TRANSPORT
ISSN 1648-4142 / eISSN 1648-3480
2020 Volume 35 Issue 1: 1–19
https://doi.org/10.3846/transport.2019.11650

INTEGRATING CA4PRS V.3 ROAD WIDENING SCHEDULE MODULE INTO US HIGHWAY EARLY CONSTRUCTABILITY PROCESS: CALIFORNIA SR-91 CORRIDOR IMPROVEMENT PROGRAM CASE STUDY

Eul-Bum LEE[1], Douglas ALLEMAN[2*], David THOMAS[3], Chang-Mo KIM[4]

[1]Graduate Institute of Ferrous Technology and Graduate School of Engineering Mastership, Pohang University of Science and Technology (POSTECH), Pohang, Korea
[2]Construction Engineering and Management, Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, United States
[3]Riverside County Transportation Commission, Riverside, United States
[4]California Pavement Research Center, University of California, Davis, United States

Received 26 November 2018; revised 17 March 2019; accepted 29 April 2019

Abstract. Performing Constructability Review Processes (CRPs) during the highway design development has been found to save transportation agencies twice their input costs. However, existing literature has identified three areas of CRP improvement: reduction of required agency resources, incorporation of Road User Cost (RUC) scheduling constraints, and integration of assessment visualizations. The authors propose to fill this gap by integrating the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) v.3 software into the CRP. This module provides agencies with road widening project schedule capabilities, which enhances CRPs by providing accurate RUC-constrained critical path schedules using minimal resources. The module was developed through interviews with subject matter experts from six public and two private California transportation organizations. Said experts also tested the CA4PRS v.3 alpha and beta pre-release versions using data collected from eight Caltrans road widening projects. The potential value-adding of integrating the CA4PRS v.3 software with existing CRPs has been tested through its application on the California State Road 91 (SR-91) Corridor Improvement Program (CIP), resulting in 24-months of construction acceleration. The findings and presentation of the schedule model within this paper provide practitioners an accurate and resource-efficient tool to estimate the schedule impacts of road widening constructability options.

Keywords: CA4PRS, road widening, schedule module, automation, traffic analysis, constructability, road user cost.

Notations

3D – three-dimensional;
4D – four-dimensional;
AB/AS – aggregate base;
ACB – asphalt concrete base;
ACPA – American concrete pavement association;
ADT – average daily traffic;
CA4PRS – construction analysis for pavement rehabilitation strategies;
Caltrans – California Department of Transportation;
CCO – contract change order;
CIP – corridor improvement program;
CPM – critical path method;
CRP – constructability review processes;
DOT – Department of Transportation;
FWHA – Federal Highway Administration;
GDOT – Georgia DOT;
GP – general purpose;
HMA – hot mix asphalt;
HOV – high occupancy vehicle;
I-15 – Interstate 15;
I/D – incentive/disincentive;
JPCP – jointed plain concrete pavement;
LCB – lean concrete base;
LCCA – life-cycle costing analysis;
MoDOT – Missouri DOT;
NAPA – National Asphalt Pavement Association;

*Corresponding author. E-mail: *doal7544@colorado.edu*

NCHRP – National Cooperation Highway Research Program;
ODOT – Oregon DOT;
PCC – portland cement concrete;
PS&E – plan specifications and estimation;
RCTC – Riverside County Transportation Commission;
ROW – right-of-way;
RUC – road user cost;
SR-241 – US California State Road 241;
SR-91 – US California State Road 91;
TMP – traffic management plan;
v.1 – version 1;
v.2 – version 2;
v.3 – version 3;
WashDOT – Washington State DOT.

Introduction

CRP have been found to increase procurement efficacy, design, construction methods, construction and maintenance staffing efficiency, team integration, and project performance and reduce change orders (Gambatese *et al.* 2007) with a resultant benefit to cost ratio of at least 2:1 (Dunston *et al.* 2001). However, CRP literature and technological integration in the transportation sector has stagnated, with few publications or advances seen within the last ten years (Kifokeris, Xenidis 2017). There exist opportunities to improve the CRP process by integrating software, which reduces agency resource burdens (Dunston *et al.* 2005), incorporates considerations of life-cycle maintenance and scheduling impacts (Anderson, Fisher 1997; Saghatforoush *et al.* 2011), and provides a visualization of the results (Kifokeris, Xenidis 2017). Thus, this paper proposes the incorporation of the CA4PRS v.3 software into existing CRP practices, which fulfils all of these agency needs (Lee *et al.* 2000). The CA4PRS v.3 schedule model software's value-addition potential is validated through its integration into the SR-91 CIP constructability analysis, found to result in a 24-month project acceleration. The findings and presentation of the schedule model within this paper provide practitioners an accurate and resource-efficient tool to estimate the schedule impacts of constructability options.

While CRPs have received significant attention in literature over the last five decades, most of the transportation CRP literature is antiquated, often over 20 years old (Kifokeris, Xenidis 2017). This discussion began with a NCHRP publication, which provided agencies with an overview of the suggested tools, processes, and best practices to be used in CRP (Anderson, Fisher 1997). A majority of agencies have disseminated findings from this publication in their own CRP manuals (Stewart *et al.* 2017). Furthermore, successful CRP modifications are catalogued by the FHWA Work Zone Management Program on their CRP Best Practices website (FHWA 2019). Twenty years after their first investigation, the NCHRP performed a follow-up assessment of the efficacy of agency CRP tools, processes, and best practices (Stewart *et al.* 2017). They found the CRPs often rudimentary, with agencies lacking confidence to calculate a measurable payback for chosen alternatives (Stewart *et al.* 2017). Agencies lack the resources, expertise, or the time to dedicate to holistic CRPs (Dunston *et al.* 2005; Stamatiadis *et al.* 2013) and bringing in external construction personnel often created conflict of interests (Stewart *et al.* 2017). Existing CPR practices succeed in evaluating the implementation challenges of the contractor but often lack in incorporating life-cycle maintenance (Saghatforoush *et al.* 2011) and/or RUC impacts in their assessments (Anderson, Fisher 1997). Finally, in comparison to the construction industry as a whole, which has a wide variety of constructability techniques and new technologies being implemented (Pocock *et al.* 2006), the transportation sector has provided very few innovative technologies to support CRP. Recent CRP innovations have focused on integrating the advancements of 3D and 4D software (CTC & Associates LLC 2012, 2014). The CA4PRS v.3 software is a supplementary advancement that can mitigate many identified CRP issues. It requires minimal time/resources after the initial data is collected and provides agencies traffic management and scheduling outputs (Lee *et al.* 2000) to integrate into CRPs. While not within the purview of this paper, CA4PRS v.3's LCCA module (Lee *et al.* 2018) also has the capability of providing agencies with operations and maintenance considerations, found to be the most significant CRP failing by Raviv *et al.* (2012).

The development of the CA4PRS module came from the Caltrans in the late 1990's when faced with an aged highway system. More than 90% of their lane-miles were built between 1955 and 1970 and many were experiencing a steady increase in user demand. Caltrans was faced with a nearly insurmountable goal of rebuilding 1700 lane-miles in a short amount of time and launched a long-life pavement rehabilitation strategies program in 1998 (Lee *et al.* 2000). This endeavor required multiple fast-track urban rehabilitation projects, equating to higher construction density and increased road user impacts. In anticipation of this, Caltrans, in collaboration with the FHWA, Minnesota, Texas, and Washington, developed a pooled-fund to develop a traffic analysis software. From this collaboration, CA4PRS v.1 and CA4PRS v.2 were developed as a highly-accurate software, which integrates RUCs into decision making activities. Since their inception, they have been incorporated into many of Caltrans pre-construction planning processes and have been included in multiple research pursuits. As shown in Table 1, these previous studies have presented CA4PRS's value-adding (Anderson *et al.* 2011), investigated the benefits and challenges of its use across multiple states (Orcutt, AlKadri 2009; Edara 2009; Collura *et al.* 2010; Jeong *et al.* 2010; Florez *et al.* 2012; Jackson *et al.* 2012), used it as a research tool to calculate cost comparisons of differing innovations (Du Plessis *et al.* 2011, 2013), and have integrated it with value engineering (Lee *et al.* 2011a), LCCA (Lee *et al.* 2011b, 2018; Chen *et al.* 2016), TMP selection (Pyeon *et al.* 2012), I/D calculations (Choi, Kwak 2012;

Table 1. Existing CA4PRS literature summary and research opportunities

Category	Citation	Findings concerning CA4PRS software	Research opportunities*
Validating claimed benefits of CA4PRS	Anderson *et al.* (2011)	CA4PRS found to aid in project acceleration through accurate calculation of I/Ds	While valuable additions to the CA4PRS body of knowledge, none of these publications discuss CA4PRS as a constructability tool
CA4PRS's agency use and evaluation	Orcutt, AlKadri (2009)	Agency CA4PRS use challenges: DOT constraints, risk aversion, unknown benefits	
	Edara (2009)	MoDOT found CA4PRS to be 2nd best software for rural interstate RUC impacts	
	Collura *et al.* (2010)	New England agencies found CA4PRS to be value-adding	
	Jeong *et al.* (2010)	ODOT's found CA4PRS value-adding but required process/database changes	
	Florez *et al.* (2012)	GDOT found CA4PRS value-adding but didn't have access to 15% of input data	
	Jackson *et al.* (2012)	Multiple states found CA4PRS cost effective in obtaining traffic impact estimates	
Research tool	Du Plessis *et al.* (2011)	CA4PRS outputs used to assess economic benefits of accelerated pavement testing	
	Du Plessis *et al.* (2013)	CA4PRS outputs used to compare cost/benefit of innovative rehabilitation options	
Value analysis	Lee *et al.* (2011a)	CA4PRS outputs used to perform value analysis of rehabilitation project	
LCCA	Lee *et al.* (2011b)	CA4PRS outputs used to perform LCCA on three pavement alternatives	
	Chen *et al.* (2016)	CA4PRS used to estimate construction/ maintenance durations in support of LCCA	
	Lee *et al.* (2018)	CA4PRS used to integrate RUC analysis into the existing FHWA LCCA process	
TMP selection	Pyeon *et al.* (2012)	CA4PRS integrated into the cost analyses of differing TMP approaches	
Rehab strategy	Li *et al.* (2012)	WashDOT integrated CA4PRS into programmatic rehabilitation strategy	
I/D calculation	Lee, Alleman (2018)	CA4PRS used to integrate road user, agency, and contractor costs into I/D model	
	Pyeon *et al.* (2012)	Used to develop a systematic I/D process	
	Lee, Alleman (2018)	CA4PRS used to integrate road user, agency, and contractor costs into I/D model	Uses the CA4PRS v.3 module but investigates its incorporation into the LCCA process and not CRP
Fast-track urban rehabilitation	Lee *et al.* (2005a)	CA4PRS aids construction management plan; constructability analysis outputs used	Constructability outputs are used, but no process details. Does not analyze road widening projects
	Lee *et al.* (2005b)	CA4PRS used to minimize construction cost; constructability analysis outputs used	
	Lee *et al.* (2005c)	CA4PRS used to optimize schedule; constructability analysis outputs used	
Rehabilitation constructability	Lee *et al.* (2000)	Detailed presentation of CA4PRS v.1 and CA4PRS v.2 use as a constructability tool	There is no discussion of CA4PRS v.3's use with road widening constructability
	Lee, Sivaneswaran (2007)	Presents CA4PRS v.1 and CA4PRS v.2 as rehabilitation constructability analysis tool	

Note: * this column is meant to illustrate this paper's uniqueness, which is described in greater detail in this paper.

Pyeon *et al.* 2012; Lee, Alleman 2018), programmatic rehabilitation strategies (Li *et al.* 2012), and fast-track urban reconstruction process (Lee *et al.* 2005a, 2005b, 2005c). Finally, literature has presented CA4PRS v.1 and CA4PRS v.2 use as a constructability analysis tool for urban rehabilitation projects (Lee *et al.* 2000; Lee, Sivaneswaran 2007).

Along with existing literature, Table 1 depicts existing research opportunities. Most of the literature shown has been limited to CA4PRS v.1 and/or CA4PRS v.2's use on rehabilitation projects. This represents an opportunity for improvement, as the execution of road widening construction projects have become common practice due to nationwide city population booms. Though similar to rehabilitation, road widening requires different construction, lane-closure, and resource strategies. This paper seeks to fill this gap by presenting the CA4PRS v.3 schedule module as it can be used to aid agencies in performing constructability analyses on road widening projects. The findings largely build upon a 2000 report prepared for Caltrans (Lee *et al.* 2000) and a 2005 publication of said report (Lee, Ibbs 2005), which both detail the CA4PRS v.2's performance as a constructability tool for analyzing long life concrete pavement rehabilitation strategies. To a lesser extent, the findings of this paper also build off of Lee and Sivaneswaran's (2007) discussion of CA4PRS's use as a rehabilitation constructability tool and publications, which have used CA4PRS's constructability outputs in their development of differing managerial processes (Lee *et al.* 2005a, 2005b, 2005c).

This publication paper also adds to the existing body of knowledge by presenting the outputs of the CA4PRS v.3, improvements to older versions. The CA4PRS v.2 uses simplified critical path and linear scheduling techniques to return the following main outputs for a given construction window: maximum rehabilitation production (lane-miles) per closure, total number of closures and duration required to complete the entire project, constraining resources and resource optimization, and balanced time allocation between demolition and paving options (Lee, Sivaneswaran 2007). CA4PRS v.3 estimates project activity and overall project durations, incorporating alternative strategies for pavement design, lane-closure tactics, contractor logistics; production rates; and activity predecessor-successor relationships. The CRP has been found to use CA4PRS v.2's outputs to understand the impacts alternatives have road users (Lee, Ibbs 2005). However, the CA4PRS v.3 outputs are used to support higher-level managerial decisions based on factors such as overall project duration, resource conflicts, work intensity, staffing, etc. Figure 1 depict a side-by-side comparison of the CA4PRS v.2 and CA4PRS v.3 outputs.

a)

b)

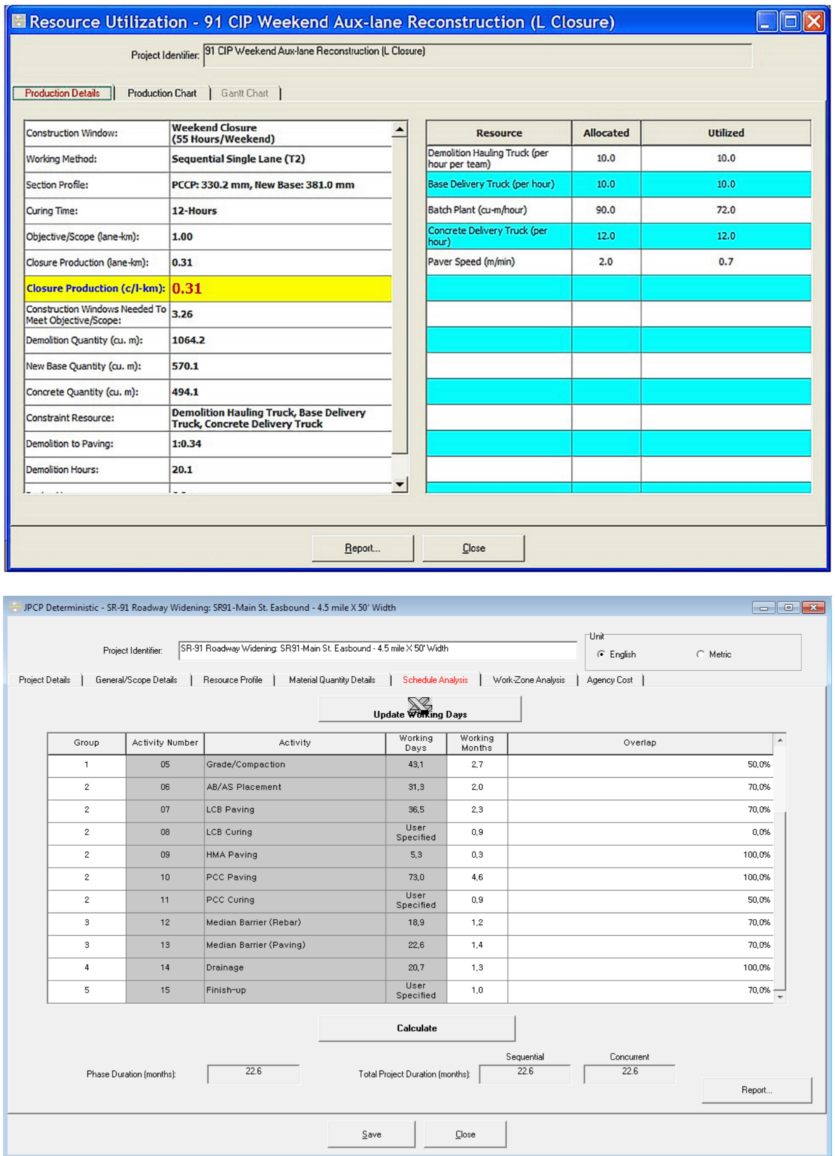

Figure 1. Schedule output screens: a – CA4PRS v.2; b – CA4PRS v.3

1. Data collection and research methodology

The objective of this paper is to investigate the potential value-adding of integrating CA4PRS v.3's schedule module into the existing agency CRP. The authors collected Caltrans road widening cost and schedule performance data and performed subject matter expert interviews to support the development of the CA4PRS v.3 module and validated its use on the SR-91 CIP project. The data was collected from all Caltrans projects that used I/Ds awarded from 2003 and 2010. I/D projects were solely chosen as they have high ADT and require RUC calculations, both necessities for developing the CA4PRS v.3's schedule module for roadway widening projects. Table 2 depicts the typical data collected for each project.

The authors collected data from 48 I/D Caltrans projects, but only 8 were road widening. The high-level data of these projects are shown in Table 3. The data collected from each project was used as inputs for the CA4PRS roadway widening pre-release alpha and beta versions to test and modify accuracy, ease of use, and clarity of outputs.

The CA4PRS v.3 module was developed and modified based on inputs by subject matter experts and the core research team. The subject matter experts were representatives from six public and two private California agencies, including: Caltrans, Orange County Transportation Authority, Riverside County Transportation Department, San Bernardino County DOT, ACPA, NAPA and two private consultant companies. The authors conducted informal interviews with said experts via face to face, phone, and/or email discussions concerning required inputs, input data sources and availability, and desired outputs. The subject matter experts also tested and commented on CA4PRS v.3 alpha and beta pre-release versions. The core research team, which includes the authors of this paper, were also involved with the development of the module, having a combined 20 years alternative contracting research experience, 20 years RUC highway research and modelling experience, and 30 years highway industry experience.

To validate the CA4PRS v.3 schedule module and its use in the constructability process, the authors sought out an agency, which had a mature CRP and experience using CA4PRS. Furthermore, a road widening project within that agency was sought out that had significant RUC impacts in urban corridor network and multiple viable and dissimilar constructability alternatives. The project chosen for this study was the SR-91 CIP, which met all requirements: within California who has a mature constructability process and extensive experience with CA4PRS, an ADT of over 250000, five opportunities of increasing project constructability, and a project initiation phase that coincided with the beginning of this study (RCTC 2019). The data collected from the project includes required inputs as defined in the following subsection's Table 5.

Table 2. Project data sample obtained from Caltrans' division of construction

Project characteristics
District
EA
County
Route project
Postmile ahead
Postmile back
ADT
CCOs days
Contract working days
Actual working days
Change order days
Other days
Weather days
Award date
Work must start date
Acceptance date
Engineers estimate
Contract award
Final contract price
Paid to date
Contract CCO's
Daily I/D amount
Maximum incentive
Contractor name
Description of work
Location description

Table 3. Summary of I/D project data by district and project type

District headquarters	Project No	ADT	Contract award amount	Contract duration
San Luis Obispo	1	82000	$ 47720000	850
Fresno	2	64333	$ 61890000	320
Los Angeles	3a	94650	$ 15468000	500
	3b	285000	$ 36310000	420
	4	103750	$ 10535000	360
San Bernardino	5	152200	$ 210650000	845
	6	72000	$ 115000000	705
San Diego	7	176666	$ 129000000	1350
Santa Ana	8	188000	$ 206968000	1530

Table 4. SR-91 project data

Project characteristics		Design-build construction summary		
Location:	Corona, CA	award date		8 May 2013
Route project:	SR-91	construction start		1 October 2013
Description:	14 miles road widening Adding: (1) auxiliary lane (1) regular lane (2) express lanes	construction finish		20 March 2017
		duration estimated		1521 days
		duration actual		1249 days
		engineer's estimate		$ 773 million
		contract award		$ 633 million
Project east boundary:	pierce street	Total project costs breakdown		
Project west boundary:	SR-241	Description	Original[1]	Final[2]
ADT:	250000	Commission[3] Design-build[4] Finance Total	$ 521 million $ 633 million $ 158 million $ 1312 million	$ 610 million $ 639 million $ 158 million $ 1407 million

Notes: [1]original cost summary detailed in SR-91 31 December 2013 Construction Progress Report (Trevino 2014);
[2] final cost summary based on 85% completion and detailed in SR-91 28 February 2017 Report (Trevino 2017);
[3]due to $ 100 million increase in right-of-way acquisitions;
[4] 92 change orders; most appear to be value-adding; see Appendix B of SR-91 2/28/2017 Report (Trevino 2017).

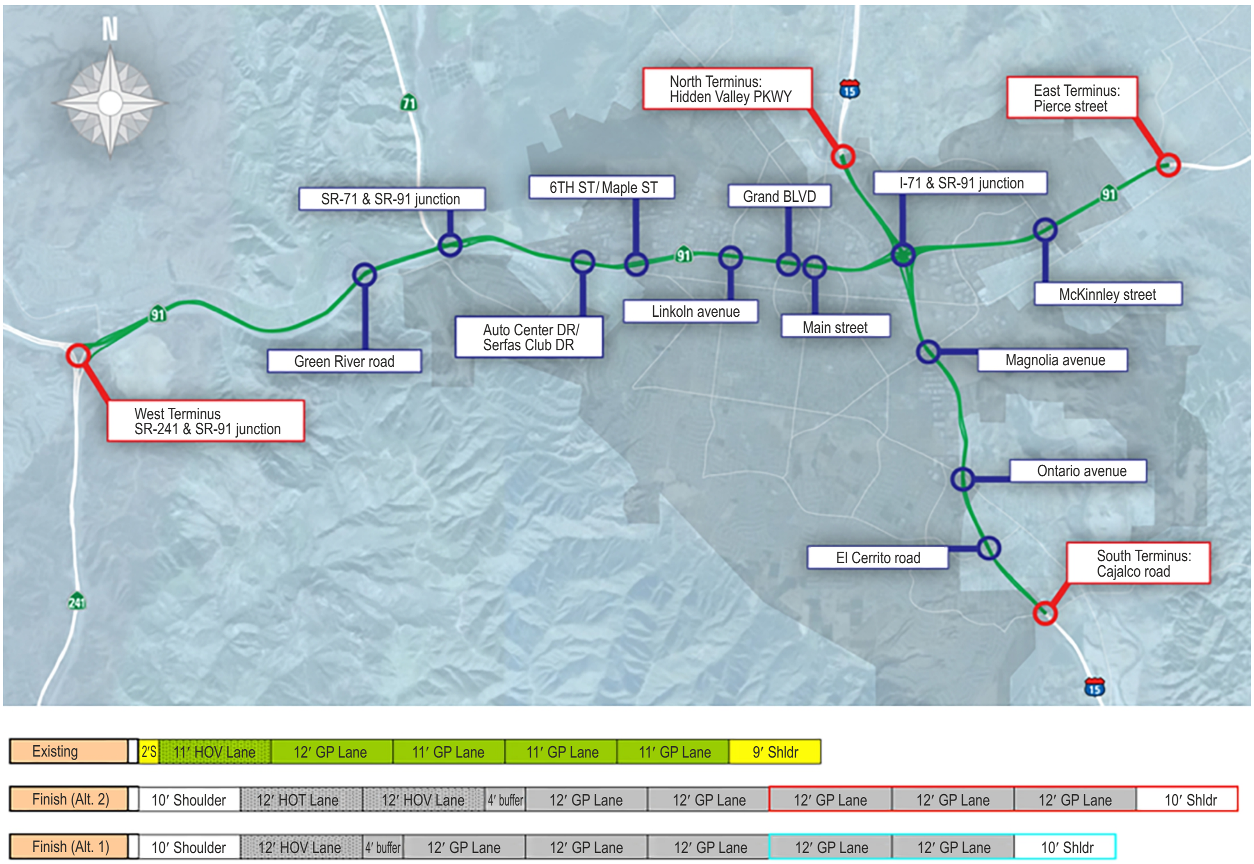

Figure 2. SR-91/I-15 project vicinity map and pavement cross-sections
(*Alt. 1 represents Alterative A and Alt. 2 represents Alternative B; both represent the section from SR-71 to I-15)

The SR-91 CIP is in Orange and Riverside Counties, southern California along SR-91 bound by State Route 241 and Pierce Street in Riverside County. The project also includes widening of I-15, bound by Cajalco Road and Hidden Valley Parkway. The SR-91 CIP project was awarded to the Atkinson Contractors, LP and Walsh Construction Company joint venture as a design-build contract for $ 632 million, $ 140 million less than the engineer's estimate. Construction began in late 2013 and was completed 2017. The final total project cost was approximately $ 1.4B, a $ 100 million increase from the original estimate. The project experienced a $ 100 million increase in expected ROW acquisitions. The basic project data and project vicinity map and pavement cross-section details are presented below in Table 4 and Figure 2, respectively (Trevino 2017).

Figure 3 shows the CRP as was used by the Caltrans SR-91 CIP team. The authors have shown the full CRP to portray where the CA4PRS v.3 software is integrated. The CRP steps in which the input data is collected are highlighted solid blue and the steps in which the CA4PRS v.3 road widening analysis is performed are highlighted solid red. While Caltrans has constructability reviews up to four times (project initiation, 30, 60 and 90%) during design progression, the CA4PRS v.3 software was only used for PS&E constructability reviews. However, the process as explained in the results section would be mirrored no matter the design stage.

2. Findings: CA4PRS v.3 schedule module's use on SR-91 corridor project

For ease of flow, the findings from using CA4PRS v.3 schedule module on the SR-91 CIP are presented as they were performed in the CRP depicted in Figure 3.

2.1. A111: establish project constructability strategies

The identified goals for the SR-91 project were to reduce congestion and improve mobility within the project limits. This corridor is well-travelled with commuters travelling from Riverside to Orange County for work, recreation, school, commerce, etc. During construction, the average daily traffic on SR-91 was 280000 vehicles and 184000 vehicles on I-15 (RCTC 2019). From a constructability standpoint, this equates to a focus on minimizing impacts to the road users. As such, alternatives that use construction practices that minimize the duration and/or magnitude of road closures are preferred, assuming they are of equal or better value than the base case.

2.2. A113: identify and evaluate means to obtain constructability inputs

CA4PRS v.3's primary purpose within the CRP was to estimate the overall schedule with consideration of major constraints. To perform this process, the module requires data input from five categories as follows, with greater detail in Table 5: (1) project details, (2) general/scope details, (3) resource profile, (4) material quantity details, and (5) schedule analysis, which generates the module's CPM output.

From the Table 5 inputs, along with historical production rates and efficiencies from similar Caltrans projects or references in consultation with the highway construction industry, the CA4PRS software calculates activity durations. From the input data, there are several different ways to calculate activity durations. For all equation variables, please reference Table 2. Also, all variables are shown in metric units for clarity. The demolition haul trucks, filling, AB/AS, LCB, HMA/ACB, and PCC/JPCP activities and are calculated using the following Equations (1–3):

$$Productivity\left[\frac{\text{tonnes}}{\text{week}}\right] = capacity\left[\frac{\text{tonnes}}{\text{truck}}\right]\cdot\frac{\left(\frac{truck}{h}\right)}{team}\times no\ of\ teams\left[\text{team}\right]\cdot\frac{h}{days}\cdot\frac{days}{week}\cdot packing\ efficiency; \quad (1)$$

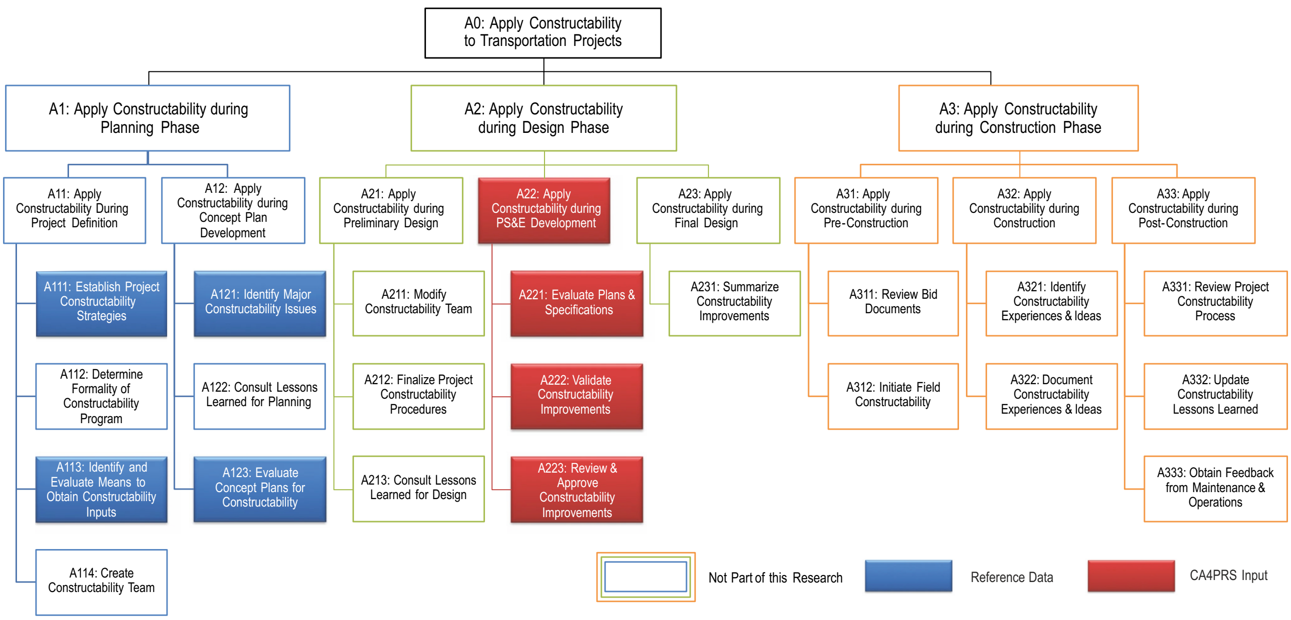

Figure 3. SR-91 CIP CRP (modified from Anderson and Fisher (1997))

$$quantity\ of\ material\left[\text{tonnes}\right] = \left(depth \cdot length \cdot lanewidth + extra\ quantity\right)\left[\text{m}^3\right] \times conversion\left[\frac{\text{tonnes}}{\text{m}^3}\right]; \quad (2)$$

$$activity\ duration\left[\text{weeks}\right] = productivity\left[\frac{\text{tonnes}}{\text{week}}\right] \times quantity\ of\ material\left[\text{tonnes}\right] \cdot work\ efficiency. \quad (3)$$

Median barrier (rebar and paving), are calculated using the following Equation (4):

$$type_B\ activity\ duration\left[\text{weeks}\right] = \frac{team\ production\left[\frac{\left(\frac{\text{m}}{\text{h}}\right)}{\text{team}}\right] \cdot no\ of\ teams\left[\text{team}\right]}{length\left[\text{m}\right]} \times \frac{h}{day} \cdot \frac{days}{week} \cdot work\ efficiency. \quad (4)$$

Site cleaning is calculated using the following Equation (5):

$$site\ cleaning\ duration\left[\text{weeks}\right] = \frac{team\ production\left[\frac{\text{km}}{\left(\frac{\text{h}}{\text{team}}\right)}\right]}{distance\ for\ road\ widening\left[\text{km}\right]} \times no\ of\ teams\left[\text{team}\right] \cdot \frac{h}{day} \cdot \frac{days}{week} \cdot work\ efficiency. \quad (5)$$

Compaction is calculated using the following Equation (6):

$$compaction\ duration\left[\text{weeks}\right] = \frac{team\ production\left[\frac{\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{team}}\right]}{distance\ for\ road\ widening\left[km\right] \cdot lane\ width\left[m\right] \cdot no\ of\ teams\left[\text{team}\right]} \times \frac{h}{day} \cdot \frac{days}{week} \cdot work\ efficiency. \quad (6)$$

Demolition is calculated using the following Equations (7–8):

$$demolition\ duration\left[\text{weeks}\right] = \frac{team\ production\left[\frac{\left(\frac{\text{m}^3}{\text{h}}\right)}{\text{team}}\right]}{demolition\ quantity\left[\text{m}^3\right]} \times no\ of\ teams\left[\text{team}\right] \cdot \frac{h}{days} \cdot \frac{days}{week} \cdot efficiency, \quad (7)$$

where:

$$demolition\ quantity\left[\text{m}^3\right] = \frac{type_A\ quantity\ of\ materials\left[\text{tonnes}\right]}{conversion\left[\frac{\text{tonnes}}{\text{m}^3}\right]}. \quad (8)$$

Drainage is calculated using the following Equation (9):

$$drainage\ duration\left[\text{weeks}\right] = length\left[m\right] \times trench, pipe, backfill\left[\frac{\text{m}}{\text{day}}\right] \cdot \frac{days}{week} \cdot work\ efficiency. \quad (9)$$

The resource profile and material quantity details contain a majority of the information required for activity duration calculation. See Figure 4 for an example of the resource profile input screen as used by the SR-91 project team.

From these activity durations, the CA4PRS v.3 schedule module, using pre-defined predecessor-successor relationships, can produce a CPM bar chart schedule (see Appendix for examples of output). The outputs are in the form of working days and working months per activity, total project duration in months, and total project duration in months if paving activities are sequential or concurrent. The user has the option to modify the overlap (predecessor-successor relationship) for activities. The CA4PRS v.3 schedule module output can be seen above in Figure 1b.

2.3. A121: identify major constructability issues

From a collaboration of design, construction, traffic, structural, and geotechnical staff, the SR-91 CIP team identified construction activities most likely to impact the project schedule. While not directly constructability issues, the team focused constructability opportunities that maximized the positive impacts procurement of ROW, demolition of buildings in ROW, utilities relocation, detours, retaining walls, excavations, bridge structures, and placement of AB/AS, ACB, and PCCP.

2.4. A123, A221, A222: evaluate plans and perform constructability analysis

The project team identified more than ten viable project alternatives, but only five used the CA4PRS v.3 road widening schedule capabilities and are detailed below.

Alternative A. Baseline: The baseline alternative was for the project to add one GP lane to SR-91 and replace the existing HOV lanes with an express lane using continuously reinforced concrete pavement on SR-91 and asphalt concrete pavement for I-15. The baseline alternative assumes road widening paving operation would be performed by one SR-91 and one I-15 crew concurrently. It is also assumed that the ACB and LCB/PCC pavement activities can occur concurrently within the SR-91 and I-15 activities. The option of having these activities occur sequentially is discussed in Alternative C and D. From these assumptions, and a CA4PRS schedule analysis, it was found that the total construction duration for Alternative A is 54 months. The CPM bar-chart is shown in comparison to all alternatives in Figure 5 and the CA4PRS CPM Alternative A output is seen in Figure A in the Appendix.

Table 5. CA4PRS v.3 road widening input data

Category	Inputs	Sub-inputs	Duration equation(s)
Project details	Project identifier	*None – used for generic project identification*	
	Unit of measurement	*None – used to set simulations in either imperial or metric units*	
	Post miles	Beginning post mile, ending post mile	
General scope details	Road information	Distance for roadway widening, lane-width, number of lanes	
	Concrete curing times	Concrete curing time for LCB and PCC in days	
	Mobilization	Daily crew mobilization/demobilization duration in hours	
	Construction information	Construction start date, days/week, hours/day, work efficiency	
	Activity groups/phases	Number of activity groups, number of phases	
	Traffic index calculation	*None – used for the work-zone analysis*	
Resource profile	Site cleaning	No of teams, team production	5
	Demolition	No of teams, team production	7–8
	Demolition hauling truck	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	Filling	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	Compaction	No of teams, team production	5
	Base (AB/AS)	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	LCB	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	Median barrier (rebar)	No of teams, team production	4
	Median barrier (paving)	No of teams, team production	4
	HMA or ACB	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	PCC or JPCP	Related capacity, trucks/h/team, packing efficiency, No of teams	1–3
	Drainage daily production	Trench, pipe, backfill	9
Material quantity details	Demolition	Depth, length, lane-width, extra quantities	1–3
	Filling	Depth, length, lane-width, extra quantities	1–3
	Base (AB/AS)	Depth, length, lane-width, extra quantities	1–3
	LCB	Depth, length, lane-width, extra quantities	1–3
	Median barrier	Length	4
	Drainage	Length	9
	HMA or ACB	Depth, length, lane-width, extra quantities	1–3
	PCC or JPCP	Depth, length, lane-width, extra quantities	1–3
Schedule analysis	Group	*None – used for development of work breakdown structure*	
	Working months	*None – enables user to manual override calculated durations*	
	Overlap	*None – enables user to manual override activity overlaps*	

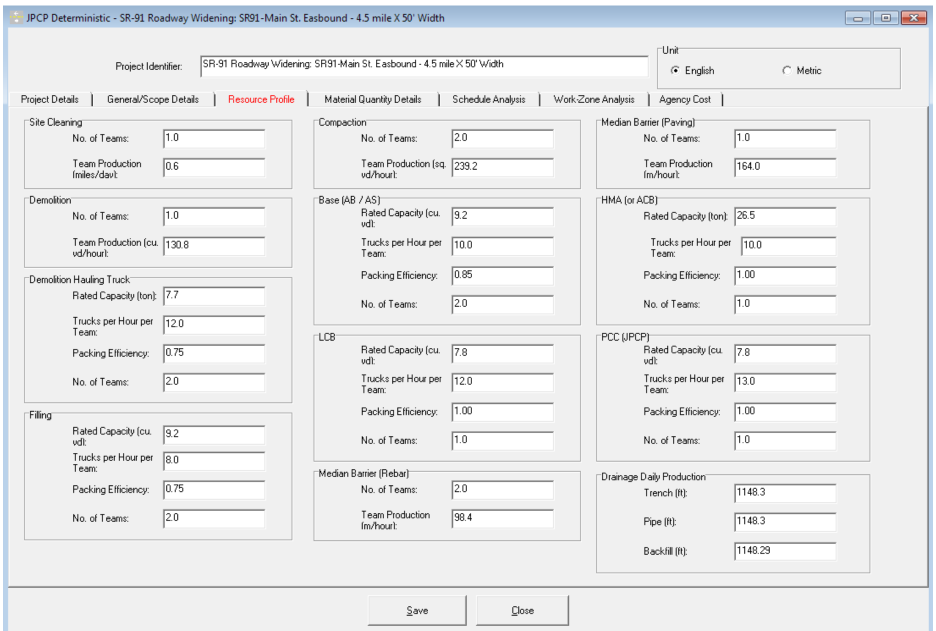

Figure 4. CA4PRS SR-91 resource profile input screen

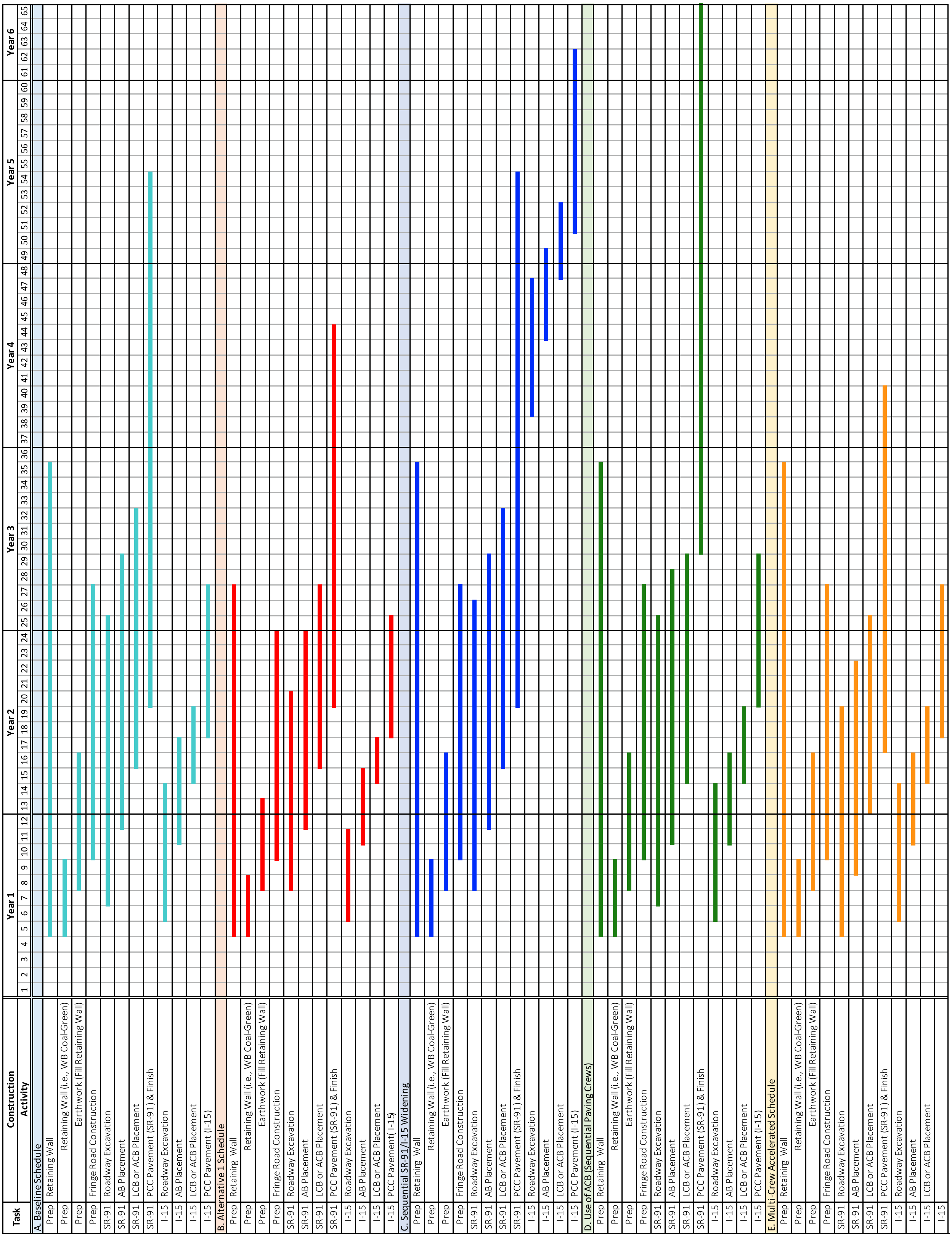

Figure 5. CPM schedule comparison of the five alternatives for SR-91 CIP project

Alternative B. No Express Lanes: Alternative B still adds one GP lane to SR-91 but does not replace the HOV lane and uses PCC pavement. The crew assumptions are the same as made in Alternative A. As Alternative B requires widening of one lane less in each direction than the baseline schedule. This reduces the amount of roadway construction such as earth-work, base paving, PCC paving, etc. As such, the duration is reduced to 44 months, 10 months less than Alternative A. The CPM schedule, Figure 5 below, illustrates that much of this reduction comes from the duration of PCC paving, 20 working months in Alternative B versus 30 for Alternative A. Figure B in the Appendix shows Alternative B's CA4PRS CPM output.

Alternative C. Sequential SR-91 and I-15 Paving Crews: This alternative uses the same layout and assumptions as the baseline alterative, with one exception. The baseline alternative assumes a concurrent schedule, in which there exist two paving crews, one for each interstate. This is a logical assumption as, from a practical point of view, the SR-91 and I-15 widening are independent construction processes. However, in order for the contractor to perform this they would be required to have adequate resources to run two separate operations, which may result in higher construction costs, and greater work-zone impacts. As such, the project team ran a schedule analysis on the option for running a singular crew. Figure 5 shows that, if the constructor chooses to run one paving crew, SR-91 and I-15 paving activities sequential, the schedule is increased to 62 months, 8 months longer than the baseline alternative. Figure C in the Appendix shows Alternative C's CA4PRS CPM output.

Alternative D. Sequential LCB/ACB and PCC Paving Crews: This alternative uses the same layout and assumptions as the baseline alterative, with the exception of the number of LCB/ACB and PCC paving crews. From lessons learned on other projects, engineers have typically designed an LCB underneath the PCC slab, as opposed to an ACB. However, the LCB and PCC paving operations are nearly identical, resulting in competition of several resources (resource restraints). Figure 5 shows that, if the constructor chooses to use LCB, the schedule is increased to 65 months, 11 months longer than the baseline alternative.

Alternative E. Multi-Crew Construction: Finally, the project team analyzed the option of executing project acceleration measures. The proposed acceleration solution was adopting a multi-crew construction for the widening operations, especially the concrete paving operation. The goal would be to accelerate the PCC paving operation by maintaining more than on paving crew simultaneously on each route. Figure 5 shows that the multi-crew solution would result in a duration of 40 months, 14 months faster than the baseline schedule. While this would theoretically work, it may be unrealistic in execution due to potential resource restraints of the chosen contractor and the agency, potentially overburdening the paving crews and quality control team resulting in subpar paving installation. However, this could be relieved if the ACB option is chosen, described in the next section.

2.5. A223: review and approve constructability improvements

Upon completing the CA4PRS analysis, the authors made four recommendations to the project team. These recommendations were also based off of work-zone user analyses, RUCs, agency costs, and LCCA (Lee *et al.* 2018), which are referenced, where applicable. However, the methodologies behind those findings are not presented as they are outside of the purview of this paper. From the above assessments, the SR-91 constructability team made the following suggestions:

Choose Alternative B: Alternative B was found to equate to 10 months of schedule acceleration and were found to have an approximate $32M life-cycle savings (Lee *et al.* 2018). As such, the cost/benefit analysis was overwhelmingly in support of Alternative B.

Have Concurrent SR-91 and I-15 Paving Activities: The ideal situation, concerning overall project duration, is to have the contractor proceed with two separate widening crews in parallel. The concerns of this option are the contractor's ability to adequately provide the necessary resources. A work-zone impact analysis was also performed to ensure this option would not increase RUCs. From the prospective of the owner, the authors found the benefits of 8 months of project schedule acceleration from having two paving crews to outweigh the potential increases in construction and RUC.

Chose ACB over LCB to Ensure Concurrent ACB and PCC Paving Activities: The project team's constructability recommendation is to use ACB instead of LCB on this project for the benefit of schedule savings as demonstrated in the CA4PRS schedule analysis. Furthermore, this option increases the ability for the contractor to also choose a multi-crew option. One downside of using ACB is that ACB operations are more subject to site ambient temperatures. Though the contractor can manipulate cooling time problems by performing paving at night. Finally, the requirement of engineering approval should not be an issue as the *Highway Design Manual: U.S. Customary Units* currently adopted ACB as an acceptable base type for long life pavement (Caltrans 2019).

Execute the Multi-Crew Option: The schedule analysis confirms that the overall duration of the baseline schedule can be reduced substantially (14 months), if the contractors have an ability to arrange and maintain multi-crew for major construction actives, especially for paving. While the multi-crew approach may have increased costs associated contractor acceleration charges, these are outweighed by the benefits of 14 months of project schedule acceleration and reduction in RUC (due to shorter construction duration).

2.6. SR-91 CIP project completion status and results

The SR-91 CIP Project construction started in late 2013 was and was completed 2017 with an approximate total $ 1.4 billion investment. This represented a $ 100 million increase from the original estimate, caused by an increase in right-of-way acquisition fees. In spite of this 7% project cost growth, the project was considered a success, receiving multiple awards including the "Transportation Project of the Year" and the "Quality of Life/Community Development". The road widening was found to save regular lane and express lane road users 12 and 90 min per day, respectively, while decreasing accidents via smart traffic planning and improved interchanges (Atkinson Construction 2019). The constructability design strategies as presented above were primarily adopted into the final design stage with minor adjustments made by the design-build team through design completion. The constructability improvements resulted in construction being accelerated by 10 months and the total project approximately 24-months. Furthermore, the design-build entity was awarded a contract value approximately $ 140 less than Caltrans estimated. The LCCA analysis of the different alternatives show that approximately $32 million of those savings came from choosing Alternative B, results shown below in Table 6.

Table 6. Constructability cost comparisons (Lee *et al.* 2018)

Constructability alternatives	Construction activity	Estimated cost ($ k)
Alternative A* (long-life CRCP/ACP)	SR-91 lanes	83366
	I-15 lanes	38486
	SR-91 ramps	20264
	Total	142116
Alternative B* (long-life PCCP)	SR-91 lanes	77213
	I-15 lanes	22075
	SR-91 ramps	11092
	Total	110380

Note: *assumes not pursuing Alternatives C, D, and E; rather, this assumes concurrent paving and multiple crews.

Conclusions

CRP have been found to increase the efficiencies of agency procurement and staffing, the quality of design, the efficacy of construction methods, and overall team integration and project performance equating to project cost/benefit ratio of 1:2 (Gambatese *et al.* 2017). While a majority of agencies have CRP manuals, which promote NCHRP and FHWA identified best practices (Anderson, Fisher 1997; Stewart *et al.* 2017; FHWA 2019), they have been found to require significant agency resources (Dunston *et al.* 2005), lack RUC and schedule considerations (Anderson, Fisher 1997; Saghatforoush *et al.* 2011), and fail to provide managers with visualizations of alternatives (Kifokeris, Xenidis 2017). This publication proposes the CA4PRS v.3 software, road widening schedule module, to mitigate these identified CRP issues.

The findings build upon literature, which detail CA4PRS v.2's theoretical performance as a constructability tool for analyzing long life concrete pavement rehabilitation strategies (Lee *et al.* 2000; Lee, Ibbs 2005). To a lesser extent this publication also builds off of literature, which uses CA4PRS v.2's constructability outputs to support differing managerial processes (Lee *et al.* 2005a, 2005, 2005c; Lee, Sivaneswaran 2007). The CA4PRS v.2 software is only applicable to rehabilitation projects and its integration into the CRP is limited to understanding the RUC of different alternatives. In comparison, the CA4PRS v.3 software is applicable to road widening construction projects and provides CRP agency decision-makers visual representations of the overall project duration, resource conflicts, work intensity, and staffing of different alternatives. Finally, this publication validates the software's value-adding through its use on an executed project, currently lacking in literature.

The CA4PRS v.3 road widening schedule module was found to aid the California State Road 91 (SR-91) CIP project team in assessing constructability alternatives by providing quick project duration comparisons, which take into account lane-closure options, productivity, construction means and methods, available resources, and materials and equipment used, as presented through its use on the California SR-91 CIP project. Through its integration into the SR-91 CIP constructability analysis, the project team choose constructability strategies, which resulted in a 24-month construction acceleration and $ 32 million cost savings. Furthermore, the CA4PRS v.3 integration resulted in lower road user and agency overhead costs.

Through the effort to incorporate the CA4PRS v.3 traffic and schedule software into the existing agency CPR, as defined by NCHRP and several agency manuals (Stewart *et al.* 2017), it is the authors' contention that these findings can be replicated with similar successes on road widening projects across the US. However, the use of the software is limited by the availability of the data, which some agencies have found not available or difficult to attain (Jeong *et al.* 2010; Florez *et al.* 2012). Furthermore, although the CA4PRS v.3 software provides quick and detailed comparisons across constructability alternatives, it is only a support tool. The most important success factors of the CRP are still having an agency constructability champion, performing detailed design quality assurance, and integrating contractor expertise (Raviv *et al.* 2012).

Acknowledgements

The CA4PRS software was developed with pooled-funding Grant No SPR-3 (098) from the US FHWA and the State Pavement Technology Consortium made of California, Florida, Minnesota, Texas, and Washington State Department of Transportations.

The research team would also like to acknowledge the information, feedback, and partial funding of field case studies contributed by the ACPA and the NAPA.

The research team also appreciate the information provided by engineers in Caltrans and RCTC, especially the SR-91 Corridor project team including Parsons Brinkerhoff.

The views expressed in this paper are solely those of the writers and do not represent those of any official organization.

Author contributions

Eul-Bum Lee developed the concept based on the analysis and drafted the manuscript.

David Thomas provided project data with validation and supervised the overall work.

Douglas Alleman provided constructability feedback and reviewed the manuscript.

All of the authors read and approved the final manuscript.

Disclosure statement

The authors declare no conflict of interest.

References

Anderson, S. D.; Fisher, D. J. 1997. *Constructibility Review Process for Transportation Facilities: Workbook*. National Cooperative Highway Research Program (NCHRP) Report 391. Transportation Research Board, Washington, DC, US. 189 p.

Anderson, S.; Shane, J. S.; Schexnayder, C. 2011. Strategies for planned project acceleration, *Journal of Construction Engineering and Management* 137(5): 372–381. https://doi.org/10.1061/(asce)co.1943-7862.0000289

Atkinson Construction. 2019. *SR 91 Corridor Improvements: a Case Study on the Benefits of Design-Build Delivery*. Atkinson Construction, Golden, CO, US. Available from Internet: https://www.atkn.com/our-work/sr-91-corridor-improvements

Caltrans. 2019. *Highway Design Manual: U.S. Customary Units*. California Department of Transportation (Caltrans), CA, US. Available from Internet: https://dot.ca.gov/programs/design/manual-highway-design-manual-hdm

Chen, F.; Zhu, H.; Yu, B.; Wang, H. 2016. Environmental burdens of regular and long-term pavement designs: a life cycle view, *International Journal of Pavement Engineering* 17(4): 300–313. https://doi.org/10.1080/10298436.2014.993189

Choi, K.; Kwak, Y. H. 2012. Decision support model for incentives/disincentives time–cost tradeoff, *Automation in Construction* 21: 219–228. https://doi.org/10.1016/j.autcon.2011.06.006

Collura, J.; Heaslip, K. P.; Moriarty, K.; Wu, F.; Khanta, R.; Berthaume, A. 2010. Simulation models for assessment of the impacts of strategies for highway work zones: eight case studies along interstate highways and state routes in New England, *Transportation Research Record: Journal of the Transportation Research Board* 2169: 62–69. https://doi.org/10.3141/2169-07

CTC & Associates LLC. 2012. *Advanced Modeling Techniques for Enhanced Constructability Review: a Survey of State Practice and Related Research*. California Department of Transportation (Caltrans), CA, US. 149 p. Available from Internet: https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/enhanced-constructability-review-pi-a11y.pdf

CTC & Associates LLC. 2014. *Advanced Modeling Techniques for Enhanced Constructability Review, Phase II: a Survey of State Practice and Related Research*. California Department of Transportation (Caltrans), CA, US. 52 p. Available from Internet: https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/ecr-phase-ii-pi-7-24-141-a11y.pdf

Du Plessis, L.; Nokes, W. A.; Mahdavi, M.; Burmas, N.; Holland, T. J.; Harvey, J.; Liebenberg, L. 2013. Case study for evaluating benefits of pavement research: final results, *Transportation Research Record: Journal of the Transportation Research Board* 2367: 63–75. https://doi.org/10.3141/2367-07

Du Plessis, L.; Nokes, W. A.; Mahdavi, M.; Burmas, N.; Holland, T. J.; Lee, E.-B. 2011. Economic benefits assessment of accelerated pavement testing research in California: case study, *Transportation Research Record: Journal of the Transportation Research Board* 2225: 137–146. https://doi.org/10.3141/2225-15

Dunston, P. S.; Gambatese, J. A.; McManus, J. F. 2005. Assessing state transportation agency constructability implementation, *Journal of Construction Engineering and Management* 131(5): 569–578. https://doi.org/10.1061/(asce)0733-9364(2005)131:5(569)

Dunston, P. S.; McManus, J. F.; Gambatese, J. A. 2001. *Cost/Benefits of Constructability Reviews*. National Cooperative Highway Research Program (NCHRP) Project 20-07/Task 124. Transportation Research Board, Washington, DC, US.

Edara, P. 2009. *Evaluation of Work Zone Enhancement Software Programs*. Report No OR10-006. Missouri Department of Transportation, MO, US. 32 p. Available from Internet: https://library.modot.mo.gov/RDT/reports/Ri07062/or10006.pdf

FHWA. 2019. *Constructability Reviews*. Federal Highway Administration (FHWA), Washington, DC, US. Available from Internet: https://ops.fhwa.dot.gov/wz/practices/best/topindex.asp?ID=90

Florez, L.; Irizarry, J.; Castro-Lacouture, D.; Abdollahipour, S.; Jeong, H. 2012. Feasibility of implementing a computer-assisted pavement rehabilitation decision support system, *International Journal of Construction Education and Research* 8(4): 281–300. https://doi.org/10.1080/15578771.2012.658960

Gambatese, J. A.; Pocock, J. B.; Dunston, P. S. 2007. *Constructability Concepts and Practice*. American Society of Civil Engineers (ASCE). 149 p. https://doi.org/10.1061/9780784408957

Jackson, N.; Mahoney, J.; Puccinelli, J. 2012. *Using the Existing Pavement in Place and Achieving Long Life*. Strategic Highway Research Program (SHRP 2) S2-R23-RR-1. Transportation Research Board, Washington, DC, US. 633 p. https://doi.org/10.17226/22684

Jeong, H. S.; Abdollahipour, S.; Flórez, L.; Irizarry, J.; Castro, D. 2010. *Evaluation of Construction Strategies for PCC Pavement Rehabilitation Projects*. Report No OTCREOS7.1-23-F. Oklahoma Transportation Center, Midwest City, OK, US. 139 p. Available from Internet: https://rosap.ntl.bts.gov/view/dot/20482

Kifokeris, D.; Xenidis, Y. 2017. Constructability: outline of past, present, and future research, *Journal of Construction Engineering and Management* 143(8): 04017035. https://doi.org/10.1061/(asce)co.1943-7862.0001331

Lee, E.-B.; Alleman, D. 2018. Ensuring efficient incentive and disincentive values for highway construction projects: a systematic approach balancing road user, agency and contractor acceleration costs and savings, *Sustainability* 10(3): 701. https://doi.org/10.3390/su10030701

Lee, E.-B.; Harvey, J. T.; Thomas, D. 2005a. Integrated design/construction/operations analysis for fast-track urban freeway reconstruction, *Journal of Construction Engineering and Management* 131(12): 1283–1291. https://doi.org/10.1061/(asce)0733-9364(2005)131:12(1283)

Lee, E.-B.; Ibbs, C. W.; Thomas, D. 2005b. Minimizing total cost for urban freeway reconstruction with integrated construction/traffic analysis, *Journal of Infrastructure Systems* 11(4): 250–257. https://doi.org/10.1061/(asce)1076-0342(2005)11:4(250)

Lee, E.-B.; Thomas, D.; Bloomberg, L. 2005c. Planning urban highway reconstruction with traffic demand affected by construction schedule, *Journal of Transportation Engineering* 131(10): 752–761.
https://doi.org/10.1061/(asce)0733-947x(2005)131:10(752)

Lee E.-B.; Ibbs, C. W. 2005. Computer simulation model: construction analysis for pavement rehabilitation strategies, *Journal of Construction Engineering and Management* 13(4): 449–458.
https://doi.org/10.1061/(asce)0733-9364(2005)131:4(449)

Lee, E. B.; Ibbs, C. W.; Harvey, J. T.; Roesler, J. R. 2000. *Constructability and Productivity Analysis for Long Life Concrete Pavement Rehabilitation Strategies*. Report No FHWA/CA/OR-2000/01. California Department of Transportation (Caltrans), CA, US. 94 p. Available from Internet: http://www.ucprc.ucdavis.edu/PDF/Constructability%20Analysis.pdf

Lee, E.-B.; Kim, C.; Ghafari, N.; Brink, G. 2011a. Value analysis using performance attributes matrix for highway rehabilitation projects: California interstate 80 Sacramento case, *Transportation Research Record: Journal of the Transportation Research Board* 2228: 34–43. https://doi.org/10.3141/2228-05

Lee, E.-B.; Kim, C.; Harvey, J. T. 2011b. Selection of pavement for highway rehabilitation based on life-cycle cost analysis: validation of California interstate 710 project, phase 1, *Transportation Research Record: Journal of the Transportation Research Board* 2227: 23–32. https://doi.org/10.3141/2227-03

Lee, E.-B.; Sivaneswaran, N. 2007. CA4PRS: a constructability analysis tool for urban highway rehabilitation projects, in J. A. Gambatese, J. B. Pocock, P. S. Dunston (Eds.). *Constructability Concepts and Practice*, 102–116.
https://doi.org/10.1061/9780784408957.ch07

Lee, E.-B.; Thomas, D. K.; Alleman, D. 2018. Incorporating road user costs into integrated life-cycle cost analyses for infrastructure sustainability: a case study on Sr-91 corridor improvement project (Ca), *Sustainability* 10(1): 179.
https://doi.org/10.3390/su10010179

Li, J.; Luhr, D. R.; Uhlmeyer, J. S.; Mahoney, J. P. 2012. Preservation strategies for concrete pavement network of Washington State Department of Transportation, *Transportation Research Record: Journal of the Transportation Research Board* 2306: 11–20. https://doi.org/10.3141/2306-02

Orcutt, L. H.; AlKadri, M. J. 2009. Overcoming roadblocks to innovation: three case studies at the California Department of Transportation, *Transportation Research Record: Journal of the Transportation Research Board* 2109: 65–73.
https://doi.org/10.3141/2109-08

Pocock, J. B.; Kuennen, S. T.; Gambatese, J.; Rauschkolb, J. 2006. Constructability state of practice report, *Journal of Construction Engineering and Management* 132(4): 373–383.
https://doi.org/10.1061/(asce)0733-9364(2006)132:4(373)

Pyeon, J.-H.; Lee, E. B.; Ellis, R. D.; Park, T. 2012. *Cost Estimate Modeling of Transportation Management Plans for Highway Projects*. MTI Report 11-24. Mineta Transportation Institute (MTI), San Jose, CA, US. 68 p. Available from Internet: https://transweb.sjsu.edu/sites/default/files/1007-cost-estimate-modeling-transportation-management-highway-projects.pdf

Raviv, G.; Shapira, A.; Sacks, R. 2012. Relationships between methods for constructability analysis during design and constructability failures in projects, in *Construction Research Congress 2012: Construction Challenges in a Flat World*, 21–23 May 2012, West Lafayette, Indiana, US, 515–524.
https://doi.org/10.1061/9780784412329.052

RCTC. 2019. *State Route 91 Corridor Improvement Project*. Riverside County Transportation Commission (RCTC), CA, US. Available from Internet:
https://www.rctc.org/projects/sr91-project

Saghatforoush, E.; Trigunarsyah, B.; Too, E.; Heravitorbati, A. 2011. Effectiveness of constructability concept in the provision of infrastructure assets, in *Proceedings of The First International Postgraduate Conference on Engineering, Designing and Developing the Built Environment for Sustainable Wellbeing*, 7–10 February 2011, Brisbane, Australia, 175–180.

Stamatiadis, N.; Goodrum, P.; Shocklee, E.; Wang, C. 2013. Quantitative analysis of state transportation agency's experience with constructability reviews, *Journal of Construction Engineering and Management* 140(2): 04013041.
https://doi.org/10.1061/(asce)co.1943-7862.0000787

Stewart, R. B.; Brink, G.; Watson, M.; Hiller, A.; Brink, M.; Daim, T.; Khalifa, R. 2017. *Applying Risk Analysis, Value Engineering, and Other Innovative Solutions for Project Delivery*. National Cooperative Highway Research Program (NCHRP) Research Report 850. Transportation Research Board, Washington, DC, US. 97 p. https://doi.org/10.17226/24851

Trevino, T. 2017. *91 Project Fast Forward: Construction Progress Report as of February 28, 2017*. Riverside County Transportation Commission, CA, US. 31 p.

Trevino, T. 2014. *91 Project Fast Forward: Construction Progress Report as of December 31, 2013*. Riverside County Transportation Commission, CA, US. 15 p.

APPENDIX

Examples of CPM schedule comparisons for alternatives on SR-91 CIP

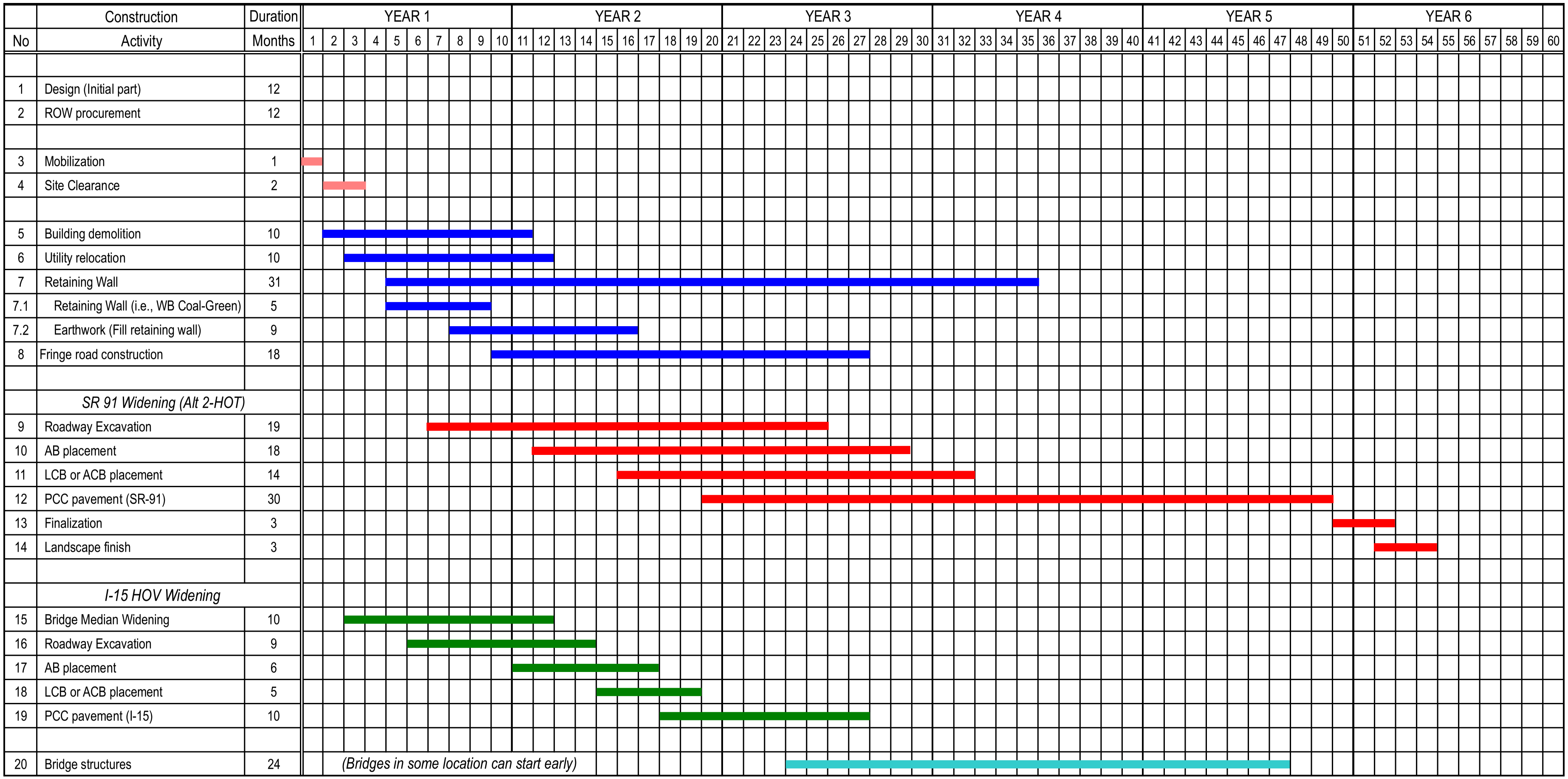

Figure A. CA4PRS CPM baseline schedule

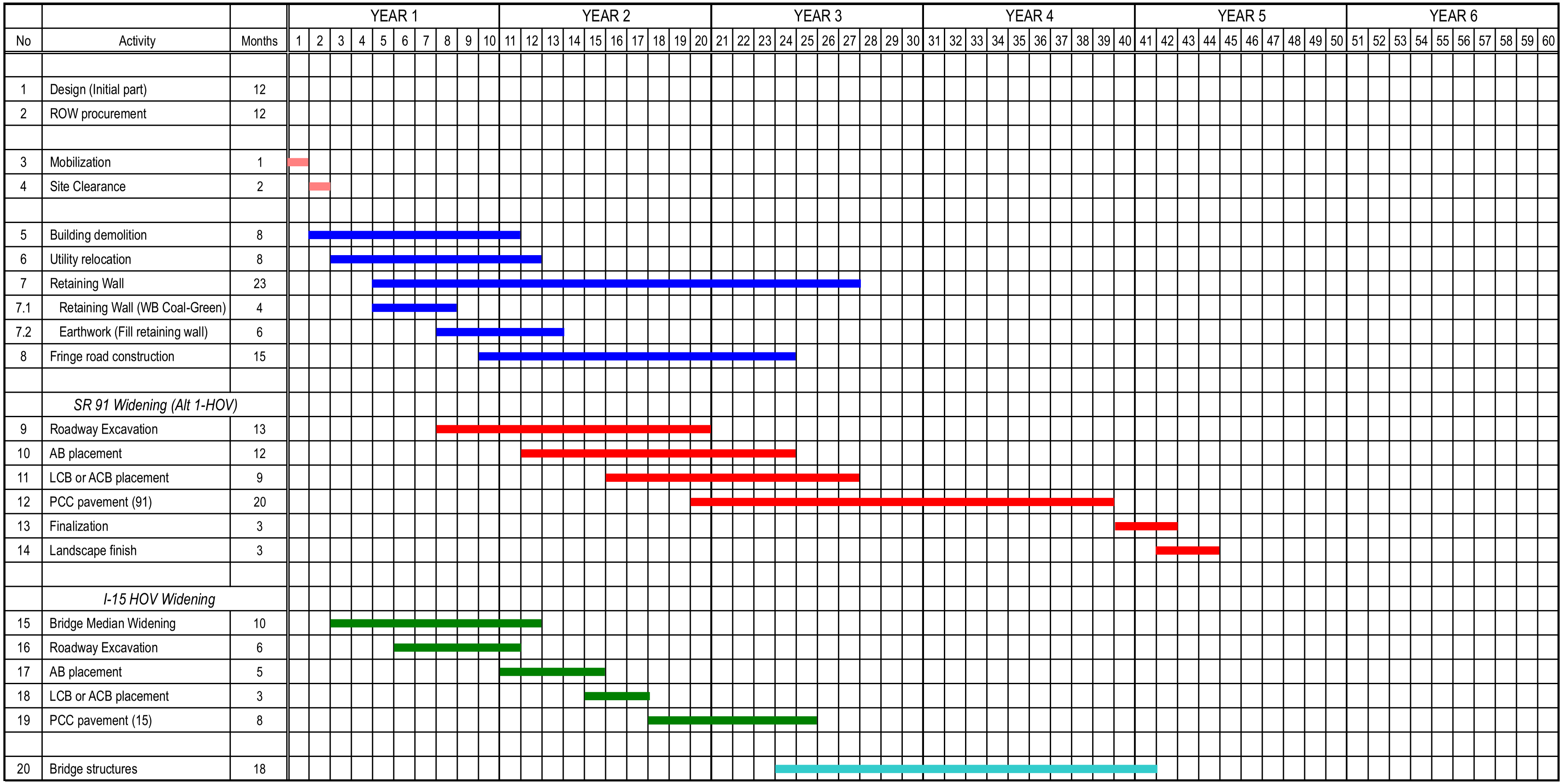

Figure B. CA4PRS CPM schedule for Alternative B

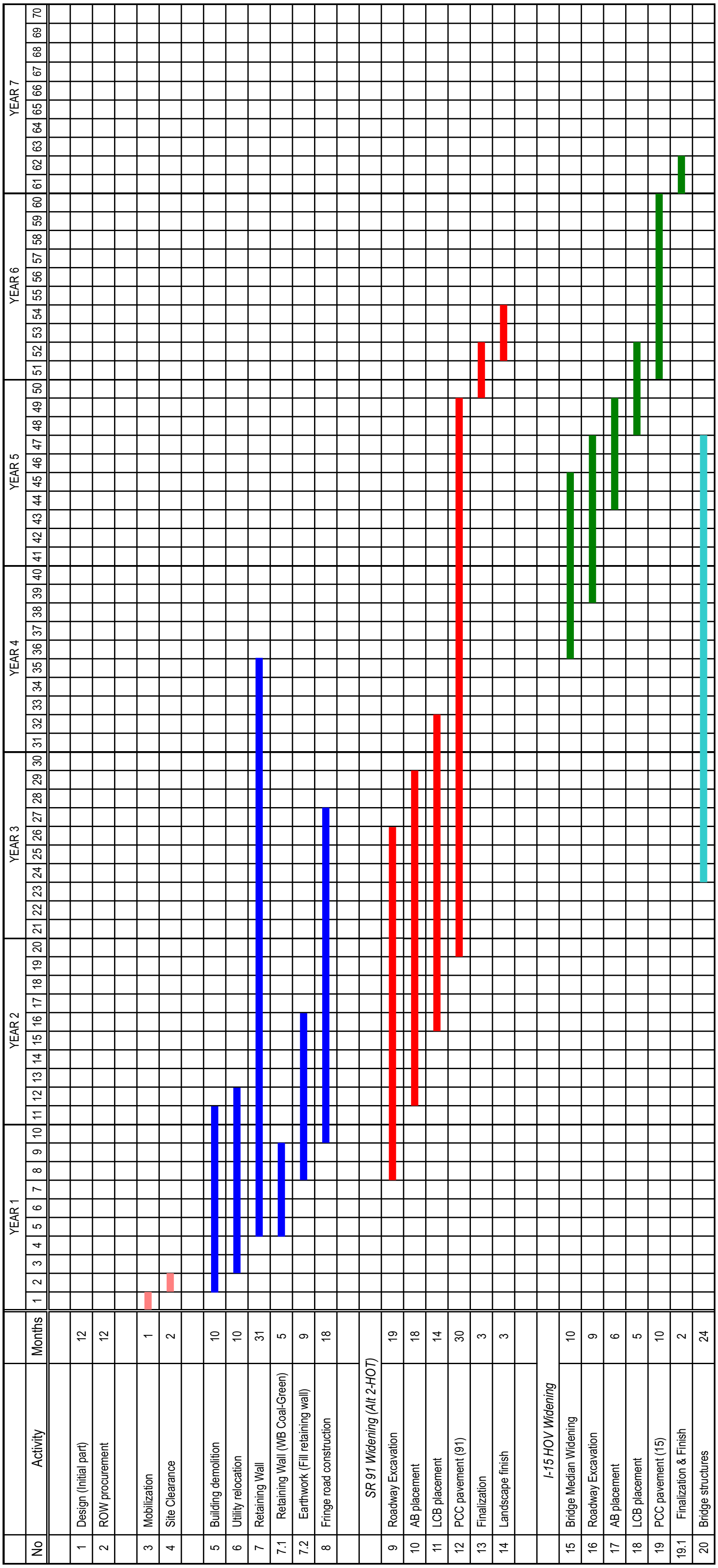

Figure C. CA4PRS CPM schedule for SR-91/I-15 sequential widening construction

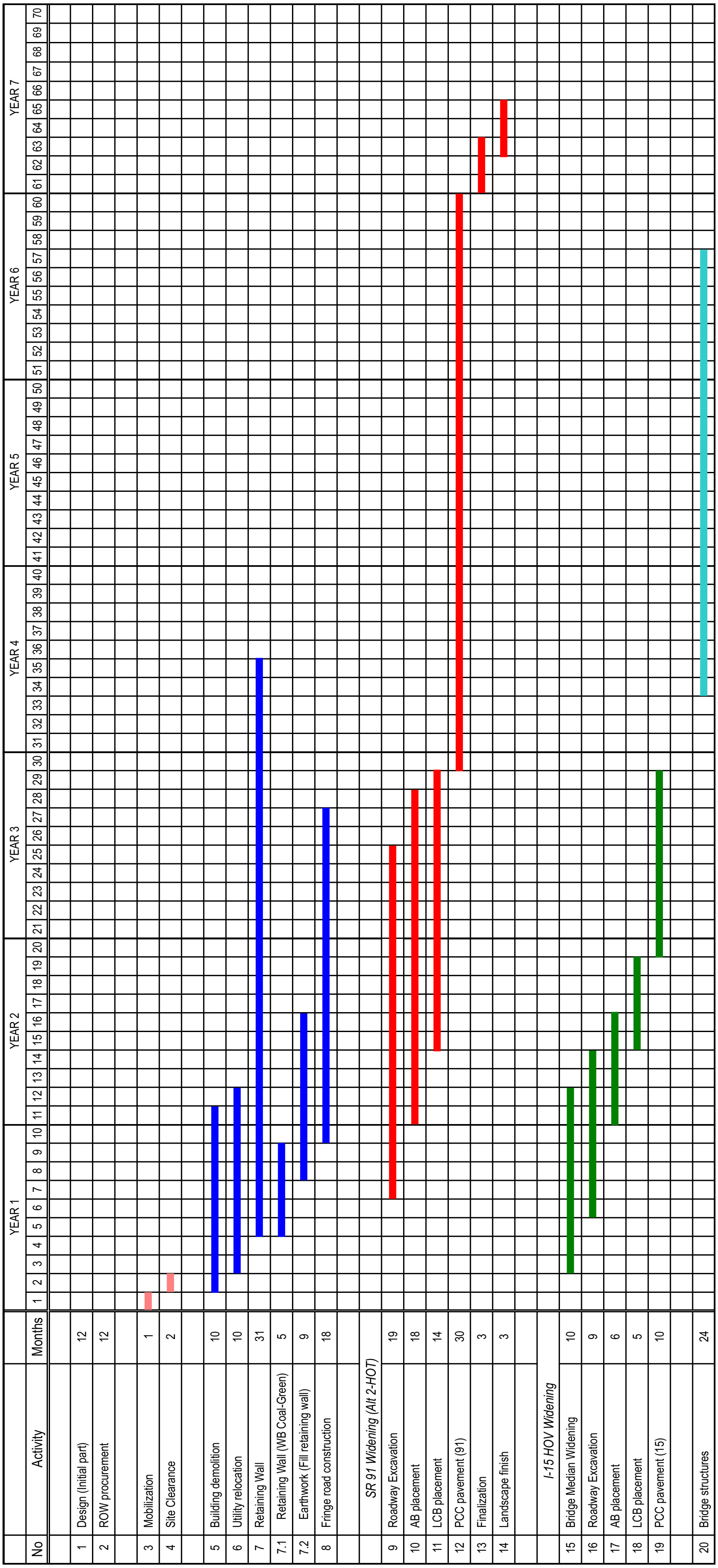

Figure D. CA4PRS CPM schedule for sequential LCB/PCC paving construction

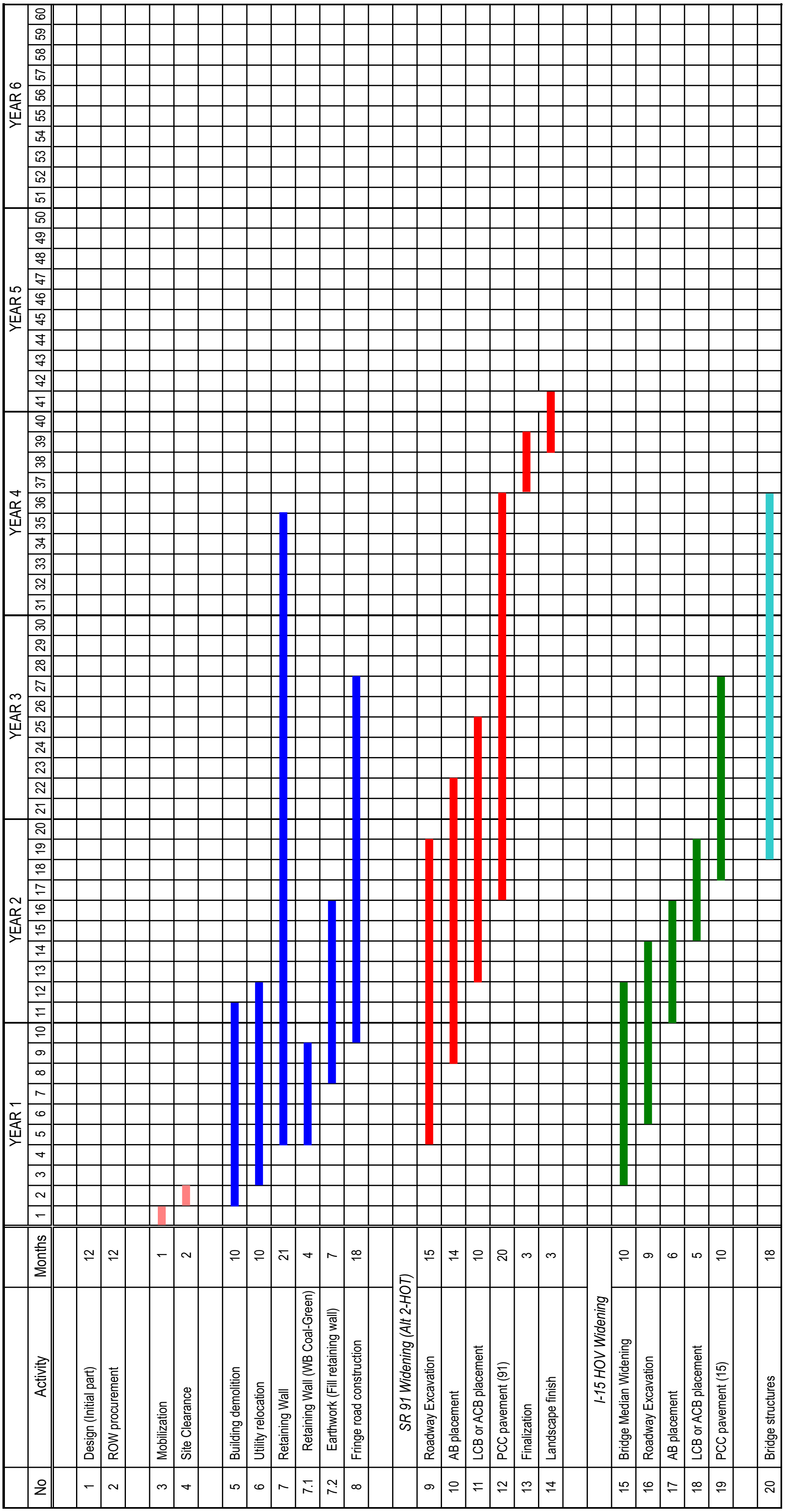

Figure E. CA4PRS CPM schedule for multi-crew accelerated constructio