



Mapping and Improving the Delivery Process of Highway Pavement Rehabilitation Projects

Final Report

Iris Tommelein, UC Berkeley

Sponsored by



2017

MAPPING AND IMPROVING THE DELIVERY PROCESS OF HIGHWAY PAVEMENT REHABILITATION PROJECTS

Iris D. Tommelein and Nigel Blampied

January 29, 2018



ABOUT THE UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES (ITS)

The University of California Institute of Transportation Studies (ITS) is a network of faculty, research- and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

ABOUT THE PROJECT PRODUCTION SYSTEMS LABORATORY (P2SL) AT UC BERKELEY

The Project Production Systems Laboratory (P2SL) at UC Berkeley is a research institute dedicated to developing and deploying knowledge and tools for project management. The Laboratory is housed under the umbrella of the Center for Information Technology Research in the Interest of Society (CITRIS).

Projects are temporary production systems. P2SL is dedicated to developing and deploying knowledge and tools for the management of project production systems and the management of organizations that produce and deliver goods and services through such systems. Project production systems include for example construction, product development, software engineering, air and sea ship building, work order systems, job shops, performing arts productions, oil field development, and health care delivery.

Companies worldwide, and especially those involved in the Northern California construction industry, are invited to team up with P2SL staff and students, and use our resources to advance the theory as well as the implementation of the lean construction philosophy, principles, and methods in the industry, its companies, and its projects. Our goal is to advance and deepen understanding of how to deliver lean projects. All members of the industry are invited to become contributors and to participate in the Laboratory: owners, regulators, architects, engineers, contractors, unions, suppliers, insurers, financiers, etc.

EXECUTIVE SUMMARY

Highway pavement rehabilitation (HPR) is a service provided by departments of transportation (DOTs) worldwide. The process of delivering HPR projects involves not only a transportation department but also many other project participants and stakeholders; furthermore, it is subject to numerous technical- as well as socio-political considerations. Interestingly—though not surprisingly—the processes DOTs use to deliver this service vary widely, not only between countries or between states in the US, but also regionally within a given state such as California. While some variation is to be expected, it is not necessarily of value to some or all concerned. Management practices such as Lean and Six Sigma can be key to driving out unwanted variation and thereby lead to performance improvements locally and overall.

Addressing “Goal 5 Operational Excellence” in Caltrans’ (2015a) Strategic Management Plan, this research set out to view HPR projects through the lenses of Lean and Six Sigma, in combination referred to as Lean Six Sigma. These management philosophies—herein broadly referred to by the broad term “Lean Thinking”—overlap in concepts and methods, but they all aim to promote continuous improvement and value delivery.

Caltrans started to launch Lean Six Sigma initiatives in 2015 (e.g., Dunning 2016, Tusup 2017) and its employees have to date already achieved significant process improvements in their day-to-day operations. However, it appears that Caltrans has not yet pursued such initiatives in the delivery of its projects. The literature overview provided in this report describes applications of Lean and Six Sigma in transportation departments in the US and abroad, and the cases referenced demonstrate the applicability of Lean and Six Sigma to project delivery. Lean applied to HPR project delivery and, more generally, applied to project-based production, in the literature gets referred to using the term “Lean Construction” (Koskela et al. 2002, Ballard et al. 2002).

The exploratory research with findings presented in this report, set out to investigate if and how a state DOT might standardize the delivery of HPR projects. The researchers investigated this by collecting data on three projects that Caltrans completed recently. Using this data and building on the Caltrans (2016) work breakdown structure, they were able to map the processes used to deliver two of them. The researchers then obtained further data and gauged the performance of these projects’ delivery processes. Comparison of the resulting process maps, and their combination into a single process map that may function as a draft “standard,” serve as the basis for formulating recommendations to Caltrans. The researchers recommend that Caltrans personnel with a Lean mindset review the maps provided and fine-tune them for further use in collaborative efforts within their organization (e.g., engaging multiple functional units within districts and engaging multiple districts) as well as with supply chain partners (e.g., contractors) while using Lean Thinking to identify and pursue opportunities for continuous improvement of its project delivery practices.

ACKNOWLEDGMENTS

The authors of this report owe many thanks to employees of Caltrans who have assisted us in this research project. We would like to single out James E. Davis and his staff in the Division of Project Management; James Appleton and his staff in the Division of Research, Innovation, and System Information including our task manager, Lee Provost; Janice Benton and her staff in the Division of Design; Tom Pyle and Bill Fahrnbach from the Division of Maintenance; Clark Peri and the Project Development Team (PDT) on project 03-3F670; Jeannie Wiley and the PDT on project 06-0Q240; and Mike Varipapa and the PDT on project 12-0H034.

We also owe thanks to Derek Drysdale and Andrew Wingrove from Highways England for their sharing of lessons learned along their Lean journey and providing the process map included in Appendix III of this report. Likewise, we owe thanks to Professor John Harvey at UC Davis for sharing his experience with mapping Caltrans processes and providing the process map included in Appendix IV.

This research was funded by UCConnect under Contractor Agreement 65A0529, Task Order Number 2007. We gratefully acknowledge this support. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of anyone interviewed for this study nor of their employer.

TABLE OF CONTENTS

| | |
|---|-----|
| Executive Summary | i |
| Acknowledgments..... | ii |
| Table of Contents..... | iii |
| List of Figures..... | iv |
| List of Tables | iv |
| 1. Introduction..... | 1 |
| 2. Aim and Rationale for Studying Caltrans’ Highway Pavement Rehabilitation | 4 |
| 3. Research Questions and Methodology..... | 4 |
| 4. “Lean” in Transportation Projects | 5 |
| 4.1. Lean Thinking and the Toyota Production System (TPS) | 6 |
| 4.2. Six Sigma and Lean Six Sigma | 7 |
| 4.3. Lean in the Public Sector and in Lean in Public Sector Construction (LIPS) | 9 |
| 4.4. Lean in DOTs and the Transportation Lean Forum | 11 |
| 4.5. Highways England | 12 |
| 4.5.1. Lean Practices | 13 |
| 4.5.2. Commercial Terms and Contracting Approaches..... | 13 |
| 4.5.3. Specifications for Lane Closures | 14 |
| 5. Caltrans HPR Projects..... | 16 |
| 5.1. Caltrans Organization for Delivery of HPR Projects..... | 16 |
| 5.2. HPR Projects Selected for Research | 17 |
| 5.2.1. Project 03-3F670 on State Route 49 in El Dorado County..... | 17 |
| 5.2.2. Project 06-0Q240 on State Route 41 in Fresno County..... | 21 |
| 5.2.3. Project 12-0H034 on State Route 73 in Orange County..... | 23 |
| 5.2.4. Comparison of Project Data..... | 25 |
| 6. Process Maps of Selected Caltrans HPR Projects..... | 28 |
| 6.1. Overview of Projects Mapped..... | 28 |
| 6.2. Process Map for Project 03-3F670..... | 29 |
| 6.3. Process Map for Project 06-0Q240 | 31 |
| 6.4. Process Map from Prior Caltrans Research..... | 34 |
| 7. Case Comparison, Recommendations, and Conclusions | 36 |
| Appendix I: Abbreviations and Acronyms | 39 |
| Appendix II: References | 40 |
| Appendix III: Process Map from Highways England..... | 43 |
| Appendix IV: Process Map of Caltrans Project Tracking and Documentation (HA-22) | 44 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1: Upper and Lower Specification Limits at Six Sigma (Source: Lean Manufacturing and Six Sigma Definitions (2017)) | 8 |
| Figure 2: State of California’s Eureka Institute’s Lean Leadership Academy, Lean Principles, and California Open Data Portal (Source: Eureka Institute (2017))..... | 10 |
| Figure 3: Work Breakdown Structure Diagram (Source: Figure on p. 7 in Caltrans 2016)..... | 16 |
| Figure 4: Overview of Phases K, 0, and 1 (Part 1), Level 5 WBS Elements, and Milestones - Note: This chart is intended as an overall pictorial of the WBS and not to be used as a logic diagram (Source: Figure on p. 13 in Caltrans 2016)..... | 18 |
| Figure 5: Overview of Phases 1 (Part 2), 2, and 3, Level 5 WBS Elements, and Milestones - Note: This chart is intended as an overall pictorial of the WBS and not to be used as a logic diagram (Source: Figure on p. 14 in Caltrans 2016)..... | 19 |
| Figure 6: Title Sheet of Project 03-3F670 on State Route 49 in El Dorado County (Source: Caltrans)..... | 20 |
| Figure 7: Title Sheet of Project 06-0Q240 on State Route 41 in Fresno County (Source: Caltrans)..... | 22 |
| Figure 8: Title Sheet of Project 12-0H034 on State Route 73 in Orange County (Source: Caltrans)..... | 24 |
| Figure 9: Process Map of Project 03-3F670 | 30 |
| Figure 10: Monthly Hours Billed by Phase on Project 03-3F670 (Source: Data provided by Caltrans)..... | 31 |
| Figure 11: Process Map of Project 06-0Q240..... | 32 |
| Figure 12: Monthly Hours Billed by Phase on Project 06-0Q240 (Source: Data provided by Caltrans)..... | 33 |
| Figure 13: Synthesis Process Map for Caltrans HPR Projects | 38 |
| Figure 14: Resurfacing Process Map created by Highways England and its Suppliers (Source: Highways England)..... | 43 |
| Figure 15: Process Map of Caltrans Project Tracking and Documentation (HA-22) (Source: Harvey et al. 2011)..... | 44 |

LIST OF TABLES

| | |
|---|----|
| Table 1: Attributes of Caltrans vs. Highways England..... | 12 |
| Table 2: Summary of Project Attribute Data (Part 1 of 2)..... | 26 |
| Table 3: Summary of Project Attribute Data (Part 2 of 2)..... | 27 |
| Table 4: Meetings of Researchers with Caltrans Personnel..... | 28 |

1. INTRODUCTION

Highway pavement rehabilitation (HPR) is a service provided by departments of transportation (DOTs) worldwide. The process of delivering HPR projects involves not only a transportation department but also many other project participants and stakeholders; furthermore, it is subject to numerous technical- as well as socio-political considerations. Interestingly—though not surprisingly—the processes DOTs use to deliver this service vary widely, not only between countries or between states in the US, but also regionally within a given state such as California. While some variation is to be expected, not all such variation is necessarily of value to any or all concerned. By distinguishing good- from bad variation, employees may focus their attention on driving out all bad variation in order to reach a level standardization in the delivery process as a means to gauge and improve their performance. Management practices such as Lean and Six Sigma can be key to driving out unwanted variation.

Individual DOTs may have an in-house standard process to deliver their HPR projects but in practice, one would expect the use of such a standard process to vary regionally across their state. To some degree, processes must be customized to suit the characteristics of the projects being delivered as well as the surrounding environment and context, that is, no “one-size-fits-all” process is likely to exist. Process customization may be deemed necessary in order to deliver customer value. Nevertheless, not all customization is 100% beneficial. Customization comes at a cost. It may result in processes being so unique that they create new complexity in-and-of their own. In addition, customized processes are more difficult to compare with other processes than standard processes are. Their uniqueness impedes assessment, learning, and thus prevents continuous improvement.

Addressing “Goal 5 Operational Excellence” in Caltrans’ (2015a) Strategic Management Plan, this research set out to view HPR projects through the lenses of Lean and Six Sigma, in combination referred to as Lean Six Sigma. These management philosophies—herein broadly referred to by the term “Lean Thinking”—overlap in concepts and methods, but they all aim to promote continuous improvement and value delivery.

Caltrans launched Lean Six Sigma initiatives in 2015 (e.g., Dunning 2016, Tusup 2017) and its employees already have achieved significant process improvements in their day-to-day operations. However, it appears that Caltrans has not yet pursued such initiatives in the delivery of its projects. The literature overview provided in this report describes applications of Lean and Six Sigma in transportation departments in the US and abroad and the cases referenced demonstrate the applicability of Lean and Six Sigma to project delivery. Lean applied to HPR project delivery and,

more generally, applied to project-based production, falls under the umbrella term “Lean Construction” (Koskela et al. 2002, Ballard et al. 2002).

The premise of the exploratory research described in this report is that, by striking a balance between standardization on the one hand and customization on the other, HPR projects can be delivered in a more globally satisfactory manner than is otherwise the case. A starting point for finding this balance is to map the current state of practice of the delivery of a select number of HPR projects and then analyzing the maps with “Lean”¹ and “Six Sigma” mindset to identify opportunities for improvement.

Lean and Six Sigma strive for standardization because it:

- Results in predictability in project performance and outcomes,
- Guides the development of education and training in-house as well as on-boarding of project participants,
- Helps those involved in the process understand what they provide to other people (in the organization or project) vs. what need from others; that is: “Who are their customers?” and “Whose customers are they themselves?”,
- Enables the establishment of process metrics and product metrics to inform data collection needs, resulting in data that can support “management by means” (Johnson and Broms 2000) (as opposed to “management by results”),
- Makes it easy for anyone involved in the project to identify deviations from the standard, thereby allowing people to take timely corrective action,
- Makes it possible to assess whether or not changes in the standard can be realized so as to result in better performance, thereby offering an opportunity to raise the standard, and do so repeatedly. This feeds the continuous improvement cycle, which is never ending: one can always do better!

The exploratory research, with findings presented in this report, set out to investigate if and how a state DOT might standardize the delivery of HPR projects. The researchers investigated this by describing three projects that Caltrans completed recently, using the Caltrans (2016) work breakdown structure to map the processes used to deliver them, obtaining further data and then gauging the performance of their delivery process. Comparison of the resulting process maps, and their combination into a single one that may function as a draft “standard,” serves as the basis for

¹ The first author has been involved in Lean Construction research and application since about 1996 (Tommelein 2016). As to whether any improvement practice should be called Lean, Six Sigma, Lean Six Sigma, or the like, she is agnostic. What matters is that people become aware of the theory, grasp the underlying principles, and apply the methods using Lean Thinking suitable to their given organizational context.

recommending how Caltrans could pursue continuous improvement of its current practices and apply Lean Thinking to the projects it delivers.

As DOT budgets are becoming increasingly inadequate to meet infrastructure needs², ways must be found to deliver more value-for-money. The adoption of Lean inspires new thinking while offering theoretical guidance and practical means to achieve this.

Bigger questions, that research following-on to this exploratory research may address, are:

1. Can a DOT such as Caltrans establish a standard process for the delivery of HPR projects? What would it look like? What would the value thereof be? E.g., might better management data and practices result from more standard delivery processes, and definition of process as well as outcome metrics, as to enable learning from one project to the next in the DOT portfolio to drive continuous improvement?
2. Provided a standard process can be articulated in a given context such as Caltrans', when and to what degree does it make sense to enforce it vs. deviate from it?

Section 2 of this report describes in more detail the aim and rationale for studying Caltrans' HPR projects. Section 3 presents the research questions and methodology. Section 4 offers a summary of the literature that supported the Lean Thinking that drives this research. It also offers pointers to the use of Lean in public sector organizations, in transportation agencies, and in project delivery (more generally referred to as Lean Construction). Section 5 gives an overview of the Caltrans organization and its delivery of HPR projects. It also details the HPR projects selected for this study. Section 6 presents, for two of the HPR projects studied, the process maps developed by the researchers in collaboration with Caltrans personnel. In addition, it offers some detail on another process map that pertains to Caltrans (the map is shown in Appendix IV). Section 7 presents the maps combined into one that may serve as a draft "standard" process map for the delivery of HPR projects. It offers recommendations and concludes this report.

Appendix I lists abbreviations and acronyms. Appendix II lists the references cited in this report. Finally, two appendices illustrate the use of process mapping in other transportation contexts. Appendix III shows a process map created by Highways England to identify improvement opportunities in their construction contractors' work flows (Wingrove 2015). Appendix IV shows

² Caltrans (2013) states: "In the last four years, Caltrans delivered about \$3.9 billion in pavement projects on almost 18,000 lane miles. However, these funds may not be available in the future and Caltrans will need to leverage dollars to do more with less. The "2013 Ten-Year Plan" anticipates pavement needs to be \$2.8 billion per year over the next decade, although only \$685 million per year is available, i.e., only twenty-three cents of every dollar. Consequently, distressed lane miles could increase from 16 percent today to 34 percent in the next 10 years." Targeting these challenges, the legislature of the State of California (2017) passed SB1 that includes augmented funding for pavement rehabilitation as well as performance measures tied to pavement conditions.

a process map that Prof. Harvey developed jointly with colleagues and staff at Caltrans to study Caltrans' transition to a new process for conducting pavement condition surveys (Harvey et al. 2011, Harvey 2016).

2. AIM AND RATIONALE FOR STUDYING CALTRANS' HIGHWAY PAVEMENT REHABILITATION

The aim of the research was to investigate jointly with personnel in Caltrans Headquarters and selected Caltrans Districts the potential use of Lean Six Sigma methods (specifically process mapping) (e.g., Rother and Shook 2003, Damelio 2011, Martin and Osterling 2013) and the extent to which:

1. Caltrans Headquarters' current HPR process description suits current practices or might need updating,
2. Districts are in effect implementing that process with or without making adaptations to the official process to better suit the project contexts they face, and
3. Caltrans staff may be inspired by learning from their own projects with a mindset of continuous improvement and by being informed about practices in use at highways agencies elsewhere, so they can envision a different standard process adaptable to suit local needs.

The rationale for selecting to study Caltrans' delivery process of HPR projects delivered is:

1. The HPR delivery process pertains to projects that are "simple," relatively speaking; that is, they are normally less complex than improvement (STIP) projects.
2. HPR projects are categorically excluded under the National Environmental Policy Act (NEPA); that is, they do not require environmental permitting, which is a common cause for project delay.
3. They generally do not require new right-of-way or utility relocations.
4. They tend to not be controversial (e.g., as compared to new projects).
5. Last, but not least, pavement rehabilitation is an essential service provided by Caltrans.

Given the many HPR projects in the Caltrans portfolio pipeline, the study of the processes used for delivering a selected number of them will allow for rapid feedback and learning cycles.

3. RESEARCH QUESTIONS AND METHODOLOGY

Research questions explored by the researchers jointly with Caltrans personnel included:

1. What standards does Caltrans currently have that describe the process of delivering its highway pavement rehabilitation projects? What function(s) do these standard processes serve? What services are delivered using them?

2. To what extent are standard processes being deployed by Districts statewide? What are the deviations from the standard and why do they occur?
3. How is performance measured according to the standard? What level of performance is achieved?
4. What opportunities may exist to improve the standards (e.g., removal of wasteful steps and enhancement of value-adding steps in the process)?
5. Can practices and standards that have been developed elsewhere (in other states and countries) inform and inspire improvements of the Caltrans standards?

The research methodology included:

1. Conducting a literature review and with colleagues discussing opportunities for continuous improvement in the transportation sector, specifically from the perspective of Lean, Six Sigma, and Lean Six Sigma, as well as on the application of Lean Thinking. The aim was to highlight uses of Lean in the delivery of projects (as opposed to uses of Lean in organizations at large).
2. Meeting key Caltrans Headquarters personnel involved in training and implementation of Lean Six Sigma at Caltrans agency-wide.
3. Meeting with Caltrans Headquarters personnel to identify specific, completed HPR projects to map for this study. By design, the research and development of process maps of selected projects was conducted, not in an isolated academic setting by the researchers alone, but jointly with Caltrans personnel.
4. Organizing and engaging in face-to-face meetings with Caltrans personnel, in workshop-like settings, to articulate current practices in the delivery of HPR projects. This involved the researchers meeting with Caltrans personnel to map and document the current state processes “on the books” and “in use” at Caltrans for the delivery of HPR projects, following up for clarification and supplementary data collection, and then identifying means for continuous improvement.
5. Analyzing the project data and cross-functional process diagrams of Headquarters and selected District processes to deliver HPR projects, gauging process implementation success using objective metrics as well as subjective evaluations provided by research participants, and identifying improvement opportunities or topics for further in-depth study.
6. Documenting research findings and recommendations.

4. “LEAN” IN TRANSPORTATION PROJECTS

Before looking at applications of Lean mapping of HPR projects, an overview is in order of the concept called Lean that was coined to characterize the Toyota Production System (TPS). More than 70 years ago, Toyota began to develop Lean principles and methods. The company continues to this date to apply and refine them, while striving to improve continuously their production

processes for new product development and manufacturing of automobiles. Since the 1980s, Lean principles and methods became more widely known. They have since spread globally and been used successfully in many domains other than large-scale manufacturing. The transportation sector is no exception.

4.1. Lean Thinking and the Toyota Production System (TPS)

Lean production is a term coined by John Krafcik who served on the MIT-Harvard team in the 1980s that studied Japanese practices in automobile manufacturing (Womack et al. 1989). The term singled out the type of production implemented by Toyota, which the team identified as being radically different from the then-prevailing practices of either mass production or craft production. The Lean Enterprise Institute (LEI 2016) defines the term Lean as “Creating more value for customers with fewer resources.”

In the years leading up to Womack et al.’s study, US automobile manufacturers had been shaken up by the oil crises of the 1970s and were losing business. They came to recognize that their thinking and practices in new product development and manufacturing were not keeping up in meeting customer demand as successfully as Japanese automobile manufacturers were. Growing rapidly after WWII, Japanese companies and in particular Toyota had become increasingly competitive in the global automobile marketplace and were gaining significant market share in the US and elsewhere.

Many studies have since been conducted on what Toyota’s underlying philosophy is for designing and making automobiles, referred to as Lean Thinking or simply the TPS (Ohno 1988). In 2001, Toyota released the document “The Toyota Way” to share their Lean Thinking for everyone in the world to gain deeper understanding and adopt it, as they pursued their globalization strategy. Liker’s (2004) book translated this work in English and articulated Toyota’s framework with its 14 management principles, thereby making this Lean Thinking broadly accessible. Fundamentally rooted in (1) respect for people and (2) continuous improvement, Toyota’s 14 principles are (e.g., Liker and Meier 2005):

1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.
2. Create a continuous process flow to bring problems to the surface.
3. Use ‘pull’ systems to avoid overproduction.
4. Level out the workload (work like the tortoise, not the hare).
5. Build a culture of stopping to fix problems, to get quality right the first time.
6. Standardized tasks and processes are the foundation for continuous improvement and employee empowerment.

7. Use visual controls so no problems are hidden.
8. Use only reliable, thoroughly tested technology that serves your people and process.
9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
10. Develop exceptional people and teams who follow your company's philosophy.
11. Respect your extended network of partners and suppliers by challenging them and helping them improve.
12. Go and see for yourself to thoroughly understand the situation.
13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.
14. Become a learning organization through relentless reflection and continuous improvement.

A strength of the TPS is its conceptual clarity on principles and the associated “systems thinking” it promotes. In addition, supporting the principles are numerous tools and methods, to be applied judiciously in any given system's context and, when used in combination, leveraging one-another.

Many practitioners have since applied Lean Thinking to a variety of domains other than automobile manufacturing, such as healthcare delivery (e.g., Alarcon et al. 2011), postal services, new product development, software development, as well as transportation system design and construction.

4.2. Six Sigma and Lean Six Sigma

Six Sigma is a term that stems from the practice of statistical quality control (SPC). It refers to a means to gauge so-called process capability, that is, the ability to reliably perform a process or produce a product or service that consistently achieves a certain standard of quality. Six Sigma was introduced as a business practice by engineers Bill Smith and Mikel Harry while working at Motorola in 1986 and then embraced and promoted by Jack Welch as the business strategy for General Electric in 1995 (Wikipedia 2017).

Figure 1 illustrates the Six Sigma concept. Lean Manufacturing and Six Sigma Definitions (2017) explains: “Sigma represents the population standard deviation, which is a measure of the variation in a data set collected about the process. If a defect is defined by specification limits separating good- from bad outcomes of a process, then a six sigma process has a process mean (average) that is six standard deviations from the nearest specification limit. This provides enough buffer between the process natural variation and the specification limits.”

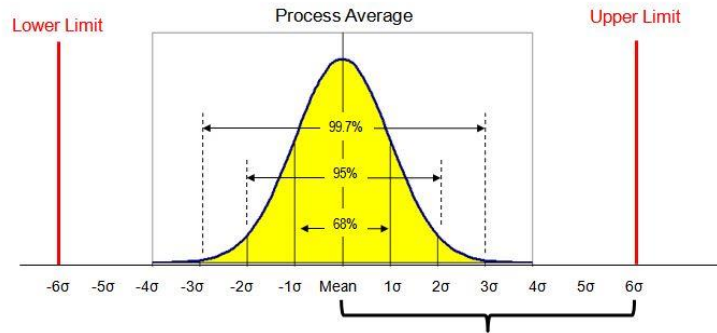


Figure 1: Upper and Lower Specification Limits at Six Sigma (Source: Lean Manufacturing and Six Sigma Definitions (2017))

Today’s literature on the schools of thoughts labeled Lean, Six Sigma, and Lean Six Sigma shows that many of their concepts and practices overlap. As Baudin (2001) cogently explains, these are not competing- but rather complementary schools of thought, all aimed at establishing quality processes to deliver quality products or services to customers. Quality must be pursued in different steps. The first step is to establish so-called “process capability.” In the case of repeatable processes, this may be done by applying Six Sigma, identifying recurring defects, and remediating them. Once process capability has been established, however, people involved in the process may still make occasional errors. Ideally of course, systems must be designed so that people cannot make errors but given that errors *will* occur the subsequent steps are therefore to make it quick and easy to detect them so that remedial action can be taken and errors will not become defects. This may be done by applying Lean methods such as one-piece flow and mistakeproofing (e.g., Shingo 1986).

Lean methods help to identify opportunities for improvement that may be identifiable well before a statistically significant number of observations can be made, i.e., well before data is available to apply Six Sigma. The applicability of Lean methods to events that occur only once or occasionally is particularly important especially in project settings. Project activities get performed once, or possibly repeated a few times, but then finish and get followed by successor activities well before statistics can be used.

Given this blending of Lean Thinking with Six Sigma, and reference to Lean Six Sigma at Caltrans, we will use Lean as the overarching term in this report to refer to related concepts, principles, and methods. The selection of specific methods to achieve process improvement at Caltrans (and elsewhere) will vary with the context in which they are applied.

4.3. Lean in the Public Sector and in Lean in Public Sector Construction (LIPS)

The application of Lean principles and methods is relatively new to government organizations. However, interest in Lean in the public sector has been growing, judging by the number of publications in this area that are “how to” guides (e.g., EPA 2008, 2017a, 2017b, Jacobs 2013), pilot studies (e.g., Feng et al. 2008), and articles in popular management magazines (e.g., Chieppo 2014, Wogan 2014).

A number of Lean government hubs have been established in recent years across the US. Among the first ones was the State of Washington’s (2013) “Results Washington.” Under the leadership of Governor Brown, the State of California forged ahead with its Lean initiatives. In 2014, the Governor’s Office of Business and Economic Development (GO-Biz) started to “offer a Lean Six Sigma implementation program to state departments that address process-based issues that are causing delays in services to both internal and external stakeholders.” (<http://www.business.ca.gov/Programs/Permit-Assistance/Lean-Six-Sigma-Program>) and other departments have done so likewise (e.g., the California Department of Human Resources at <http://www.calhr.ca.gov/Training/Pages/lean.aspx>).

To pool efforts, the Government Operations Agency has organized its performance improvement initiatives under the statewide center called the Eureka Institute (Figure 2). The Institute’s goal “is to institutionalize tools and training that can drive GovOps’ mission to modernize the processes of government through lean, data, leadership, and performance improvement” (<https://www.govops.ca.gov/eureka-institute/>). The Institute “supports and integrates innovation and drives continuous improvement throughout state government. It embodies the spirit of discovery that leads to improvement and innovation” (<https://www.govops.ca.gov/eureka/>).

Under the Institute’s umbrella, the California Lean Academy “hosts training and development opportunities for staff to improve processes to better serve their customers.” It “offers Lean process improvement training at different levels of depth, starting with the one-day White Belt training and extending to the six-month project-based Lean Six Sigma training, which the state offers through contracted experts. The Lean Academy’s White Belt training, which now has certified more than 6,000 state employees, is the foundation of the Eureka Institute’s performance improvement efforts, as it introduces employees to Lean methodologies and expands shared understanding of continuous improvement concepts.”

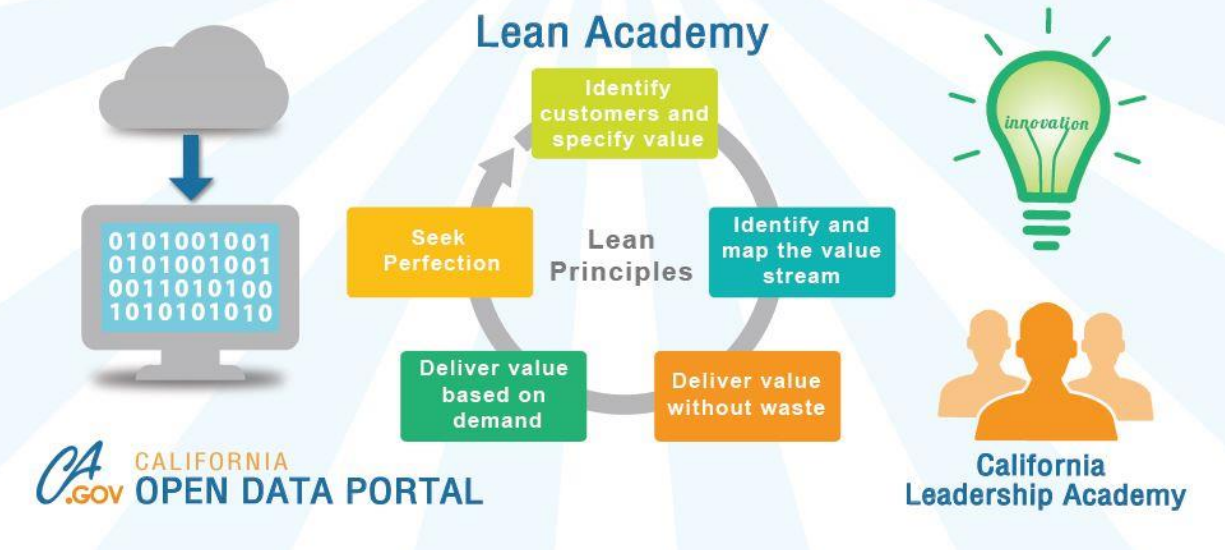


Figure 2: State of California’s Eureka Institute’s Lean Leadership Academy, Lean Principles, and California Open Data Portal (Source: Eureka Institute (2017))

While Lean Thinking originated in the private sector, its principles and methods can be made-to-suit the public sector as well. Bhatia and Drew (2006) noted: “Crucially for the public sector, a lean approach breaks with the prevailing view that there has to be a trade-off between the quality of public services and the cost of providing them... Although lean programs may cut the number of public-sector jobs, the goal is to make the remaining ones more rewarding” and “increasing operational effectiveness can free employees from one part of an organization to deliver new or better services in other areas, within existing budgets and without layoffs.” The goal of Lean, to do more with less, will resonate with mandates given to many public sector agencies to meet their agency’s constituents’ increasing needs and expectations, despite ever-reducing budgets.

Public sector practitioners who feel that “received traditions” and many rules and regulations hamper their potential use of Lean Thinking, stand to gain by participating in concerted efforts and sharing experiences on how to distinguish real- from perceived barriers. They may find that laws may be subject to broader interpretations than were given in past practice and can be changed. One such concerted effort is put forth by participants in the Lean in the Public Sector (LIPS) international forum “where practitioners share lessons learned during lean transformation in public

sector and non-profit organizations. Content that educates, informs, and inspires Lean Construction, Lean Government, Lean Service, and Lean Enterprise is a focus of the group” (<http://leaninpublicsector.berkeley.edu>).

4.4. Lean in DOTs and the Transportation Lean Forum

The idea of applying Lean in governmental transportation departments has been around for some time (e.g., Hanna et al. 2010). In the UK, Highways England became an early adopter in 2009 (O’Sullivan 2016). In the US, Lindquist et al. (2009) compiled the then-current popular writing in Lean management for the Washington DOT, though this synthesis was not specific to Lean in DOTs. Since then, significant strides forward have been made in the application of Lean Thinking in DOTs. Notably, the Multinational Transportation Lean Forum (TLF) was formed in 2012 to share lessons learned between DOTs; its secretariat is based at the Colorado Department of Transportation (CDOT) (TLF 2014). Employees from twenty-three State DOTs including Caltrans, four Canadian Provinces, England, and the Netherlands now participate in this Forum.

TLF participants may join a video conference every other month and share information, ideas, and experiences with Lean practices pursued by DOT employees in their respective organizations. DOT employees have engaged hands-on in pilot projects aimed at achieving improvements in every-day management, mainly home-office operations. Example studies performed by CDOT employees include streamlining the process to obtain environmental project clearance (Jepson 2012), creating a statewide master calendar to aid in schedule coordination (Bly and Edwards 2017), and developing processes for workflow tracking (Sanders 2017).

In addition, TLF participants have access to the Lean Interchange Network (n.d.) website that archives video conference recordings, presentations, and numerous other resources available to DOT personnel and anyone else. The archive includes the presentation by Dunning (2016), Lean Program Manager at Caltrans, reporting on the first 5 projects of Caltrans’ Lean Six Sigma Journey that started in 2015. The following year, at the Transportation Lean Forum teleconference, Tusup (2017), Chief of Innovative Business Solutions at Caltrans, reported on 18 projects at Caltrans, 6 of which specifically had an impact on State Highway projects:

1. Authorization for Methacrylate Resin Materials (14% were completed with 5 days, now 80% are completed within 5 days),
2. Construction Support Cost (was 22% of construction capital. Outcome TBD),
3. Unnecessary Real Estate Holds (54% were deemed unnecessary. Outcome TBD),
4. Building Projects Design Time (average time was 455 days, now 91 days),
5. Initial construction project set-up in accounting system (average time was 10 days, now 4 days), and

6. Asphalt Material Sample Testing (average turn-around time was 48 days, now 15 days).

It is clear that Lean Thinking applies to both everyday operations in DOTs as well as to the delivery of transportation projects that DOTs engage in with their service providers in their supply chains.

O’Sullivan (2016) outlined a vision for Highways England to further embrace Lean Thinking in their transportation organization. Caltrans and other DOTs in the US appear to be well on their way to also advance Lean Thinking in their organizations and the project delivery systems they are engaged in.

4.5. Highways England

In a separate project (Blampied 2018), the researchers examined the work of Highways England on their pavement rehabilitation projects, which are in a number of ways similar to Caltrans’ HPRs. Among the public highway agencies in the world, Highways England is the agency arguably most akin to Caltrans in the highway system that it manages. Both Caltrans and Highways England are responsible for the freeways (called “motorways” in England) and interregional conventional highways in their respective jurisdictions. Table 1 provides some comparative attributes.

Table 1: Attributes of Caltrans vs. Highways England

| Attribute | Caltrans | Highways England |
|---|--|---|
| Population served | 38,332,521 (2013 est.) | 53,012,456 (2011) |
| Land area | 163,696 square miles | 50,346 square miles |
| Highway miles managed | 15,133 miles | 4,300 miles |
| Percent of road miles | 8.60% | 2.30% |
| Percentage of total Vehicle Miles Traveled (VMT) on agency’s facility | 54% of vehicle miles traveled | 33% of motorway and “A” road traffic in England |
| VMT on system | 180 Billion | 130 Billion |
| Number of employees | Caltrans 19,543; Highway Patrol 11,051 | 3,512 (including 1,652 traffic officers) |

Caltrans and Highways England differ quite in their approaches to pavement rehabilitation. They also differ in their use of Lean practices, commercial terms and contracting approaches, and specifications for lane closures.

4.5.1. Lean Practices

As mentioned, Caltrans personnel has begun to engage in Lean Six Sigma initiatives. The processes addressed to date appear to have focused mainly on improving Caltrans' day-to-day operations.

In contrast, Highways England uses Lean Thinking in general (not only Six Sigma) (e.g., Jacobs 2013, O'Sullivan 2016, Aziz et al. 2017). It focused its early Lean initiatives on their project supply chain (e.g., construction processes performed by contractors and subcontractors) and later began to also look for in-house improvement opportunities.

To illustrate, Appendix III shows a Resurfacing Process Map (Figure 14) created by Highways England and its suppliers with activities spelled out in a separate swim lane for each project delivery participant. While construction contractors were not keen to share how they do their work, the map helped the project delivery team identify improvement opportunities in their work flows (Wingrove 2105). Furthermore, Highways England personnel is using Lean methods such as collaborative planning (using a system akin to the Last Planner® System that was developed by Ballard (2000)), built-in quality, visual management (Tezel et al. 2016), etc. (O'Sullivan 2016).

Despite their very different technical- and socio-political contexts, Caltrans and Highways England may learn from one another. Caltrans may explore opportunities to identify processes in its supply chain where Lean can be used—not to copy, but to be inspired by examples where Highways England has succeeded. Likewise, Highways England may explore opportunities to identify processes in-house where lean can be used—again, not to copy, but to be inspired by examples where Caltrans has succeeded.

4.5.2. Commercial Terms and Contracting Approaches

Caltrans uses a design-bid-build approach in which state employees design the projects and prepare plans, specifications, and estimates (PS&E). Caltrans then advertises the contract and awards each project to its lowest responsible and responsive bidder.

In contrast, Highways England established a Highways Agency Lean Division in April 2009, charged with deploying Lean construction methods in three target areas, namely (1) Managed Motor-ways, (2) Traditional Widening, and (3) Maintenance Schemes (Tam and Sinhal 2011, KPMG 2017).

Going back to about 2001, Highways England divided the region it manages into 12 areas, and awards a 5-year contract for all maintenance and rehabilitation work in each area. Five consortia, between them, hold all 12 of the 5-year area contracts called “Asset Support Contracts.” Each

consortium includes a group of design and construction firms and their subcontractors sufficient to perform the maintenance and rehabilitation work for the area, including rehabilitation design.

Under the Asset Support Contracts, the responsible consortium in each area reviews the pavement condition and prepares rehabilitation plans, which it reviews with Highways England in a value management workshop. Once a strategy is agreed, the member firms in the consortium proceed with design and construction. There is no bidding process.

It should be noted that Highways England is changing its contracting approach. It is in the process of bringing back in-house the management of the maintenance and rehabilitation. We speculate this is to regain control over transportation facilities data, that otherwise stays within the purview of the contractor or of the designer-contractor joint venture. Such data is vital to Highways England's long-term ability to manage its assets through the numerous contracts it holds. In the new process, project managers will be employees of Highways England, but maintenance, design, and construction will continue to be performed by contractors under long-term contracts. During the transition, the number of Asset Support Contracts is decreasing, and these contracts will eventually be phased out. Thus, Highways England is pursuing continuous improvement, experimenting with new opportunities, and adjusting based on contextual changes and lessons learned.

4.5.3. Specifications for Lane Closures

The PS&E on a Caltrans pavement rehabilitation contract normally lists upfront the time windows during which the contractor may close lanes on the highway. Caltrans makes these closure commitments many months before the closures occur, and they are inputs into the contractor's bid. If Caltrans were to change these times, that would constitute a change in conditions and be the basis for a potential contract claim.

In contrast, the 5-year nature of Highways England's Asset Support Contracts and the uncertainty about where the rehabilitation will occur make it unreasonable to specify permitted lane closure times upfront. In addition, traffic officers make up a large and influential part of the Highways England staff (in contrast with Caltrans, where the Highway Patrol is a separate government agency and has little influence on the specification of lane closure times). Officers are reluctant to commit to closure times months in advance. Instead, they prefer to wait until the time of the closure, when they can observe the traffic and determine whether to permit a closure. Their focus is on minimizing the inconvenience to the travelling public more so than on the effect on the Asset Support Contractor and subcontractors.

Due to the uncertainty about the closure times, the Asset Support Contractors delay requests for materials until they are certain when the closure will occur. In a Lean improvement study, Highways England found that the contractors were laying on average 240 metric tons of asphalt during each nighttime closure. The Lean improvement study team observed and timed two nighttime closures, and found that the asphalt pavers were operating for an average of only 2 hours and 11 minutes per night (Bradshaw and Foster 2015, Moore 2015).

The study team set a challenge goal of laying 1,000 metric tons in a single nighttime closure, and thus acquired the name “The 1,000-ton Project.” The study team agreed to take risks by preparing equipment off-site while waiting for approval of the closure, and agreed to order materials to be delivered at a time that seemed reasonable. If the closure was cancelled, the advanced preparation would incur costs, and the early ordering of materials would lead to costly wastage if the closure was delayed. By taking these risks, however, the study team increased the paver operating time to 6 hours and 50 minutes. In a single nighttime closure, 1,024 metric tons of asphalt were laid. As this is more than four times the average production, this change could eliminate 75% of the nighttime closures if it were replicated as a standard practice. It would also lead to considerable savings in labor hours and equipment rental. The success of The 1,000-ton Project has encouraged the Highways England Board to set ambitious targets for achieving efficiencies through improvements in pavement rehabilitation.

The British government has established “efficiency” goals for Highways England, which has a road investment plan for the five-year period beginning in April 2015 with an estimated cost of £15.2 billion. The government has tasked Highways England to find £1.2 billion in efficiencies and to complete the plan for £14 billion. Highways England must document every efficiency, and the Office of Road and Rail is auditing that documentation. Audits confirmed that during 2010-2015, Highways England achieved £100 million savings from Lean interventions; for 2015-2020, Highways England targets £250 million savings towards the £1.2 billion (O’Sullivan 2016).

Undoubtedly, Caltrans and Highways England can learn from one another as they progress on their respective Lean journeys while pursuing different approaches, each one to suit the nature of their specific contexts. Not many approaches will transfer directly from one context to another however. For example, legislative change would be required in California for Caltrans to engage in collaborative contracts of the kind Highways England is using (e.g., Asset Support Contracts). To date, Caltrans has been using “partnering” as a means to establish more collaborative working relationships with its low-bid contractors but while it can promote the practice with them, in the end Caltrans cannot contractually enforce it.

5. CALTRANS HPR PROJECTS

5.1. Caltrans Organization for Delivery of HPR Projects

The Caltrans organization provides engineering design services using mainly in-house personnel; it contracts with private consultants for only up to about 10% of this work. Caltrans contracts out all construction work.

Caltrans personnel manages HPR projects, like other projects that Caltrans delivers, using the Work Breakdown Structure (WBS) (Figure 3) that is specified by Caltrans (2016). A WBS is a tool used in project management for planning and controlling work. Caltrans mandates that project managers detail their projects to at least Level 5 by task name as illustrated, and leaves the use of levels 6, 7, and 8 as optional.

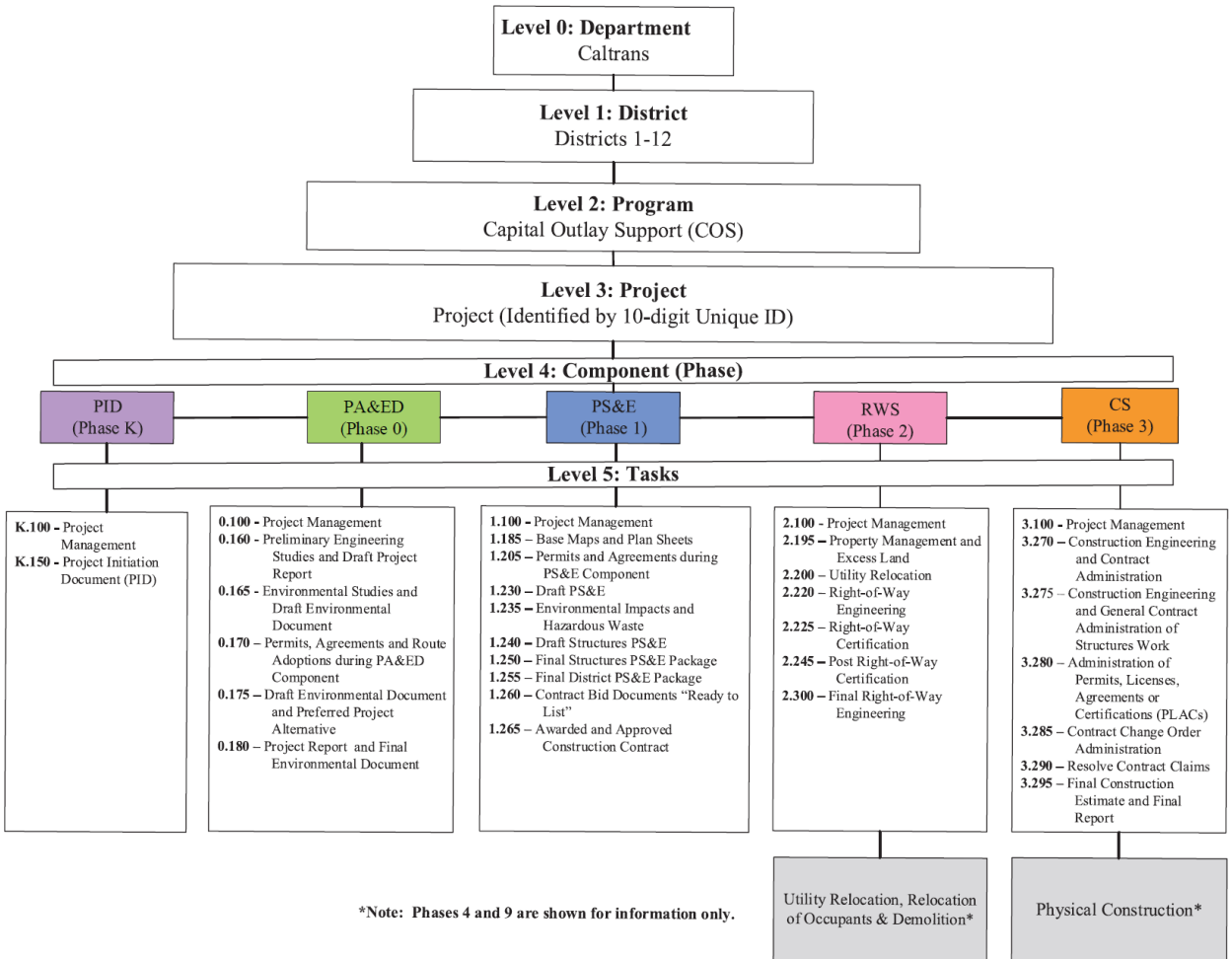


Figure 3: Work Breakdown Structure Diagram (Source: Figure on p. 7 in Caltrans 2016)

This WBS serves as the backbone for reporting and tracking project data in Caltrans' project management software called PRSM. The WBS focuses on deliverables and who is responsible for them, but not on sequencing of work. In fact, pages 13-14 in Caltrans (2016) (Figures 4 and 5) show how the WBS elements can be lined up by phase, but a note states that "This chart is intended as an overall pictorial of the WBS and not to be used as a logic diagram." Of course, the WBS must serve all Caltrans project needs and thus cannot be expected to include logic in general. Nevertheless, some Caltrans Districts (e.g., Districts 6 and 9) have developed their own HPR templates (and coded them as Open Workbench Gantt charts that can be customized and the uploaded in the PRSM system that Caltrans uses to track projects) based on these. Thus, it appears feasible (at least to some degree) to define logic that can get replicated from one HPR project to the next and it may be useful for Caltrans to start using such templates in all Districts.

5.2. HPR Projects Selected for Research

The researchers consulted with Caltrans personnel to identify three HPR projects for the purpose of this research study. The rationale for selection included: (1) the HPR project was completed relatively recently, (2) it was in several regards "typical" for an HPR project in its District. The researchers obtained plans, specifications, bid results, timelines, and expenditure data to understand each project. They then visited each project team and obtained data to map and further document the process that the team had followed to deliver the project.

5.2.1. Project 03-3F670 on State Route 49 in El Dorado County

Caltrans Project 03-3F670 rehabilitated the pavement of State Route 49 (SR 49) in El Dorado County from 0.1 miles north of Coloma to 0.5 miles north of Cool (Figure 6). This 11.1-mile section of 2-lane highway is in the Sierra foothills. It passes from the valley of the South Fork of the American River near Coloma over Pilot Hill to the valley of the North Fork of the American River near Cool. The route climbs as one drives from south to north and has many curves. SR 49 provides access to many of the early California gold mines and former mining towns. The first gold discovery by westerners occurred at Coloma in 1848, and the number 49 apparently commemorates the area's association with the "49er" gold rush of 1849.

This Project's section of SR 49 has three traffic counting stations, with annual average daily traffic (AADT) counts of 5,400, 3,100, and 3,600 vehicles/day respectively (Caltrans 2015b). Peak hour counts are 500, 350, and 420 vehicles/day respectively. The largest counts are at the southern end of the Project, near Coloma. This section also has one truck counting station at Cool. This station shows truck making up 14.2 % of the AADT. The largest number of trucks have 5 or more axles (36.3% of the trucks), followed by 2 axles (34.2%) and 3 axles (24.0%) (Caltrans 2015c).

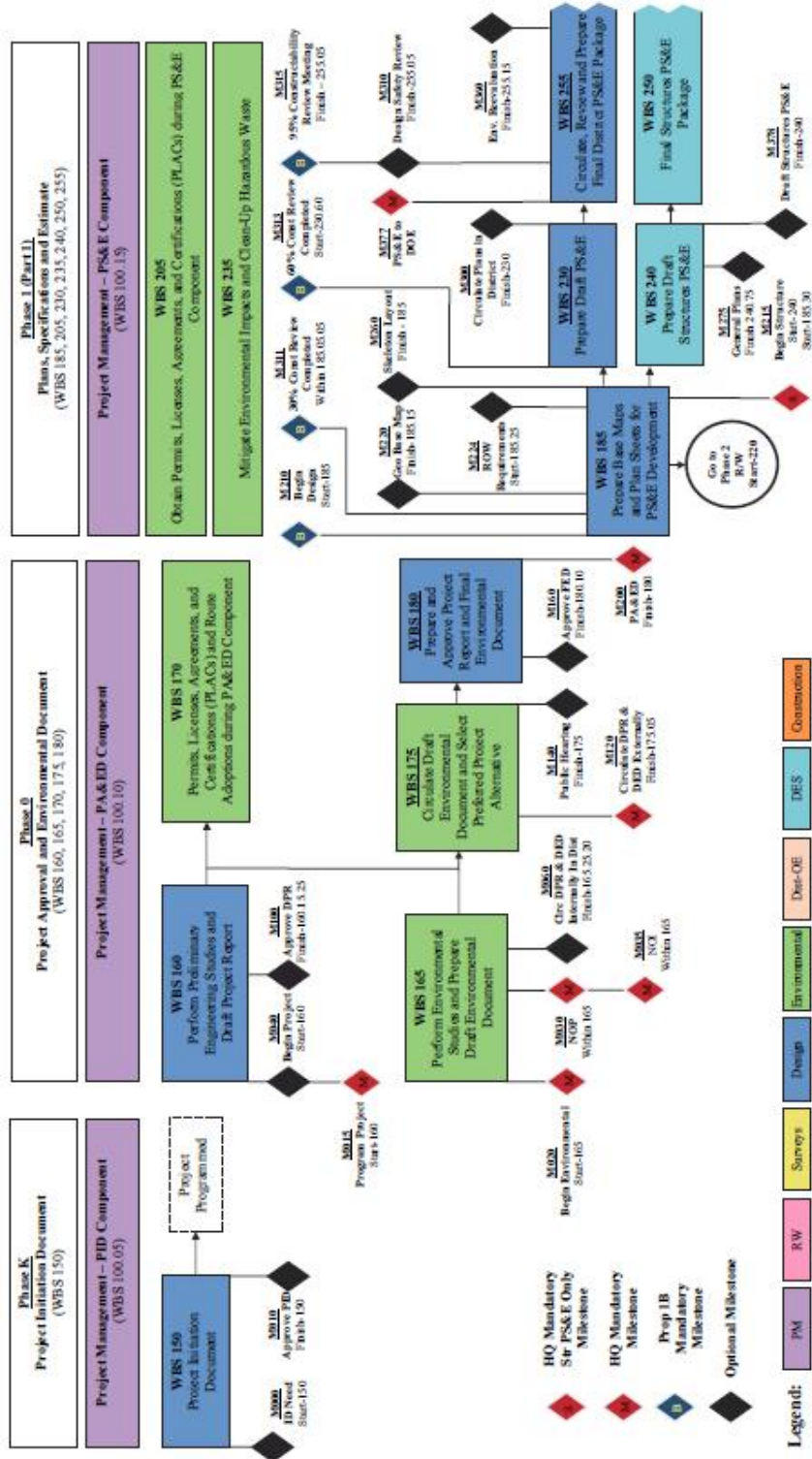


Figure 4: Overview of Phases K, 0, and 1 (Part 1), Level 5 WBS Elements, and Milestones - Note: This chart is intended as an overall pictorial of the WBS and not to be used as a logic diagram (Source: Figure on p. 13 in Caltrans 2016)

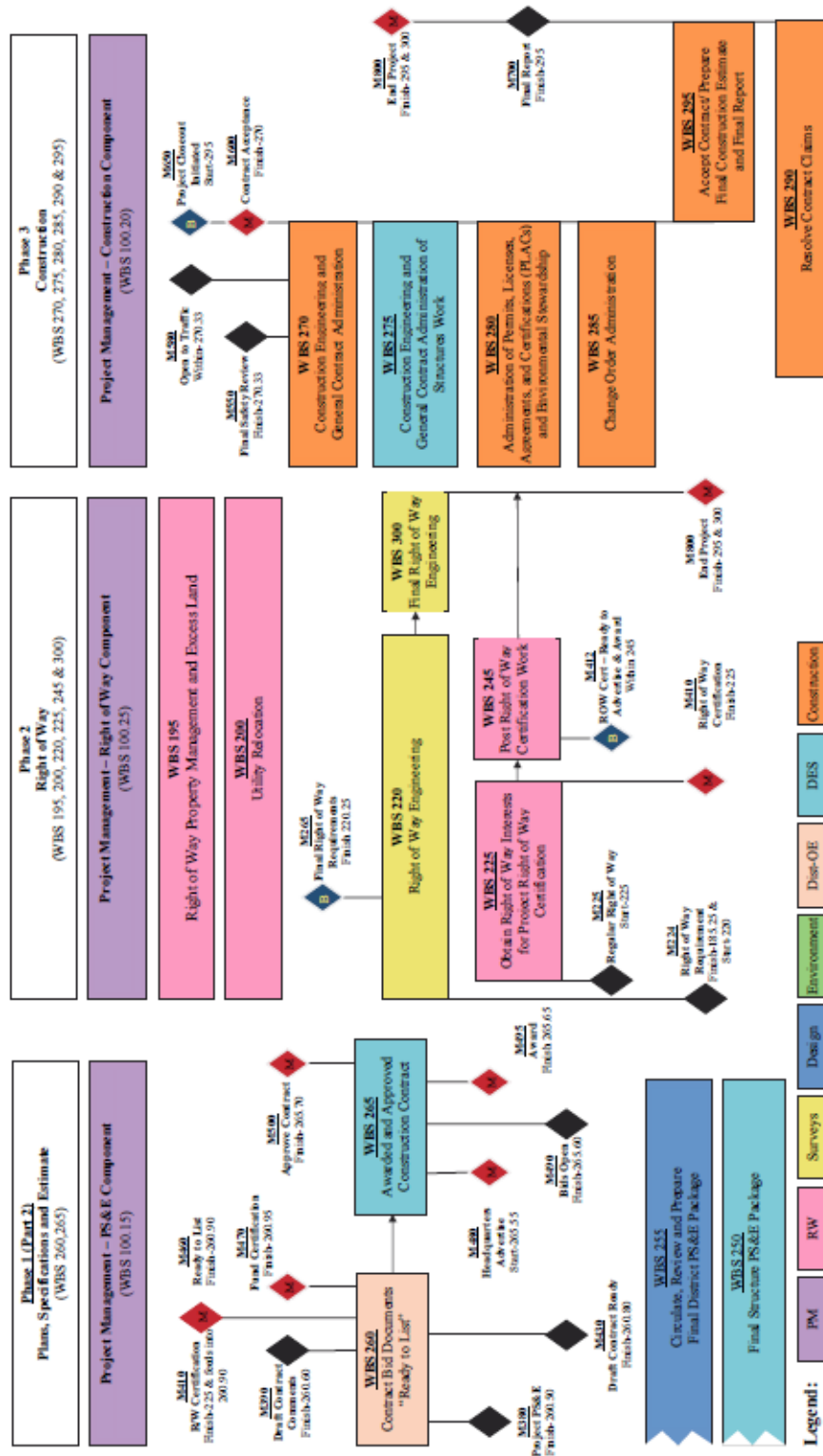


Figure 5: Overview of Phases 1 (Part 2), 2, and 3, Level 5 WBS Elements, and Milestones - Note: This chart is intended as an overall pictorial of the WBS and not to be used as a logic diagram (Source: Figure on p. 14 in Caltrans 2016)

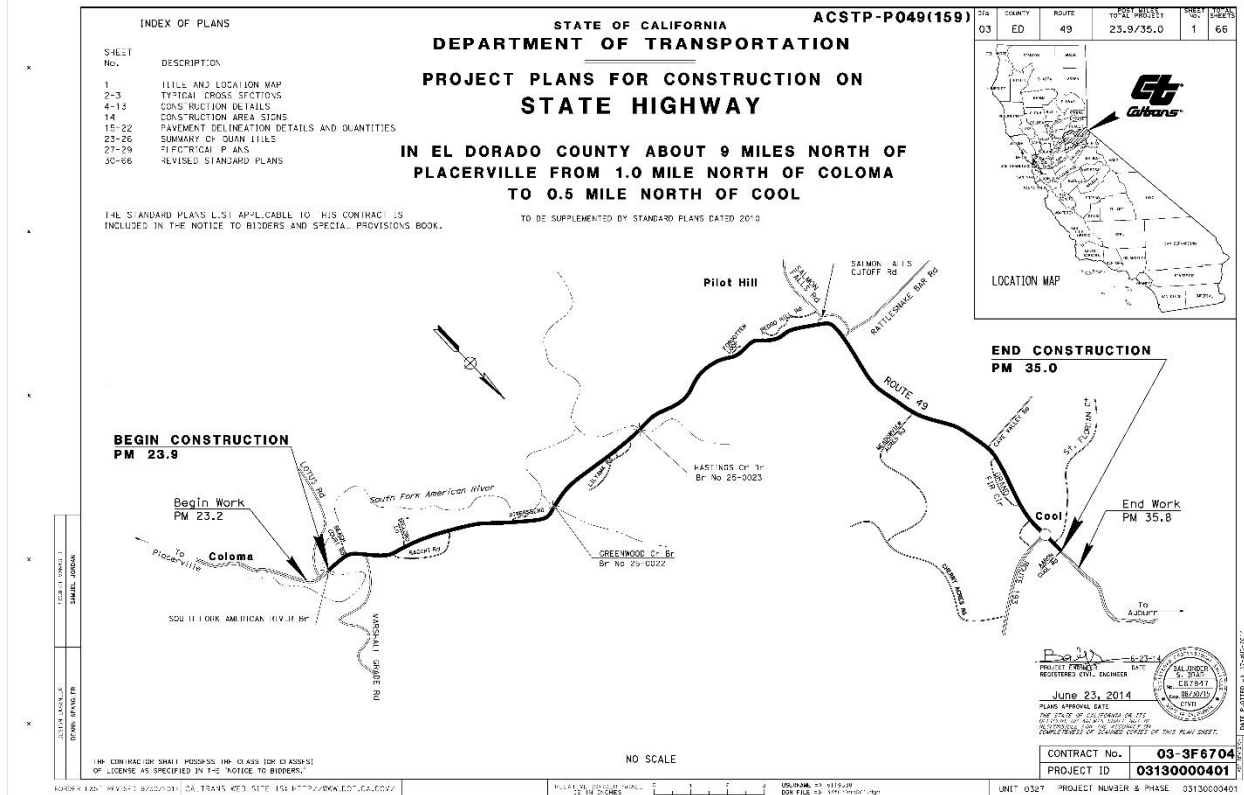


Figure 6: Title Sheet of Project 03-3F670 on State Route 49 in El Dorado County (Source: Caltrans)

In this Project section, SR 49 is a two-lane rural highway with left-turn lanes over much of its length. The lane width is 12 feet, with an additional 12 feet for left-turn lanes, for total travelled width that varies from 24 feet to 36 feet. The route has shoulders on both sides, with a standard shoulder width of 6 feet, narrowing to as little as 1 foot in places.

The existing pavement prior to the Project consisted of 0.30 feet to 0.75 feet of asphalt concrete over an aggregate base.

The Project consisted mainly of cold in-place recycling of the top 0.15 feet to 0.25 feet of asphalt concrete and the subsequent placement of a 0.15-foot hot-mix asphalt overlay. The new overlay required the placement of new-hot mix asphalt dykes and re-positioning of guardrails.

The Project timeline included the following milestones dates (with WBS elements listed in parentheses):

- **Programming:** Caltrans began work on the Project Initiation Document (PID) on July 31, 2012 (ID Need Milestone, M001). Caltrans approved the PID on May 31, 2013 (Milestone M010), and received approval for the environmental document, a categorical exclusion, two

days later, on June 2, 2013. The PID included the environmental document. This Project had no separate environmental phase.

- **Plans, Specifications, and Estimate:** The California Transportation Commission (CTC) programmed the project on August 5, 2013 (Milestone M015) and the project was Ready to List on June 23, 2014 (Milestone M460). Design thus took 11 months.
- **Construction:** Caltrans received the Attorney General's approval for the contract on December 19, 2014 (M500) and the contract immediately went into winter shut-down. Inferring from the fact that the first monthly progress payment to the contractor was made in May 2015, the contractor must have started work in April 2015 so the shut-down was about 4 months long. The contractor achieved Construction Contract Acceptance (CCA) on March 20, 2016 (M600).

Caltrans received 3 bids for construction of this Project. It rejected the low bid of \$5,411,737.50 submitted by Knife River Construction and awarded the contract to the second-lowest responsible and responsive bid of \$5,918,358.50 to Martin Brothers Construction. The three largest bid items were:

- 27,100 short tons of hot mix asphalt at \$93.50/ton, for a total of \$2,533,850 or 47% of the total bid.
- 211,000 square yards of cold in-place recycling at \$3.40/yd², for a total of \$717,400 or 13%.
- 820 short tons of emulsified recycling agent at \$616.00/ton, for total of \$505,120 or 9%.

An additional 65 smaller bid items together accounted for the remaining 31% of the total bid.

5.2.2. Project 06-0Q240 on State Route 41 in Fresno County

Caltrans Project 06-0Q240 rehabilitated the pavement of State Route 41 (SR 41) in Fresno County from Harlan Avenue to Elkhorn Avenue, near the southern boundary of Fresno County (Figure 7). This 3.1-mile section of 2-lane highway is in the California Central Valley south of the City of Fresno. The surrounding area is flat agricultural land, and SR 41 has a straight, level alignment in this area.

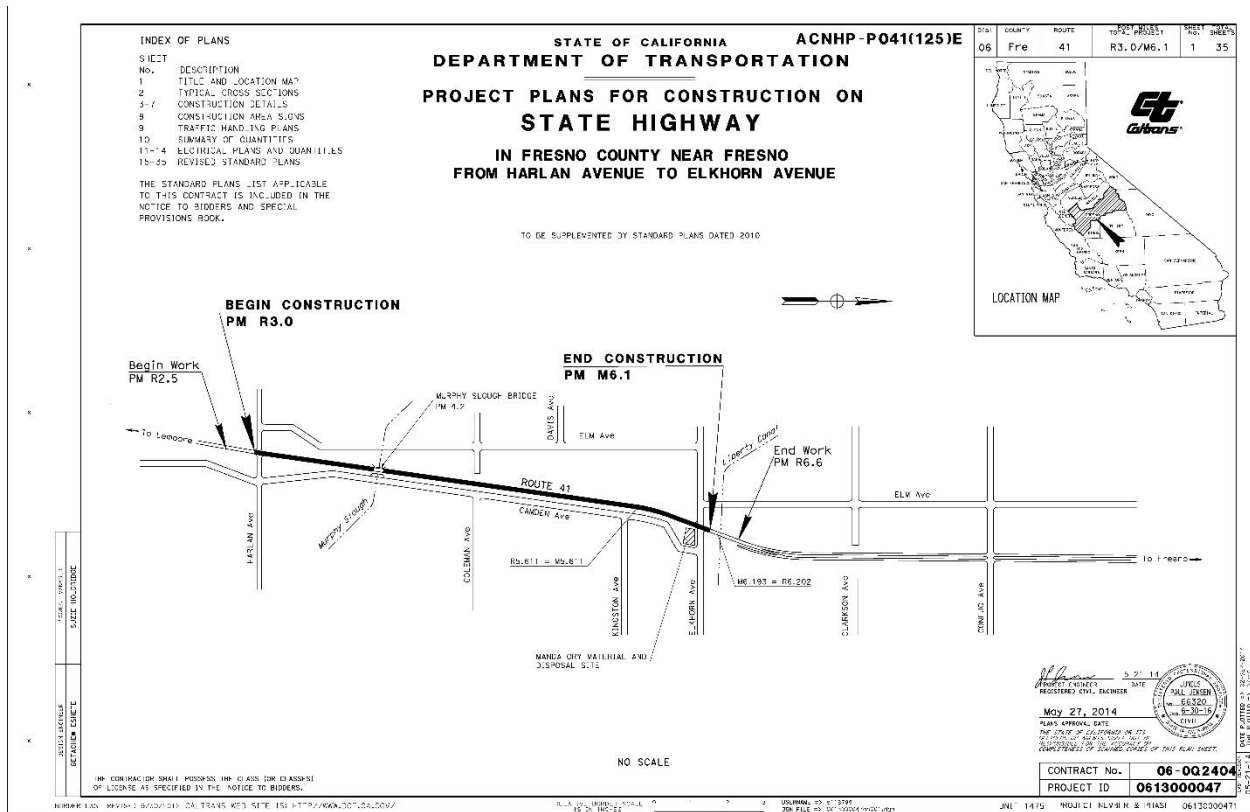


Figure 7: Title Sheet of Project 06-0Q240 on State Route 41 in Fresno County (Source: Caltrans)

This Project’s section of SR 41 has one traffic counting station, with an AADT count of 15,300 vehicles/day (Caltrans 2015b). The peak hour count is 1,400 vehicles/day. The nearest truck counting station is 3.1 miles south of the Project, at the border between Fresno and Kings Counties. This station shows trucks making up 16.0% of the AADT. The largest number of trucks have 2 axles (51.06% of the trucks), followed by 5 or more axles (31.47%), and 3 axles (9.54%) (Caltrans 2015c).

In the Project section, SR 41 is a two-lane rural highway. The lane width is 12 feet, for total travelled width of 24 feet. The route has shoulders on both sides, with a shoulder width that varies between 8 and 10 feet.

The existing pavement prior to the Project consisted of 0.60 to 1.00 feet of asphalt concrete over 0.75 feet of aggregate base.

The Project consisted mainly of the removal of the top 0.50 feet of the existing asphalt concrete, with the lower 0.30 feet to be cold in-place recycled and the upper 0.20 feet to be cold planed and replaced with hot mix asphalt.

The Project timeline included the following milestones dates (with milestones listed in parentheses):

- **Programming:** Caltrans began work on the Project Initiation Document (PID) on April 28, 2013 (ID Need Milestone, M001) and received approval for the environmental document, a categorical exclusion, on the next day, April 29, 2013. The PID included the environmental document. This Project had no separate environmental phase.
- **Plans, Specifications, and Estimate:** The California Transportation Commission (CTC) programmed the project on July 22, 2013 (M015) and the project was Ready to List on June 4, 2014 (M460). Design thus took 10 months.
- **Construction:** Caltrans opened bids on October 16, 2014 and received the Attorney General's approval for the contract on November 24, 2014 (M500) and the contract immediately went into winter shut-down. Inferring from the fact that the first monthly progress payment to the contractor was made in June 2015, the contractor must have started work in May 2015 so the shut-down was about 6 months long. The contractor achieved Construction Contract Acceptance (CCA) on August 6, 2015 (M600).

Caltrans received six bids for construction of the Project and awarded the contract to the lowest responsible and responsive bidder, Teichert Construction, who submitted a bid of \$1,747,374.00. The three largest bid items were:

- 9,630 short tons of Hot Mix Asphalt at \$75.00/ton, for a total of \$722,250 or 41% of the total bid.
- 54,500 square yards of Cold In-Place Recycling at \$5.00/yd², for a total of \$272,500 or 16%.
- 292 short tons of emulsified recycling agent at \$625.00/ton, for total of \$181,250 or 10%.

An additional 35 smaller bid items together accounted for the remaining 33% of the total bid.

5.2.3. Project 12-0H034 on State Route 73 in Orange County

Caltrans Project 12-H034 rehabilitated the pavement of State Route 73 (SR 73) in Orange County from 0.1 miles north of Campus Drive to Route 405 (Figure 8). This 2.3-mile section of urban freeway is lies entirely within the boundaries of the City of Costa Mesa. At its southern end, the section begins at the John Wayne Airport, the principal airport in Orange County. It passes through an interchange with State Route 55 (SR 55), which is also a freeway. It has a local interchange with Bear Street, and proceeds in a north-westerly direction to its interchange with Interstate Freeway 405, where SR 73 terminates. The southern two-thirds of the section passes through a developed commercial area and the northern third passes through a developed single-family residential area. In this section the route has a straight, level alignment.

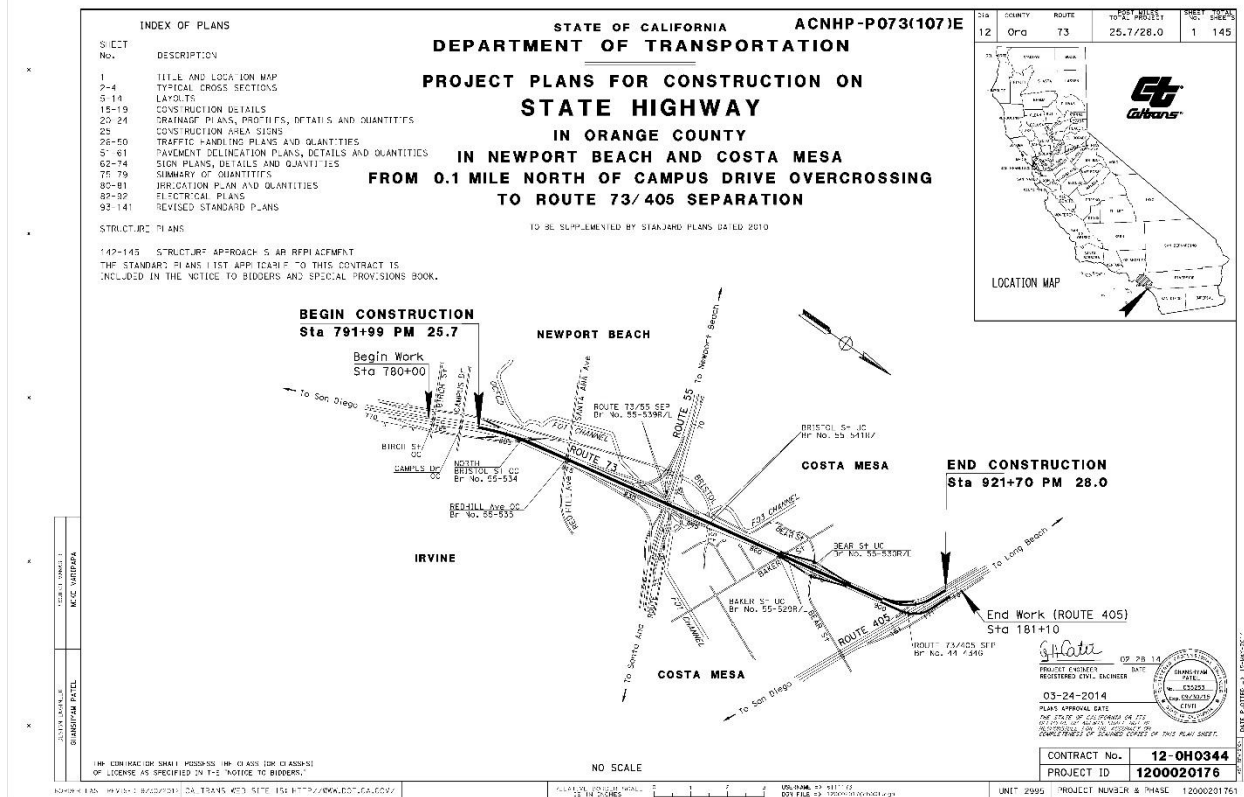


Figure 8: Title Sheet of Project 12-0H034 on State Route 73 in Orange County (Source: Caltrans)

This Project's section of SR 73 has two traffic counting stations, with AADT counts of 175,200 and 117,500 vehicles/day respectively (Caltrans 2015b). Peak hour counts are 12,800 and 8,100 vehicles/day respectively. The larger count is south of the interchange with SR 55. This section also has one truck counting station, located immediately before the junction with Interstate Freeway 405. This station shows trucks making up 2.35% of the AADT. The largest number of trucks have 2 axles (67.5% of the trucks), followed by 3 axles (13.5%), and 5 or more axles (13.0%) (Caltrans 2015c).

In the Project section, SR 73 has three lanes in each direction. It has two auxiliary lanes in both directions south of SR 55, two northbound auxiliary lanes, and one southbound auxiliary lane from SR 55 to Bear Street, and one auxiliary lane in each direction from Bear Street to Interstate Freeway 405. All lane widths are 12 feet. The route has shoulders on both sides of each carriageway, with standard shoulder widths of 10 feet on the outside and 16 feet at the median.

The existing pavement prior to the Project consisted of 0.70 feet of Portland cement concrete, 0.45 feet of class A cement treated base, and 0.5 feet of aggregate base. Some auxiliary lanes and

the outer shoulders had 0.40 feet of asphalt concrete over 0.75 feet of class 2 aggregate base and 1.10 feet of class 4 aggregate subbase.

The Project consisted mainly of grinding the existing pavement and replacing some Portland cement concrete slabs using rapid-strength concrete. The asphalt concrete auxiliary lanes received 0.20 feet of cold planing replaced by 0.20 feet of gap-graded rubberized hot mix asphalt, and the outer shoulders received 0.15 feet of cold planing replaced by 0.15 feet of gap-graded rubberized hot mix asphalt.

The Project timeline included the following milestones dates (with milestones listed in parentheses):

- Caltrans began work on the Project Initiation Document (PID) for project 12-0H030 on January 1, 2005 (ID Need Milestone, M001), and approved the PID on August 22, 2005 (M010). The PID was for an extensive section of highway and was split into several smaller projects for construction. The number “4” as the fifth character in the project number indicates that 12-0H034 is the fourth split of the original PID for 12-0H030. Caltrans received approval for the 12-0H030 environmental document on October 20, 2005.
- Plans, Specifications, and Estimate: The Project was Ready to List on April 1, 2014 (M460).
- Construction: The contractor achieved Construction Contract Acceptance (CCA) on December 31, 2015 (M600).

Caltrans received 7 bids for construction of the Project. It awarded the contract to the lowest responsible and responsive bidder, Autobahn Construction, who submitted a bid of \$2,496,863.50. Their three largest bid items were:

- 5,850 short tons of Rubberized Hot Mix Asphalt (gap graded) at \$100.00/ton for a total of \$585,000 or 23% of the total bid.
- 99,500 square yards of Grinding Existing Pavement at \$2.90 per square yard, for a total of \$288,550 or 12%.
- Traffic control system for a lump sum of \$250,000 or 10%.

An additional 79 smaller bid items together accounted for the remaining 55% of the total bid.

5.2.4. Comparison of Project Data

Tables 2 and 3 show the data of these three projects side-by-side.

Table 2: Summary of Project Attribute Data (Part 1 of 2)

| Project 03-3F670 | Project 06-0Q240 | Project 12-0H034 |
|--|---|--|
| Location | | |
| State Route 49 in El Dorado County from 0.1 miles north of Coloma to 0.5 miles north of Cool. | State Route 41 in Fresno County from Harlan Avenue to Elkhorn Avenue. | State Route 73 in Orange County from 0.1 miles north of Campus Drive to Route 405. |
| Length of section | | |
| 11.1 miles | 3.1 miles | 2.3 miles |
| Nature of route | | |
| 2-lane highway with left-turn lanes in places (24-foot travelled way, widening to 36-foot at left-turn lanes). | 2-lane highway (24-foot travelled way). | Freeway, 3-lanes in each direction with auxiliary lanes in places (36-foot travelled way in each direction, widening to 48-foot at auxiliary lanes). |
| Terrain and alignment | | |
| Rural foothills, undulating, with curves. | Rural Central Valley, straight, level alignment. | Urban, straight, level alignment. |
| Traffic volume, annual average daily traffic (AADT) 2015, at the station with the largest count in the section | | |
| 5,400 | 15,300 | 175,200 |
| Peak-hour traffic, 2015 | | |
| 500 | 1,400 | 12,800 |
| Truck percentage, 2015 | | |
| 14.20% | 16.00% | 2.35% |
| Truck AADT to nearest 10 (calculated) | | |
| 770 | 2,450 | 4,120 |
| Nature of work | | |
| 0.00 to 0.25-foot cold in-place asphalt recycling plus 0.15-foot hot mix asphalt overlay. | 0.00 to 0.30-foot cold in-place asphalt recycling plus 0.20 to 0.50-foot hot mix asphalt overlay. | Grind and groove existing concrete pavement; slab replacements; 0.15-foot cold plane shoulders and replace with hot mix asphalt; 0.20-foot cold plane shoulders and replace with hot mix asphalt on ramps. |

Table 3: Summary of Project Attribute Data (Part 2 of 2)

| Project 03-3F670 | Project 06-0Q240 | Project 12-0H034 |
|---|--------------------------|-------------------------------|
| Low bid | | |
| \$5,411,737.50 (disqualified) \$5,918,358.50 (awarded) | \$1,747,374.00 | \$2,496,863.50 |
| Successful bidder | | |
| Martin Brothers Construction | Teichert Construction | Autobahn Construction |
| Number of bidders | | |
| 3 | 6 | 7 |
| Largest bid item in awarded bid | | |
| Hot mix asphalt (Type A) | Hot mix asphalt (Type A) | Rubberized hot mix asphalt. |
| Largest bid item amount in awarded bid | | |
| \$2,533,850 | \$722,250 | \$585,000 |
| Largest bid item quantity in awarded bid | | |
| 27,100 short tons | 9,630 short tons | 5,850 short tons |
| Largest bid item as percentage of total bid | | |
| 47% | 41% | 23% |
| ID need date (M001) | | |
| 7/31/2012 | 4/28/2013 | 1/1/2005 |
| Program project (M015) | | |
| 8/25/2013 | 7/22/2013 | 8/22/2005 |
| Ready to List (RTL: M460) | | |
| 6/23/2014 | 6/4/2014 | 4/1/2014 |
| Construction Contract Acceptance (CCA: M600) | | |
| 3/20/2016 | 8/6/2015 | 12/31/2015 |
| Duration ID Need to Programming | | |
| 13 months | 15 months | 7 months |
| Duration Programming to RTL (Preliminary Engineering) | | |
| 10 months | 10 months | 100 months (8 years 4 months) |
| Duration RTL to CCA (Advertise, Award, and Construct) | | |
| 21 months | 14 months | 21 months |

6. PROCESS MAPS OF SELECTED CALTRANS HPR PROJECTS

6.1. Overview of Projects Mapped

The researchers met with the Project Development Teams (PDT) for each of the three projects that Caltrans had recommended for this study. Table 4 summarizes the dates, locations, types and attendees at each meeting. Note that the researchers participated in two meetings in a single day in Marysville: a Project Development Team meeting in the morning and a “Lessons Learned” session for construction phase of project 03-3F670 in the afternoon. Note also that representatives from a different combination of Caltrans functional areas attended each meeting. One would expect the work of the attendees’ functional areas to be discussed in more detail than the work of functional areas not represented. In some cases, the participants might have little or no knowledge of the work of non-represented functional areas.

Table 4: Meetings of Researchers with Caltrans Personnel

| | 03-3F670 | 03-3F670 | 06-0Q240 | 12-0H034 |
|---|-----------------------|------------------------------|---------------|---------------|
| Meeting date | Oct. 24, 2016 morning | Oct. 24, 2016 afternoon | Jan. 13, 2017 | Feb. 24, 2017 |
| Meeting location | Marysville | Marysville | Fresno | Irvine |
| Meeting type | PDT | Construction Lessons Learned | PDT | PDT |
| Functional areas represented in meeting | | | | |
| Project Manager | ✓ | ✓ | ✓ | ✓ |
| Project Management | ✓ | | ✓ | |
| Construction | ✓ | ✓ | ✓ | |
| Design | ✓ | ✓ | | ✓ |
| Electrical Construction | | ✓ | | |
| Engineering Services | | ✓ | | |
| Environmental | | | ✓ | |
| Maintenance | | | ✓ | |
| Pavement Advisor | | | | ✓ |
| Right of Way | ✓ | | | |
| Surveys | ✓ | | | |

In Districts 3 and 6, the researchers were able to gather sufficient information to prepare a process map for the HPR projects in the study. In addition, the researchers also obtained hourly cost data charged to each project by Caltrans personnel from the project starts in 2012 onward (note that Caltrans fully deployed their PRSM system only in 2014 so that not all projects studied benefited from having all their data tracked in it).

The information the researchers were able to gather at their meeting in District 12 was insufficient to prepare a process map. Given the goals of this specific research, the researchers decided to not pursue further data collection on this District 12 project as it was quite different from the other two projects, being an urban concrete slab replacement project rather than a rural asphalt project, and therefore harder to identify cross-case similarities.

6.2. Process Map for Project 03-3F670

The process map for Project 03-3F670 (Figure 9) shows the standard Caltrans milestones using diamonds, and standard Caltrans tasks using rectangles. The Caltrans (2016) Workplan Standards Guide provides detailed descriptions of each milestone and task. Thanks to representatives of the Surveys functional area in the meeting (Table 4), the process map includes more information on surveys than was the case in the District 6 project.

Figure 10 depicts the monthly hours billed by Caltrans personnel involved in each of this project's three phases (enumerated below). These hours were tracked in PRSM since it became fully deployed agency-wide in 2014. The researchers did not obtain data more detailed than Level 5 in the WBS as, barring a few exceptions, greater detail generally appears to not be shown in PRSM.

- 1 The Project Initiation Document (PID) phase (Phase K) which lasted from July 2012 to August 2013. The work peaked in February 2013. It consumed 1,001 hours of Caltrans employee effort.
- 2 The Plans, Specifications, and Estimate (PS&E) phase (Phase 1) which lasted from August 2013 to January 2015. It consumed 5,906 hours of effort. Right of Way (R/W, Phase 2) began during PS&E and continued at low levels of effort during construction. The total R/W effort amounted to 2,267 hours including a 661-hour spike on October 2014. Of the R/W effort, 1,779 hours occurred contemporaneously with PS&E and the remaining 488 hours occurred while construction was under way.
- 3 The Construction phase (Phase 3) began with contract award in December 2014 and continued until filing of the Final Report in December 2016. This phase consumed 8,835 hours of state employee effort (i.e., not including the contractor's effort).

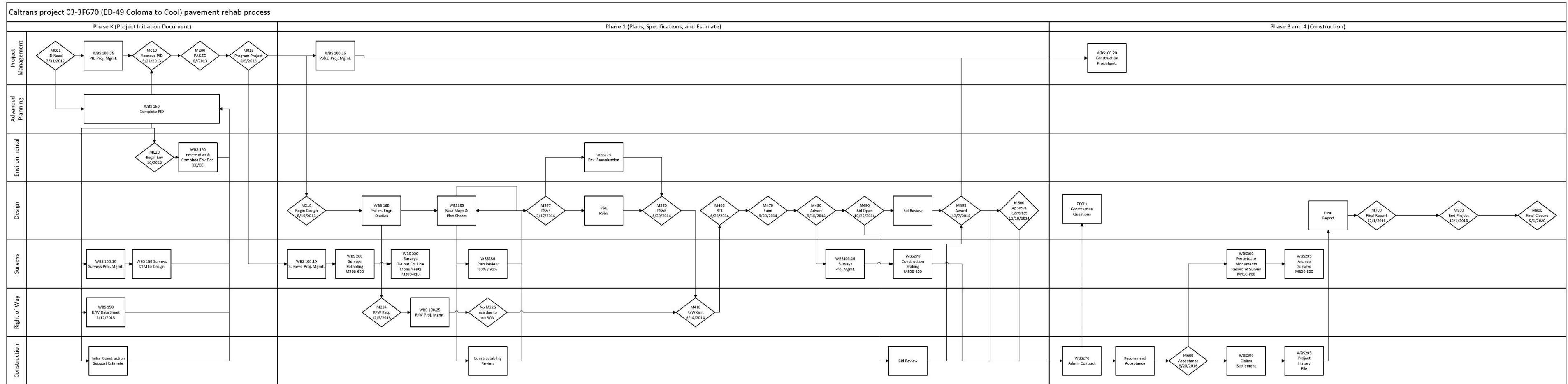


Figure 9: Process Map of Project 03-3F670 (ED-49 Coloma to Cool)

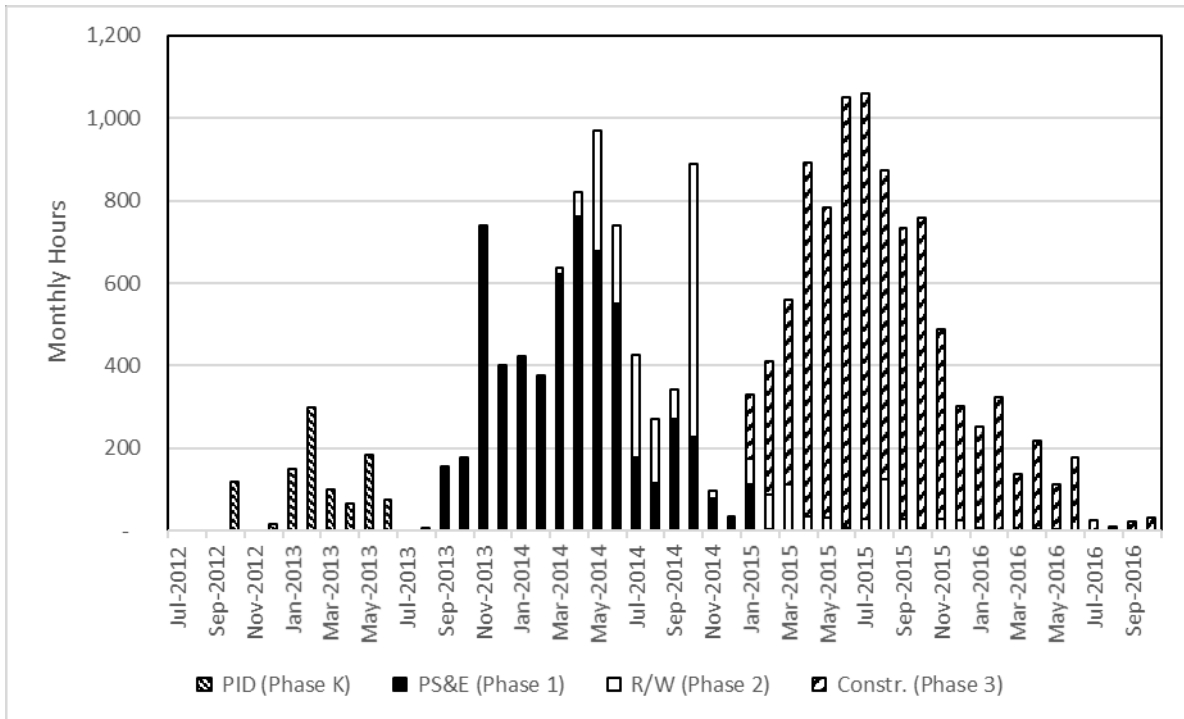


Figure 10: Monthly Hours Billed by Phase on Project 03-3F670 (Source: Data provided by Caltrans)

While not depicted in Figure 10, the billing data obtained by the researchers showed hours broken down not only by phase but also by unit. This breakdown revealed that on project 03-3F670 not many units worked on more than one phase. Technically speaking, unit personnel can work on multiple phases (e.g., see discussion of the District 6 project). Doing so is desirable as it enhances the continuity of shared understanding in project delivery.

A significant feature of this project was the fact that the categorical exemption environmental document was completed as part of the PID (Phase K), thereby eliminating the need for an Environmental phase (Phase 0). The project proceeded directly from the PID (Phase K) to PS&E (Phase 1). This allowed for a smooth project flow as it avoided both (1) the time that would have been needed for Phase 0 and (2) the need to ramp-up and ramp-down staffing to work through Phase 0.

6.3. Process Map for Project 06-0Q240

Figure 11 maps the process that was used to deliver Project 06-0Q240. Like the District 3 project, this shows the standard Caltrans milestones using diamonds, and standard Caltrans tasks using rectangles in accordance with the Caltrans (2016) Workplan Standards Guide.

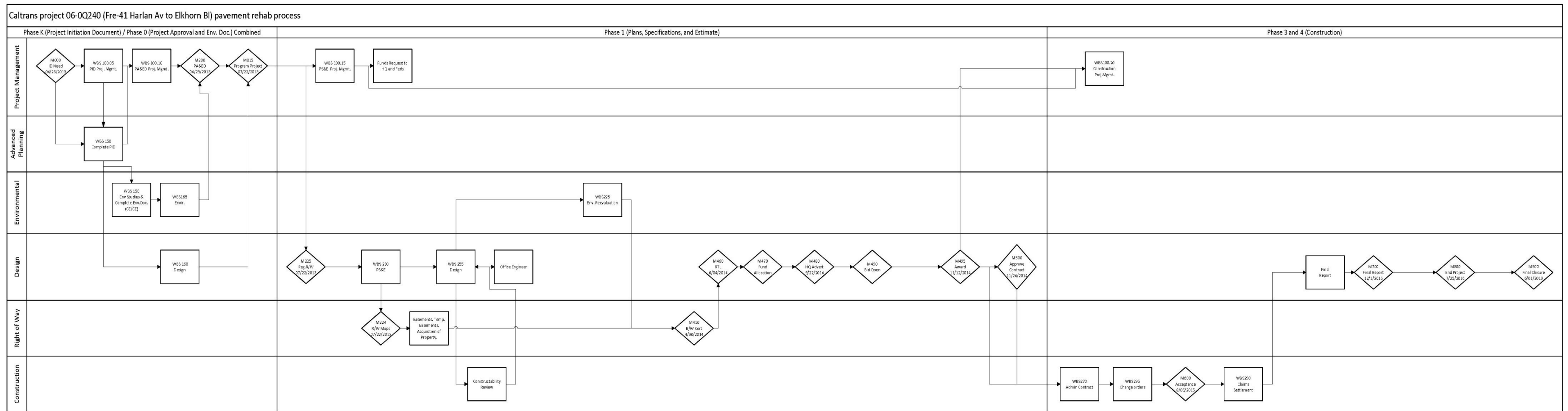


Figure 11: Process Map of Project 06-0Q240

Figure 12 depicts monthly hours billed by phase for this project that, like the District 3 project, went through three phases:

- 1 The Project Initiation Document (PID) phase (Phase K) which lasted from October 2012 to July 2013. The work peaked in January 2013. It consumed 986 hours of Caltrans employee effort.
- 2 The Plans, Specifications, and Estimate (PS&E) phase (Phase 1) which lasted from August 2013 to January 2015. It consumed 3,809 hours of effort.
- 3 The Construction phase (Phase 3) began with contract award in November 2014 and continued until December 2015, when the Final Report was filed. This phase consumed 2,408 hours of state employee effort (i.e., not including the contractor’s effort).

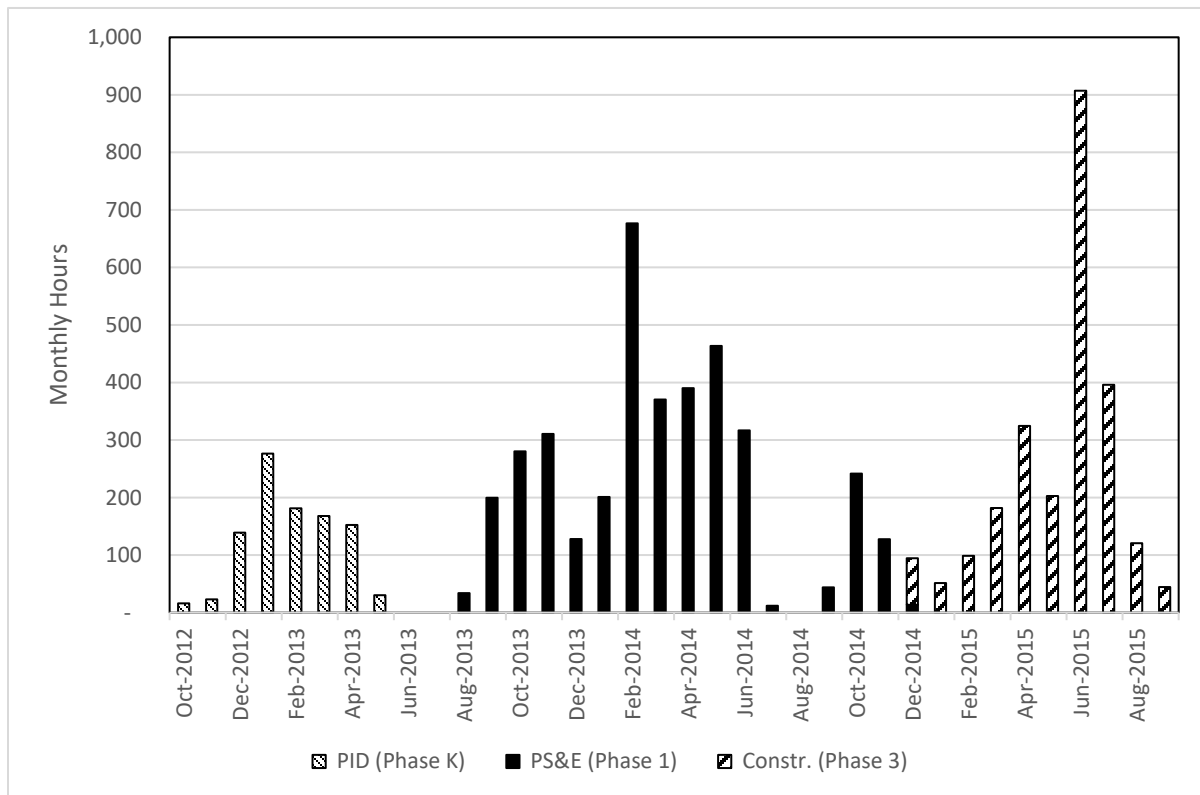


Figure 12: Monthly Hours Billed by Phase on Project 06-0Q240 (Source: Data provided by Caltrans)

While not depicted in Figure 12, the billing data for this project (as was the case for the District 3 project) showed hours broken down not only by phase but also by unit. Here, this breakdown revealed that on project 06-0Q240 the same units (possibly the same people, but the researchers were not privy to the data at that level of detail) worked on the PID and the PS&E phases, and they

also charged time to Construction. With fewer unit changes (and possibly fewer individual staff changes) one might expect this project to have progressed more smoothly than project 03-3F670 in terms of the continuity of shared understanding in project delivery. However, the researchers obtained no data that could test this expectation.

Of note is the unevenness of the billing histogram (Figures 10 and 12) and the interruptions in billing (some months with no charges). The challenge of effectively using employees' time is presumed to be addressed by Caltrans management at the project portfolio level, likely with employees multi-tasking by working on several projects at the same time. Such practices tend to extend project delivery times. Here too, the researchers obtained no data that could test this expectation.

Like the District 3 project, a significant feature of this project was the fact that the categorical exemption environmental document was completed as part of the PID (Phase K). It was therefore not necessary to have an Environmental phase (Phase 0). The project proceeded directly from the PID (Phase K) to PS&E (Phase 1). This improved the project flow and avoided both the time that would have been needed for Phase 0 and the need to ramp-up and ramp-down staffing as one worked through Phase 0.

6.4. Process Map from Prior Caltrans Research

Early on in the project, the research team met with Prof. John Harvey at University of California, Davis to discuss HPR process mapping. They received a process map that he had developed jointly with Caltrans personnel and consultants to inform development of the Caltrans PaveM database (Harvey et al. 2011). This map has not been published previously and is included in this report (Figure 14 in Appendix IV) to provide the reader with another illustration of what process maps may look like and be used for.

This process map differs from the District 3 and 6 process maps in at least two significant respects: (1) The process steps do not identify the standard milestone and task numbers defined in Caltrans' (2016) Workplan Standards Guide and (2) The map includes "PaveM" and "CTIPS" processes that Caltrans considers to be external to its projects, and that are not billed directly to projects.

The process steps in Harvey's process map are:

1. **Automated Pavement Condition Survey:** Historically, Districts have identified sections of pavement that are most in need of repair. In recent years, Caltrans has begun to conduct detailed automated annual pavement condition surveys, using technology that was not previously available. The automated survey provides an annual record of the current condition of every section of the state highway system. Data is collected by sensors and ground-penetrating radar

measured from a vehicle travelling at normal highway speeds, and includes a video film of the highway both forward-looking and downward-looking at the pavement. This is a significant change from previous surveys, which were conducted by engineers who took measurements at discrete locations and were obliged to assume that the tested locations were representative of the intervening sections of highway.

2. **Trigger Project and Develop Project List:** The automated survey opens the possibility of data-driven identification of the projects that would provide the optimal use of pavement funds. The Caltrans PavEM database includes information of all prior pavement treatments at any given location of the state highway system. Through the use of algorithms, the Headquarters Pavement Program within the Division of Maintenance identifies the most likely best strategy for each location and creates a list of tentative pavement projects.
3. **Override, Analysis. Revise Project List:** Districts review the headquarters list and, based upon local knowledge, revise the list.
4. **Caltrans District 10-year Plan:** Streets and Highways Code 164.6 requires Caltrans to submit a 10-year state highway rehabilitation and reconstruction plan to the California Transportation Commission (CTC), and to update that plan in every odd-numbered year. The pavement rehabilitation project list is a part of that 10-year plan.
5. **Project History:** As already noted, the PavEM system includes a history of past pavement treatments on every section of state highway, as well as algorithms for predicting the best pavement strategy for each section of state highway. The PavEM algorithms contribute to the 10-year plan, especially in identifying projects and costs for the later years of the plan.
6. **Field Review, Field Notes, Draft Report, Draft Estimate:** During the PID phase, Headquarters Pavement Advisors participate in field reviews to validate the intended pavement treatments in a project. These reviews contribute the PID document and to the estimation of the project cost.
7. **Candidate Project and Cost:** After the PID is completed, the project scope and cost is added to the list of projects that are candidates for programming.
8. **SHOPP Cycle Program of Shelve Project? Shelve Project, Program Project:** Government Code 14526.5 requires Caltrans to submit a 4-year State Highway Operation and Protection Program (SHOPP), to the CTC by January 31 of every even-numbered year, although amendments can be submitted to the CTC at any of its monthly meetings.

To create the SHOPP, Caltrans selects the highest priority projects from among the candidate projects that can be funded within the constraints of the fund estimate previously adopted by the CTC (the Fund Estimate requirement is in Streets and Highways Codes 163 and 164, and Government Codes 14524 and 14525).

9. **FY, Project cost, Escalation:** The PID cost estimate is a “present year” estimate. In developing the SHOPP, Caltrans assigns the project to a specific year in the 4-year SHOPP

and applies an escalation factor to reach a requested programming amount for the projects in its programmed year.

10. **Allocate Construction Funds:** Before Caltrans can advertise a contract for construction, it must obtain an allocation of construction funds from the CTC.

7. CASE COMPARISON, RECOMMENDATIONS, AND CONCLUSIONS

The research as described set out if and how a state DOT might standardize the delivery of HPR projects. To that end, the researchers articulated two process maps (Figures 9 and 11) that describe largely the same process from slightly different perspectives. Using these as a basis, and building on the Caltrans WBS while also considering HPR templates that exist as Open Workbench Gantt charts in use in Caltrans Districts 6 and 9, the researchers combined them into a “synthesis” process map (Figure 13). This process map may serve as a draft standard for HPR project delivery at Caltrans. Unquestionably, this draft must be further scrutinized by Caltrans personnel in a collaborative effort within their organization (e.g., engaging multiple functional units within districts and engaging multiple districts) as well as with supply chain partners (e.g., contractors) while using Lean Thinking to identify and pursue opportunities for continuous improvement of its project delivery practices. By involving project delivery personnel from all its Districts and Headquarters agreement may be reached on a standard process suitable to managing Caltrans HPR projects.

A standard process is necessary to track project metrics to a larger extent than the researchers were able to do based on the data they obtained from Caltrans. More detailed data already is available in Caltrans accounting and project tracking systems (e.g., hourly data by individual). It could be used to compute lean metrics such as resource capacity and utilization. Given a project’s estimated demand for resources, managers can then decide how to balance work load and judiciously underload (committing resources to work at less than 100% of their capacity, so that they can be reliable in accomplishing their work) while aiming to achieve predictable activity durations and process cycle times.

As observed from the data, winter shutdowns (which in part reflect the timing of the State’s funding cycles) extend the duration of project delivery (process cycles times). They do allow contractors time to prepare their work, nevertheless, uncertainty around the end of winter conditions and thus the start of construction affects performance.

Other data to compute lean metrics is currently not systematically captured in the Caltrans PRSM system (e.g., only a few activities are broken down in the WBS at a level greater than 5), though it could be and would be useful to support continuous improvement processes.

A standard process will include not only a well-defined set of activities in a certain temporal order, it must also have durations for those activities that can be reliably achieved. That is, the process must be stable in execution. To that end, Caltrans may want to consider implementing the Last Planner® System (Ballard 2000), first implemented in Lean Construction settings in pursuit of achieving reliable work flow. The Collaborative Planning system used by Highways England is based on it. Implementation of this systemic planning approach in all phases of work would require Caltrans personnel to adopt new practices and collect new kinds of data, e.g., to compute the metric Plan Percent Complete that gages plan reliability. A number of other lean methods such as using visual management (Tezel et al. 2016) and building-in quality also offer good opportunities for Caltrans to drive its continuous improvement efforts.

Follow-on research can explore opportunities to more broadly apply lessons learned from studying the HPR delivery process to other service processes across Caltrans. It can also test and assess the extent to which lessons learned can be scaled-up to address the delivery of more value-for-money on projects more complex than the relatively straightforward HPR projects.

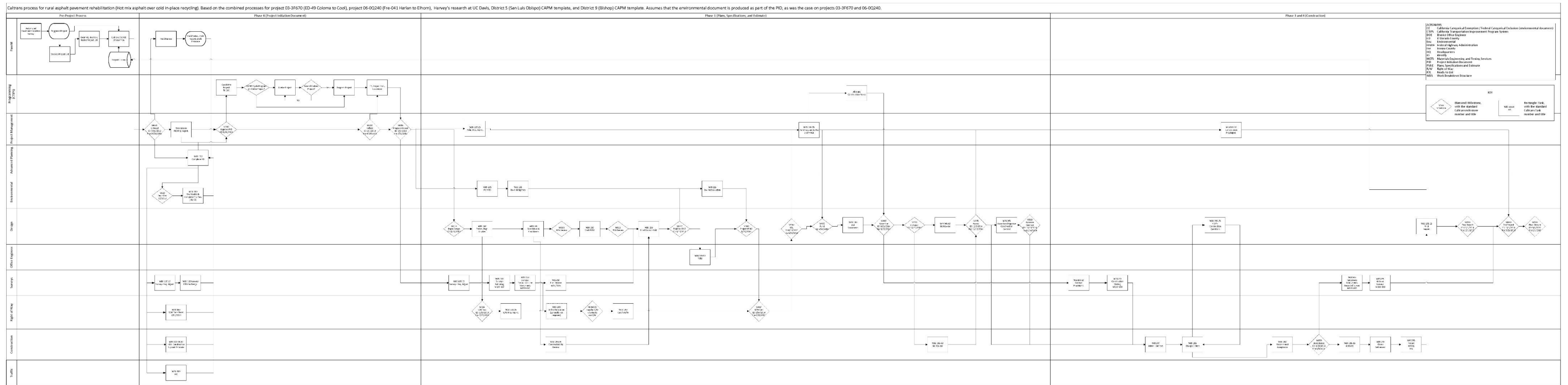


Figure 13: Synthesis Process Map for Caltrans HPR Projects

APPENDIX I: ABBREVIATIONS AND ACRONYMS

| | |
|-----------|---|
| AADT | annual average daily traffic |
| ASCE | American Society of Civil Engineers |
| Caltrans | California Department of Transportation |
| CCA | Construction Contract Acceptance |
| CITRIS | Center for Information Technology Research in the Interest of Society, http://citris-uc.org |
| CTC | California Transportation Commission |
| DOT | Department of Transportation |
| HPR | Highway Pavement Rehabilitation |
| ISO | International Organization for Standardization |
| LIPS | Lean in the Public Sector, http://leaninpublicsector.berkeley.edu |
| NEPA | National Environmental Policy Act |
| P2SL | Project Production Systems Laboratory, http://p2sl.berkeley.edu |
| PID | Project Initiation Document |
| PDT | Project Development Team |
| RTL | Ready To List |
| SHOPP | State Highway Operation and Protection Program |
| STIP | State Transportation Improvement Program |
| TPS | Toyota Production System |
| UC | University of California |
| UCB | University of California, Berkeley |
| UCCONNECT | University of California Center on Economic Competitiveness in Transportation (a center within ITS, supporting research at UC Berkeley, UC Irvine, UC Los Angeles, UC Riverside, UC Santa Barbara, and California Polytechnic State University at San Luis Obispo) |
| UCTC | University of California Transportation Center |
| US | United States (ISO standard two-letter country code) |
| VMT | Vehicle Miles Traveled |
| WBS | Work Breakdown Structure |

APPENDIX II: REFERENCES

- Alarcon, I., Christian, D., and Tommelein, I.D. (2011). “Collaborating with a permitting agency to deliver a healthcare project: case study of the Sutter Medical Center Castro Valley (SMCCV)” *Proc. 19th Ann. Conf. Int’l. Group for Lean Constr.*, Lima, Peru.
- Aziz, Z., Qasim, R.M., Wajdi, S. (2017). “Improving productivity of road surfacing operations using value stream mapping and discrete event simulation.” *Construction Innovation*, 17(3) 294-323, <https://doi.org/10.1108/CI-11-2016-0058>
- Ballard, G. (2000). *The Last Planner System of Production Control*. PhD Dissertation, University of Birmingham, UK.
- Ballard, G., Tommelein, I., Koskela, L., and Howell, G. (2002). “Lean Construction Tools and Techniques.” Chapter 15 in Rick Best and Gerard de Valence (editors, 2002). *Design and Construction: Building in Value*. Butterworth-Heinemann, Elsevier Science Ltd, pp. 227-255.
- Bhatia, N. and Drew, J. (2006). “Applying lean production to the public sector.” McKinsey & Company, June, <https://www.mckinsey.com/industries/public-sector/our-insights/applying-lean-production-to-the-public-sector> visited 4 August 2016.
- Bly, M. and Edwards, D. (2017). “Statewide Coordination on Master Calendar: Easier Said, but now it’s Done!” Colorado DOT, June 7, <https://www.codot.gov/business/process-improvement/local-lean/statewide-coordination-on-master-calendar-easier-said-but-now-it2019s-done>
- Bradshaw, A. and Foster, C. (2015). “Optimising Surfacing Productivity: The 1000 T Target.” Powerpoint presentation, LCI-UK Summit 2015. <http://leanconstruction.org.uk/wp-content/uploads/2015/11/Charlotte-Foster-Highways-England.ppt>
- California Department of Transportation (2002). *Caltrans Project Management Handbook*, Sacramento, CA.
- Caltrans (2013). *State of the Pavement Report*. Sacramento, CA.
- Caltrans (2015a). *Caltrans Strategic Management Plan 2015-2020*. Sacramento, CA.
- Caltrans (2015b). *Caltrans Improvement Project*. Sacramento, CA.
- Caltrans (2015c). *Caltrans Improvement Project Mid-Year Report, 2015*. Sacramento, CA.
- Caltrans (2016). *Workplan Standards Guide, Release 11.2*. Headquarters Division of Project Management, California Department of Transportation. Sacramento, CA.
- Chieppo, C. (2014). How Colorado’s Transportation Department is Institutionalizing Improvement. *Governing*, April.
- Damelio, R. (2011). *The Basics of Process Mapping*. 2nd ed., Productivity Press, 183 pp.
- Dunning, J. (2016). “Caltrans Lean Journey.” Powerpoint presentation, <https://sites.google.com/a/state.co.us/lean-interchange/documents/Lean%20Transportation%20Forum-Caltrans%20Lean%20Journey%20%28v3%29.pptx?attredirects=0&d=1> accessed 12 Dec. 2017.

- EPA (2008). *Working Smart for Environmental Protection: Improving State Agency Processes with Lean and Six Sigma*. Publication #EPA-100-R-08-007. US Envir. Protection Agency and the Envir. Council of States, March, <https://www.epa.gov/lean>, visited August 2017.
- EPA (2017a). “Lean Government - Successful Mission Delivery through Process Improvement.” <https://www.epa.gov/lean/lean-government>
- EPA (2017b). *The State of Lean at EPA*. 231-R-17-002, April, 8 pp. <https://www.epa.gov/sites/production/files/2017-04/documents/state-of-lean-040317.pdf>
- Eureka Institute (2017). <https://www.govops.ca.gov/eureka-institute/> visited 6 April 2017.
- Feng, P.P., Tommelein, I.D., and Ballard, G. (2008). “Modeling the Effect of an Alternative Review Process: Case Study of a State Permitting Agency.” *Proc. 2009 Constr. Research Congress (CRC2009)*, April 5-7 in Seattle, WA, ASCE, Reston, VA, 2:866-875.
- Hanna, A.S., Wodalski, M. and Whited, G. (2010). “Applying Lean Techniques in Delivery of Transportation Infrastructure Projects.” *Proc. 18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel, 14-16 July, pp. 609-619.
- Harvey, J.T. et al. (2011) *UCPRC/Caltrans internal communications*, June.
- Harvey, J.T. (2016). Personal communication with Iris Tommelein and Nigel Blampied, 9 Sept., University of California, Davis, CA.
- Jacobs (2013). *Highways Agency Lean Deployment Handbook*. Highways Agency, Manchester, UK.
- Jepson, D. (2012) “Streamlining Environmental Project Clearance.” Division of Transportation Development (DTD), Colorado DOT, May 17, <https://www.codot.gov/business/process-improvement/local-lean/streamlining-environmental-project-clearance>
- Johnson, H.T. and A. Broms (2000). *Profit Beyond Measure: Extraordinary Results through Attention to Work and People*. New York: The Free Press.
- Koskela, L., Howell, G., Ballard, G., and Tommelein, I. (2002). “The Foundations of Lean Construction.” Chapter 14 in Rick Best and Gerard de Valence (editors, 2002). *Design and Construction: Building in Value*. Butterworth-Heinemann, Elsevier Science Ltd, pp. 211-226.
- KPMG (2017). “Review of Highways England’s Maintenance and Renewals Delivery.” http://orr.gov.uk/__data/assets/pdf_file/0015/25170/kpmg-review-of-highways-england-maintenance-and-renewals-delivery-march-2017.pdf visited 12 June.
- Lean Interchange Network (n.d.). <http://sites.google.com/a/state.co.us/lean-interchange>
- Lean Manufacturing and Six Sigma Definitions (2017). “Six Sigma.” <http://leansixsigmadefinition.com/glossary/six-sigma/> visited 14 May.
- LEI (2016). <http://www.lean.org/WhatsLean/>, Lean Enterprise Institute, visited 14 April.
- Liker, J.K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill Education, 330 pp.
- Liker, J.K. and Meier, D. (2005). *The Toyota Way Fieldbook*. McGraw-Hill Education, 476 pp.
- Lindquist, K., Wendt, M., and Oman, L (2009). *State DOT and Related Industry Organizational Structures and Best Practice: Synthesis*, Washington State Department of Transportation, Olympia, WA.

- Martin, K. and Osterling, M. (2013). *Value Stream Mapping: How to Visualize Work and Align Leadership for Organizational Transformation*. McGraw-Hill, 224 pp.
- Moore, A. (2015) *Area 9 Pavement Process Improvement Improving Road Surfacing Productivity – 1000t project*. unpublished paper, Highways England, Manchester.
- Ohno, T. (1988). *Toyota production system: beyond large-scale production*. Productivity Press, Cambridge, Mass.
- O’Sullivan, J. (2016). *Lean Support to Highways England 2015-2020*. http://www.highwaysindustry.com/wp-content/uploads/2016/04/Lean_Strategy_Document_2015-2020__2_.pdf
- Rother, M. and Shook, J. (2003). *Learning to see: value stream mapping to add value and eliminate muda*. Lean Enterprise Institute. Brookline, MA.
- Sanders, C. (2017). “Using Kanban Principles in Trello Helps Organize Resources and Save Time.” Colorado DOT, Aug. 16, <https://www.codot.gov/business/process-improvement/local-lean/using-kanban-principles-in-trello-helps-organize-resources-and-save-time>
- State of California (2017) California Legislature 2017 SB1 Transportation Funding, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1
- State of Washington (2013). *Results Washington: A more efficient, effective and transparent state government*, September, <https://www.results.wa.gov>
- Tam, A. and Sinhal, R. (2011). “Maintenance and Making Better Use – Value Management of the Regional Roads Programme.” Available at [http://assets.highways.gov.uk/specialist-information/guidance-and-best-practice-road-renewal/RoR_VM_Guidance_Update_January2011\(Final\).doc](http://assets.highways.gov.uk/specialist-information/guidance-and-best-practice-road-renewal/RoR_VM_Guidance_Update_January2011(Final).doc)
- Tezel, A., Aziz, Z., Koskela, L., and Tzortzopoulos, P. (2016). “Benefits of Visual Management in the Transportation Sector.” *Proc. 24th Ann. Conf. of the Int’l. Group for Lean Construction*, Boston, MA, US, 6 pp. 123-132.
- Tommelein, I.D. (2015). “Journey toward Lean Construction: Pursuing a Paradigm Shift in the AEC Industry.” *ASCE, J. Constr. Engi. Manage.*, DOI: 10.1061/(ASCE)CO.1943-7862.0000926.
- Tusup, T. (2017). “Innovative Business Solutions.” Powerpoint presented at the Transportation Lean Forum (TLF) teleconference held on 17 October 2017. Available at: <http://www.results.wa.gov/sites/default/files/Transportation%20Lean%20Forum%20-%20Vansuch.pdf>
- TLF (2014). *Multinational Transportation Lean Forum (TLF)*. Effort ledt by G. Vansuch, CDOT Director of Process Improvement, <https://www.codot.gov/business/process-improvement/multinational-transportation-lean-forum-tlf>, visited 28 November 2016.
- Wingrove, A. (2015). Personal communication with Nigel Blampied, UK.
- Wogan, J.B. (2014). “Forget Technology; Denver Turns to Its Employees to Fix Problems.” *Governing*, February.

APPENDIX III: PROCESS MAP FROM HIGHWAYS ENGLAND

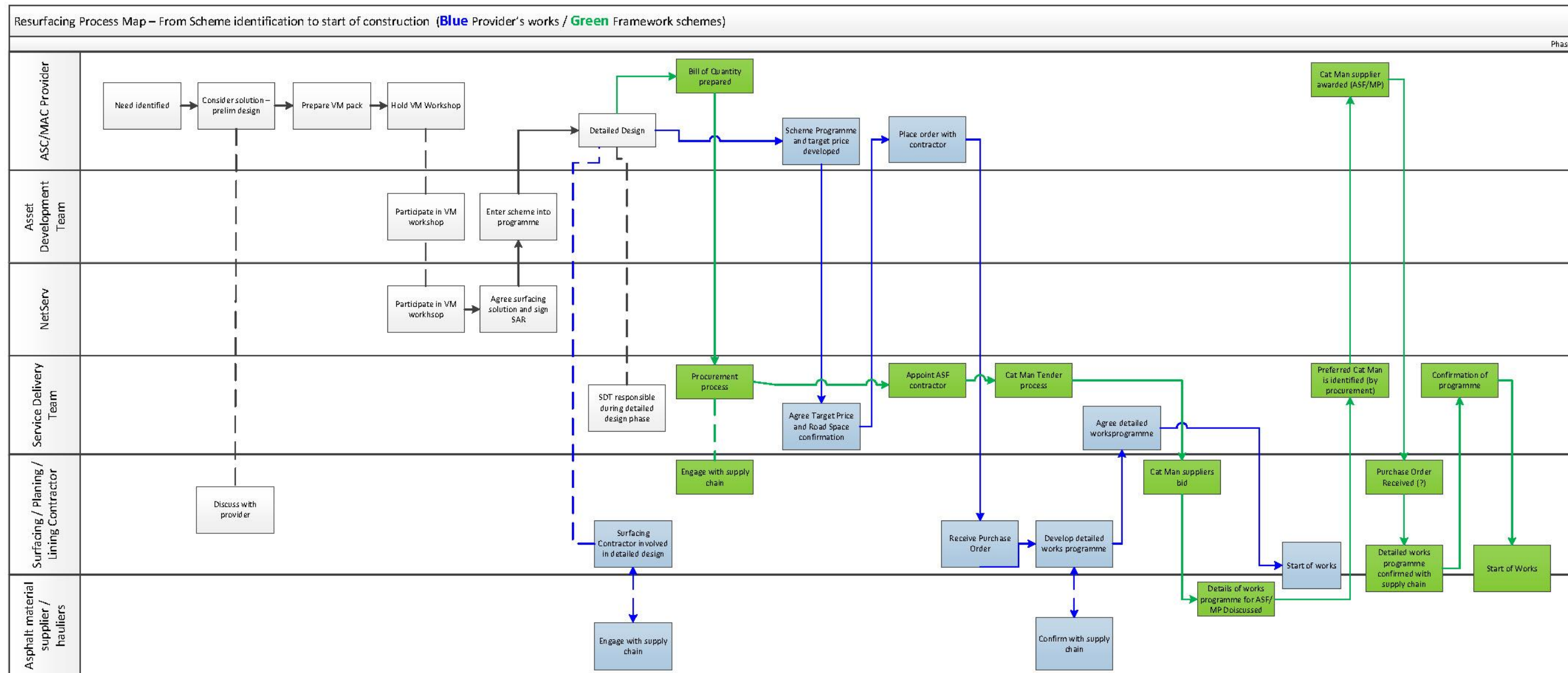


Figure 14: Resurfacing Process Map created by Highways England and its Suppliers (Source: Highways England)

APPENDIX IV: PROCESS MAP OF CALTRANS PROJECT TRACKING AND DOCUMENTATION (HA-22) FOR PAVEM

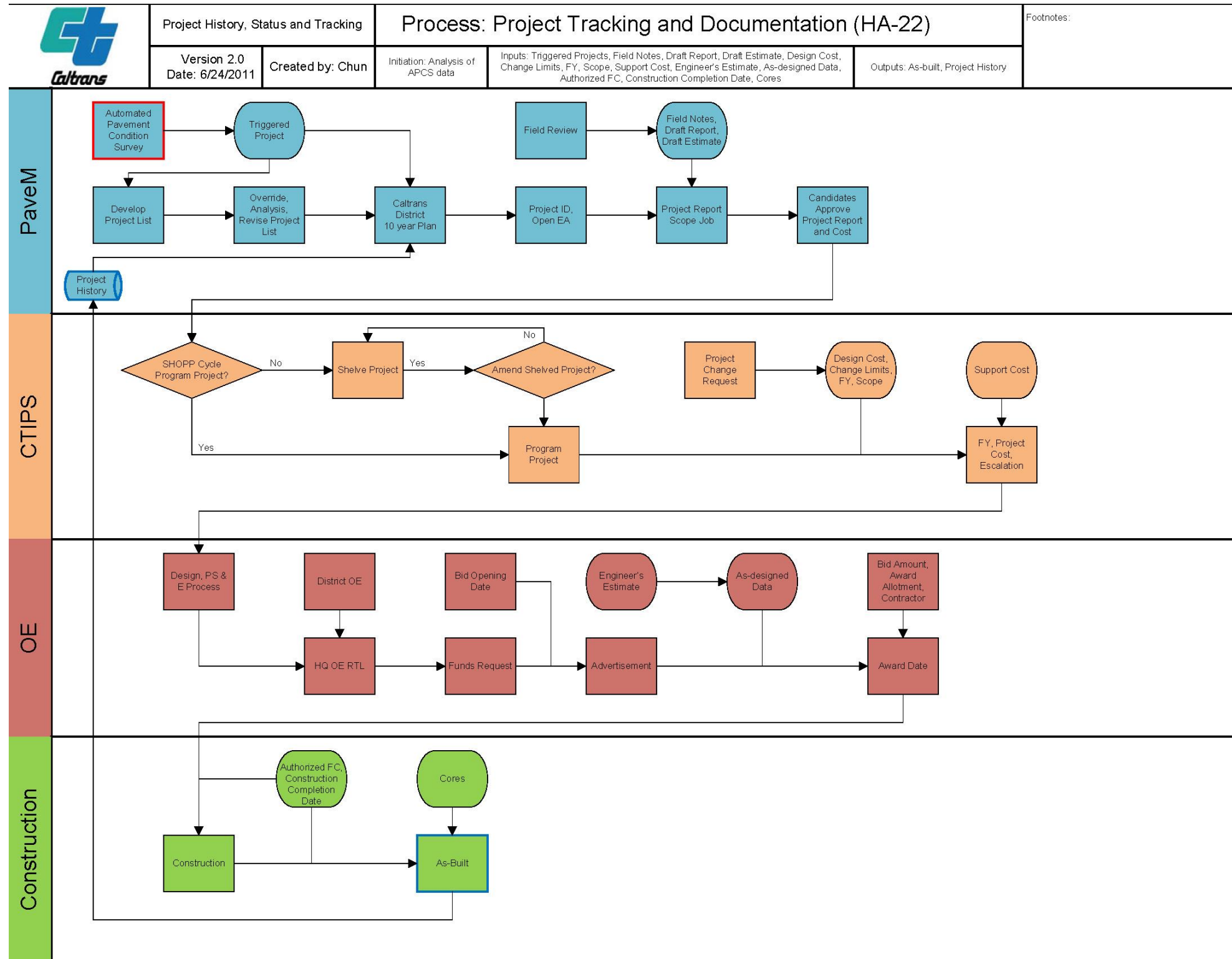


Figure 15: Process Map of Caltrans Project Tracking and Documentation (HA-22) for Pavem (Source: Harvey et al. 2011)