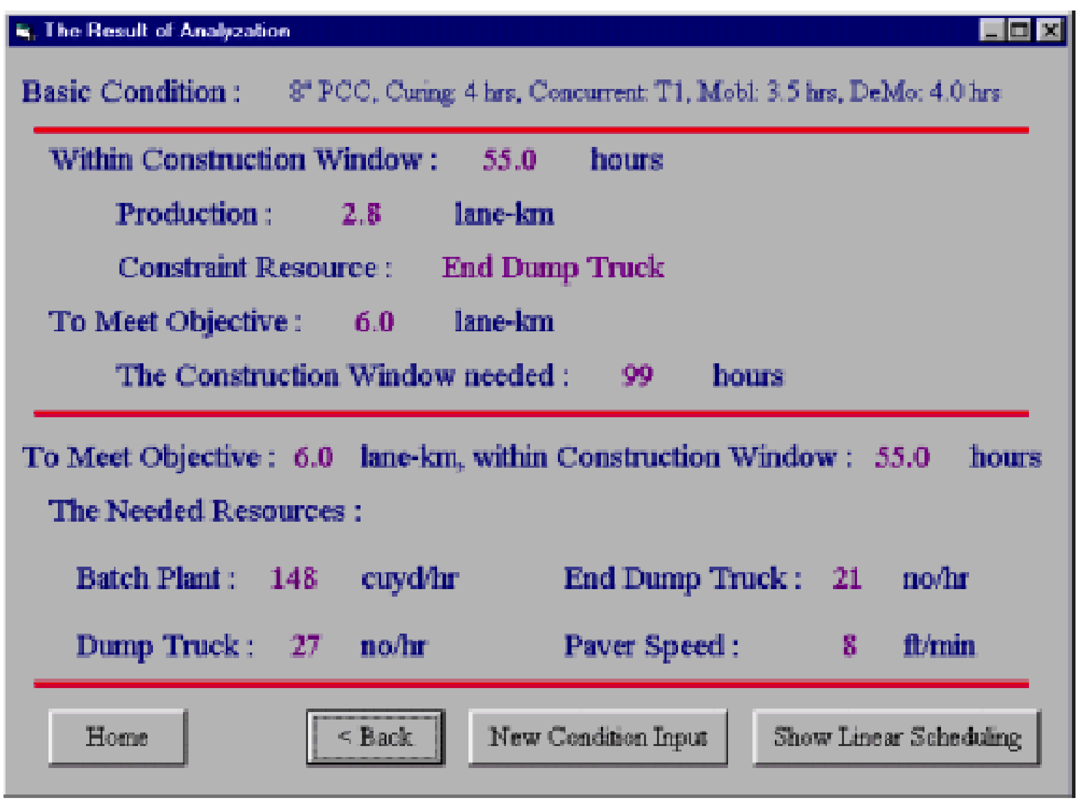

Figure 66. Sample output screen of the UCB analysis model.

Planned resource profile:

- Lower boundary of productivity = 2.8 lane-km
- Mean productivity = 3.7 lane-km
- Upper boundary productivity = 5.0 lane-km
- Standard deviation = 1.0 lane-km

Actual resource profile:

- Lower boundary of productivity = 2.2 lane-km
- Mean productivity = 2.8 lane-km
- Upper boundary productivity = 3.4 lane-km

4.1.2 Stochastic Analysis

For more realistic results with the UCB model, a stochastic analysis was implemented by treating resource profiles as random variables. For the stochastic engine, Crystal Ball, from Decisioneering was used along with the UCB analysis program shown in Figure 65. The following two stochastic analyses were completed:

1. contractor's planned resource profile and their formal CPM schedule
2. actual resource profiles recorded by the research team and the actual CPM schedule (Table 13).

The actual resource profiles, as illustrated in Figure 32, for demolition and Figure 50 for concrete delivery were used as Probability Distribution Functions (PDF), as well as resource profiles for the batch plant and paving screed. Assumed PDFs were used for the planned resource profiles because actual profiles were not known prior to construction. The resource profiles were assumed to be normally distributed along with the results.

The results of the stochastic analysis, with a one standard deviation confidence interval (68 percent likelihood of occurrence in the output productivity), are shown in Figure 67 for the planned resource profile and Figure 68 for the actual resource profile. The results and are summarized above.

The lower bound productivity of 2.8 lane-km as the predicted productivity from the stochastic analysis is identical with the actual performance of the project. Although the contractor achieved only the lower limit productivity of 2.8 lane-km, this is still within a 68 percent confidence interval.

The mean productivity from the stochastic analysis using the measured resource profiles was the same as the deterministic analysis and the actual I-10 project productivity. One of the advantages of the stochastic analysis is that the results show the worst and best case scenario along with the average productivity for a given rehabilitation project. The contractor or agency can then select what is the most realistic productivity given past experience on actual versus predicted productivity.

A sensitivity chart of the stochastic analysis with the actual resource profile is shown in Figure 69. The sensitivity chart shows that the concrete mixer truck delivery has the largest impacts on the productivity of the pavement rehabilitation. Given that the concrete deliverytrucks are the most significant element in achieving the target rehabilitation amount, an innovative technique should focus on the concrete delivery system to improve the rehabilitation productivity. Figure 69 also demonstrates that the mixer truck capacity has some influence on the overall project productivity.

4.2 Validation and Calibration of UCB Model from the Case Study

The I-10 demonstration project played an important role for the validation of the UCB constructability analysis model. The results of the deterministic and stochastic productivity analysis turned out to be consistent with the actual performance of the project

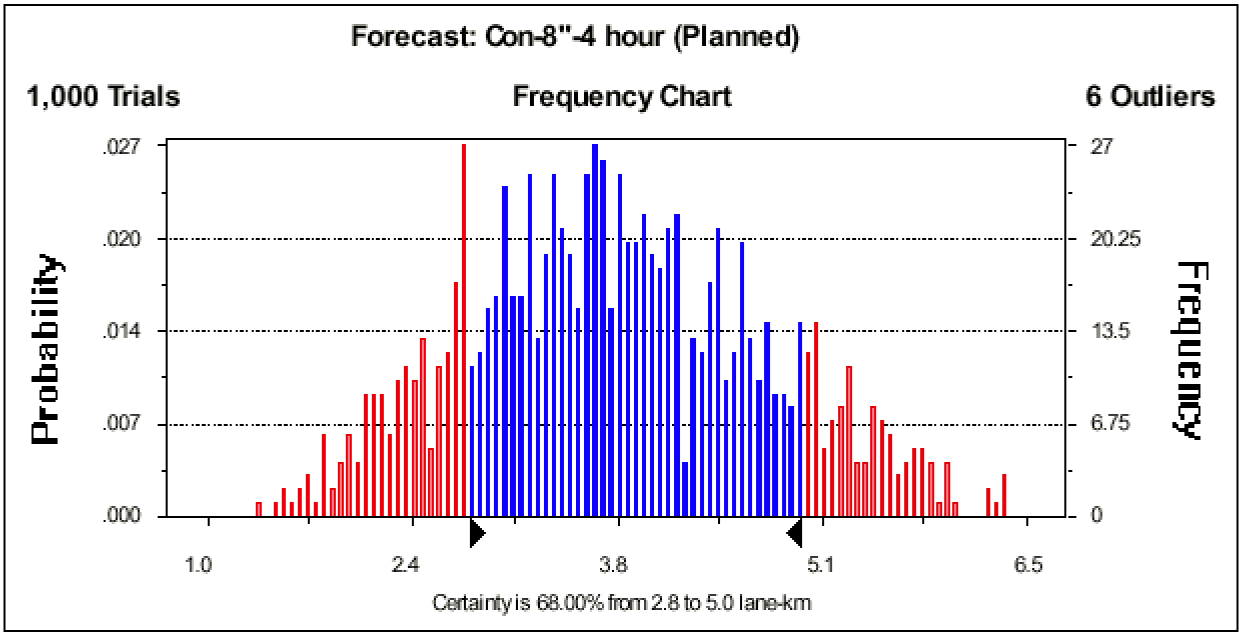

Figure 67. Result of stochastic analysis with planned resource profile.

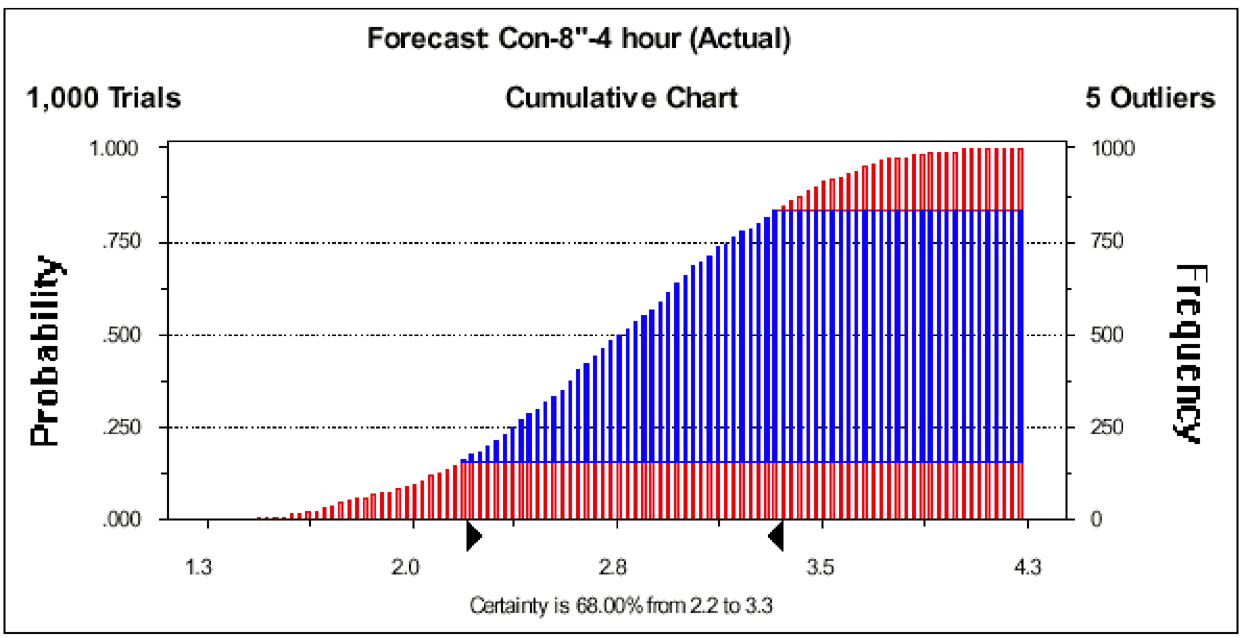

Figure 68. Result of stochastic analysis with actual resource profile.

when the correct number and capacity of the resources was assumed. The UCB constructability analysis model can be used as a planning and analysis tool for paving contractors and transportation agencies. Based on the outcome of the I-10 case study, the UCB constructability analysis model should be adjusted for several key inputs such as concrete and demolition truck efficiency.

4.2.1 Calibration of the Demolition Operation

As discussed in Section 3.8.1, the non-impact demolition used in the I-10 project was quicker than impact demolition in loading of slabs, but the packing ratio (only 47 percent for the I-10 project) was much

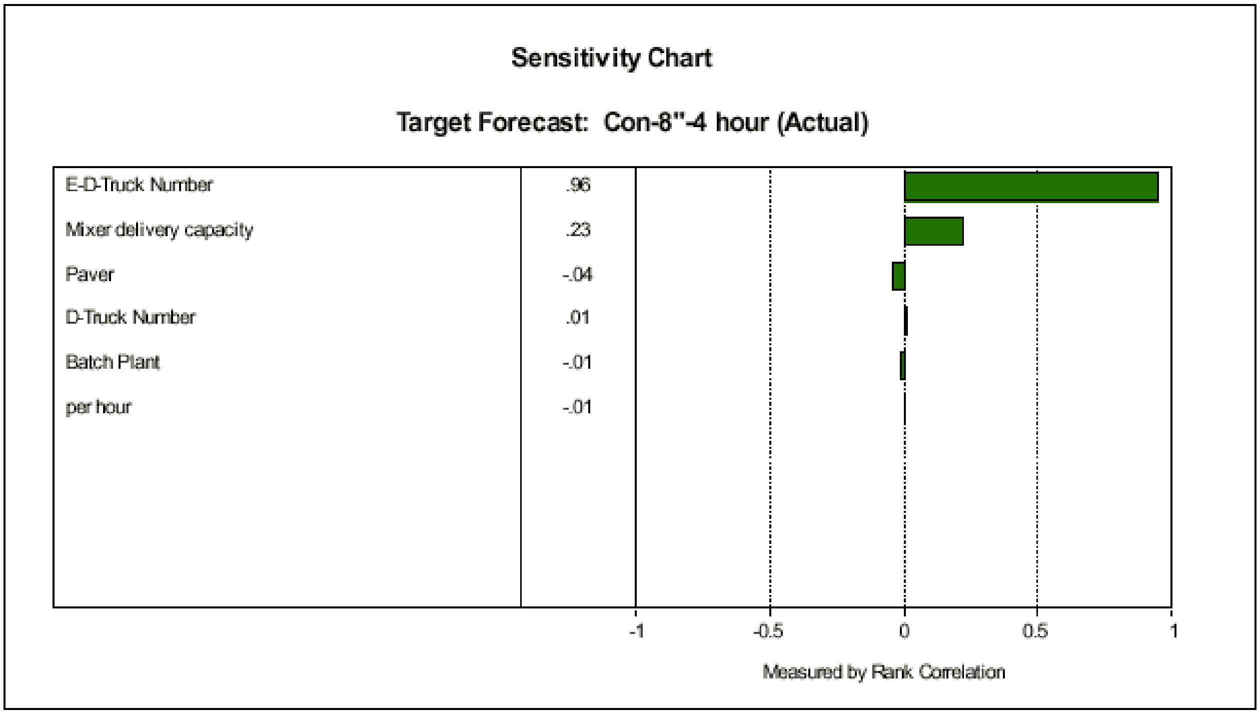

Figure 69. Sensitivity chart of the stochastic analysis with actual resource profile.

less than that of impact demolition. The UCB model should be improved to handle different packing ratios and progress rates for several demolition types.

It was observed on the I-10 project that multiple demolition crews could work simultaneously and effectively with a minimum space between the crews as long as a minimum of two access lanes were provided. Two or three crews can easily be converted into a single crew in the UCB model for simplicity, but only for the concurrent working method in which demolition and paving operation are working simultaneously with two access lanes. The sequential working method cannot have multiple crews because only one access lane is allowed so that the number of lanes closed is minimized. Utilization of multiple crews could also be successful for concrete delivery and paving for the concurrent working method as long as the concrete mix production operation has sufficient capacity to supply multiple crews.

4.2.2 Calibration of the Concrete Delivery and Paving Operation

The reduced capacity of concrete delivery mixer trucks for FSHCC due to buildup in the mixer drum should be differentiated from normal PCC delivery capacity. FSHCC had a delivery efficiency of 87 percent versus 95 percent for typical PCC delivery (8). The ability to adjust for concrete delivery efficiency of various concrete materials should be added to the UCB analysis model, as should be done for hauling efficiency of various demolition methods.

CHAPTER 5

5.0 CASE STUDY CONCLUSIONS

1. The rehabilitation project on the I-10 near Los Angeles using fast setting hydraulic cement concrete (FSHCC) with a 4-hour curing time and a 55-hour weekend closure was completed successfully. The completion of the 55-hour weekend closure indicates that state agencies should be confident that 2.8 lane-km of pavement rehabilitation in a weekend is an achievable goal, even with the use of a non-traditional concrete, assuming the same pavement section used on the I-10 project. Under the Caltrans incentives/disincentives clause in the contract, the contractor qualified for a $500,000 bonus payment for completion of the 2.8 lane-km stretch of rehabilitation during the weekend closure.
2. A series of 7- and 10-hour nighttime closures were also performed as part of this contract. The average performance during the 10-hour

nighttime closures (10 p.m. – 8 a.m.) was approximately 10 slab slabs per hour. During the 7-hour nighttime closures (9 p.m. – 4 a.m.), average performance was approximately 7.5 slabs per hour. The 10-hour nighttime closures were 33 percent more productive per hour than the 7-hour closures because approximately 5 hours were available for the actual slab replacement work versus 2 hours for the 7-hour closures. Five hours are needed in both types of nighttime closure for mobilization, demobilization, and curing.

3. During the 55-hour weekend closure, an average of 14 slabs were paved per hour. The weekend closure was therefore 54 percent more productive in terms of slabs replaced per hour compared with the average nighttime closures.
4. The single 55-hour weekend construction window accounted for approximately 16 percent of the entire rehabilitation work for the 10-month contract. The amount of the rehabilitation work performed over the 55-hour extended closure would have normally taken 2.5 weeks (16.4 days) of average nighttime lane closures.
5. From the road user's point view, 2.5 weeks (16.4) days of nighttime closure is less convenient than one 55-hour weekend closure. The total duration of the 55-hour weekend closure was 38 percent of the total duration of 16.4 nighttime closures (average of 8.9-hour nighttime windows).
6. During the 55-hour weekend closure, slab demolition took 76 percent longer than the contractor's proposed CPM schedule, mainly due to an intentional slowdown of the demolition operation resulting from:
   i. a requirement applied by Caltrans as a contingency for minimizing the traffic delay on I-10, which required the contractor to maintain a maximum of 20 slabs of separation between paving and demolition crews; and
   ii. a reduction in construction access from two lanes to one because of a sound wall adjacent to the outside shoulder on two-thirds of the project length.

   These factors adversely affected the demolition rate but did not affect the overall progress of the project because paving was on the critical path for the majority of the project.
7. The overall progress of the concrete delivery and paving was similar to the contractor's original plan. Although a number of equipment breakdowns occurred, the rehabilitation goal of 2.8 lane-km was still completed in 55-hours.
8. The concrete delivery and discharge at the site were found to be the constraining factors. The average efficiency of the concrete delivery trucks was found to be 87 percent. The FSHCC played a role in reducing the overall efficiency of the concrete mixer truck deliveries, primarily due to material buildup in the mixer drum. In order to increase the productivity rate, an increased volume of concrete would needed to be delivered to the site.
9. A series of "what if" questions were asked and answered by the productivity data gathered at the site (assuming no external constraints would slow down progress). The "what if" results found that the fastest completion time for the demolition operation was approximately 22 hours, instead of the actual duration of 30 hours and proposed duration of 17 hours based on the initial progress rate of the demolition. The maximum amount of demolition under the contractor's process for 55-hours of work could have been 5 lane-km, assuming the concrete paving was not on the critical path.
10. For the concrete delivery and paving, if the initial paving progress had been maintained throughout the project length and no breakdowns had occurred, the paving operation could have been completed within approximately 41 hours instead of the actual duration of 47 hours. With this optimistic progress for the paving operation, the entire rehabilitation project could have been completed within 46 hours rather than the planned 55 hours. Alternatively, the maximum amount of the rehabilitation that could have been completed within the 55-hour weekend was 3.5 lane-km instead of the actual 2.8 lane-km, if the initial concrete paving progress had been maintained throughout the project.
11. In order to identify the impact of the 55-hour weekend closure on road users, traffic volume data were measured during the weekend closure construction and compared with a typical weekend data.
    i. Even with two lanes closed on the I-10 freeway during the weekend, the remaining two lanes were still within the capacity limit of 1500 vehicle per hour per lane set by Caltrans.
    ii. During peak-hours (Saturday and Sunday 9 a.m. – 9 p.m.), traffic through the construction was reduced by 30 to 60 percent compared with the peak traffic during typical weekends. The percentage of traffic diverting to other routes doubled during the 55-

hour weekend closure during the daylight hours, but was only approximately 5 percent more than normal during the nighttime hours.

iii. Daylight hourly volumes measured upstream from the site indicated that traffic flow through the work site was 5 to 35 percent less than normal during the 55-hour weekend closure. This indicated driver awareness of the weekend construction window and traffic lane closures, and the effectiveness of the publicity campaign.

iv. The maximum measured traffic delay for the entire project was 19 minutes.

Overall, Caltrans traffic management and publicity programs enabled the contractor to have excellent access to the site and minimized the turnaround time of the contractor's demolition and mixer trucks.

12. Caltrans' main objective for the use of FSHCC was to increase the productivity of the rehabilitation within a given construction window by decreasing the curing time of the concrete. The benefits of FSHCC are absolutely required for short construction windows, for example, 7- to 10-hour nighttime closures, especially when slab replacement is non-sequential. However, there does not seem to be an added benefit to using FSHCC in long closures for lane replacement, such as a 55-hour weekend closure, especially when an entire lane is being replaced (i.e., sequential slabs). This indicates FSHCC is appropriate for short closures such as 7- and 10-hour nighttime closures, and PCC is more appropriate for long closures such as lane replacement. Facts supporting this conclusion include:

    i. FSHCC costs 3 to 5 times more than PCC, which is not justifiable if the productivity of the two materials are similar and rapid strength gain materials are only needed at the very end of the project.

    ii. FSHCC includes additional operating costs, such as the need for concrete washout areas for the concrete mixer drums, chipping out the built-up concrete in the mixer drums, and surface grinding if the pavement does not meet ride quality standards due to hand-pouring of the FSHCC instead of slip-forming.

    iii. If enough concrete can be supplied to the jobsite, then paver speed will be the critical constraint on production (for this project only) and a manually operated rotating screed will not be efficient. Furthermore, a paver is preferred to help improve consolidation and finishability and to avoid the need to diamond grind the new pavement surface to achieve smoothness.

    iv. FSHCC required about a 30 percent longer turnaround time for mixer trucks due to use of a dry mix plant, washing out the concrete truck drum, checking for buildup at the plant, and waiting at the plant to complete the proper number of revolutions.

    v. Finally, if PCC had been used in the concrete mixer trucks, a 25 percent increase in volume per load would have been achieved as compared to FSHCC.

13. The measured construction productivity data from the demolition and paving operation was used to validate constructability and productivity analysis software coded by UCB. The average results from a deterministic and stochastic analysis were in agreement with the actual project productivity. The stochastic analysis showed that the expected range for the project productivity was between 2.2 and 3.4 lane-km for a 68 percent confidence interval with the average productivity being 2.8 lane-km.

CHAPTER 6

6.0 References

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