Parametric functions for conceptual and feasibility estimating in public highway project portfolios

By

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Committee in charge:

Professor Iris D. Tommelein, Chair
Professor C. William Ibbs
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Abstract

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Owners face challenges in setting priorities between potential projects to maintain, rehabilitate, and improve their infrastructure. The estimated cost of each potential project is a factor that owners use in setting priorities between projects and in developing their long-term maintenance and construction project portfolio. Owners face a dilemma: considerable effort is needed to develop accurate estimates of the cost of each project, but this effort will be wasted if the particular project is not selected for the long-term plan. They therefore need estimating methods that will enable them to develop reasonably accurate early stage cost estimates without an excessive amount of effort. These early stage estimates are "conceptual cost estimates" and "feasibility cost estimates."

This research examines the tools that are available to owners for performing early stage cost estimates for infrastructure projects. It then compares alternative parametric functions that could be used for that purpose, using data from public agencies in California. These functions are the linear parametric, common exponential parametric, and modified Cobb-Douglas exponential parametric models.

This research tests the models on 1 common type of project, pedestrian access facility projects on highways. In the United States (US) these projects result, directly and indirectly, from the Americans with Disabilities Act (ADA) that Congress passed in 1990. On highways, they produce three types of improvement: 1. wheelchair ramps at street corners to allow people in wheelchairs to cross streets at designated pedestrian crossings, 2. wheelchair-accessible sidewalks, and 3. audible signals at signalized intersections to inform visually impaired people when a pedestrian signal is in their favor.

The author developed a data set of 39 pedestrian access facility projects on state highways in California, used multiple regression analysis to find 4 best-fit versions of each of the 3 functions (i.e., 12 alternatives in all), and evaluated them using the Choosing By Advantages (CBA) method.

The author then benchmarks the preferred state highway cost estimating model identified in the CBA against 10 city-street pedestrian access facility projects that had been completed by 4 cities in the San Francisco Bay Area. He finds a significant difference between the state highway project

cost data and the city street project cost data, and further rationalizes that these differences have their roots in both the contracting methods used by the agencies and the fact that Caltrans prepares detailed designs while cities do only minimal design. The data suggests that there is an opportunity to increase output and lower the costs of pedestrian access projects (and perhaps other types of highway projects as well) by decreasing the Caltrans design effort and transferring more of the design effort and consequent risk to contractors. This could be tested through experimentation on selected pedestrian access facility installations.

This dissertation contributes to knowledge by providing a review of the place of conceptual and feasibility estimating both with respect to the overall project timeline and with respect to the methods used. It provides specific examples of the use of the various classes of estimates in the development of highway projects, and it provides a synthesis of the research on conceptual and feasibility estimating methods, most notably of parametric estimating. It then provides specific examples of parametric estimates on pedestrian access projects on California State Highways and in San Francisco Bay Area cities. Finally, it unveils the successful use by Bay Area cities of a minimal amount of design when developing design-bid-build contracts for pedestrian access facilities.

The dissertation aims to provide an approach that could be used both for project-by-project conceptual estimating prior to the start of work on highway projects and for evaluating the overall credibility of the estimates on large portfolios of highway projects.

Dedication

To the eight amazing people who have stood by me and encouraged me through this crazy endeavor, prior crazy endeavors, and perhaps future crazy endeavors: my daughters, Carol Blampied, Susan Blampied, and Dr. Omideh Miri who have grown into wonderful, mature, smart, and responsible adults; my mother, Estelle Blampied, and my sister, Brenda Blampied, who have supported me, sometimes tactfully corrected me, and tolerated me over many decades, from both near and afar; my best friend, companion, confidant, advisor, editor, spouse and lover Dr. Lisa Blampied to whom I owe a greater debt than can be imagined; and my grandchildren Zohreh Sloan and Andrew Sloan whose irrepressible spirit fills me with joy and hope for the future.

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Definitions

Price	The amount of money that a seller demands for an item.
Cost	The amount of money that a buyer pays for an item.
Cost estimate	The amount of money that a buyer expects to pay for an item that has not yet been bought.
Conceptual cost estimate	A cost estimate that is made when a problem or opportunity has been named, before any project work has been done, before any project charging codes have been established, before any possible solutions or alternatives have been identified, and taking at most a few minutes, in order to decide whether to start a feasibility study.
Feasibility cost estimate	A cost estimate that is made when possible solutions and alternatives have been named, but before any solutions and alternatives have been studied, in order to decide whether to study the solutions and alternatives with a goal of selecting a preferred alternative.
Budget authorization estimate	A set of cost estimates for the possible solutions and alternatives, including the "no build" alternative, that have been studied in sufficient detail to select one of them, in order to decide whether to assign funds to complete the selected alternative.
Control estimate	A cost estimate for the selected alternative that is prepared for the sponsoring organization, typically by the designers or by specialist cost engineers or quantity surveyors, at a stage where the plans and specifications are sufficiently detailed to enable a competent contractor to submit a bid that consists of firm fixed prices and then to complete the work with minimal further information from the sponsoring organization or designers.
Bid/tender estimate	A cost estimate for the selected alternative that is prepared by a contractor, who adds a markup to establish a bid/tender price that they then submit to the sponsoring organization or its agents with a firm contractual commitment to complete the work for that price.

Abbreviations, Acronyms, and Standard Terminology

The American National Standard[1] for project management is published with a glossary of standard terms (PMI 2017). Almost 6 million copies of this standard are in circulation, making it by far the most widely read book on project management in the world. In addition, more than 2 million people have passed a test that, in large part, examines their knowledge of the glossary (PMI 2018).

The Project Production Systems Laboratory at the University of California, Berkeley (P2SL) has also published a glossary, the *Lean Construction Glossary* (P2SL 2017). The dissertation uses the P2SL glossary as a supplement to the PMI glossary. If terms appear in both glossaries, this dissertation uses the PMI definition to reach the largest audience. If a term appears in the P2SL glossary but not the PMI glossary, it has the P2SL definition. If the dissertation itself provides a definition, that definition overrides both the PMI and the P2SL glossaries.

The author uses the PMI and P2SL glossaries to make the dissertation broadly understandable to the worldwide project management community.

3D	3 Dimensions
4D	4 Dimensions
AACE	AACE International. Formerly the American Association of Cost Engineers
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
ANN	Artificial Neural Network
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
BIM	Building Information Modelling
CA PPM	A software program produced and marketed by CA Technologies. Formerly called CA Clarity and, prior to that, Niku
CADD	Computer-Aided Design and Drafting
CalSTA	California State Transportation Agency
Caltrans	California Department of Transportation
CBA	Choosing By Advantages
CBR	Case-Based Reasoning
CDF	Collaborative Delivery Framework

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[1] Capitalization of references to standards in this dissertation conforms to the directives of the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO). References to standard registered by ANSI or ISO are capitalized “American National Standard” or “International Standard.” Generally recognized *de facto* standards that are not a registered by ANSI or ISO are not capitalized, e.g. “American national standard” or “international standard” (ISO 2011:1). For example, standards set by the American Association of State Highway and Transportation Officials (AASHTO) are not normally American National Standards or International Standards even though they are widely recognized throughout the world and are often mandatory on federally-funded and federally-owned facilities in the US. In some cases, AASHTO co-develops standards with other organizations, such as ASTM International (formerly the American Society for Testing and Materials) or the American Welding Society, and those organizations apply for ANSI registration. Only ANSI-Accredited Standards Developers can apply for ANSI registration.

CDR	Californians for Disabilities Rights, Inc.
CE	Categorical Exclusion / Exemption
CELSOC	Civil Engineers and Land Surveyors Of California
CEQA	California Environmental Quality Act
CES	Cost Estimation System
CHCCI	California Highway Construction Cost Index
CON	Construction
CSA	California State Architect
CTC	California Transportation Commission
DCO	Development Consent Order
DGS	California Department of General Services
D/L	Day Labor
DOF	California Department of Finance
DOT	Department of Transportation
ECI	Early Contractor Involvement
e-FIS	electronic Financial Information System (a software system)
EFNIM	Evolutionary Fuzzy Neural Inference Model
EIS/EIR	Environmental Impact Statement /Environmental Impact Report
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
FONSI/ND	Finding Of No Significant Impact/Negative Declaration
IEC	International Electrotechnical Commission
IRI	International Roughness Index (for pavements)
ISO	International Organization for Standardization
LRT	Light Rail Transit
MAP-21	Moving Ahead for Progress in the 21st Century, US Public Law 112-141
MAS	Multiple Award Schedule
MRA	Multiple Regression Analysis
NCHRP	National Cooperative Highway Research Program
NEPA	National Environmental Policy Act
NRMCA	National Ready Mix Concrete Association
OMB	Office of Management and Budget
P2SL	Project Production Systems Laboratory (a research laboratory at the University of California, Berkeley)
PA&ED	Project Approval and Environmental Document
PBCM	Process-Based Cost Modeling
PCC	California Public Contract Code
PDF	Probability Density Function
Phase K	The project initiation documents (PID) phase of Caltrans projects
Phase 0	The Permits and environmental studies (a.k.a., PA&ED) phase of Caltrans projects
Phase 1	The Plans, specifications, and estimates (PS&E) phase of Caltrans projects
Phase 2	The right-of-way operations (RWO) portion of the right-of-way phase of Caltrans projects

Phase 3	The construction engineering (CE) portion of the construction phase of Caltrans projects
Phases 4 and 5	The construction capital (CON) portion of the construction phase of Caltrans projects
Phase 8	Payments to local government agencies for work on Caltrans projects
Phase 9	The capital portion of the right-of-way phase of Caltrans projects
PID	Project Initiation Document
PISA	Project Information and System Analysis (a software system)
PJD	Project development
PMBOK® Guide	*A Guide to the Project Management Body of Knowledge*, published by PMI
PMI	Project Management Institute
POC	Point Of Contact
PRSM	Project Resourcing and Schedule Management (a software system)
PS&E	Plans, Specifications, and Estimate(s)
PY	Person Year
PYPSCAN	Person-Year Project Scheduling and Cost ANalyis
R/W	Right of Way
RWO	Right-of-way Operations
SEM	Structural Equation Model
SHOPP	State Highway Operation and Protection Program
SI	*Système International*
SPMIT	Statewide Project Management Improvement Team
STC	Structures Construction
STD	Structures Design
SysML	System Modelling Language
TEA-21	Transportation Equity Act for the 21st Century (TEA-21), US Public Law 105-178
Trns*port	A software system produced by AASHTO
TVD	Target Value Design or Target Value Delivery
TxDOT	Texas Department of Transportation
UCConnect	University of California Center on Economic Competitiveness in Transportation
UK	United Kingdom (reserved ISO two-letter country code. The ISO 3166-1 standard two-letter country code is GB)
US	United States (ISO 3166-1 standard two-letter country code)
USDOD	United States Department of Defense
USDOJ	United States Department of Justice
WBS	Work Breakdown Structure

1 Introduction

This introductory chapter consists of Section 1.1, the background to the research; Section 1.2, the author's motivation in pursuing this research; Section 1.3, the research questions; Section 1.4, the research methodology, and Section 1.5, the dissertation structure.

1.1 Background and relevance

1.1.1 Use of alternative parametric functions in conceptual cost estimating

Infrastructure owners face challenges in setting priorities between potential projects to maintain, rehabilitate, and improve their infrastructure. The estimated cost of each potential project is normally one of the factors that owners use in setting priorities between projects and in developing their long-term maintenance and construction project portfolio. (The projects that an organization selects to work on are collectively the organization's "project portfolio.") Owners face a dilemma: considerable effort is needed to develop accurate estimates of the cost of each project, but this effort will be wasted if the particular project is not selected for the long-term plan. The owners therefore need estimating methods that will enable them to develop reasonably accurate early stage cost estimates without an excessive amount of effort. This early stage is referred to as the "conceptual" and "feasibility" stages, which will be discussed in greater detail in the dissertation.

One factor in the owners' favor is the fact that potential maintenance and rehabilitation projects are normally of similar types in different locations, and also similar to projects that have been undertaken in the past. The same is true of many potential improvement projects. For instance, highway pavement normally needs some form of rehabilitation every 10 years, and highways agencies own many miles of pavement. As an example, the California Department of Transportation (Caltrans) owns 50,000 lane-miles of highway (Caltrans 2015). To provide some form of rehabilitation every 10 years, Caltrans would need to rehabilitate 5,000 lane miles per year. If it maintains a database of its past rehabilitation projects, as most large infrastructure-owning organizations do, that database provides a tool that could be used to create a parametric model for estimating the costs of future pavement rehabilitation project.

Owners need tools to enable them to make the transition from a database of many past projects to a cost estimate for a specific potential new project. This research examines the tools that are available to owners and compares 3 alternative functions for performing early stage cost estimates for infrastructure projects, using data from public agencies in California. Those functions are the linear parametric, common exponential parametric, and modified Cobb-Douglas exponential parametric models.

1.1.2 Pedestrian access facility projects

This research tests the 3 models on 1 common type of project, pedestrian access facility projects on highways. In the United States (US), these projects result, directly and indirectly, from the Americans with Disabilities Act (ADA) that Congress passed in 1990. On highways, they produce three types of improvement: 1. wheelchair ramps at street corners to allow people in wheelchairs to cross streets at designated pedestrian crossings, 2. wheelchair-accessible sidewalks, and 3. audible signals at signalized intersections to inform visually impaired people when a pedestrian signal is in their favor.

The author selected this type of project because they 1. produce small well-defined units (mainly wheelchair ramps), creating the possibility of further research with short turn-around times, 2. have assured funding in California for a 30-year period, 3. do not normally require extensive environmental reviews that could delay projects and introduce large cost variances, and 4. are of interest to agency management, elected officials, and the public.

1.1.3 Serendipitous digression into risk strategy and contracting approaches

As the research progressed, however, it became clear that there was a significant difference between the data from the different agencies that contributed pedestrian access facility project data, and that those differences had their roots in the contracting methods used by the agencies. As a result, the research developed two threads – the original, and primary, thread on cost estimating, and a subordinate thread on risk strategy and alternative contracting approaches. The subordinate thread will be discussed, but it remains secondary to the primary focus on cost estimating.

1.2 Motivation

This dissertation is intended as an initial contribution to the understanding of project management problems in highway agencies. It stems from the author's personal experience during 36 years performing highway engineering and project management. Since the 1980s transportation departments in the United States (US) have been adopting and attempting to implement the "generally recognized" approaches that are reflected in the American National and International Standards for project management (PMI 1983, 1996, 2000, 2004, 2008, 2013, 2017; ISO 2012). The author has developed a sense that these "generally recognized" approaches do not satisfactorily address the challenges faced by public highway agencies. Some elements of the author's experience that brought him to this research include:

- Senior management in a highway agency: The author retired in 2011 from the position of Division Chief for Project Management and BATA Support in the California Department of Transportation (Caltrans) District 4, Oakland, office. In that position he directed a staff of 170 people who provided project management support, funding, procurement, drafting and CADD services to the project managers and project teams on a $1.5 billion per year capital program.

- Development of statewide project management processes: Prior to his position in Oakland, the author spent 10 years as Chief of the Caltrans Statewide Office of Project Management Improvement, where he led the Statewide Project Management Improvement Team (SPMIT), a team of more than 100 Caltrans employees, divided into several sub-teams that re-engineered each of the processes that Caltrans uses to manage State Highway projects with the goal of managing resources to efficiently and effectively develop and construct those projects (Caltrans 1998). He directed the development of, reviewed, and co-authored Caltrans project management guides.

- Development of statewide project skills training: The author initiated and led the early stages of the development of a comprehensive training program for more than 10,000 Caltrans employees who worked on State Highway projects. This training program received funding from the California Legislature in 2000, with a commitment of $12,000,000 per year for 3 years to provide specific training in each of the 491 work elements performed by state employees to deliver highway projects. This funding provided for 47 full-time state employee instructors and 9 state employees as support staff, together with $6,700,000 for "operating expenses" (outside instructors, facilities, materials, travel, and equipment). The training covered all aspects of state employee work on highway projects and was not limited to project management (Caltrans 2000).

- Development of national standards for highway project management: From 2004 to 2011 the author was one of 4 representatives of the Western States (the states west of the Mississippi, excluding Kansas) on the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee on Preconstruction Engineering Management. In that capacity, he co-authored the AASHTO *Guide for Consultant Contracting* (AASHTO 2008). He also served on the advisory panel for the development of two publications on cost estimating published by the National Cooperative Highway Research Program (NCHRP) (Anderson et al. 2007 and 2009).

- Development of international standards for project management: From 2007 to 2012, the author served as secretary and then convener of the Working Group on Project Management Guidance, a group within the International Organization for Standardization (ISO). The working group consisted of more than 80 project management experts assigned by the National Standards Bodies of 27 countries. It was one of three working groups that, together, wrote the International Standard for project management, ISO 21500 (ISO 2012). From 1999 to 2002, the author also led a 26-person team that wrote the *Government Extension to a Guide to the Project Management Body of Knowledge* (PMI 2002). This team came from 8 countries and represented 17 government departments and 7 consulting firms. Based on numerous literature searches over the past 16 years, it appears that this was the first book to be published on project management in government that was not specific to one agency.

- Development of American National standards: From 1999 to 2001 the author was also a core editorial team member for the PMI's *Practice Standard for Work Breakdown Structures* (PMI 2001) and, from 2002 to 2004, for the *PMBOK® Guide - Third Edition* (PMI 2004). He has contributed to several other PMI standards.

This dissertation is informed by an awareness of the strengths and weaknesses of the work that has gone before by Caltrans, PMI, other organizations, and in the academic literature, as well as by the author's research since 2011, and it is fuelled by a desire to contribute to addressing project management issues on highway projects.

1.3 **Research questions**

1.3.1 Cost estimating

This research aims to contribute to the body of knowledge of project management by answering the following interrelated principal research questions:

1. What are the available parametric cost estimating methods for conceptual and feasibility cost estimating in public highway project portfolios?
2. How do the available parametric cost estimating methods compare in their mathematical best fit, what are their relative advantages and, based upon the importances of advantages, which is preferable?
3. How might the preferred method be used for portfolio-wide validation of cost estimates in a large project portfolio?

1.3.2 Risk strategy and alternative contracting approaches

In a subordinate thread, the author attempts to answer an additional question: What are the root causes of significant differences between agencies in the cost and duration of pedestrian access facility projects developed in compliance with apparently similar procurement statutes?

1.4 **Research methodology**

This research relies on qualitative and quantitative methods to develop statistical relationships between the costs of projects and the outputs of those projects. It follows these steps:

1.4.1 Literature review

The research began by identifying the types of cost estimates and the cost estimating methods that have been described in the literature.

1.4.2 Data gathering

The author obtained 10 years of detailed project cost data for one type of project, pedestrian access facility projects, from Caltrans, and searched the Caltrans as-built database to find pedestrian access facility projects with as-built plans. The plans were examined to identify the pedestrian access facility product outputs.

The author obtained similar data for pedestrian access facility projects completed by cities in the San Francisco Bay Area.

1.4.3 Model development

Using the Caltrans data, the author developed several versions of linear parametric, common exponential parametric, and modified Cobb-Douglas exponential parametric models for Caltrans pedestrian access facility projects.

1.4.4 Data analysis

The author performed a “Choosing By Advantages” (CBA) analysis to compare the models and identify a preferred model.

1.4.5 Test on city projects

The author tested the preferred model on the set of city projects and found significant cost differences between the Caltrans and city projects sets.

1.4.6 Root cause analysis

The author investigated the differences between the Caltrans and city project plans and specifications and spoke to contractors who had submitted bids on projects from both sets in order to find probable causes for the differences in cost between the Caltrans and city projects sets.

1.4.7 Future application

The work in this dissertation is the first step in a larger three-step process to decrease variation and lower costs on large project portfolios. The second step would be to develop statistical data on the expected variation in outcomes. Several reports and studies have indicated that “conceptual” and “feasibility” estimates at the early stage of a project can vary considerably from the actual final costs. These reports and studies include work by AACE (2016), AbouRizk et al. (2002), Flyvbjerg (2011 and 2014) and Flyvbjerg et al. (2003).

The third step would be to introduce approaches to managing costs that might lead to a decrease in variation as well as a lowering of the costs. The first two steps are needed to determine statistically whether the management approaches might produce the desired results.

1.5 Dissertation structure

This dissertation contains the following chapters:

- **Chapter 1: Introduction** provides a background to the dissertation and the author’s work on developing conceptual and feasibility cost estimating methods as part of the author’s ongoing quest to improve project management in public highway agencies.

- **Chapter 2: Literature review** discusses the literature on public and private agency contracting, the 5 types of cost estimates, estimating methods in general, specific methods for conceptual and feasibility estimating, exponential parametric methods, use of estimates in project cost management, forms of specification, and contracting approaches.

- **Chapter 3: Case study: Pedestrian access facilities on public roads** applies the principles from the literature review to one particular common type of highway project, pedestrian access facilities. This chapter includes a motivation for the choice of this type of project, the nature of data obtained, the standards and regulations that affect this type of project, the parametric models that were developed, an analysis of the results, identification of a preferred method, and a conclusion.
- **Chapter 4: Case study 2: Comparison with local agency projects and processes** tests the models developed in Chapter 3 on a set of projects of a similar type developed by local agencies (whereas the projects in Chapter 3 were developed by Caltrans) and finds significant cost differences. The chapter begins to explore possible causes of these differences.
- **Chapter 5: Discussion** follows-up from the literature review in the light of the data found in Chapters 3 and 4 and discusses the implications of the data and the literature for the areas reviewed in Chapters 3 and 4.
- **Chapter 6: Conclusions** closes the dissertation with a summary of the findings, the contributions to knowledge, and a discussion of questions for future research.

2 Literature review

Given this dissertation's focus on project cost estimating methods at the conceptual or feasibility stage, particularly in public agencies in California (versus contracting by private organizations), this review discusses the literature relevant to that topic. To address the subordinate thread on risk strategy and alternative contracting approaches, the review also considers literature on the distinction between forms of specifications and contracting approaches. The review begins, in Section 2.1, by setting the stage in describing public versus private agency contracting. Sections 2.2 through 2.7 then discuss estimate classes and estimating methods. Section 2.2 describes the estimate classes used at different stages of a project. Section 2.3 describes the application of the estimate classes in two public highway agencies and provides two specific examples of conceptual estimates in 1 agency. Section 2.4 describes the broad estimating methods that can be used within each of the estimate classes, given the amount of information available at each stage. Section 2.5 introduces the literature on estimating methods for the conceptual and feasibility estimate classes, Section 2.6 discusses a subset of those methods, parametric estimating methods, and Section 2.7 discusses non-parametric estimating methods. Section 2.8 takes a step beyond the initial estimates and discusses the use of the estimates in the management of project costs. Section 2.9 shifts to a different topic and discusses forms of project specifications that relate to Section 2.10, project contracting approaches. Finally, Section 2.11 provides a synopsis and gap identification.

2.1 Public versus private agency contracting

2.1.1 Background

Miller (2000) gives a specific date for the beginning of modern project management, July 11, 1916, the date on which President Woodrow Wilson signed the Rural Post Roads Act. This was the first law in the US to provide Federal assistance to the states for the construction of roads. It required states to submit plans, specifications, and estimates (PS&E) when requesting funds. Although not specifically required in the Act itself, this resulted in the nationwide standardization of the practice of advertising the PS&E and awarding construction contracts to the contractors who submitted the lowest price, a process now referred to as "design-bid-build." This had been the practice beforehand in some states, but it was not mandated nationwide. For instance, the California legislature had adopted design-bid-build in 1876 under Public Contract Code (PCC) 10120 although it did not use the phrase "design-bid-build". In searches on Google books and Google scholar the earliest uses of this phrase appeared in 1972 (Featherstone 1972, Lamison et al. 1972, Raymond 1972).

Miller may be correct in finding that the 1916 Act was a critical juncture in the adoption of design-bid-build, leading to this becoming the standard public contracting approach in the US, and then being copied by the British Commonwealth, the World Bank and many other countries and public institutions. For a discussion of such critical junctures, see Capoccia and Kelemen (2007). Nevertheless, the California law demonstrates that design-bid-build did not originate in 1916. This contracting approach had been used by at least one US state for 40 years before it was first mandated by the US government. When the US government issued the mandate, states could refer to many prior design-bid-build contracts in preparing specifications, advertising, and managing design-bid-build contracts.

Before the adoption of design-bid-build, boards selected contractors, taking a variety of factors into account. That made it possible for the selection to be subject to favoritism and bribery. Under the new system, however, the selection board opened the contractors' sealed bids and immediately read the bid prices in public. Each contractor could hear and affirm its price, and the process of selecting the lowest bid could be seen to be non-partisan.

Although favoritism in contracting may continue in some government jurisdictions around the world, and from time to time people are charged and convicted of bid-rigging in California, the law in California requires that public contracts be awarded through open impartial competitive selection. This is the case, as well, for all projects in the US that receive Federal funding.

To promote competition, California also places limits on the duration of contracts. No firm is to be permitted to establish a monopoly on any government service, and firms must re-compete for work at regular intervals. Although nothing in the law prevents a firm from winning successive contracts, the repeated awarding of a particular type of work exclusively to one firm raises concerns in California government and is often reported upon unfavourably both in the press and in the Legislature.

In contrast, private contracts have no similar requirements, and it is common for private clients to have long-term preferential relationships with contractors. Such long-term relationships are advocated by firms and organizations that have adopted the "Total Quality Management" philosophy. This philosophy includes Deming's fourth principle of management, "End the practice of awarding business on the basis of price tag. Instead, minimize total cost. Move toward a single supplier for any one item, on a long-term relationship of loyalty and trust" (Deming 1986).

There have been efforts to apply Deming's principles to government in the US, in the form of "multiple award schedules" (MAS). The US government and the State of California both use MAS, although generally only for small individual non-construction procurements. The US government developed multiple award schedules in 2002 in response to the Total Quality Management movement (Deming 1986, US Congress 2002). In this form of contract, an agency pre-qualifies several firms to create a pool of firms that agree to perform work for pre-approved prices that the agency has determined to be reasonable. The agency then selects individual firms for each subsequent project as the need arises. In principle, the MAS allows an agency to form a long-term relationship with a particular firm and re-employ that firm for many small projects over a long period of time. In practice, however, the repeated re-employment of a firm for MAS contracts over time in California has on occasion led to the publication of objections and accusations of favouritism in the press, and the expression of concerns by the legislature.

These concerns are not shared by all governments. In fact, MAS contracts are the preferred and in some cases the only permitted form of contracting for some government services in the United Kingdom (UK), where they are referred to as "Framework" contracts (UK 2015).

Unlike the UK, MAS contracts are not used for public construction work in California. The preference here is for design-bid-build contracts except in a few limited circumstances where the Legislature has given specific permission for the use of alternative forms of contract. For example, the University of California has permission to award construction work through "best value" contracting (permitted under PCC sections 10506.4 to 10506.10, amended most recently by Assembly Bill 1424 of 2017, Chapter 850 of the Statutes of 2017). Similarly, Caltrans has permission from the Legislature to use the construction manager / general contractor procurement method on 24 construction contracts (permitted under PCC sections 6700 to 6708, added by Assembly Bill 2498, Chapter 752 of the Statutes of 2012) (California Legislature 2012).

For the work discussed in this dissertation, however, California law requires the selection of construction contractors through the "low-bid" design-bid-build process that has been the federal norm since 1916.

2.1.2 Transaction costs and Caltrans organization

Caltrans is today's successor to the Bureau of Highways that the California Legislature formed in 1895 (Forsyth and Hagwood 1996). From the start, the legislature chose to contract for the physical construction of state highways using the design-bid-build process that it had mandated in 1876. For all other work, however, they chose to hire state employees. They used state employees to perform all pre-construction work, right of way acquisition, construction engineering, and maintenance on state highways.

On the scale between short-term market-based low-bid contracts with higher transaction costs and long-term employment contracts with lower transaction costs, the State Legislature chose market-based low-bid contracts for the physical construction but long-term employment contracts for all other state highway work.

This arrangement became part of the state constitution in 1934 when the voters passed Proposition 7. This added Article VII to the Constitution which reads, "(a) The civil service includes every officer and employee of the State except as otherwise provided in this Constitution. (b) In the civil service permanent appointment and promotion shall be made under a general system based on merit ascertained by competitive examination." However, the State Courts since 1934 have consistently interpreted this law in the light of its "Argument Pro" on the ballot. That argument said "to prohibit appointments and promotion in State service except based on merit, efficiency and fitness ascertained by competitive examination." The courts have interpreted Article VII as meaning that any work in State service, once performed by civil servants in state government, must always be the exclusive domain of civil servants.

In 2000, the Consulting Engineers and Land Surveyors of California (CELSOC) succeeded in gathering the signatures needed to place an initiative constitutional amendment on the statewide ballot that would exempt engineering and related work from the civil service protections in Article VII. It would permit government agencies to contract with private engineering firms to perform engineering services without regard for whether that work had historically been done by civil servants or whether civil servants might be displaced. This was on the November 2000 ballot as Proposition 35 and it passed with 55.2 percent of the electorate voting "Yes" (Secretary of State, 2000).

Although Caltrans is now permitted to contract-out its engineering and land surveying work, the Legislature has chosen to limit contracting-out to approximately 10 percent of the project work that historically was performed by state employees. The Legislature designates a fixed amount of Capital Outlay Support in each year for work by consultants. In standard State of California terminology "support" refers to the cost of state employee salaries and related work. Capital Outlay Support, a term exclusive to Caltrans, refers to pre-construction work, right of way acquisition, and construction engineering on state highway projects (project Phases 0, 1, 2, and 3, discussed in Section 2.3.1). Table 2-1 provides a summary of the budgetary allocations for Capital Outlay Support and work by consultants in 2015-2016 through 2018-2019.

Table 2-1 Proportion of Caltrans Capital Outlay Support budget allocated to work by consultants (California Legislature 2015, 2016, 2017:2 and 2018, and DOF 2017 and 2018)

Factor	2015-2016	2016-2017	2017-2018	2018-2019
External consultant budget	$227,041,000	$227,041,000	$227,041,000	$266,215,000
Total Capital Outlay Support	$1,696,377,000	$ 1,772,543,000	$1,801,695,000	$2,027,558,000
Consultant $ percentage	13.4%	12.8%	12.6%	13.1%
Consultant FTE	973.0	973.0	973.0	1,031.8
Total FTE	9,703.0	9,703.0	9,512.4	9,802.2
Consultant FTE percentage	10.0%	10.0%	10.2%	10.5%

2.1.3 From the Rural Post Roads Act to project management

The low-bid selection process that began in 1916 placed pressure on contractors to produce work at the lowest possible cost. Contractors who produced work at lower costs than their competitors could undercut those competitors and win contracts. More costly firms would fail to win Federally funded contracts, lose money on contracts where they had submitted bids below cost, or give up competing for Federal work.

In their pursuit of cost savings, Federal contractors began to adopt processes that are now collectively known as "project management." Wilson (2003) finds the earliest references to the use of Gantt charts in projects in 1924 (Alford 1924) and 1925 (Clark 1925). Morris (1994) dates the start of modern project management to the 1930s, although he finds that the term "project management" does not emerge until 1952 (Morris 2013). In these early references, project management emerged in a milieu that had two core characteristics:

1. It developed among private firms competing for government contracts.

2. The competition was for construction work only, the PS&E having been completed beforehand.

Building from these characteristics, the US and International Standards for project management both describe projects as beginning with a charter, or contract, issued by the project sponsor, or owner (PMI 2017 and ISO 2012). In standard project management terminology, a project does not include the work and discussions that occur before the sponsor issues the charter. Conceptual cost estimates are part of the work that occurs before the sponsor issues the charter, and they will be discussed greater detail in Section 2.2.

2.1.4 Public agency project portfolios

Although project management processes may have roots going back to 1916 and the term "project management" may have first appeared in 1952, a new term "project portfolio" has become common in the past few years. This term appeared in the American National Standard for project management for the first time in 2000. That first brief reference reads:

> Project portfolio management refers to the selection and support of projects or program investments. These investments in projects and programs are guided by the organization's strategic plan and available resources (PMI 2000).

This brief reference led, 6 years later, to the publication of an American National *Standard for Portfolio Management* (PMI 2006). Prior to 2000, the term "project portfolio" was rarely used. A search of the Scopus database of journals, books, and conference proceedings found this phrase in the title, abstract, or keywords of only 56 articles before 2000. The earliest use of this phrase is in 1969 in reference to a "research and development project portfolio," and the largest number

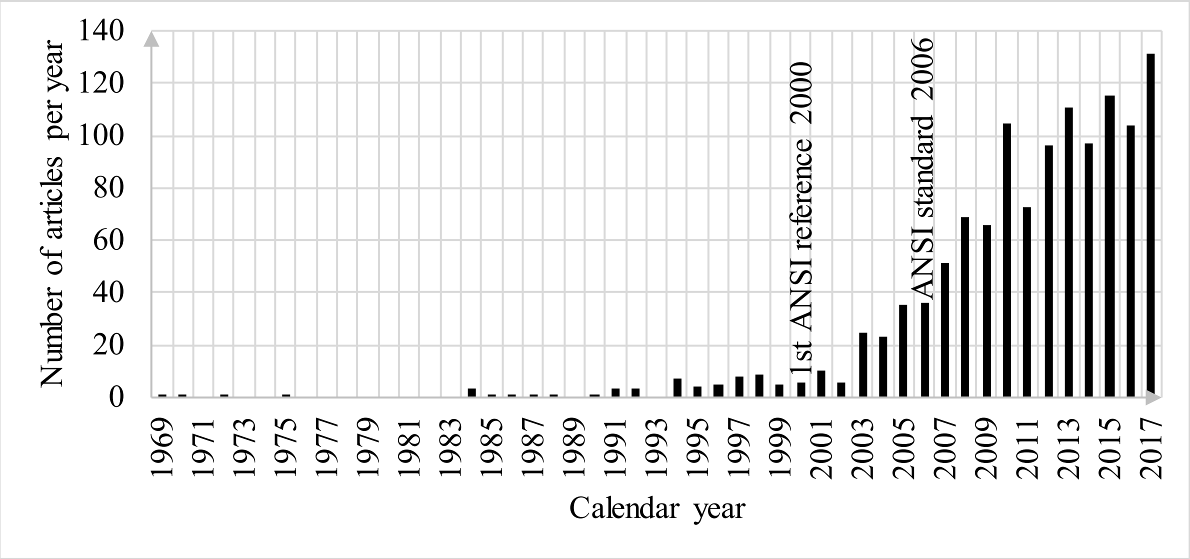


Figure 2-1 Annual number of articles and conference proceedings with the phrase "project portfolio" in their title, abstract, or keywords

of articles referring to “project portfolio” in 1 year was 9 articles in 1998. Figure 2-1 illustrates the growth in interest in project portfolios since 2000.

In the period 2000 to 2017 Scopus finds the phrase “project portfolio” in 1,159 articles, an average of 64 articles per year. Articles on project portfolios have become more frequent over these years, with the largest single-year usage coming in 2017 when Scopus finds 131 articles on this topic.

The Google book database is another source that illustrates the growth in interest in project portfolios. Figure 2-2 charts the data from this database. Like the Scopus data illustrated in Figure 2-1, the Google data reflect an increase in the number of references to project portfolios since 2000 (Google 2018). Unfortunately, the most recent data in the Google charts is for the year 2008. With only two data points after 2006, the Google chart does not provide an indicator of any trend that may have occurred since the 2006 publication of the ANSI standard for portfolio management. By contrast, the Scopus data in Figure 2-1 suggests that there has been a considerable increase in interest since 2006.

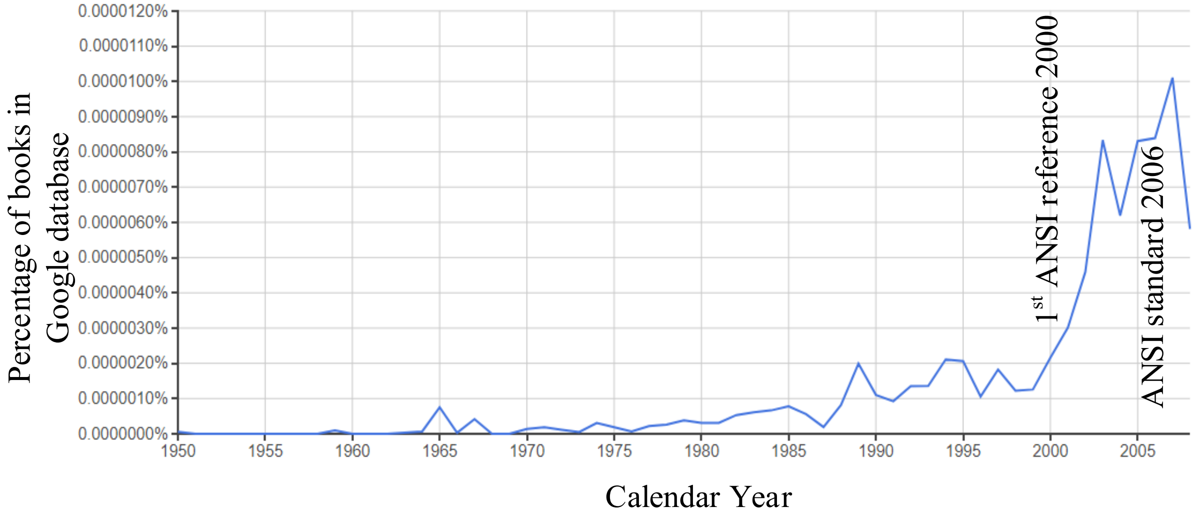


Figure 2-2 Annual use of the phrase “project portfolio” as charted by Google books

The fact that the phrase “project portfolio” has become more common since 2000 does not necessarily point to causation by the use of that phrase in the ANSI standard in 2000. To establish causation, one would need to read the articles and books that appeared after 2000. That additional research is beyond the scope of this dissertation.

The current definitions of the term “project portfolio” are:

- American National Standard: Projects, programs, subsidiary portfolios, and operations managed as a group to achieve strategic objectives. (PMI 2017)

- International Standard: [A] collection of portfolio components (projects, programmes, portfolios, or other related work) grouped together to facilitate their management to meet, in whole or in part, an organization's strategic objectives. (ISO 2015).

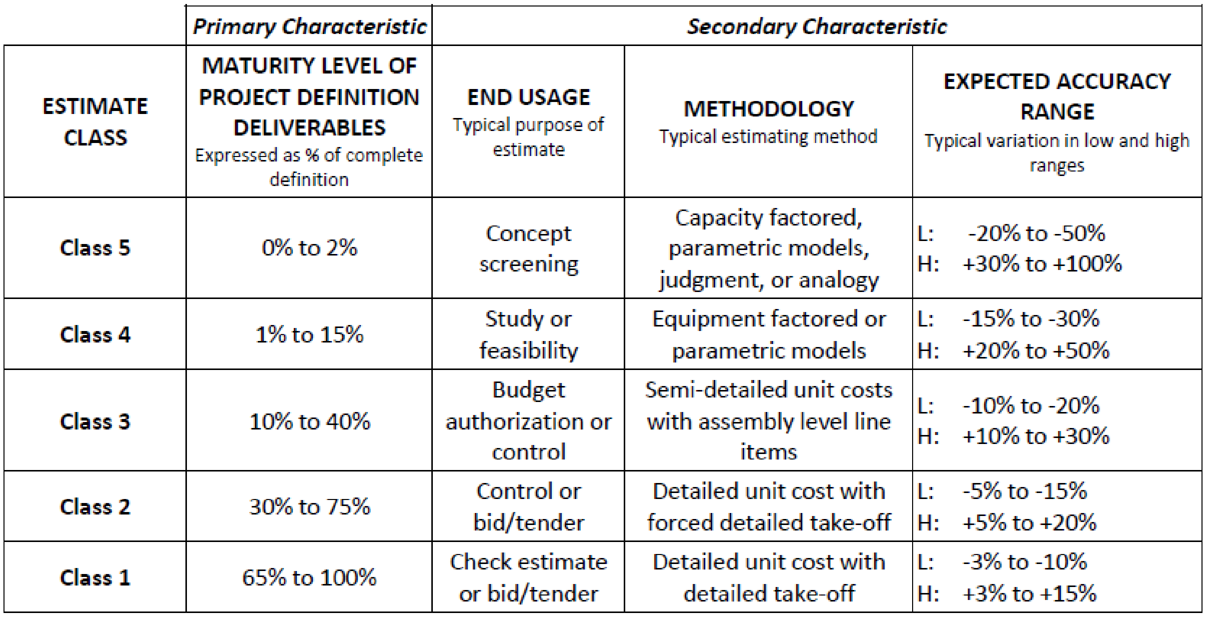
California and England, the two jurisdictions considered in Section 2.3, are governed by elected legislative bodies (the California Legislature and the UK Parliament) that set strategic objectives for public agencies. This is true not only for these two jurisdictions but for many others as well. The strategic objectives determine what projects will become part of the agency's project portfolio, and the legislative body will often establish procedures for project selection. The estimated cost of each project is almost invariably one of the considerations used in the selection of projects that will become part of the project portfolio. As described at the start of this chapter, the sections that follow go into progressively greater detail on project cost estimating beginning, in Section 2.2, with a discussion of the classes of cost estimates.

2.2 Estimate classes and their definitions

2.2.1 AACE International classification

Organizations that own large amounts of infrastructure of a given type often manage large portfolios of projects that are similar to each other in nature. As they plan ahead for the development of these projects, they find a need for tools to estimate project costs. Such tools would be applied at the "conceptual" or "feasibility" stage of project development.

The terms "conceptual estimate" and "feasibility estimate" are in common use among project management professionals (AACE 2016, AASHTO 2013, PMI 2011 and 2017, Ibbs 2015). AACE International (AACE) calls them "Class 5" and "Class 4" estimates as part of a 5-level



	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Figure 2-3 Five AACE Estimate Classes (AACE 2016, Table 1, page 3)

classification of cost estimates, ranging from Class 5, the earliest estimates with the largest variances, to Class 1, with the smallest variances. Each of the 5 classes has different outcomes (Figure 2-3):

- Class 5: Concept screening
- Class 4: Study or feasibility
- Class 3: Budget authorization or control
- Class 2: Control or bid/tender
- Class 1: Check estimate or bid/tender

The American Association of State Highway and Transportation Officials (AASHTO) uses an estimate classification system that is similar to that of AACE (AASHTO 2013). Table 2-2 compares the AACE and AASHTO classes. While similar, they differ in 4 respects:

Table 2-2 Comparison of AACE (2016) and AASHTO (2013) estimate classes

AACE Class	AACE "Maturity Level"	AASHTO "Project Maturity"	AACE "End Usage"	AASHTO "Purpose"	AACE "Expected Range"	AASHTO "Estimate Range"
Class 5	0% to 2%	0% to 2%	Concept screening	Estimate potential funds needed	-50% to +100%	-50% to +200%
Class 5 / 4	N/A	1% to 15%	N/A	Prioritize	N/A	-40% to +100%
Class 4	1% to 15%	10% to 30%	Study or feasibility	Establish baseline cost	-30% to +50%	-30% to +50%
Class 3	10% to 40%	30% to 90%	Budget authorization or control	Manage project budgets	-20% to +30%	-10% to +25%
Class 2	30% to 75%	90% to 100%	Control or bid/tender	PS&E - Compare with bid	-15% to +20%	-5% to +10%
Class 1	65% to 100%	N/A	Check estimate or bid/tender	N/A	-10% to +15%	N/A

1. AASHTO has an intermediate class between AACE's classes 5 and 4 with a maturity level similar to that of AACE Class 4 and an estimate range similar to the expected range of AACE Class 5.

2. AASHTO does not have an estimate class that is equivalent to the AACE Class 1 estimate because the final estimate produced by AASHTO members (state Departments of

Transportation (DOTs)) is the estimate that forms part of the PS&E. That estimate is an AACE Class 2 estimate.

3. The AASHTO project maturity refers to the level of completion of the PS&E, which is the product that Departments of Transportation (DOTs) use to solicit bids. The DOTs are the intended audience of the AASHTO document and from their perspective the project is mature when they complete the PS&E. From the AACE perspective, the project is mature when construction is complete and claims are settled.

4. The AASHTO estimate range compares the estimate with the price submitted by the successful bidder whereas the AACE expected range compares the estimate with the final project cost.

Organizations with large infrastructure programs normally have standard phases, or stages, through which projects must pass on the path to their completion. At each the end of each phase, the organization reviews projects and makes go/no go decisions as to whether to proceed with the project, abandon it, or proceed with a modified version of the project. The end of a phase, at which this decision is made, is referred to as a "stage gate" (AACE 2016, PMI 2017) Section 2.3 describes the phases and the application of the stage gates in two large public agencies, the California Department of Transportation (Caltrans) and Highways England.

While each organization may follow a different path and have more or fewer than the 5 phases implied by the AACE classes, the cost estimate is one of the factors that organizations consider at each stage gate. No organization has unlimited resources, and prudent management requires that the organization use its available resources to achieve its organizational purposes to the greatest extent possible. To this end, the organization will typically calculate the expected cost of the project and compare that cost against the expected benefits or revenue using tools such as a benefit-to-cost ratio or a return on investment calculation. Although they may not use the AACE terminology, organizations will consider the end uses that AACE identifies for their 5 estimate classes:

- <u>"Concept screening" end use (AACE Class 5)</u>: When the organization knows only that a problem or possible opportunity exists, should it initiate any work at all on finding a solution to the problem or on exploiting the possible opportunity? In every organization there are many problems and a vast number of possible opportunities, and the organization cannot work on every one. It must therefore perform some form of screening to decide which problems or opportunities should advance to the first project phase. That screening is the first stage gate. If the organization considers cost estimates as part of this screening, those estimates are "conceptual cost estimates" (AACE Class 5). A conceptual estimate is an estimate of the cost to the customer organization, or organizations, which will pay for the project. Each conceptual cost estimate takes no more than a few minutes to prepare. This small pre-project effort does not incur direct project expenses because 1. the time spent on making a timesheet entry would often equal or exceed the time spent on making the cost estimate itself, and 2. there is no project-specific charge code for the project because 3. that code must be established through a code authorized process which inevitably takes far more time than the few minutes spent on making the estimate. Section 2.3.3 provides two specific examples of conceptual estimates. AACE indicates that Class 5 estimates should typically have an 80 percent confidence level of being with a range from +100 percent to -50 percent (AACE 2016). That is, if the conceptual estimate is $1,000,000, the final cost should be between $500,000 and $2,000,000 with an 80 percent certainty. AASHTO gives an even broader range, stating that the estimate range for conceptual cost estimating when making 20-year plans is from +200 percent to -50 percent (AASHTO 2013). In an example with real projects, AbouRizk et al. (2002) studied 107 municipal road projects, including 84 roadway rehabilitation projects, and found that conceptual estimates deviated from the low bid amount by factors ranging from +192 percent to -93 percent.

- <u>“Study or feasibility” end use (AACE Class 4)</u>: If there is a feasibility study, it is the first phase in which recording direct project expenses might be reasonable. If the concept screening identified a problem, the feasibility study identifies possible solutions to the problem, if they exist. If the concept screening identified an opportunity, the feasibility study determines whether the organization has a reasonable chance of exploiting the opportunity and what alternative approaches it might take to exploiting the opportunity. Regardless of whether it addresses a problem or an opportunity, the feasibility study is intended to be the organization’s tool for deciding whether to proceed to the budget authorization phase. In some cases, the solutions or alternatives are deemed to be self-evident and the organization skips the feasibility study. It would be unusual for an organization not to consider cost as part of the decision to proceed, and cost estimates prepared at this stage are “feasibility estimates” (AACE Class 4). As in the case of a conceptual estimate, a feasibility estimate is an estimate of the cost to the customer organization(s) which will pay for the project. AACE indicates that Class 4 estimates should typically have an 80 percent confidence level of being with a range from +50 percent to -30 percent of the final cost (AACE 2016). AASHTO refers to feasibility estimates as “scoping estimates” when establishing baseline costs for programming, and finds, like AACE, that the range is from +50 percent to -30 percent (AASHTO 2013).

- <u>“Budget authorization or control” end use (AACE Class 3)</u>: Budget authorization occurs when the organization selects a preferred alternative and allocates funds for completing that alternative. The organization may select “no build” as its preferred alternative and not proceed further with the project. To reach this point, the organization must investigate each of the solutions and alternatives identified in the feasibility study in sufficient detail to choose the preferred alternative.

  California environmental law requires an investigation of this nature for every project “which could have a significant effect on the environment of the state” (California Legislature 1970). Every capital project in California falls within the purview of this law. “Capital project” here refers to the construction, expansion, renovation, or replacement of a facility that is permanently fixed in or on the ground, or any change in the terrain. A similar law applies to all capital projects that use US federal funds or that are built on US federally owned land (US Congress 1970). Similar laws exist in other US states and in more than 100 countries (Eccleston 2008). Although it may go by different names, a “budget authorization” phase is therefore a nearly universal requirement for capital projects. Environmental law does not require that cost be considered in choosing an alternative, but it would be unusual for an organization not to do so.

The allocation of funds normally requires a cost estimate, and cost estimates prepared at this stage are "budget authorization estimates" (AACE Class 3). As in the case of conceptual and feasibility estimates, a budget authorization estimate is an estimate of the cost to the customer organization(s) which are paying for the project. AACE indicates that Class 3 estimates should typically have an 80 percent confidence level of being with a range from +30 percent to -20 percent of the final cost (AACE 2016). AASHTO refers to budget authorization estimates as "design estimates" and finds that the range is from +25 percent to -10 percent (AASHTO 2013).

- "Control or bid/tender" end use (AACE Class 2): After completing the budget authorization phase, the organization normally needs to do additional design work before construction can begin. California and US environmental laws, as interpreted by the courts, require that the amount of design performed in the budget authorization phase must be no more than what is needed to select a preferred alternative. The courts have determined that any additional design work could prejudice the choice of the preferred alternative (US District Court for the District of Minnesota 1984). For most public works projects in the US, the additional pre-construction design work is quite extensive because most of the construction work on these projects is awarded through a design-bid-build process in which the construction contract is awarded to the qualified bidder who offers the lowest price. The design must therefore include sufficient detail to establish a "level playing field" to ensure a reasonable expectation that all contractors will have a common understanding of the contract requirements. PCC 10120 illustrates this requirement, "Before entering into any contract for a project, the department shall prepare full, complete, and accurate plans and specifications and estimates of cost, giving such directions as will enable any competent mechanic or other builder to carry them out." The estimates here are "control estimates" (AACE Class 2). As in the case of conceptual, feasibility, and budget authorization estimates, a control estimate is an estimate of the cost to the customer organization(s) which are paying for the project. AACE indicates that Class 2 estimates should typically have an 80 percent confidence level of being with a range from +20 percent to -15 percent (AACE 2016). AASHTO refers to control estimates as "final design estimates" and finds that the range is from +10 percent to -5 percent of the final cost (AASHTO 2013).

- "Check estimate or bid/tender" end use (AACE Class 1): Upon receiving the plans and specifications described in California PCC 10120, in similar laws, or in the practices of organizations that demand firm fixed-prices from contractors, as Caltrans does, the contractors need to perform the most detailed estimates in order to provide a bid to the customer organization. This estimate carries a higher risk than any of the prior 4 types of estimate because the estimator's firm is at risk. If the estimate is too high, in low-bid contracting, the firm will not win the contract. Several repetitions of too-high bids will therefore result in the firm going out of business due to lack of work. If the estimate is too low, the firm will lose money, and several repetitions of too-low bids will cause the firm to run out of money and go bankrupt. These estimates are “bid/tender estimates” (AACE Class 1). In US usage, the word “bid” is more common, while in Commonwealth countries the word “tender” is prevalent. Unlike the previous four estimate classes, the bid/tender estimate is an estimate of the cost to the contractor, and not to the customer organization or organizations that are paying for the project. AACE indicates that Class 1 estimates should typically have an 80 percent confidence level of being with a range from +15 percent to -10 percent (AACE 2016). AASHTO does not recognize an estimate like the bid/tender estimate, probably because state transportation agencies do not perform this class of estimates themselves (see AASHTO 2013). The contractor adds a mark-up to the bid/tender estimate in order to establish a bid/tender price that the contractor will offer to the customer organization with a firm contractual commitment to complete the work for the bid/tender price. If there are no subsequent changes, the bid/tender price will become the cost to the customer organization.

2.2.2 Definition of estimate classes

Although the AACE classification is cited frequently in the literature, it is not unique. For example, Bledsoe (1992) provides a 4-level classification, ranked from least reliable to most reliable:

1. Preliminary or “Ballpark” Estimate.
2. Square Foot Estimate.
3. Assembly or Conceptual Estimate.
4. Final Detailed Estimate.

Bledsoe’s classification can cause confusion because he names the second-most reliable class of estimate the “Conceptual Estimate” whereas among those who use AACE’s classification system this name refers to the least reliable class. In Bledsoe’s case, “conceptual” indicates that design decisions have been made, and the design “concept” is therefore known. Bledsoe further indicates that “conceptual estimate” is a synonym for “assembly estimate.” He then describes the estimating method that AACE defines, as Bledsoe does, as “assembly level.” AACE assigns this method to its Class 3 (budget authorization), the third most reliable class among 5 classes. Bledsoe assigns it to his second most reliable class among 4 classes. Both classification systems therefore place this method near the median reliability in their classification systems.

The term “conceptual estimate” occurs frequently in academic literature, uniformly following the AACE definition, rather than Bledsoe’s definition (Akeel 1989, An et al. 2007, Anderson et al. 2007, AASHTO 2013, Catalina 2016, Choi et al. 2013, Fayek and Rodriguez Flores 2010, Gardner et al. 2016, Holmlin 2016, Hyari et al. 2016, Ji et al. 2010, Jrade 2004, Kim 2011, Kim et al. 2012, Kwak and Watson 2005, Mahamid 2013, Membah 2016, Migliaccio et al. 2013, Molenaar 2005, Peng 2006, Phaobunjong 2002, Phaobunjong and Popescu 2003, Salamah 1989, Siqueira and Moselhi 1998, Sonmez 2004, Trost 1998, Williams et al. 2009, and Zhang et al. 2104). The AACE classification system is cited as a standard by AASHTO (2013), Anderson et al. (2007), Choi et al. (2013), Holmlin (2016), Jrade (2004), Kim (2011), Kim et al. (2012), Migliaccio et al. (2013), Molenaar (2005), Peng (2006), Phaobunjong (2002), Phaobunjong and Popescu (2003), Siqueira and Moselhi (1998), and Trost (1998).

In this dissertation, the following definitions apply:

- Conceptual cost estimate: A cost estimate that is made when a problem or opportunity has been named, before any project work has been done, before any project charging codes have been established, before any possible solutions or alternatives have been identified, and taking at most a few minutes, in order to decide whether to start a feasibility study.

- Feasibility cost estimate: A cost estimate that is made when possible solutions and alternatives have been named, but before any solutions and alternatives have been studied, in order to decide whether to study the solutions and alternatives with a goal of selecting a preferred alternative.

- Budget authorization estimate: A set of cost estimates for the possible solutions and alternatives, including the "no build" alternative, that have been studied in sufficient detail to select one of them, in order to decide whether to assign funds to complete the selected alternative.

- Control estimate: A cost estimate for the selected alternative that is prepared for the sponsoring organization, typically by the designers or by specialist cost engineers or quantity surveyors, at a stage where the plans and specifications are sufficiently detailed to enable a competent contractor to submit a bid that consists of firm fixed prices and then to complete the work with minimal further information from the sponsoring organization or designers.

- Bid/tender estimate: A cost estimate for the selected alternative that is prepared by a contractor, who adds a markup to establish a bid/tender price that they then submit to the sponsoring organization or its agents with a firm contractual commitment to complete the work for that price.

These definitions are consistent with AACE (2011, 2015, 2016, and 2018) and with numerous references in the academic literature.

2.3 Application of estimate classes in public highway projects

2.3.1 Application of the estimate classes in Caltrans

This section and the next describe how the 5 estimate classes align with the project delivery processes of two large public highway agencies, Caltrans and Highways England. This section refers to the former and the following section discusses the latter.

The Caltrans "project lifecycle" consists of the 5 phases. These are illustrated in Figure 2-4 (based on Caltrans 2007). Caltrans plans each phase in its electronic project management system, Project Resourcing and Schedule Management (PRSM), and records the cost of each phase in its electronic accounting system, electronic Financial Information System (e-FIS). PRSM is an installation of the CA PPM software produced by CA Inc. (formerly Computer Associates), and e-FIS is an installation of the AMS Advantage software produced by CGI Group, Inc.

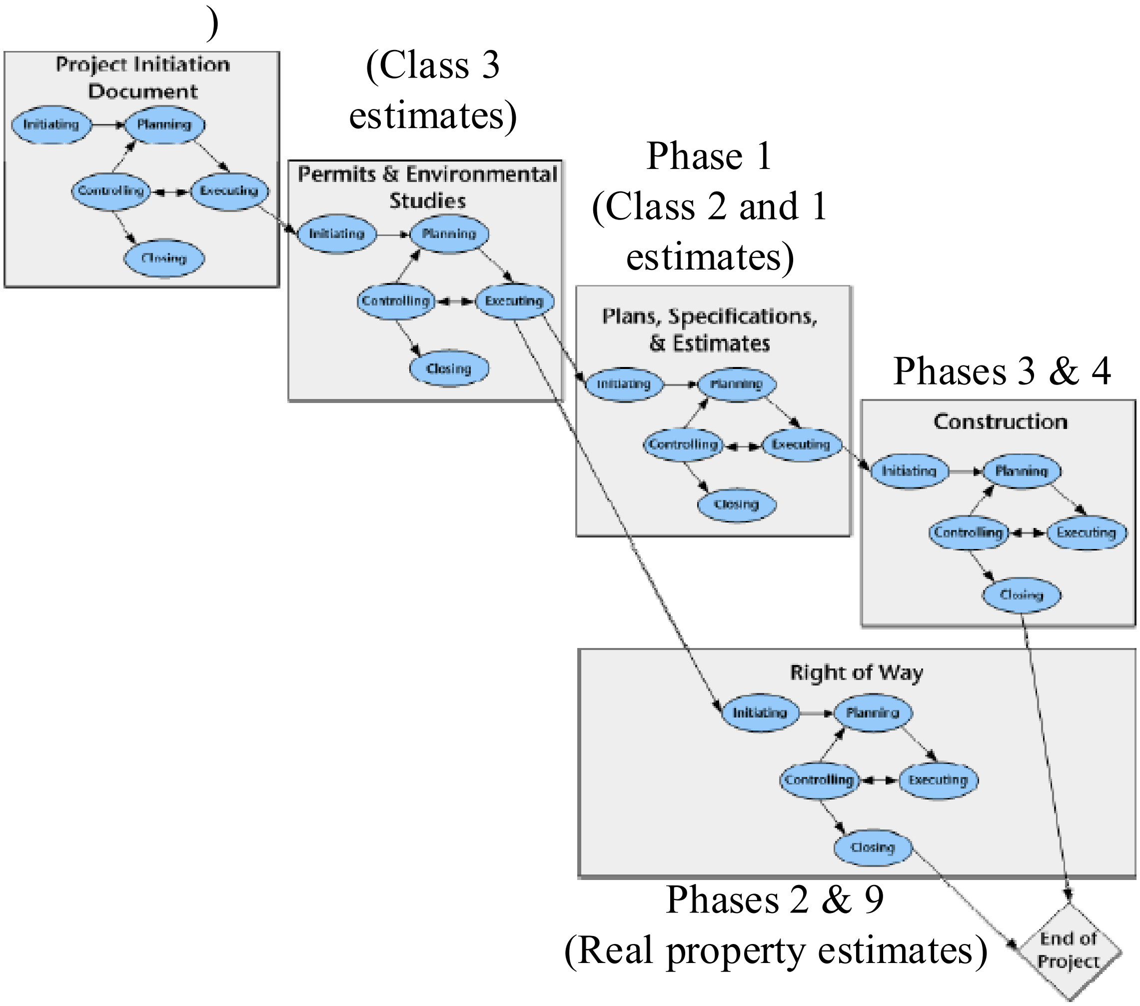


Figure 2-4 Annotated Caltrans "project lifecycle" of project phases (based on Caltrans 2007, page 18).

The levels in the Caltrans work breakdown structure (WBS) differ from the general recognized practice. In a standard WBS, the phases would be "Level 1" of the WBS corresponding to the principal deliverables of the project (PMI 2001). In the Caltrans standard WBS, the principal deliverables of projects are set as "Level 4" of its standard WBS; "Level 3" is the project; "Level 2" is the state highway project portfolio for each Caltrans district; "Level 1" is the entire district (i.e., including work other than state highway projects); and "Level 0" is all of Caltrans (Caltrans 2016:1).

All 5 of the Caltrans phases require cost estimates, and these estimates correspond to the AACE Class 2 to 4 estimates as follows:

- Phase K, Project initiation documents (PID), uses AACE Class 4 "feasibility" estimates. The Caltrans term "project initiation document" is a collective term that Caltrans has adopted to describe several types of documents that are required in California law or Caltrans policy before the California Transportation Commission (CTC) approves the commencement of work on the environmental document.

  The names given to these documents in the law or policy include feasibility study (Government Code 14556.40), project studies report (Government Code 65086.5), project study report (Government Code 14526(c) and 14527(g)), major investment study (Government Code 14526(c) and 14527(g)), as well as several names listed in Chapter 8 of the Caltrans Project Development Procedures Manual: project scope summary report, damage assessment form, project information report, noise barrier scope summary report, and permit engineering evaluation report (Caltrans 2016:2). The purpose of the estimate at this stage matches the description of that for the AACE Class 4, in that it occurs when the organization has identified feasible alternatives and before work is started on examining those alternatives with the intent of selecting a preferred alternative.

  The description of the Class 4 feasibility estimate indicates that some organizations may skip this phase if the feasible alternatives seem self-evident. That was the case in Caltrans before 1989. However, in response to concerns about project cost overruns (Forrest 1987), the Legislature added a requirement in 1989 for Caltrans to prepare a project study report before submitting each project to the CTC (California Legislature 1989). Caltrans created a new phase, the PID phase (Phase K) to manage the development of these reports. Caltrans employee Roger Lehman was responsible for implementing this phase, and the author was among the people whom Mr. Lehman consulted during the implementation process.

- Phase 0, Permits and environmental studies, uses AACE Class 3 "budget authorization" estimates. Caltrans staff sometimes refer to this phase as PA&ED because it ends at the "Project Approval and Environmental Document" milestone. The name "permits and environmental studies" derives from Government Code 14529(b) which describes "permits and environmental studies" as the product of this phase for projects in the State Transportation Improvement Program. Other similar phrases occur in the California constitution's Article XXII, Section 1, which authorizes the State to use private firms for "permitting and environmental studies," Government Code 14529(b) which describes "studies, environmental review, and permits" as the product of this phase for projects in the Traffic Congestion Relief Program, and Government Code 14526.5(c)(1) which describes "Project approval and environmental documents" as the product of this phase for projects in the State Highway Operation and Protection Program. Caltrans considers all these terms to be equivalent to each other and performs the work as "Phase 0." This phase ends when the CTC approves an environmental document and selects a preferred alternative. Unless the preferred alternative is the "no build" alternative, the CTC also authorizes the start of the plans, specifications, and estimates phase (Phase 1).

The description of the Class 3 budget authorization estimate indicates that this phase is a nearly universal requirement for capital projects, due to environmental laws. Consistent with this statement, Caltrans established Phase 0 in 1970 when Congress passed the National Environmental Policy Act (NEPA) and California passed the California Environmental Quality Act (CEQA) (US Congress 1970 and California Legislature 1970).

- Phase 1, Plans, specifications, and estimates (PS&E), uses AACE Class 2 "control" estimates. Caltrans designers or their consultants submit this estimate to the CTC toward the end of this phase with a request for an allocation of construction capital funds. Once approved, Caltrans publishes the plans and specifications and invites contractors to submit bids. Contractors then develop AACE Class 1 "bid/tender" estimates in order to submit their bid prices. The Class 1 estimates are confidential and are not provided to Caltrans. Instead, contractors submit bid prices, as described in section 2.1.1. On some contracts, Caltrans requires the successful contractor to "escrow" their Class 1 estimate calculations at a bank. This escrowed data might give an indication of the contractor's assumptions, and it can be used in the event that the contractor submits a claim for differing conditions and Caltrans disputes that claim.

- Phases 3 and 4, Construction, requires new estimates from Caltrans only for potential construction change orders. If the contractor requests a change, Caltrans may perform a Class 2 estimate to evaluate how reasonable the request is. It is more likely, however, that both Caltrans and the contractor will use the contractor's actual costs as a basis for establishing the amount that Caltrans must pay for the work. The construction phase is recorded in the Caltrans system as if it were two simultaneous phases, 3 and 4, because state law requires that "capital outlay" payments to contractors for construction (Phase 4) be kept separate from the state's other "state operations" (Phase 3). California also refers to "state operations" as "support" – the two terms are used interchangeably. The separation of capital outlay from support is established in law for each year in Section 3 of each annual budget, and as policy in Section 6806 of the State Administrative Manual (DGS 2017).

  The separation of the PS&E phase from the construction phase dates back at least to 1876 when the Legislature established the design-bid-build process as the standard process for awarding public contracts in California (California Legislature 1876). The adoption of the numbers 1 and 3 for these phases probably stems from the Federal regulations that followed the passage of the 1916 Rural Post Roads Act (US Congress 1916). The US government required states to submit invoices for reimbursement as either preliminary engineering, right of way, or construction. In Caltrans, these three federal categories became project phases 1, 2, and 3.

- Phases 2 and 9, right of way, refers to the acquisition of real estate and the relocation of utilities. The cost estimates in Phase 2 are real property estimates and may use different processes from those used in project cost estimating. While real property estimating processes are outside the scope of this dissertation, they are discussed in detail in Anderson et al. (2009).

The right of way phase, like construction, is recorded in the Caltrans system as if it were two simultaneous phases, 2 and 9, because payments to property owners and utilities are "capital outlay" (Phase 9) that must be kept separate from the state's other "state operations" (Phase 2). Right-of-way work is protected under the civil service provisions in Article VII of the California Constitution. This means that work performed by Caltrans right-of-way agents may be performed only by government employees and cannot be contracted out.

The apparently missing phases in the sequence (5, 6, 7, and 8) were established and used by Caltrans at one time, but they were dropped when Caltrans installed the e-FIS system.

It may be noted that this discussion makes no reference to the use of Class 5 "Conceptual" estimates in Caltrans. That is because Class 5 estimates are pre-project estimates, as stated in the Class 5 estimate discussion. The discussion uses an illustration of the Caltrans project lifecycle, Figure 2-4, from the Caltrans *Project Management Handbook* (Caltrans 2007) to illustrate the relationship between phases and estimate classes. Figure 2-5 provides an additional perspective, from the Caltrans publication *How Caltrans Builds Projects* (Caltrans 2011). The first edition of this publication was written in 1999 by the late Gene Berthelsen, who later worked as a project manager in the author's office (Caltrans 1999). The core difference between Figure 2-4 and Figure 2-5 is that Figure 2-4 is confined to work that is charged to projects and is therefore the responsibility of the project manager while Figure 2-5 includes work that is external to the project and affects the project progress. Figure 2-5 therefore includes 3 sets of activities that are not charged to projects:

- Identify need and decision to prepare a PID. This occurs before the start of the project and uses, at this time, AACE Class 5 "conceptual" cost estimates.
- Secure project programming after completion of the PID and before starting the project report and environmental studies. Funding is normally voted on by the CTC, but it may be from sources controlled by local government agencies and sometimes by private firms.
- Secure project approval after completion of the project report and environmental studies and before starting work on the PS&E.

Figure 2-5 illustrates the place of AACE Class 5 "conceptual" cost estimates before the start of Caltrans project work. Section 2.3.2 discusses the use of estimate classes in another agency, Highways England.

2.3.2 Application of the estimate classes in Highways England

This section shifts from a focus on Caltrans to provide a second example of how the 5 estimate classes align with the project delivery processes of a large public highway agency, namely Highways England. This agency is comparable to Caltrans in the products that it produces and manages (freeways and inter-regional roads), the size of the population that it serves, and the size of its budget. Although Highways England follows a different process to reach similar outcomes to Caltrans, its use of the types of estimates is similar, as the following discussion shows.

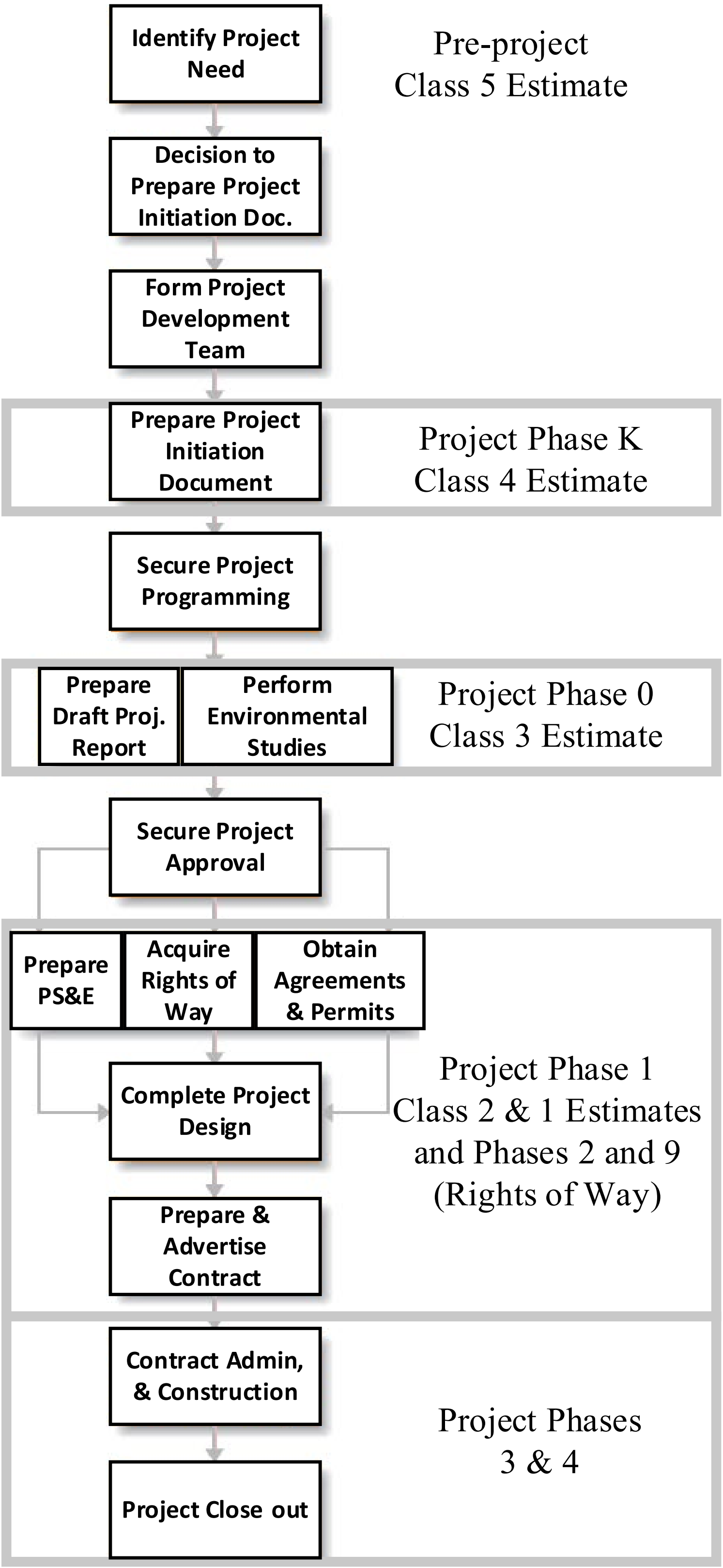
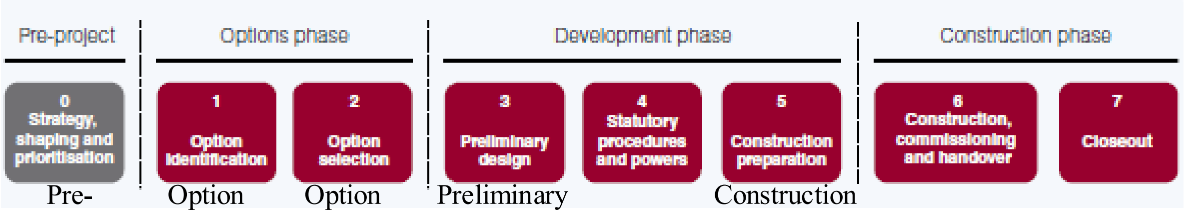


Figure 2-5 Annotated expanded Caltrans project lifecycle (based on Caltrans 2011)

Highways England uses an 8-stage process on its major projects, illustrated in Figure 2-6 (Highways England 2017).

Figure 2-6 illustrates the 8-stage Highways England Project Control Framework (Highways England 2017). The first stage, Stage 0, is not part of the project. The remaining stages, numbered 1 through 7, are project stages.



Pre-project Class 5 Estimate
Option Identification Class 4 Estimate
Option Selection Class 3 Estimate
Preliminary Design Class 2 Estimate
Construction Preparation Class 2 or 1 Estimates

Figure 2-6 Highways England project stages (based on Highways England 2017)

Although Highways England uses different processes from Caltrans, it nevertheless has:

- A pre-project stage, Stage 0, that corresponds to the Caltrans "identify project need" stage which occurs before the start of the project (see Figure 2-5). The focus of this stage, like the corresponding stage in Caltrans, is on identifying the problem and prioritizing which potential projects should proceed to options identification. Estimates at this stage are Class 5 estimates.

- An options identification stage, Stage 1, which corresponds to the Caltrans PID phase (Phase K). The options identification stage produces a "Technical Appraisal Report" similar to a PID with Class 4 estimates.

- An option selection stage, Stage 2, which corresponds to the Caltrans PA&ED phase (Phase 0). The outcome of this stage is a "Preferred Route Announcement" with Class 3 estimates.

- A preliminary design stage, Stage 3. Despite the "preliminary" name, this stage is more detailed than the Caltrans PS&E phase (Phase 1), although it does not result in construction bid documents. The designers provide detailed designs and reports that are subjected to public review and lead to a Development Consent Order (DCO). In interviews with designers, the author found that the documentation for a DCO can run to tens of thousands of pages, far more than the amount of documentation Caltrans would prepare for the PA&ED and PS&E phases combined. Estimates at this stage, however, are Class 2 estimates developed by designers rather than the more detailed estimates produced by contractors.

- A statutory procedures and powers stage, Stage 4, that consists mainly of external reviews and processes, although it may require revisions to some of the documents developed in

Stage 3. This is functionally equivalent to Caltrans obtaining an allocation of money for construction from the CTC, but it appears from interviews that it is more involved and takes longer than the Caltrans and CTC process.

- A construction preparation stage, Stage 5, construction commission and handover stage, Stage 6, and closeout stage, Stage 7. After approval of the DCO, there is a transfer of responsibility from the preliminary designers to the construction team. Although the documentation for the DCO includes a considerable amount of detail, it does not include the construction plans and specifications. Developing these is the responsibility of a new combined team of a designer and contractor that Highways England employs through one of two alternative procurement approaches (Masters 2017):

    a. A team formed by Highways England by selecting a design firm and a construction firm from its Collaborative Delivery Framework (CDF) lists. These two firms then follow Highways England's Early Contractor Involvement (ECI) process in which the contractor works alongside the designer to finalize construction documents. Both the designers and the contractors are paid their actual costs plus a fee, and there is no bidding (Trauner Consulting Services 2007), or

    b. An Alliancing approach in which the designer, contractor, sub-contractors and Highways England agree on a proportional share of the difference between the actual cost and the project budget. The designer, contractor, and sub-contractors are paid their actual costs provided that their combined actual costs do not exceed the project budget, or "guaranteed maximum price." If the combined actual costs exceed the budget, the team completes the work for no additional charge. In the US, this approach is akin to integrated project delivery and the contract is an integrated form of agreement (Thomsen et al. 2010).

From the author's discussions with contractors, it did not appear that a Class 1 estimate is prepared on Highways England projects because there is no bidding. As the contractor is paid its actual costs, the effort required for a Class 1 estimate would be unnecessary.

2.3.3 Two cases of conceptual estimating in Caltrans

Returning to a discussion of cost estimating in Caltrans, this section describes 2 specific examples of Class 5 "conceptual" cost estimates in that agency. The first was described in a letter that the author wrote to his parents on February 4, 1996. It read, in part:

> "I was called into a lunch-time meeting on Tuesday to discuss the increased cost of seismic reinforcement for the seven toll bridges in California. My part was to advise on what the design cost will be. The big shocker is the Oakland-San Francisco Bay Bridge. We originally guessed that we could strengthen this bridge for $200 million, which is 10 percent of the replacement cost. We have had a team of about 100 engineers analysing the bridge and they now think it will be necessary to replace half the bridge. The estimated cost is now $1,300 million. This assumes that the bridge will need to withstand an 8.3 magnitude earthquake on the San Andreas fault. The numbers we put together at lunchtime on Tuesday became the main front-page heading in both the San Francisco Chronicle and the Los Angeles Times on

> Wednesday morning. It's not often that engineers achieve such notoriety." (Blampied 1996, quoted in Frick 2016).

“Tuesday" was January 30, 1996 and at that time the author was Chief of the Caltrans Office of Workload and Data Management, in charge of support cost estimating. The earlier $200 million estimate was a Class 5 “conceptual” estimate for the construction capital cost (Phase 4) only and had been made by the late Jim Roberts in a brief meeting with the author shortly after the 1994 Northridge Earthquake. Mr. Roberts was then the Caltrans Chief Bridge Engineer. The author added $50 million for support (Phases 0, 1 and 3), to get $250 million. That $250 million estimate was a conceptual estimate, and it became part of Senate Bill 146 of 1995 (Maddy) which passed the Legislature on July 17, 1995. SB 146 came before the voters of California on March 26, 1996 as Proposition 192 which provided $2 billion for seismic retrofit, including $650 million for Bay Area toll bridges.

The second arose when Congress was working on the surface transportation bill that became the Transportation Equity Act for the 21st Century (TEA-21) enacted on June 9, 1998, as Public Law 105-178 (US Congress 1998). US Senator Diane Feinstein’s office called and asked urgently for an estimated cost for a “Southern Crossing” of the San Francisco Bay. Again, Mr. Roberts huddled with the author and a few others. We considered a route joining Route 238 in Alameda County to Route 380 in San Mateo County, assumed a “per mile” cost similar to the current estimate for the eastern section of the San Francisco-Oakland Bay Bridge and returned a Class 5 estimate of $7 billion to the senator’s staff within less than an hour. This was essentially a guess, and is described in Section 2.4.1 as the “judgement” method. Senator Feinstein subsequently requested a study of this route (Matier and Ross 2000). The Metropolitan Planning Commission performed the study and found that the crossing would cost at least $8.2 billion (Cabanatuan 2002).

These 2 examples illustrate typical circumstances under which conceptual cost estimates are made for large and unique projects, and the level of effort involved. In both cases they are analogous estimates, which are discussed and more fully described in Section 2.4.1.

2.4 Estimating methods and their relationship to estimate classes

Sections 2.2 and 2.3 describe the 5 classes of estimates and their use in 2 public highway agencies. The distinction between the classes lies in the level of definition of the project deliverables and corresponding uses of the estimates in “stage gate” go/no go decisions as to whether to proceed with the project, abandon it, or proceed with a modified version of the project.

The classes, therefore, refer to the level of definition of the project and the purpose of the estimate. Each of the 5 classes uses different estimating methods, and the differences in methods are driven by the level of definition of the project deliverables. A project at the conceptual stage does not have the detailed information needed for a bid/tender (Class 1) estimate. Conceptual (Class 5) estimates must therefore use different methods than those that are available at the bid-tender stage.

The purpose of this section is to identify and describe the broad categories of estimating methods found in professional project management literature. It will be followed, in the next section, by a review of the specific methods of conceptual and feasibility cost estimating described in academic literature. Those specific methods will be related back to the broad categories to determine whether, or how, they align with the broad categories and the degrees of novelty of the cost estimating methods introduced in the academic literature.

As indicated in Figure 2-3, AACE finds that Class 5 estimates are made by capacity factoring, parametric models, judgment, or analogy. Methods for Class 4 estimates are equipment factoring or parametric models. None of these methods is used for Class 1, 2, and 3 estimates. Those more detailed classes use several forms of unit costs, assembly level line items, and detailed take-offs. Table 2-3 summarizes the estimating methods identified by AACE. It shows 4 estimating methods for Classes 4 and 5, two of which overlap these 2 classes. None of those 4 methods is used for Classes 1 to 3, which use a different set of 3 methods.

Table 2-3 Estimating methods identified by AACE (2016)

	AACE Estimate Class				
Estimating method	Class 1: bid / tender	Class 2: control	Class 3: budget authorization	Class 4: feasibility	Class 5: conceptual
Analogy					✓
Judgment					✓
Parametric				✓	✓
Factoring				✓	✓
Assembly level			✓		
Unit costs	✓	✓	✓		
Detailed take-off	✓	✓			

Taking a broader approach than that of AACE, PMI (2011) indicates that estimating methods fall into just three categories that it refers to as analogous techniques, parametric techniques, and bottom-up techniques. The author finds that the 6 AACE estimating methods nest into the 3 PMI categories, as shown in Table 2-4 and discussed in the paragraphs that follow.

Table 2-4 Nesting of PMI estimating method categories and AACE estimating methods (PMI 2011 and AACE 2016)

PMI estimating method categories	AACE Estimating methods
Analogous techniques	Analogy Judgment
Parametric techniques	Parametric Factoring
Bottom-up techniques	Assembly level Unit costs Detailed take-off

2.4.1 Analogous techniques

PMI defines analogous estimating as "a technique for estimating the duration or cost of an activity or a project using historical data from a similar activity or project" (PMI 2017). It adds (PMI 2011):

> "Analogous techniques, also known as top-down estimating, are used when very little information is available about the project, or the new project is very similar to a previous project or the estimators have great experience with what is going to be estimated. This category of technique results in a total project estimate and is the technique of choice for early estimates where detailed information is not available."

All estimates are based on experience. That experience may be the estimator's personal experience, the experience of people whom the estimator consults (who thereby become co-estimators), or experience recorded in documents about past projects by people who may be unknown to the estimator.

AACE's "analogy" method, as the name implies, falls into PMI's analogous techniques category. In this method, the estimator finds a project of known cost that is similar to the new project being estimated and makes an estimate for the new project in proportion to the project of known cost, perhaps with an adjustment for inflation. The 2 cases of conceptual (Class 5) estimating in Caltrans described in Section 2.3.3 are both analogous estimates.

In AACE's "judgment" method the estimators draw from their experience to develop an estimate. They achieved that experience on prior projects and make analogies, consciously or unconsciously, to those prior projects as they prepare their estimates. The "judgment" method, therefore, is a form of analogous estimating in which the analogies may be unconscious whereas in the "analogy" method, the analogies are conscious.

2.4.2 Parametric techniques

PMI defines parametric estimating as "an estimating technique in which an algorithm is used to calculate cost or duration based on historical data and project parameters" (PMI 2017). It adds (PMI 2011):

> "Parametric techniques use statistical relationships between historical data and other variables (e.g., square meters in construction) to calculate an estimate for an activity cost, duration, or resource."

AACE's "parametric" method, as the name implies, falls into PMI's parametric techniques category. In this method, estimators use an algorithm that has been developed from historical data to make an estimate for the new work. The experience upon which the estimators rely is not their own experience, but rather is experience developed by many people over the course of a large number of prior projects. The resulting estimates are historic mean numbers that may be supplemented by ranges similar to AACE's 80 percent confidence level that a Class 5 estimate will range from +100 percent to -50 percent (AACE 2016), AASHTO's confidence level from +200 percent to -50 percent (AASHTO 2013), and the finding by AbouRizk et al. (2002) that conceptual estimates deviate from the low bid amount by factors ranging from +192 percent to -93 percent.

AACE's "factoring" method refers to projects whose cost is driven mainly by the purchase, installation, and commissioning of new equipment. Examples include factories, power plants, chemical plants, and refineries. AACE (2011) provides this standard factoring equation:

$\mathrm{Cost_B}/\mathrm{Cost_A} = (\mathrm{Cap_B}/\mathrm{Cap_A})^r$ (Equation 1)

Where $\mathrm{Cost_A}$ and $\mathrm{Cost_B}$ are the costs of two similar plants, $\mathrm{Cap_A}$ and $\mathrm{Cap_B}$ are the capacities of the plants and r is an exponent that typically lies between 0.15 and 0.85. The r factor is developed by the equipment manufacturers based on their capacity calculations or experimentation. Equation 1 is a typical parametric estimating equation, similar to other equations that are found later in this dissertation.

2.4.3 Bottom-up techniques

PMI defines bottom-up estimating as "a method of estimating project duration or cost by aggregating the estimates of the lower-level components of the work breakdown structure" (PMI 2017). It adds (PMI 2011):

> "Bottom-up techniques are applied as the estimating tool of choice when the detailed project data becomes available. Using this technique, the expenditure of every resource of every component of the project is estimated as a prelude to rolling up these estimates to the intermediate levels and to the total project. This technique will result in a transparent and structured estimate for the project, which can be tracked and managed."

Table 2-4 lists three bottom-up methods: assembly-level, unit costs, and detailed take-off. AACE indicates that the "assembly-level" method is used in Class 3 (budget authorization) estimates; the "unit costs" method is used in Class 1 (bid/tender), 2 (control), and 3 estimates; and the "detailed take-off" in Classes 1 and 2.

As an anecdotal aside that speaks to the use of such estimates the author began his career in 1975 assisting in the preparation of Class 1 estimates for Dorbyl Stuart Construction, a firm that was acquired in the 1990s by LTA Construction which, in 2000, became part of Aveng, one of the largest construction companies in Southern Africa. The author later prepared many Class 2, and Class 3 estimates while employed by SNA Civil and Structural Engineers, the City of Torrance, and Caltrans.

In AACE's "assembly-level" the estimator finds prices for new equipment "assemblies" that are to be incorporated into the planned facility. AACE describes an "assembly" as the parts or components and subsystems needed to fabricate a manufacturing product (AACE 2018). Like AACE's "factoring" method, "assembly-level" estimates refer to projects whose cost is driven by the purchase, installation, and commissioning of new equipment, such as factories, power plants, chemical plants, and refineries. The difference from the "factoring" method is that the numbers and sizes of the equipment assemblies are now known. In the "assembly-level" method, the estimator will generally consult with the equipment manufacturer, and obtain prices directly from the manufacturer, to develop the estimate.

Bledsoe (1992) defines an assembly thus: "Assemblies group the work of several trades or disciplines and/or work items into a single unit for estimating purposes." As noted in Section 2.2.2, Bledsoe used the name "conceptual estimate" as a synonym for "assembly estimate." Bledsoe continues, "Some cost estimating software products use the name "work package" instead of assembly." While the AACE and Bledsoe definitions of "assembly" are slightly different, both definitions function as work packages as that term is defined by PMI, "The work defined at the lowest level of the work breakdown structure for which cost and duration are estimated and managed" (PMI 2017).

Turning to a second bottom-up estimating method, in AACE's "unit costs" method, the estimator calculates quantities of items that are part of the project (the work packages) and multiplies the quantities by costs per unit. The estimate takes the form of equation 2:

Cost = $\sum_{i=1}^{i=n} b_i X_i$ (Equation 2)

Where b_i is the cost per unit of item i and X_i is the quantity of item i. Unit cost estimating becomes feasible only when the design is sufficiently advanced to calculate accurate quantities for each item associated with a cost. Since the advent of systems for building information modelling (BIM) and computer-aided design and drafting (CADD), features have been incorporated into these systems to enable the computers to generate the quantities, a process sometimes referred to as "model-based quantity take-off" (Nguyen 2010). In Class 2 (control) and 3 (budget authorization) estimates, the unit cost is normally obtained by reviewing the unit costs submitted by bidders on recent projects and selecting a unit cost that was submitted for a project where the item work appears, to the estimator, to be similar to the work to be estimated. The estimator may add an inflation factor and location multiplier. The unit costs are therefore forms of analogous estimate at a detailed level.

In AACE's third bottom-up method. "detailed take-off," the estimator considers the unit costs in greater detail than is the case for the "unit cost" method. In this greater detail, the unit costs consist of two elements:

1. Materials and equipment that will be incorporated into the facility and that will remain once the project is complete. The equipment here is "permanent" equipment to distinguish it from:

2. Labor and equipment used to complete the project, measured as hours worked multiplied by hourly cost. The equipment here is "rented" equipment in contrast to the "permanent" equipment above. Rented equipment may be owned by an equipment rental company or by the organization that is performing the project. In both cases, it is normally charged to the project at a rental rate, which would be an external rental rate for equipment rented from rental companies and an internal rental rate for owned equipment.

The cost of materials and permanent equipment is determined by the prices offered to contractors by suppliers who, in turn, have their own detailed estimates in which they make estimates of their costs of materials and permanent equipment, on the one hand, and their labor and rented equipment, on the other. The supplier's internal detailed estimate is of no concern to the contractors to whom they submit their prices. Under the common law principle of promissory estoppel, a contractor can enforce a supplier's price if it was knowingly submitted to be part of the contractor's bid. If a supplier or sub-contractor gives prices to a contractor for materials, equipment (both permanent and rented), or portions of the project during the bidding process, the contractor can rely on those prices. Uncertainty about those portions of the project, and their associated risks, is transferred from the contractor to the supplier or subcontractor.

The hourly costs of labor is determined by collective bargaining agreements, if such exist. Otherwise the estimator may use the firm's current labor rates and apply inflation factors.

As the risks for materials and permanent equipment as well as for hourly rates for rental equipment and labor are transferred, to a significant extent, to suppliers and employees through subcontracts and agreements, the principal uncertainty in the "detailed take-off" method is in the estimated hours of labor and rented equipment. As with the unit costs, these are analogous estimates at a detailed level – the estimator produces an estimate of the hours needed based upon his or her experience, often referring to the actual hours expended on similar projects. The estimator may also refer to databases of average hours needed, which may be internal databases maintained by the estimator's firm or publicly-available subscription databases such as that maintained by RS Means (rsmeans.com).

Whether the estimator uses the "unit cost" or the "detailed take-off" method, the higher accuracy of the detailed analogous estimates used in Class 1 (bid/tender) estimates as compared with the less detailed analogous estimates for Class 5 (conceptual) estimates has its roots in the combined standard deviation of independent variables:

$\sigma_{(a+b+c+\ldots n)} = (\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \ldots . \sigma_n^2)^{0.5}$ (Equation 3)

Sections 2.2 through 2.4 have described the generally recognized terms, concepts, and practices used by practitioners of project cost estimating. Sections 2.5 through 2.7 turn the focus to the academic literature that is specifically concerned with the methods used to perform conceptual and feasibility estimating. Sections 2.5 through 2.7 narrow the focus in three respects. First, they focus on academic literature (with a few digressions to discuss some applications that are or were in daily use by departments of transportation). Second, they focus on conceptual and feasibility estimating and, third, they focus on methods.

2.5 Sources of literature on conceptual and feasibility estimating methods

2.5.1 Estimating methods on highway projects

Barakchi et al. (2017) provide a review of the literature on cost estimating methods for transportation projects. They find that parametric estimating is the most frequently used. The next most frequent approaches are artificial neural networks (ANN) and unit cost. The literature on cost estimating that follows in this literature review differs from Barakchi et al. in two respects. First, this literature review is concerned only with cost estimating at the conceptual and feasibility stages (AACE Class 4 and 5 estimates) whereas Barakchi et al. considered all phases.

Second, this literature review is drawn from work on all types of civil engineering facilities and is not limited to transportation projects.

Nevertheless, Barakchi et al. (2017) do provide an initial categorization of cost estimating methods. That characterization assists in informing the literature review that follows.

2.5.2 Literature review of articles and conference papers on conceptual and feasibility estimating methods

This section describes the method that the author used to find articles and conference papers on conceptual and feasibility estimating methods, and summarizes the numbers, years, and topics, addressed by those articles and papers. This section provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1.

In order to find literature on conceptual estimating methods the author consulted the Scopus database, which claims to be "the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings." The author queried this database using these criteria:

- Title, abstract or keywords include one of the phrases "conceptual cost estimate" or "conceptual cost estimating" or "conceptual cost estimation" or "feasibility cost estimate" or " feasibility cost estimating" or " feasibility cost estimation"
- And the subject area is "Engineering"
- And the document type is "Article" or "Conference proceeding"

This search produced a list of 68 papers. When the same search omitted the 3 feasibility cost estimate options it had produced a list of 67 papers. It therefore appears that references to the 3 feasibility cost estimate options are rare, and that articles and conferences are far more likely to refer to conceptual cost estimates than to feasibility cost estimates.

The author examined the abstracts of the 68 papers to determine whether they focus on conceptual cost estimating methods. If there was doubt, he reviewed the document itself. From this search, the author determined that 34 of the papers do focus on conceptual or feasibility cost estimating methods. The remaining 34 papers addressed a variety of topics including accuracy assessment, building information modelling, the process of estimating, knowledge transfer between team members, probability densities, quality assessment, real estate cost estimating, firm-specific processes, reliability indices, scope modelling, software macros, and cost estimates in general. Because the focus of this review is on cost estimating methods, these 34 papers were excluded from further consideration.

The author reviewed and categorized the 34 papers that focus on conceptual cost estimating methods. The following discussion provides more detail on those reviews. The author found that the papers fall into 5 categories:

- Artificial neural networks (ANN): 18 papers.

- Comparison between ANN and linear parametric estimates: 5 papers.
- A hybrid of ANN and linear parametric estimates: 2 papers.
- Linear parametric estimates: 5 papers.
- Case-based reasoning: 4 papers.

Figure 2-7 displays the distribution of the 34 papers by year of publication. Rao et al. (1993) produced an early proposal for ANNs without actually developing an ANN. The Scopus database has no further papers on ANNs for several years. This may indicate that the database is lacking in material from the 1990s or that the technology to develop ANNs was not yet available.

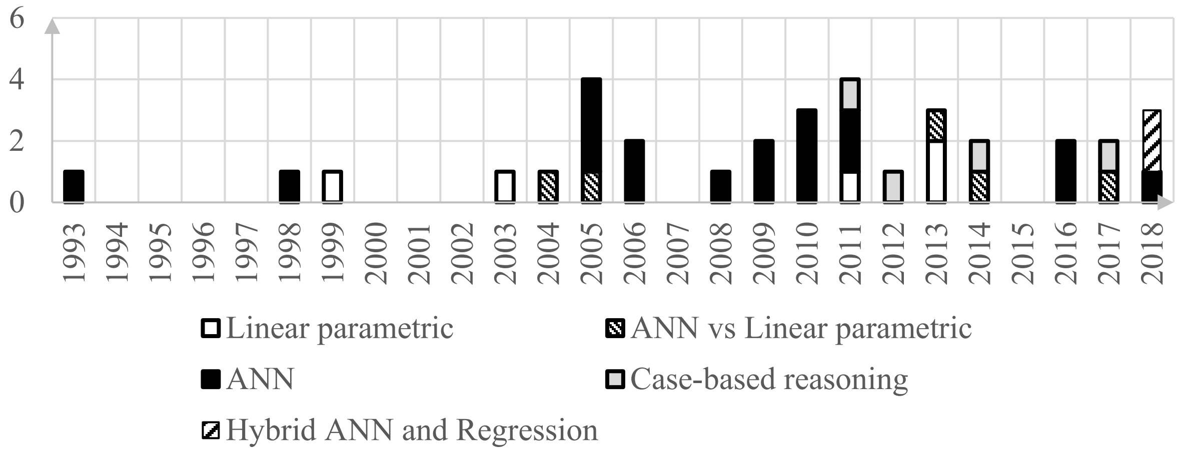


Figure 2-7 Distribution of papers on conceptual cost estimating methods by year

Two further papers appear later in the 1990s, followed by a steady flow of papers beginning in 2003, although only 4 papers or fewer per year. The focus of most papers from 2004 to 2011 was on particular uses of ANNs and on comparisons between ANNs and their linear parametric alternatives.

From 2012 onwards, most research appears to have moved to case-based reasoning rather than ANNs, although the number of papers per year was fewer than the number of papers on ANNs during their heyday.

An alternative perspective on the data in Figure 2-7 is to consider the numbers of citations. The 34 papers, between them, have been cited 208 times. Figure 2-8 displays these citations by the year in which each paper was published.

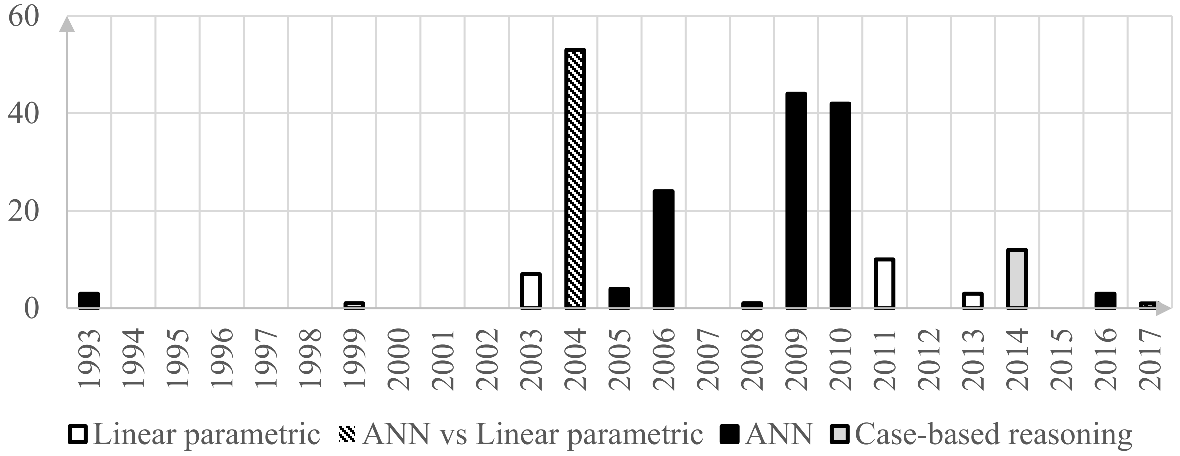


Figure 2-8 Distribution of citations on conceptual cost estimating method papers by the year in which each paper was published

The largest numbers of citations of 1 paper are of Sonmez' (2004) comparison of linear parametric models with an ANN, using a data set of 30 continuing care retirement community projects in the US (Sonmez 2004). That paper has been cited 53 times, making 25 percent of all the citations on the 34 papers.

The largest number of citations of 1 first author are the 83 citations of the 4 papers by Cheng et al. (2005, 2009:1, 2009:2, and 2010).

The numbers of citations can be expected to increase in the future, and the low numbers of citations of the more recent papers might not be significant.

Nevertheless, this search indicates that the literature focuses on 3 types of estimates, 1 comparison, and a hybrid – linear parametric, ANNs, comparisons between ANNs and linear parametric, case-based reasoning, and a hybrid of ANN and parametric. Sections 2.6.2, 2.7.1, 2.7.2, 2.7.3 and 2.7.4 discuss these 3 types of estimate. the comparison, and the hybrid.

2.5.3 Literature review of doctoral dissertations on conceptual estimating methods

This section describes the method that the author used to find doctoral dissertations on conceptual and feasibility estimating methods, and summarizes the numbers, years, and topics, addressed by those dissertations. This section provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1.

In order to find further literature on conceptual estimating methods the author next consulted the ProQuest database of doctoral dissertations. The author queried this database using these criteria:

- One of the phrases “conceptual cost estimate" or "conceptual cost estimating" or "conceptual cost estimation" or “feasibility cost estimate" or " feasibility cost estimating" or " feasibility cost estimation" occurs anywhere in the dissertation.
- And the subject is “Civil Engineering.”

This search produced a list of 31 doctoral dissertations. The author examined the abstracts of these dissertations to determine whether they focus on conceptual cost estimating methods. From this search, the author determined that 9 of the dissertations include the development of conceptual cost estimating methods. The remaining 22 dissertations addressed a variety of topics including risk, wind loading, procurement, sustainability, engineering management, value management, materials management, strategic estimating, recycled materials, project duration, road design, target value design, reuse of waste, reservoir capacity planning, reducing uncertainty, sustainable development, integrated bridge delivery, data management, and decision making.

The author read and categorized the 9 dissertations that include the development of conceptual cost estimating methods. He found that the dissertations fall into 5 categories:

- Development of an artificial intelligence expert system or a knowledge-based system: 2 dissertations.
- Development of linear parametric estimates: 4 dissertations.
- Development of a two-phase estimate using a Cobb-Douglas exponential parametric estimate in the first phase and a linear parametric estimate in the second phase: 1 dissertation.
- Development of a common exponential parametric estimate: 1 dissertation.
- Development of Cobb-Douglas exponential parametric estimates: 1 dissertation.

The 9 dissertations, their data sets, types of model, and variables, are summarized in Table 2-5.

The objectives of the 9 dissertations are quoted next. These quotes begin with the most recent dissertation and are sorted in chronological sequence with the intent of determining whether there is a progression of ideas. From a review of these objectives, there does not appear to be a progression of ideas in which dissertations build upon each other. The discussion below lists which dissertations referred back to prior dissertations in this set. Rather than exhibiting a progression of ideas, the distinction between dissertations lies in the domains from which they selected their data sets.

Table 2-5 Summary of dissertations on conceptual and feasibility cost estimating

		Model Type				Variable Types Used		
Dissertation	Data set used	Expert system	Linear	Exponential	Cobb-Douglas	Outputs	Project Characteristics	Process
Akeel (1989)	Defence ministry buildings in Saudi Arabia (number not provided)				✓	✓	✓	
Salamah (1989)	240 Defence ministry buildings in Saudi Arabia	✓				✓	✓	
Serpell (1990)	none	✓					✓	
Trost (1998)	67 "process industry" projects		✓					✓
Phaobunjong (2002)	168 building projects in Texas		✓			✓		
Peng (2006)	Structures on 1,118 state highways projects in Texas		✓		✓		✓	
Catalina (2016)	54 light rail projects in the US			✓			✓	
Holmlin (2016)	5 Student Health Centers in the US		✓			✓		
Membah (2016)	79 tunnels in North America		✓				✓	
This dissertation	39 state highway and 10 local street pedestrian access projects in California		✓	✓	✓	✓		
Number of dissertations (10 max.)		2	6	2	3	5	6	1

Membah (2016):

> "The prime objectives of this study are to develop novel parametric cost function(s) and quantify associated risks to address the uncertainty and risks associated with transportation tunnel projects."

Holmlin (2016):

> "The objective of this project is twofold; first, to develop a cost model to allow the pre-design cost estimate of a new 23,000SF student health center at the College of William and Mary. Second, to estimate the duration of construction of this project."

Catalina (2016):

> "The objective of this research is to develop a capital cost estimating methodology for the LRT [Light Rail Transit] mode that can be replicated reliably in a full range of urban environments."

Peng (2006):

> "The primary purpose of this research was to improve the preliminary cost estimating procedures at TxDOT."

Phaobunjong (2002):

> "The main objective of this research is to develop an accurate and practical method of systematic conceptual cost estimating that can be used by organizations involved in the planning and execution of building construction projects."

Trost (1998):

> "The first objective was to develop a procedure to score an early estimate in order to assess the thoroughness, quality and accuracy of the estimate."

Serpell (1990)

> "The general purpose of this research is to identify the problems and needs of conceptual estimating and develop the conceptual framework of a methodology for improving and measuring its expected performance, based on intelligent utilization of conceptual estimating knowledge and expertise. This methodology will hopefully assist estimators to carefully estimate the cost of a project at the conceptual stage and enable them to assess the expected accuracy of their estimates."

Salamah (1989):

> "A primary goal of this research is to confirm the applicability of expert systems technology to the estimate field by establishing the essential rules and heuristics for building conceptual cost estimates, rules and heuristics gained by experts in the field through years of experience and textbook knowledge."

Akeel (1989):

> "There are three objectives in conducting this research. The first is a basis for effective support for construction management decision making. The second objective is to explore the issues that arise in incorporating data base management systems with statistical packages. The third objective is to demonstrate methods for collecting, screening, coding, and analyzing historical building data for the purpose of conceptual estimating."

In addition to their direct contribution to this literature review, each of the 9 dissertations also provides an indirect contribution. This is because each dissertation includes an extensive literature review. The author can therefore not only draw on his own literature searches but also on the literature searches of these 9 dissertation writers. As one would expect, many of the dissertation writers find and cite common sources. Because the author has examined and drawn from all of these literature searches, it seems unlikely that he has missed many documents that are significant to his search for conceptual and feasibility cost estimating methods.

The linear parametric, Cobb-Douglas, and ANN estimates developed in the 9 dissertations are discussed in Sections 2.6.2, 2.6.6, and 2.7.1 respectively.

2.6 Parametric conceptual and feasibility estimating methods

The purpose of this section and Section 2.7 that follows is to identify the conceptual and feasibility estimating methods that are discussed in the literature, the types of facilities for which the cost estimates are performed, the types of input variables, the frequency of occurrence of each method, the claimed advantages of each method, the changing trends in the literature (i.e., whether some methods have been written about more or less frequently over time). The authors' claims are not evaluated for two reasons. First, a meaningful evaluation would require one to repeat their experiments and test their findings and, second, such an evaluation is not the intent of this section. This section is intended to provide a broad context for Section 2.7, which focuses only on exponential methods. A comparative evaluation of exponential methods versus the methods described in this section is one of the ideas for future research discussed in Chapter 6.

It should be noted that the estimating methods described here and also in Section 2.7 provide the "best fit" line estimates only. They do not provide upper and lower confidence limits. As noted in Section 2.2.1, AACE indicates that conceptual (Class 5) estimates typically have an 80 percent confidence level of being with a range from +100 percent to -50 percent (AACE 2016) and AASHTO gives an even broader range, +200 percent to -50 percent (AASHTO 2013). Similarly, AACE indicates that feasibility (Class 4) estimates should typically have an 80 percent confidence level of being with a range from +50 percent to -30 percent (AACE 2016) and AASHTO uses same range (AASHTO 2013). There is a body of literature that explores and tests these ranges, but that is not discussed in this dissertation. Upper and lower confidence limits are proposed as future research in Chapter 6.

Parametric estimates are the most frequent form of cost estimate identified by Barakchi et al. (2017) who say:

> "using parametric method is claimed to be very common in the feasibility and prefeasibility phases because of the powerful mathematical aspect, simplicity in application and easiness in obtaining the information needed."

Hamaker (1987) traces the origins of parametric estimating to the Rand Corporation in the late 1950s, saying:

> "The application of statistical modeling techniques to the problem of estimating cost was first methodically pursued and documented by the Rand Corporation in the late 1950s in attempts to predict military hardware cost at very early phases of the design."

2.6.1 Exponential relationship between cost and output

As noted in Section 2.4.3, project costs consist of materials and permanent equipment, labor, and rented equipment. With regard to labor, Wright (1936) postulated the “Wright Curve” as a predictor of labor cost in production:

$F = N^X$ (Equation 4)

Where F is the labor cost to produce the Nth identical unit, and X is a learning factor such that $0 < X < 1$ (Wright 1936).

In Wright’s work, the formula refers only to labor productivity. He deals separately with costs of materials and overhead costs, and provides no estimating method for equipment, whether permanent or rented.

Delionback (1987), writing in Stewart and Wyskida (1987), provides an extensive discussion of Wright’s work with a particular focus on the range of coefficients for the “X” factor in equation 4. Hamaker (1987), in the same book, describes how parametric estimating and the Wright curve came together, saying:

> “The technique [statistical modelling] was quickly married with that of learning curve theory to estimate entire design and production run costs for hardware that was still in very conceptual design stages of the drawing board.”

Due to work by Wright, Delionback, Hamaker, and others, it is widely accepted that workers exhibit a “learning curve,” in which they increase productivity with experience, and that this increase follows an exponential function. While the exponential curve has been used many times, the value of “X” is uncertain.

Henderson (1968) restates Wright’s Curve as “Henderson’s Law.” This reads “Costs decline by some characteristic amount each time accumulated experience is doubled.” Henderson found that the characteristic decline is 20-30 percent each time that production is doubled.

Hax and Majluf (1982) cite Henderson as their source in restating “Henderson’s Law” as a formula which is essentially identical to Wright’s:

$C_t = C_0 \left(\frac{P_t}{P_o}\right)^{-a}$ (Equation 5)

Where C is cost and P is volume of production at times 0 and t respectively.

Using Wright’s terms and formula, $F_0 = N_0^x$ and $F_t = N_t^x$, therefore $F_t = F_0 \left(\frac{N_t}{N_o}\right)^x$. The two formulae are essentially identical with $-a = x$, except that Wright refers to the Nth unit while Henderson refers to volume of production when the Nth unit is produced. Both formulae indicate that productivity increases exponentially, following a curve similar to the exponential ($0 < c < 1$) curve in Figure 2-9.

Economists distinguish fixed from variable costs in production. Fixed costs are incurred irrespective of the quantity produced, while variable costs, as the name suggests, increase with increased production. The Wright Curve describes the variable costs. The combination of fixed and variable costs, then, results in a cost function similar to the exponential curve shown in Figure 2-9, which illustrates all possible mathematical forms of the function

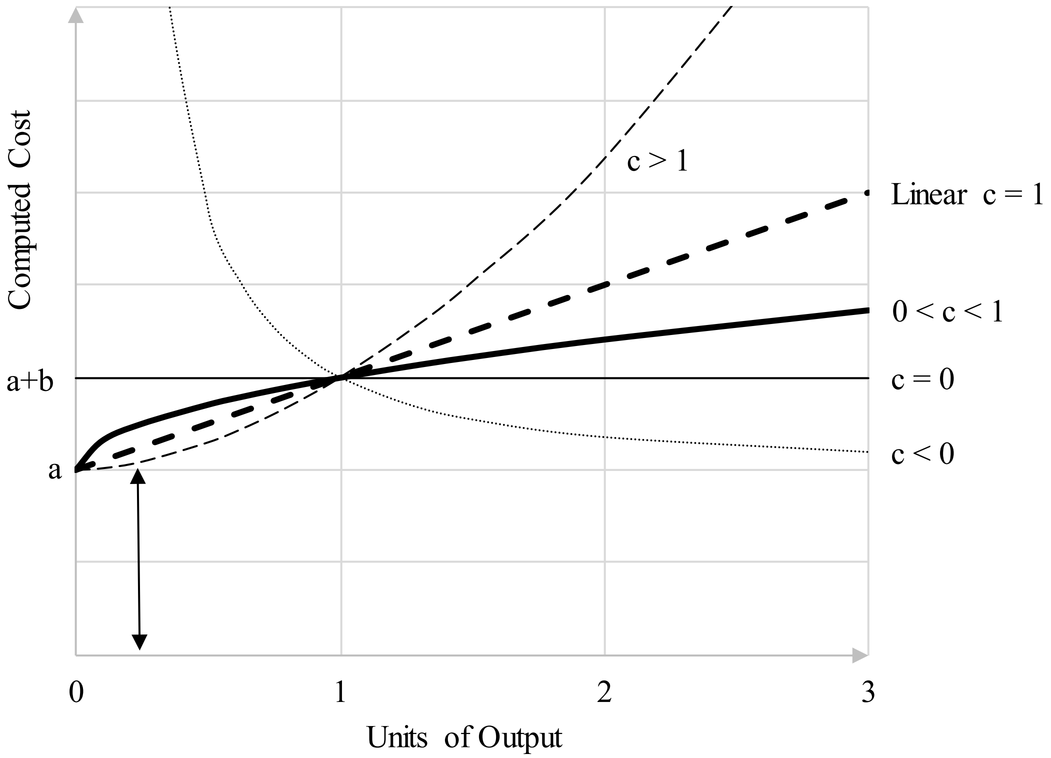


Figure 2-9 Forms of the function Cost = a + b.X^c where X is units of output

Cost = a + b.X^c (Equation 6)

where X is units of output and a, b, and c are constants, and X > 0. Figure 2-9 exhibits these characteristics:

- The value “a” in Figure 2-9 corresponds to the fixed cost. If c > 0 and X = 0 then cost = a.
- If c > 0 and X = 1 the cost = a + b.
- Although it is mathematically possible for c to be less than zero (the c < 0 line in Figure 2-9), this would be illogical because the cost would decrease as output increased. As output approached infinity, the variable cost would approach zero (i.e., infinite output for a fixed cost). The possibility that the production-cost function could follow the c < 0 curve is therefore rejected.

- Although it is mathematically possible for c to be 0 (the c = 0 line in Figure 2-9), this would be illogical in similar fashion to the c < 0 case because the cost would be constant for all quantities of output. As output increased, there would be no increase in cost and additional units, irrespective of their number, would be produced for free. The possibility that the production-cost function could follow the c = 0 curve is therefore rejected.

- Although it is mathematically possible for c to be greater than 1 (the c > 1 on Figure 2-9), this would contradict the principles of the Wright learning curve – workers would become less efficient with experience. The possibility that the production-cost function could follow the c > 1 curve is therefore rejected.

The two remaining possible functions, which are not rejected, are the linear parametric function, with c = 1, and the exponential function with 0 < c < 1. The linear parametric function will be discussed in Section 2.6.2. The possible exponential functions will be discussed in Sections 2.6.4 to 2.6.6.

While Wright's formula refers only to labor productivity and excludes materials and overhead costs, Henderson broadens the formula to encompass the entire production cost, apparently ignoring costs of materials and overhead. He either assumes them to be insignificant or proportional to labor costs.

The nature of the work, and the environment in which work is performed, play a role in these analyses. For example, at the time that Wright and Henderson were writing, equipment was operated by humans. Automated factories, using computer-controlled robots, had not yet developed. With automation the Henderson and Wright formulae might no longer apply in factories. It seems questionable that purpose-built robots would continuously improve their productivity, although there might be a small initial improvement as humans adjust the robot controls.

While factories are increasingly becoming automated, thereby reducing the need for human operators, this is less true for construction projects although automation is making a huge impact. Projects, by definition, involve unique non-repetitive tasks. The performance of such unique tasks requires some level of intelligent intervention. With the present state of technology, intelligent intervention means human intervention. The work of Wright and his successors indicates that work that requires human intervention is performed more efficiently as humans become more experienced. For project tasks that require human intervention, then, the author will assume that the Wright Curve continues to hold at present, though might not continue to hold with automation in the future. This theoretical assumption will be tested in Chapter 3.

Sections 2.6.2 through 2.6.6 provide summaries of research on different types parametric cost estimates and describe 2 applications of parametric cost estimates in state departments of transportation in the US.

2.6.2 Linear parametric estimates

Membah (2016) develops a linear parametric model (equation 7) for estimating the cost of transportation tunnel projects. The linear parametric model takes the form:

Cost = $a + \sum_{i=1}^{i=n} b_i X_i$ (Equation 7)

Where a and b_i are constants and X_i is the project's quantity of variable i.

Comparing equations 2 and 7, it is apparent that unit cost estimates are a form of linear parametric estimate with a = 0 and i being the various work packages (discussed in Section 2.4.3).

Membah's data source is a set of 79 tunnels in North America. As variables, he uses project characteristics: geology, environmental requirements, tunnel length, tunnel diameter, project duration, excavation method, depth of burial, and support requirements.

Holmlin (2016) develops a linear parametric model for estimating the cost of the Student Health Center at the College of William and Mary. His data source is a set of 5 comparable student health centers at other universities in the US. He uses only 1 variable, floor area.

Oh et al. (2013) develop a linear parametric model for estimating the cost of substructures of steel box girder bridges. Their data source is a set of 52 steel box girder bridges in Korea. As variables, they use bid-item quantities (e.g., cubic meters of concrete, tons of reinforcing bars, square meters of formwork) and characteristics (e.g., height of piers, number of piles). As they rely largely on unit prices, their model takes the linear parametric form shown in equation 7.

Mahamid (2013) develops a linear parametric model, using the formula in equation 7, based on 52 road projects in Saudi Arabia. His variables are three bid items: cubic meters of earthwork, cubic meters of base, and cubic meters of asphalt concrete.

Fragkakis et al. (2011) develop a linear parametric model for estimating bridge foundation costs, based on 646 concrete bridges on the Egnatia Motorway in northern Greece. His variables are project characteristics: ground classification, and the length, width, and pier heights of the proposed bridge.

Both Phaobunjong and Popescu (2003) and Phaobunjong (2002) develop a linear parametric model for estimating building costs, based on 168 building projects in Texas. Their variables are outputs: project type, square footage, and number of floors.

Al Khalil et al. (1999) develop a linear parametric model for estimating water reservoir costs, based on 12 projects in Oman. Their variables are project characteristics: duration, location, ground conditions, distance from the contractor's base; and one output: storage capacity.

Trost (1998) develops a linear parametric model for estimating construction costs on 67 projects for the "process" industries such chemical manufacturing, electrical generation, oil refining, and pulp and paper manufacturing. His input variables are assessments by an expert team on factors relating to the process used in preparing the estimate, and economic factors such as the bidding and labor climate.

Trost and Oberlender (2003) build on Trost (1998) by adding an analysis of the factors that have the most significant impact on estimate accuracy. This is similar to the analysis of Gardner et al. (2016) and overlaps the analysis in Section 5.1.2 and 6.4.4 of this dissertation.

Kouskoulas (1984) develops 2 linear parametric models, one for estimating the cost of highway pavement rehabilitation and the other for mass transit systems. His data sources are 18 highway pavement projects in Wayne, Oakland, and Macomb Counties in Michigan; and 10 mass transit projects in US cities. All but 1 of his input variables are project characteristics: length, lane width, earthwork excavation quantities, intersections and interchanges for highway pavement rehabilitation; and number of stations, number of interchanges, number of vehicles, and control systems for transit projects. The additional input variable in both cases is an economic factor: the price index.

AASHTO Trns*port software, discussed in the following section, provides an example of the use of linear parametric estimating in state departments of transportation in the US.

This section has summarized research on linear parametric estimates. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section provides an example of the day-to-day use of linear parametric estimates by state departments of transportation in the US.

2.6.3 AASHTO Trns*port linear parametric cost estimation system (CES)

Anderson et al. (2007) described the cost estimating system (CES) that forms part of the Trns*port software produced by the American Association of State Highway and Transportation Officials (AASHTO). This software is designed for estimating the construction capital costs of a highway project (i.e., Caltrans Phase 4 costs) and it is used by many state departments of transportation in the US. CES includes a module for parametric estimating from project characteristics such as length and location along with quantities and prices of major items. According to Anderson et al., lane-mile historic cost averages are a very popular calculating approach among CES users. The use of averages implies a linear parametric model. The Trns*port system includes modules for managing projects all the way through construction. As projects are completed, their data remains in the system and becomes available to CES for analogous estimates along lines that are similar to Case Based Reasoning (see Section 2.7.4).

This section has briefly described a linear parametric estimating system used by many state departments of transportation in the US. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section discusses another type of parametric estimating function, the common exponential.

2.6.4 Common exponential function

The author considers and compares 3 possible parametric functions to model project costs and applies them the pedestrian access facility projects that are considered in the next chapter. His goal is to test whether any of these 3 functions proves to be a better predictor of project costs, having a higher coefficient of determination, and to test the theoretical assumption from section 2.6.1 that exponential models will be better predictors of project costs than the linear parametric functions discussed in Section 2.6.2. The first of the 3 functions is the linear parametric function discussed in Section 2.6.2. The second is a common exponential function:

$\text{Cost} = a + gX_1^b + hX_2^c + iX_3^d + jX_4^e + kX_5^f$ (Equation 8)

Where a, b, c, d, e, f, g, h, i, j, and k are constants. X_1 is the required number of ramps (the first of three pedestrian access facility outputs). X_2 is the length in linear feet of sidewalk (the second output, normally 1.22 meters [four feet] wide). X_3 is the number of audible traffic signals (the third output). X_4 is the dollar amount paid by the agency to property owners and utility companies for right-of-way (land, easements, and utility relocations) and X_5 is the number of hours that employees spent on obtaining right of way. The author assumes that the right-of-way costs and effort are independent of the three pedestrian access facility outputs and therefore should be considered as separate outputs.

Comparing equations 7 and 8, factors g, h, i, j, and k in equation 7 are constants similar to constants b_i in equation 7; and X_1 to X_5 in equation 8 are similar to X_i in equation 7. The difference between the equations comes in the introduction of exponential factors in equation 8.

Catalina (2016) develops a common exponential cost estimating model for light rail transit systems. His inputs are two project characteristics: length of the system, and the number of stations. His inputs are 54 projects listed in a database maintained by the US Federal Transit Administration.

This section has summarized research on common exponential parametric estimates. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section provides an example of the of common exponential parametric estimates by a state department of transportation in the US.

2.6.5 PYPSCAN: prior use of the common exponential in Caltrans

In the 1970's Caltrans began to develop a common exponential system for estimating state employee hours on its projects. It named the system, Person-Year Project Scheduling and Cost Analysis (PYPSCAN) and placed in service in 1980 (Caltrans 2017:1). Caltrans stopped updating PYPSCAN in 1997 and no longer uses it as its official system for estimating state employee hours (Caltrans 2017:1). This system has been discussed in Blampied et al. (2017).

PYPSCAN calculated an average project milestone schedule and person year (PY) resource needs based on several variables:

- Project Type: each project in a database of over 12,000 projects was identified as having a project type. There were initially 107 project types (McManus 1981), and this number increased to 119 by 1992. Each project could have only one project type (Caltrans 1992).
- Weather zone: There were five weather zones, ranging from Zone 1, the driest, to Zone 5, the wettest.
- Location: Urban or Rural.

- Environmental type: There were three environmental types: Environmental Impact Statement /Environmental Impact Report (EIS/EIR), Finding Of No Significant Impact / Negative Declaration (FONSI/ND), and Categorical Exclusion / Exemption (CE), being the three standard types of environmental document in Federal and State law respectively (NEPA and CEQA).

- Function: For PYPSCAN purposes, PY resources were calculated for six "functions": highway preliminary engineering (or "project development," PJD), right of way (RWO), structures design (STD), structures construction (STC), and highway construction (CON). At first, PYSCAN had a formula for day labor (D/L), but it was later dropped (McManus 1981 compared with Caltrans 1992).

- Capital Cost: Three inflation-adjusted capital costs were considered, namely total construction cost, right of way capital, and structures construction cost. A specific capital costs was used for each phase: PJD, CON and D/L used total construction cost; STC and STD used structure construction cost; and RWO used right of way capital. Costs were adjusted for inflation using the Caltrans Construction Cost Index.

- Right of way information, including numbers of appraisals, acquisitions, utilities, relocation assistance cases, demolitions, railroad agreements, and condemnations.

The typical PYSCAN formula had the common exponential form:

$P = aX^b$ (Equation 9)

Where P is the PY resources, a is a constant, X is the applicable capital cost, and b is a constant such that $0 < b < 1$. This produced a possible 12 separate formulae for each project type (6 for PJD: 3 environmental types x 2 location types; and 2 each, for each location type, for STD, STC, and CON). A single formula, regardless of project type, was developed for RWO based on the number and complexity of the Right of Way parcels that were affected. This then produced a possible 1,429 formulae (12 x 119 + 1). Each formula was developed by regression analysis of projects from the database that matched the particular combination of factors. In practice, there were fewer than 1,429 formulae because some project types could not include structures and most had only one possible environmental type.

Until 1996, Caltrans used PYPSCAN to develop the annual Capital Outlay Support budget. Caltrans used PYPSCAN to calculate an estimated person year complement for each project, added those complements and submitted the sum as its personnel need for direct project work in the coming year. Both Caltrans and the Legislature recognized that the number for each individual project would probably be either higher or lower than needed, but the surpluses and deficits would cancel and the sum over several thousand state highway projects would be as accurate as one could achieve. This concept is discussed is greater detail in Sections 5.4.2 and 5.4.3. In 1996, Caltrans used PYSCAN but then adjusted the total. The Legislative Analyst reported:

> "Caltrans uses a statistical model to estimate its capital outlay support staff requirements, based upon the number, size, and complexity of scheduled projects. For 1996-97, this

> workload model calculated a higher staffing requirement than in the current year. However, Caltrans reduced the modeled workload by 19 percent in order to attain the staffing level proposed in the budget. Caltrans reports that it made the adjustments in order to account for anticipated efficiencies and shortcomings in the model." (LAO 1996)

Later in the same report, the Legislative Analyst continued, "Caltrans must, therefore, improve its workload forecasting models and practices."

At that time, the author directed the office that assembled the PYPSCAN data. In response to the Legislative Analyst's critique and under the direction of Caltrans executives, the author devised and led the implementation of a process whereby unit supervisors estimated the hours required for their units' work on each project, and staff entered those estimates into the Caltrans electronic project management system, eXpert Project Manager (XPM). Caltrans began using this XPM-based process in 1997. The basis of the supervisors' estimates was not documented but if it were, it would probably be based on the supervisors' experience and the estimates would therefore be analogous estimates.

In 2014, Caltrans replaced XPM with more modern project and portfolio management software, CA PPM. As previously noted, Caltrans refers to its installation of CA PPM as "Project Resourcing and Schedule Management" (PRSM).

This section has briefly described a common exponential parametric estimating system used by a state department of transportation in the US. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section discusses another type of parametric estimating function, the Cobb-Douglas exponential.

2.6.6 Cobb-Douglas exponential function

The third function is a modified version of the Cobb-Douglas production function, which has the form (Douglas 1976):

$\text{Output} = aL^{b}.K^{b-1}$ (Equation 10)

Where L and K are the inputs of labor and capital respectively in an economy, and a and b are constants, with $b>1$.

The difference between the common exponential and the Cobb-Douglas exponential is that the common exponential assumes that each variable is independent while Cobb-Douglas assumes that the variables are interdependent. A change in a variable in the common exponential will affect only that variable's contribution to the total function. The contributions of the other variables will remain unchanged. In the Cobb-Douglas function, by contrast, the entire function changes if either of the two original variables changes.

Although Cobb and Douglas wrote their function with only two variables, labor and capital, as a tool to predict an economy's output, later authors have modified the function to use multiple variables. Equation 11 is a typical example, and the function that the author uses later in this research:

$\text{Cost} = a + bX_1^c.X_2^d.X_3^e.X_4^f.X_5^g$ (Equation 11)

Where a, b, c, d, e, f, and g are constants, and X_1 through X_5 are as in equation 7, except that they are each increased by one unit to address the problem that a zero for any factor would produce a zero result for the cost in Cobb-Douglas. If, for instance, X_3 is zero in the common exponential (equation 8) it will be 1 in the modified Cobb-Douglas (equation 11). While zero is the null coefficient in the common exponential, 1 is the null coefficient in the modified Cobb-Douglas.

Other authors have made similar multi-variable modifications of Cobb-Douglas. For example, in civil engineering literature it has been modified for use as a predictor of:

- Water turbidity in 12 communities in Ohio given inputs of daily water volume, retention time, and upstream erosion (Forster et al. 1987).
- Water turbidity from 430 water treatment plants in the US given inputs of annual water production, pipe fitter wages, and electricity cost levels (Holmes 1988).
- Water turbidity in communities in the Maumee and Great Lakes Basins given inputs of volume treated annually, and pesticide use (Murray and Forster 2001).
- The operating cost of an airline in the US given inputs of passenger miles, freight tonnage, fuel cost, number of flights, and number of points served (Hansen et al. 2000).
- The marginal increase in Gross Domestic Product given increases in water supply to the Huang-Huai-Hai River Basin in China, as a tool for evaluating the South-North water transfer project from the Yangtze to Yellow Rivers (Wang et al. 2006).
- Freight rates of trucks in Japan (expressed as yen/ton/km) given inputs of transport distance (km); truck size (ton); the availability of railways, expressways, and ferries as competitors to trucks; and contract durations (Li et al. 2008).
- The utility function for a family given their goods consumption and the amount of waste (Wu et al. 2009).
- The highway network density in 25 developed countries given the population density and gross domestic product per capita for each year from 1963 to 2007 (Wang and Lin 2011).
- The gross output and total profits of the construction sectors in China and the US given fixed capital assets and the number of employees from 1990 to 2011 (Li et al. 2014).
- Regional economic output in Northwest China given local human capital investment, highway infrastructure investment, highway infrastructure stock, and highway infrastructure in neighboring regions (Lei et al. 2015).
- Railway output in China given the number of employees in the transportation industry, total wages, and net fixed assets (Li et al. 2015).

The original search of the Scopus database found no references to Cobb-Douglas. A second, revised, search dropped the word "conceptual" and added a requirement for "Cobb-Douglas," thus:

- Title, abstract or keywords include one of the phrases "cost estimate" or "cost estimating" or "cost estimation" Or "feasibility estimate" or "feasibility estimating" or "feasibility estimation."
- Title, abstract or keywords also include the term "Cobb-Douglas."
- And the subject area is "Engineering."
- And the document type is "Article" or "Conference proceeding."

This second search produced only one paper, Irfan et al. (2012), which used a modified Cobb-Douglas method to develop cost estimates of highway pavement treatments. Irfan et al. compared the Cobb-Douglas results to a linear parametric model and found that the former provided a better fit to the observed data. Their variables were outputs such as number of lanes, and project characteristics such as surface type, and functional class.

As noted in Section 2.5.3, the detailed reading of doctoral dissertations found 2 dissertations that develop Cobb-Douglas exponential parametric estimates. These are Akeel (1989), and Peng (2006). In addition, Membah (2016) refers to the Cobb-Douglas formula but does not develop a Cobb-Douglas exponential parametric estimate. None of them use the term "Cobb-Douglas."

Akeel (1989) says that there are "generally two basic models," additive and multiplicational. Akeel's "additive" model is referred to in this dissertation as the linear parametric model (equation 7). His "multiplicational" model is the Cobb-Douglas exponential parametric model. Akeel sets the zero intercept, a, in equation 11 to zero (i.e., a = 0) and converts the first multiplier, b, into its exponential equivalent, 10^k such that $b = 10^k$. This allows him to convert equation 10 into a logarithmic expression:

$$\text{Log(Cost)} = k + c.\log(X_1) + d.\log(X_2) + e.\log(X_3) + f.\log(X_4) + g.\log(X_5) \quad \text{(Equation 12)}$$

Akeel quotes Wallace (1978) in support of using equation 12, saying:

- "Most real world cost relationships are non linear."
- "If the additive model were used, any variable would be purely an additive term and would not vary as a function of the size of the base cost. In the multiplicational model, variables come in as percentage factors which means, as the base cost goes up or down a proportional allowance is made, not a fixed one."
- "Most raw cost data is not normally distributed. However the logs tend to be closer to a normal distribution."

Akeel applies equation 12 to data for buildings constructed for the Saudi Arabian Ministry of Defense and Aviation (the same source as Salamah – see section 2.5.3). Akeel's parameters are project characteristics such as the project duration, number of similar buildings in the development, and location. They also include outputs such as user-desired quality, type of building, finishes, floor area, heating, ventilation, cooling, building height, and type of floor.

In contrast, Peng (2006) develops a two-step estimating process. His Step 1 is to estimate the quantities of likely bid items for highway structure on projects developed by the Texas Department of Transportation (TxDOT) using equations similar to equation 12, by using natural logarithms (i.e., base e) rather than logarithms to base 10. This requires the development of a separate predictive equation similar to equation 12 for each potential bid item. Peng creates models for a total of 28 potential bid items. Typical examples of bid items are cubic yards of backfill, square feet of shoring, and linear feet of prestressed concrete piling. As input variables for the 28 versions of equation 12, Peng uses project characteristics: project type, project length, project width, urban or rural location, divided or undivided roadway, bridge deck area, concrete or steel bridge, number of bridges, average daily traffic, and number of trucks.

Peng's Step 2 is to use the quantities from Step 1 as inputs to the AASHTO Trnsp*rt cost estimating system described in Section 2.6.3 of this dissertation. This multiplies the quantities from Step 1 by inflated historic unit costs of the bid items in order to obtain a project cost estimate.

This section has summarized research on Cobb-Douglas exponential parametric estimates. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section summarizes the 3 forms of parametric estimate that have been discussed in Sections 2.6.2 through 2.6.6.

2.6.7 Summary: three forms of parametric estimate found in the literature.

Although Membah (2016) develops a linear parametric model (see Section 2.6.2), he discusses the linear parametric, common exponential parametric, and Cobb-Douglas exponential models. His version of the Cobb-Douglas model is the logarithmic form shown in equation 12 and used by Akeel (1989). Membah indicates that "in general" these are the 3 possible forms of a parametric cost estimating model, and cites Stewart et al. (1995) as his source for these three choices.

Hamaker (1987), writing in Stewart and Wyskida (1987), provides an earlier version of the 3 possible forms of a parametric cost estimating model cited by Membah (2016). He offers the linear parametric as the "linear curve" (a slightly incorrect term because the linear does not curve), the common exponential as the "power curve" and the logarithmic form of the Cobb-Douglas as the "Logarithmic Curve." In all three cases, Hamaker provides the equations (equations 7, 8, and 12) in a form that has no fixed cost at the zero intercept.

An additional search found Kouskoulas (1984) who offers the same 3 possible parametric forms as those cited by Membah. Kouskoulas refers to the Cobb-Douglas form as the "multiplicative model," a term that shares etymological roots with Akeel's "multiplicational" model, and he gives it the exponential form in equation 11 rather than the logarithmic form in equation 12.

In this dissertation the author compares all 3 forms of parametric estimate discussed by Membah (2016), Stewart et al. (1995), Akeel (1989), Hamaker (1987), and Kouskoulas (1984). The comparison is made in Chapter 3 and the results are discussed in Chapter 5.

Section 2.6 has discussed 3 parametric forms of conceptual and feasibility cost estimates that are discussed in the literature. Section 2.7 discusses non-parametric conceptual and feasibility cost estimating methods found in the literature.

2.7 Non-parametric conceptual and feasibility cost estimating methods in the literature

The purpose of this section is to identify the non-parametric conceptual and feasibility estimating methods described in the literature, as contrasted with the parametric methods described in Section 2.6. From the timeline provided in Figure 2-7 and discussed in Section 2.5.2, it is apparent that these non-parametric methods have been introduced recently, with a focus on ANNs from 2004 to 2011 and on case-based reasoning since 2012.

A comparative evaluation of parametric methods from Section 2.6 versus the methods described in this section is one of the recommendations for future research discussed in Chapter 6.

2.7.1 Artificial neural networks (ANNs)

The following discussion describes the literature on the use of ANNs for conceptual cost estimating that the author found and reviewed. In general, ANNs attempt to simulate the functioning of the human brain.

Barakchi et al. (2017) find that ANN estimating is not observed in the transportation cost estimating literature before 2009 but has become common since then. They operate with three "layers," an input layer, hidden later, and output layer. Shehab et al. (2010) indicate that ANNs produce more accurate estimates than parametric methods. Barakchi et al. (2017) make several positive observations about ANNs:

- ANNs work well in complex cases with many parameters.
- Unlike parametric estimates, ANNs do not need specific statistical distributions, and the relationships between variables need not be identified.
- ANNs are a good substitute for linear regression.
- ANNs work well with noisy, inaccurate, or corrupted data.

They also list three weaknesses of ANNs:

- ANNs use a time-consuming trial and error process.
- ANNs require a large amount of data if they are to be dependable.

- ANNs are difficult to explain and describe.

Although Barakchi et al. (2017) find that ANN estimating is not observed in the literature before 2009, they refer only to transportation project cost estimating. The Scopus search (Figure2-7) found several non-transportation ANN papers before 2009.

Hyari et al. (2016) use an ANN to estimate the engineering services cost, rather than the total project cost, based on a data set of 244 varied projects in Jordan. The variables used in their model are project type, phase, location, capital cost, and whether the project is for new construction or maintenance.

Although the title of their paper refers to the development of a parametric estimate, Adel et al. (2016) actually develop an ANN for estimating highway construction costs in Egypt. As their data source, they use a set of 38 highway maintenance projects and 37 new highway construction projects. They do not compare their ANN to any other estimating method. The variables used in their model are project characteristics such as duration, length of structures, and average daily traffic and geographic factors such as region, and terrain type.

Hyari et al. (2016) use an ANN to estimate the engineering services cost, rather than the total project cost, based on a data set of 244 varied projects in Jordan. The variables used in their model are project type, phase, location, capital cost, and whether the project is for new construction or maintenance.

Vahdani et al. (2011) develop a conceptual cost estimating model and validate it by applying it to a set of 100 multi-storey housing projects in Taiwan. Their chosen model is a form of ANN known as a Support Vector Machine. They find this to be superior to prior ANNs. The variables used in their model are project characteristics such as site area, geology, earthquake impact, and one output: floor area.

Juszczyk (2018) performs a similar study to that of Vahdani (2011), using a set of residential buildings in Poland. Juszczyk’s variables are project characteristics such as floor area, building volume, number of storeys, and type of foundation.

Marzouk and Omar (2011) develop an ANN model for pump station costs based on a data set of 44 projects. The variables that they used are project characteristics such as site type and location, and outputs such as population served and station capacity.

Petroutsatou and Lambropoulos (2010) introduce a structural equation model (SEM) and compare it with MRA and an ANN. They find that the SEM produces better results than the MRA or ANN. In their case, they test the three models on a data set of 149 sections of road tunnel. Their model was developed using the LISREL 8.80 program (LInear Structural RELation). Although they make a distinction between this model and ANNs, from the user perspective the LISREL 8.80 functions in a similar fashion to an ANN. Both LISREL 8.80 and ANNs provide “black boxes” whose internal functions are explained in general terms, but not in detail. For their variables, Petroutsatou and Lambropoulos (2010) use project characteristics, such as height of overburden and geology, and bid item quantities, such as cubic meters of concrete and kilograms of steel.

Yu and Skibniewski, (2010) use a form of ANN that they refer to as the adaptive neurofuzzy inference system (ANFIS) to estimate costs of high-rise residential projects in China, based on a data set of 110 projects. The variables used in their model are project characteristics: foundation and structure type; and outputs: floor area and number of floors.

Cheng et al. (2009:1) use a form of ANN that they refer to as the Evolutionary Fuzzy Neural Inference Model (EFNIM). They base this this model on a data set of 28 projects in Taiwan of unspecified type (although the variables suggest vertical buildings). The variables used in their model are project characteristics such as geotechnical work, structural work, interior decoration, and electromechanical work.

Siqueira and Moselhi (1998) consider 75 building projects in Canada and develop an ANN based on one project variable, joist span, and three output variables: area height, and vertical loads.

Serpell (1990) develops a knowledge-based expert system and writes the computer code for that system, although he does not load the system with historical data or test the system. The variables in this system are project characteristics such as the type of foundation, type of structure, wall-to-floor ratio, and partition-to-floor ratio.

Salamah (1989) also develops a knowledge-based expert system. He quotes Chadwick and Hannah (1987) in defining an expert system as "a computer program that simulates the reasoning of a human expert." Salamah's system asks sequential questions to reach an estimated cost for buildings. His parameters are project characteristics such as building shape, height, foundation, structural frame type, roof type, and exterior wall type. They also include outputs such as interior finishes, plumbing, heating, ventilation, cooling, lighting, circulation, and fire protection. He develops this system based on the data for 240 buildings constructed for the Saudi Arabian Ministry of Defense and Aviation.

This section has summarized research on the use of ANNs for conceptual and feasibility cost estimates. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section summarizes research on the comparison of ANNs with parametric estimates in conceptual and feasibility cost estimating.

2.7.2 Comparison of artificial neural networks (ANNs) with linear parametric

Wang et al. (2017) consider 46 residential housing projects in Taiwan and develop both a linear parametric model and an ANN model. They used an ANN tool, FALCON (Fuzzy Adaptive Learning Control Network), and found that the ANN model produced a higher correlation coefficient than the linear parametric model. Note that the current dissertation produces exponential, as well as linear, parametric models and such models are not considered by Wang et al. (2017).

Shehab et al. (2014) developed a neural network based on 20 bid items on 54 projects. They found that these 20 bid items contributed 80 percent of the cost of their 54 projects. For their analysis they needed to know the quantities for each of these bid items, as is the case for unit cost estimates. If the bid items match the desired outputs of the project that are known at project inception, then this method could be used for conceptual estimating and feasibility estimating

(AACE Class 5 and 4 estimates). If, however, the quantities for each bid item are not known at project inception, this particular use of ANNs would not work for conceptual and feasibility estimating. This title and abstract of the paper by Shehab et al. (2014) both refer to conceptual estimating, but the text uses the word "conceptual" only once and, despite the paper's title, it is not clear that their particular use of the ANN method is, in fact, feasible for conceptual cost estimating.

Cirilovic et al. (2013) consider 200 road projects in a World Bank data set from Europe and Central Asia and develop a linear parametric model and an ANN model. They used an open source data mining product, WEKA, to develop the ANN model, and found that the ANN model produced a higher correlation coefficient than the linear parametric model. The linear parametric model takes the same form as equation 7. The variables used by Cirilovic et al. (2013) are (1) macroeconomic and factors such oil prices, Gross National Income, fuel consumption, number of bidders and number of local bidders, and (2) geographic factors such as climate and terrain.

Cocodia (2005) considers 12 offshore oil-drilling structures and develop a linear parametric model and an ANN model. Her variables are project characteristics: weight, water depth, number of wells per structure, topside operating weight, location conditions, and storage capacity.

Sonmez (2004) compares three versions of linear parametric models (equation 7) with an ANN, using a data set of 30 continuing care retirement community projects in the US. The three linear models used different selections of project variables ("i" in equation 7). Those variables are outputs such as building area, number of floors, and size of parking area. Sonmez finds that the linear parametric models and the ANN both yield reasonably accurate estimates. The three linear regression models produced remarkably high coefficients of determination r^2 of 0.949, 0.950 and 0.951 respectively.

This section has summarized research that compares ANNs with parametric estimates in conceptual and feasibility cost estimating. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section summarizes research on hybrid ANNs and parametric estimates in conceptual and feasibility cost estimating.

2.7.3 Hybrid of artificial neural networks (ANNs) and parametric

Recent authors have begun to combine ANNs with parametric estimating techniques to create a hybrid estimating approach. Two papers fall into this category, ElMousalami et al. (2018) and Jumas et al. (2018).

ElMousalami et al. (2018) develop their model for projects to improve the field canals that provide agricultural irrigation in Egypt. They test an ANN and five different versions of parametric regression models – linear, quadratic, reciprocal, log, and power. As variables, they use project characteristics such as area served, the existence of parallel canals, maximum canal discharge, and pump discharge.

Jumas et al. (2018) follow a similar approach, using a set of 78 state building projects in West Sumatra, Indonesia.

This section has summarized research on hybrid ANNs and parametric estimates in conceptual and feasibility cost estimating. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. The next section summarizes research on case-based reasoning (CBR) in conceptual and feasibility cost estimating.

2.7.4 Case-based reasoning (CBR)

Case-based reasoning (CBR) is a process that retrieves projects from a data set that are similar to a proposed new project and uses them to produce an analogous estimate. It uses Multiple Regression Analysis (MRA) or other methods to find the most similar projects in the data set.

Chan et al. (2017) develop a CBR model based on a data set of 13 industrial projects. For their variables, they use 13 project characteristics, most of which are outputs such as high or low building, multi-use, or single-user building, whether the building is for heavy manufacturing, and whether it is a stack-up or specially engineered building. For the analysis, they use SysML (System Modelling Language).

Du and Bormann (2014) develop a CBR model based on a data set of 47 powerplant projects to estimate the likely degree of involvement of 20 different construction crafts in a project. They use 3 variables – the megawatt reading of the project, type of project, and engineering company.

Choi et al. (2013) develop a CBR model based on a data set of 171 road projects in Korea to develop a case-based reasoning model. The variables that they use are project characteristics – the owner, project location, project type (new construction or expansion of an existing road), road length, road width, number of lanes, width of a single lane, road quality grade, design speed, region, terrain, minimum radius of curvature, maximum slope of vertical section, quantity of earthwork, and land acquisition area.

Kim et al. (2012) describe a "hybrid" conceptual cost estimating model in which they combine "historical" and "quantitative" methods. The "historical" method that they describe matches the description of the CBR method and the "quantitative" method matches the description of unit costs. They use data from 291 mixed-use buildings, and their variables are project characteristics such as earthwork, substructure, superstructure, plumbing and electrical work.

Kim (2011) develops a conceptual cost estimating model using a modified version of Case-Based Reasoning (CBR), which he considers to be a form of ANN, and applies it to a data set of 123 railway bridges. His variables are project characteristics such as single or double track, length, number of spans, and height.

Ji et al. (2010), like Kim (2011), use CBR to develop conceptual estimates. Unlike Kim, however, they consider CBR to be distinct from ANN rather than a form of ANN. Ji et al. (2010) make this distinction because the user of the CBR can identify the most similar projects whereas Ji et al. say that ANNs use "black box" machine learning algorithms that are hidden from the user.

Ji et al. (2010) apply their CBR model to a data set of 164 publicly-funded apartment buildings in Korea. They use a calculation of the Euclidian distance to find the most similar projects in their data set to any proposed new project. As their variables, they use the outputs such as number of apartments, floor area, number of floors, and number of elevators.

Section 2.7 has discussed discusses non-parametric conceptual and feasibility cost estimating methods found in the literature. It provides data only, and draws no conclusions. The conclusions are provided in the synopsis in section 2.11.1. Section 2.8 is a digression from conceptual and feasibility cost estimating methods, and introduces the use of conceptual and feasibility cost estimates in the management of project costs.

2.8 **Beyond estimates: managing project costs**

2.8.1 Target costs

Thus far, conceptual (Class 5) and feasibility (Class 4) estimates have been discussed in the context of their use by infrastructure owners as one of the inputs to the stage-gate decisions about whether to initiate the project's feasibility phase or to move the project forward to the budget authorization phase. AACE (2016) and AASHTO (2013) list these contributions to the stage-gate decisions as the end usage (AACE) or purpose (AASHTO) of the estimates (see Figure 2-3).

There is another possible use of estimates, as a management tool in controlling project costs. This is a standard usage of Class 1 "bid/tender" estimates. After winning a bid, the successful contractor normally provides its Class 1 estimate to its construction project manager. The project manager then uses that estimate as a tool in the management of the project. As discussed in Section 2.4.3, a Class 1 estimate includes details about the materials and permanent equipment, labor, and rented equipment that the estimator priced in developing the estimate. The estimates for labor and rented equipment indicate the estimator's expectation of the means that will be used to complete the work. The Class 1 estimate will often include the estimator's more detailed plan of what labor and equipment will be used at given times on the project, where equipment will be placed, etc. The estimate may include some preliminary shop drawings and sketches and design calculations for temporary works. The project manager uses this information to understand how the estimator developed the bid and as a starting point in finalizing the sequence of work, hiring of labor, rental of equipment, purchasing of materials and permanent equipment, completion of shop drawings, and design of temporary work.

This detailed planning of the work is based on the Class 1 estimate. The less detailed estimate classes can serve a different management purpose – validating the reasonableness of later cost estimates and as a starting point for setting target costs. Parametric estimates, in particular, provide objective validations because they are calculated from actual historic data rather than being based upon judgement, which is subjective and can often be over-optimistic.

Ballard and Pennanen (2013) provide an example of a process in which estimates are used as a starting point for setting target costs for buildings. They refer to AbouRizk et al. (2002) for an indicator of how much variation there can be in conceptual cost estimating, and then use target costing to narrow that variation, with a goal of increasing the reliability of their cost estimates. They describe the cost estimating process in Haahtela Project Management Group:

> "Haahtela engages buyers in specifying what they want and understanding the consequences of their choices (Whelton, 2004; Pennanen and Ballard, 2008). Once project scope and budget are aligned, Haahtela steers design and construction to deliver scope within budget; i.e., what the client expects to get for what the client is willing and able to pay. In Haahtela's process, the first step is to input into the cost model what the client wants in order to calculate that project cost."

Although their paper is title "Conceptual estimating and target costing," this process is at a more detailed level than conceptual cost estimating as it is defined by AACE, AASHTO and this dissertation. Ballard and Pennanen (2013) require that the buyer be engaged in "specifying what they want and understanding the consequences of their choices." That would require a level of detail that is at least that of a Class 3 (budget authorization) estimate. Prior to the Class 3 estimate, the preferred alternative has not yet been determined and the buyers have not yet specified, and cannot yet specify, what they want.

Ballard and Pennanen continue, "In Haahtela's process, the first step is to input into the cost model what the client wants in order to calculate that project cost." In this paper, however, they do not describe the model. That description comes in another paper, Pennanen and Ballard (2008). There, they name the model TaKu^{TM}. Using the specifications described in the earlier quote from Ballard and Pennanen (2013), Haahtela identifies, "components, such as cooling system, frame and external wall" (Pennanen and Ballard 2008). The components are entered into the TaKu^{TM} model, which "produces first component level costs and combines the component level costs into product level cost." From an interview with Ballard, the author learned that the "product level" may refer to subsystems within a building. The TaKu^{TM} model includes, as part of its code, many of the equations used by designers in determining quantities and grades of items to be included in a building, such as the numbers and powers of luminaires, and the numbers and sizes of elevators. TaKu^{TM} produces an initial building design solution that meets the buyers' identified needs, but is not necessarily the solution that the buyers and designers will select. This initial solution is then priced by a "black box" pricing model that is "updated once or twice a year" (Pennanen and Ballard 2008). Pennanen and Ballard say, "TaKu^{TM} application sets expected cost in the middle of the observed cost distribution (after extremes has been removed) twice a year." The word "middle" normally refers to the statistical median, but this might not be true of the algorithms used in TaKu^{TM} which uses complex algorithms and includes more than 200,000 lines of code.

The TaKu^{TM} model, then, is a highly complex system of algorithms and a most sophisticated form of parametric model, bearing in mind the definition of parametric estimating cited in Section 2.4.2, "an estimating technique in which an algorithm is used to calculate cost or duration based on historical data and project parameters" (PMI 2017).

The output from TaKu^{TM} is an initial building design solution and a market price for that solution. Pennanen and Ballard (2008) say, "Project management can then decide where to set the target cost" and that "Typically the observed costs vary +- 20 percent from the mean value."

Having developed an initial solution and a target cost, the project team then works to "steer" the project cost towards the target (Pennanen et al. 2010). By applying this target costing process to

20 building projects, Ballard and Pennanen (2013) found that 13 of the 20 projects were completed for less than the target cost, that the final costs ranged from 15 percent below the target cost to 11.58 percent over the target, and that the average final cost was 0.01 percent above target.

The "target costing" approach engages the estimator in the execution of the projects and steers the design and construction toward the target costs, which Ballard and Pennanen had set on the basis of the TaKu^{TM} model estimates.

This section has introduced the use of "target costs" in the management of project costs, based on the work of Ballard and Pennanen. The next section discusses Process-Based Cost Modelling (PBCM), another approach to the management of project costs.

2.8.2 Process-Based Cost Modeling (PBCM)

Nguyen (2010) and Nguyen et al. (2008, 2018) describe a different approach from that of Ballard and Pennanen (2013) but with a similar goal. Their goal is target value design (TVD), which Nguyen (2010) says "broadens the concept of Target Costing, with the focus on "value." TVD covers additional design criteria beyond cost, including constructability, time, process design, design collaboration, etc. (Lichtig 2005)." Nguyen (2010) and Nguyen et al. (2008, 2018) describe a "Process-Based Cost Modelling (PBCM)" method that consists of three steps: "(1) collecting process- and cost data, (2) mapping process- and cost data to objects of a Building Information Model (BIM), and (3) providing cost feedback to inform TVD" (Nguyen 2010). This approach requires 4-dimensional (4D) BIM software, the four dimensions being the normal 3 dimensions (3D) of height, width, and length, and time as the fourth dimension. This method consists of the following steps:

- It begins from a completed 3D model, which is provided by designers, showing the objects to be constructed.

- The construction team then provides process information "such as schedule, resource, equipment, site logistics, and construction process."

- It then combines the 3D objects with the processes to provide a simulation of the construction process.

The 4D system permits the construction team to both simulate the construction process and experiment with alternative construction processes. Because the system includes resources, it can also be used to prepare a bottom-up cost estimate in which (1) the materials and permanent equipment quantities would be calculated and priced, and (2) the labor and rental hours would also be calculated and priced. The system would thus provide a detailed take-off and the cost estimate would be a Class 1 (bid/tender) estimate.

Nguyen et al. (2018) point out that "traditional" Class 1 cost modelling methods are based upon prior experience rather than upon a consideration of what might be possible in the future. The ability to simulate construction processes places a focus on the future and enables the construction team to consider how they might go about construction. If the designers are involved, as Nguyen et al. (2018) advocate that they should be, then the PBCM process would also facilitate changes in the design that could make construction easier and less costly. Design changes that are made during the simulation process could also enable the facility to function more effectively for the users.

Section 2.8 has introduced the use of conceptual and feasibility cost estimates in the management of project costs. This will be discussed further in the synopsis in section 2.11.3. Section 2.9 introduces forms of specification.

2.9 Forms of specification

In addition to the conceptual and feasibility estimating classes and methods discussed in Sections 2.2 to 2.7, this dissertation considers the approaches to contracting by Caltrans and Bay Area cities. Chapter 4 describes how the author sought to test the parametric models that he had developed on Caltrans projects, and found significant cost differences between the Caltrans and city project sets. This led to secondary research into the root causes of these differences.

Three bodies of literature are considered with regard to the specification of these two sets of projects. They are:

- Prescriptive specifications
- Performance specifications
- Warranty specifications

The common thread through all three of these topics is the degree to which risk is shared between the public agency client and the contractor who is responsible to delivering the work.

2.9.1 Prescriptive specifications

Prescriptive specifications, also known as a “method specifications” are the baseline against which to compare performance-based and warranty specifications. Definitions of prescriptive specifications include:

- “A prescriptive specification describes a predetermined method and material.” (Molenaar et al. 1999).
- “Method specifications (also called material and method specifications or prescriptive specifications) explicitly identify the materials and work methods or procedures a contractor should use to complete the work included in the contract.” (FHWA 2018).
- “A prescriptive specification is one that includes clauses for means and methods of construction.” (NRMCA 2018)
- “Prescriptive specifications are recipes: do this, then do this, then do this, etc. If you do all those things, you know we will accept whatever the results are.” (Lowe 2018).

The author encountered prescriptive specifications early in his career, working for a construction contractor, finding specifications such as, “The base course shall be compacted with three passes of a 10-ton vibrating roller.” Such specifications generally originated from clients with limited engineering and testing resources that had not yet transitioned to test-based performance specifications.

When performance specifications are used, the client carries any risk of failure if the specified methods and materials do not achieve the client’s desired performance. In the 10-ton vibrating roller example in the previous paragraph, for instance, the contractor fulfills its obligation and is entitled to payment once it has completed the three passes. If the three passes do not achieve the client’s desired degree of compaction, the client would need to pay the contractor for any extra work that might be needed to achieve the client’s desired compaction.

2.9.2 Performance specifications

Performance specifications focus on the outcome that the client desires rather than on the methods or materials to be used. Definitions of performance specifications include:

- “A performance specification describes the quality or end result required.” (Molenaar et al. 1999).

- “Performance specifications describe the required work in terms of operational characteristics or ultimate use. The performance characteristics are designed to predict or monitor performance over time. Unlike method specifications, performance specifications tend not to include instructions that dictate or suggest methods, material definitions, material processing, time and temperature controls, constituent properties, construction equipment descriptions, and similar prescriptive elements.” (FHWA 2018).

- “A performance specification is a set of instructions that outlines the functional requirements for hardened concrete depending on the application. The instructions should be clear, achievable, measurable and enforceable. For example, the performance criteria for interior columns in a building might be compressive strength and weight since durability is not a concern. Conversely, performance criteria for a bridge deck might include strength, permeability, scaling, cracking and other criteria related to durability since the concrete will be subjected to a harsh environment.” (NRMCA 2018)

- “The kinds of specifications that might fit a little bit better with design-build projects are what we would call performance specifications. These specifications aren’t recipes. They don’t tell the contractor how to do the work. What they tell the contractor is what we want.” (Lowe 2018).

Most work on performance-based specifications has to do with ensuring the durability of the products produced. The contractor is required to provide products that will last for an expected design life. The challenge for the client, then, is in validating that the contractor’s products will last for the required time period. The literature on performance-based specifications therefore focuses on the development tests that clients can perform to ensure, within a reasonable degree of certainty, that the contractor's products will last for the required design period. A search of the American Society of Civil Engineers (ASCE) database found 27 papers with the words "performance" and "specification" in their titles. Of these, 21 titles included one of the phrases "performance specification," "performance-related specification," "performance-based specification," "specifying performance," or "performance-specified." Those 21 papers were papers on:

- Highway or airport pavement performance specifications: 12 papers
- Concrete performance specifications: 4 papers
- Maintenance performance specifications: 2 papers
- Highway work zone performance specifications: 1 paper
- Use of fatigue cracking as a factor in performance specifications: 1 paper
- Perceived effect of performance specifications on highway construction: 1 paper

The remaining 6 papers were on bioretention media specification and performance (2 papers), cross-sectional mode choice models specification and forecast performance, performance of shear walls designed in accordance with the National Design Specifications, and Public-private partnership performance indicators and specification theory, and specifying and verifying performance of aerated turbines.

As the numbers and content of these papers suggest, the focus in research on performance specifications is largely on highway materials. There are three probable causes for this focus.

1. Highway specifications are produced mainly by public agencies. Although there are some private highways, they make up only a small part of the worldwide highway inventory. In private contracts it is possible to specify specific proprietary products, but this is frowned upon in the public sector and forbidden in federally funded construction in the US because all citizens (and therefore all suppliers) are entitled to equal treatment. Public agencies must therefore produce specifications that do not favor any specific proprietary products. If the public agency chooses to use a performance specification, it must craft a specification that will meet the public need without giving an advantage to any particular solution. This is not easy to do, and requires careful crafting and research. Hence the extensive literature and research on highway performance specifications.

2. Highway materials are expected to last for a considerable time, typically at least 10 years and as many as 50 years. This time period is far longer than the life of a construction contract and the warranty periods normally included in design-bid-build contracts (see Section 2.10.1). The public agency client therefore needs some method of evaluating the materials at the time of construction to verify that they will last for the design life. Research is therefore needed to find tests that will mimic the loading that the materials will undergo over an extended period and assure the public agency client that the materials will be fit for their purpose.

3. Loading on highway pavements is different from that experienced by other facilities. Highway pavement loading consists principally of repeated high-speed dynamic impacts by heavy vehicle axles, often several million impacts over the design life. These impacts are referred to as Equivalent Single Axle Loads (ESALs) of 18,000 pounds apiece (i.e., 9,000-pound point load per dual wheel) (Caltrans 2017:2). As a result, highway pavements fail due to the fatigue that they experience from these repeated impacts. By contrast, other facilities, such as buildings and dams, experience constant loading and their non-seismic dynamic loading is not as frequent and intense as the dynamic loading experienced by pavements. In earthquake-prone areas facilities such as buildings and dams experience infrequent highly intense seismic loading. Their failure mode is from shear and torsion rather than fatigue. Buildings may also experience dynamic loading from snow or wind but this is unlikely to take the form of millions of repetitions of 9,000-pound point loads. As a result, a performance specification for non-highway facilities will generally need to ensure that the facility can withstand its one-time maximum credible load whereas a performance specification for highway pavements needs to ensure that the pavement can survive the fatigue from millions of repetitions of a heavy load.

Highway pavement performance specifications are based upon assumptions about the weather conditions and, especially, the number of ESALs that the pavement will experience over its design life. Pavement design life can be as long as 50 years, and it is impossible to predict the weather or the ESALs for that length of time with confidence.

2.9.3 Warranty specifications

Warranty specifications are a form of performance-based specification in which the contractor continues to maintain the facility for a period of time after construction is complete. The problem of ensuring that the facility performs as intended is addressed by the contractor's ongoing work rather than by the testing described in Section 2.9.2. Scott et al. (2011) describe three types of warranty specification:

- Type 1 – Materials and workmanship. In this type of warranty, the contractor is required to correct problems for a short period after construction, typically 3 years or less, that are determined to result from poor quality materials or failures in workmanship. The contractor is therefore not responsible for correction of problems occurring due to weather events, unexpectedly high traffic loading, or other similar factors that are outside the contractor's control. Type 1 warranties normally form part of a design-bid-build contract awarded to the lowest qualified bidder.

- Type 2 – Short-term performance. In this type of warranty, the contractor is responsible for maintaining of the facility for a period that is typically 5 to 10 years. Unlike Type 1, this responsibility includes repairing failures that result from weather and traffic conditions and other similar events. The contractor therefore carries greater risk that is the case for Type 1. The contractor may receive an annual "availability payment" during the maintenance period. Type 2 warranties may form part of a design-bid-build contract awarded to the lowest qualified bidder, although the contractor carries partial responsibility for the design, especially as it relates to the selection of materials.

- <u>Type 3 – Long term performance.</u> In this type of warranty, the contractor is responsible for maintaining of the facility for a period that is typically 20 to 30 years (Scott et al. 2011). Like Type 2, this responsibility includes repairing failures that result from weather and traffic conditions and other similar events. Due to the length of the maintenance period, the contractor carries greater risk than is the case for Type 2 and, like Type 2, the contractor receives an annual "availability payment" during the maintenance period. According to Scott et al. (2011), Type 3 warranties normally occur only in conjunction with design-build-maintain contracts where the contractor is responsible for the final design of the facility, for construction, and for maintenance through the 20 to 30-year performance period. Design-bid-maintain contracts, as the name suggests include a requirement for the contractor to maintain the facility for a defined period after construction is complete.

Cui et al. (2008) precedes Scott et al. (2011) in providing a synopsis of warranty contracting by state Departments of Transportation (DOTs) in order to advise the Alabama DOT on its potential use of this contracting type. They find that while other states have had success with warranty contracts, contractors in Alabama are leery of such contracts. They therefore recommend a careful gradual introduction of warranty contracts, with warranties of up to 5 years on pavements, to give contractors experience in this type of contracting and to develop solutions for any issues that may arise.

Scott et al. (2011) find that 12 of the 50 US state DOTs use warranty specifications. Of these:

- 3 state DOTs use warranties of 3 years or fewer, corresponding to Scott et al.'s Type 1 warranty

- 8 state DOTs use warranties of 3 to 7 years, corresponding approximately to Scott et al.'s 5-to-10-year Type 2 warranty

- 1 state DOT uses 10-year warranties, corresponding to Scott et al.'s Type 3 warranty

Kentucky, the state with Type 3 warranties, issues design-bid-build projects in which the contractor is required to design the pavement and guarantee a pavement life, which can be anywhere from 5 to 10 years. The contractor receives a credit for the guaranteed pavement life during the bid evaluation.

Sadeghi et al. (2016) review 10 years of experience with warranted pavements in Indiana and find that "Warranted asphalt pavements deteriorate more slowly and their service lives can be 10 to 14 years longer than traditional nonwarranted asphalt pavements." They do not describe the type of warranty specification used in Indiana, but Scott et al. (2011) classify the Indiana contracts as Type 2 warranties.

Zlatkovic et al. (2015) discuss Utah's experience with warranty specifications for pavement markings on a single project. This is a different focus than that of other researchers, who have studied warranties on the pavement itself, rather than markings. Utah's movement warranties are for a 4-to-6-year period with the contractor providing maintenance during the warranty period. They are therefore an example of Scott et al.'s "Type 2" warranties. The paper, based on interviews with stakeholders, found a consensus that the new specification was effective.

Qi et al. (2013) provide a statistical analysis of the pavement quality outcomes on 2,738 sections of pavement that had been constructed as part of 18 warranty projects in Mississippi, 13 of which were still active at the time of writing. The data on these warranted sections was compared with similar data on 6,166 non-warranted pavement sections for which data was available in the Mississippi DOT database. The researchers found a that the outcomes for the warranted sections were statistically better than the outcomes for the non-warranted sections. They also cited published work on Colorado, Indiana, and Wisconsin that reported similar outcomes to the Mississippi outcomes.

It should also be noted that the Mississippi contracting method provides for tests to be made on warranted sections during the warranty period and for "deduct points" to be levied against the contractor if the pavement condition falls below designated thresholds.

Section 2.9 has introduced forms of specification. This will be discussed further in the synopsis in section 2.11.4, where forms of specification are correlated with contracting approaches, which are introduced in Section 2.10.

2.10 **Contracting approaches**

2.10.1 Design-bid-build

The concept of design-bid-build contracts has been introduced in Section 2.1 on public versus private agency contracting. In the case of Caltrans, design-bid-build is rooted in PCC 10120 (introduced in 1876 and most recently revised in 1981). It specifies "Before entering into any contract for a project, the department shall prepare full, complete, and accurate plans and specifications and estimates of cost, giving such directions as will enable any competent mechanic or other builder to carry them out."

The process with design-bid-build is as follows:

1. The client produces a set of plans and specifications for a facility.
2. Contractors submit bids to complete the specified work.
3. The client awards a contract to the lowest qualified bidder.
4. The contractor builds the facility according to the plans and specifications.
5. The client inspects the built facility for conformance with the plans and specifications.
6. After accepting the built facility, the client assumes any further risks should the facility not perform as expected.

In the US, this process is governed by the "Spearin Doctrine," a case settled by the US Supreme Court in 1918 (US Supreme Court 1918). The Court found, "if the contractor is bound to build according to plans and specifications prepared by the owner, the contractor will not be responsible for the consequences of defects in the plans and specifications." In the terms of

California Law, the contractor needs only to have the competence of a “mechanic or other builder,” and is not expected to exhibit advanced technical knowledge.

2.10.2 Design-build

Section 2.9.3 has already noted that Type 2 and Type 3 warranties are forms of design-build in that the contractor must provide elements of the design and then warrant those elements. Design-build, as a whole, is a form of performance specification in that the client does not prescribe the methods that the contractor is to use. Gransberg and Windel (2008) note with surprise, however, that they found prescriptive specifications for materials and methods in 15 of 17 design-build requests for proposals that they reviewed. In design-build, the contractor must provide the complete design, ensuring that it meets the customer’s documented need, and then build the designed facility. Rather than issuing a prescriptive specification, the client provides a more general set of outcomes that will be used to evaluate the contractor’s performance.

As noted earlier, Miller (2000) dates the start of design-bid-build contracting in US Federal contracts to the 1916 Rural Post Roads Act. The author has found that California law required design-bid-build contracting from an earlier date, namely 1876 (California Legislature 1876). Prior to those times, the normal approach was to combine the design and construction of facilities into a single design-build contract. Songer and Molenaar (1996) trace the origins of design-build to the ancient “Master Builder” concept in which the builder both designed and constructed the facility. They indicate that under the Code of Hammurabi (c. 1800 b.c.) the master builder was responsible for both design and construction. They also indicate that there has been a resurgence of design-build since 1986, although they do not give a reason for choosing that year as the starting point.

Design-build contracting requires that the contractor be selected when the design is not known, which makes it difficult to estimate the cost. There are two approaches that can be used to address this problem. One approach is to wait until the contractor has substantially completed the design and then negotiate a construction cost. The other approach is to give the contractor a target cost and require the contractor to design a facility that meets minimum scoping standards within the given cost. Both approaches preclude the use of cost as a factor in the initial selection of the contractor. The contractor must therefore be selected on the basis of qualifications.

Design-build is common in the private sector, where clients frequently have favored contractors who have done good work in the past and with whom the client has a good relationship. Contractors appreciate and value such ongoing relationships and are committed to providing the client with a valuable service. In these circumstances it is common to use the target costing alternative described in the previous paragraph, and the “qualification” required for contractor selection is the fact that the client trusts the favored contractor.

Transferring the design-build concept to the public sector in the US creates a challenge because public clients are forbidden by law from having favored contractors. Contracts must be the subject of an open competitive selection process. To address to this need, Potter and Sanvido (1995) provide guidelines for implementing design-build in the public sector.

Numerous papers have been written regarding design-build over the past 20 years. They include Ibbs et al. (2003) who find that while time savings is a probable benefit of design-build over design-bid-build, but their analysis of 67 projects found no statistically relevant difference in cost between the two types of specification. A later analysis of 1,512 projects by Park and Kwak (2017) reaches similar conclusions. Slightly more recently, Sullivan et al. (2017) considered 30 studies totalling 4,623 projects and again found results that are similar to those of Ibbs et al. (2003) and Park and Kwak (2017).

Design-build contracts may have several variations that include more than just design and build. Possible variations include: "Finance" in which the contractor arranges for the construction funding and is then reimbursed through "availability payments" for a period of years after construction; "Maintain" in which the contractor is responsible for maintenance for a period of years after construction; and "Operate" in which the contractor is responsible for operating the facility, performing specified functions such as toll collection and policing, for a period of years after construction before transferring it back to the owner. This leads to several modifications of the design-build name:

- Design-build-maintain.
- Design-build-finance.
- Design-build-operate-maintain-transfer.
- Design-build-finance-operate-maintain-transfer.

Section 2.10 has introduced contracting approaches. This will be discussed further in the synopsis in section 2.11.4, where contracting approaches are correlated with forms of specification.

2.11 Synopsis and gap identification

2.11.1 Synopsis of conceptual and feasibility cost estimating methods

Table 2-6 summarizes the papers and dissertations relating to conceptual cost estimating methods that have been reviewed in this chapter. Although Barakchi et al. (2017) find that parametric estimates are most common in the literature for transportation projects, more recent literature on conceptual and feasibility estimating (not limited to transportation) appears to focus on the use of ANNs and CBRs. Table 2-6 divides parametric estimates into three categories – linear functions, common exponential functions, and Cobb-Douglas exponential functions.

This dissertation considers the linear, common exponential, and Cobb-Douglas forms of parametric estimate, and contributes to the literature on the use of common exponential and Cobb-Douglas exponential functions, which have received relatively little attention (see Table 2-6).

Table 2-6 Summary of papers and dissertations on conceptual and feasibility cost estimating

	Model Type					Variable Types Used					
	ANN	CBR	Linear	Exponential	Cobb-Douglas	Outputs	Bid Items	Project	Process	Economic	Geographic
Kouskoulas (1984)			✓					✓		✓	
Akeel (1989)					✓	✓					
Salamah (1989)	✓					✓		✓			
Serpell (1990)	✓							✓			
Caltrans (1992) and McManus (1981)				✓				✓			✓
Siqueira and Moselhi (1998)	✓					✓		✓			
Trost (1998)			✓						✓		
Al Khalil et al. (1999)			✓			✓		✓			
Phaobunjong (2002)			✓			✓					
Phaobunjong and Popescu (2003)			✓			✓					
Sonmez (2004)	✓		✓			✓					
Cocodia (2005)	✓		✓					✓			
Peng (2006)			✓		✓			✓			
Anderson et al. (2007)		✓	✓				✓	✓			
Cheng et al. (2009:1)	✓							✓			
Petroutsatou and Lambropoulos (2010)	✓						✓	✓			
Marzouk and Omar (2011)		✓				✓		✓			
Ji et al. (2010)		✓				✓					
Yu and Skibniewski (2010)	✓					✓		✓			
Fragkakis et al. (2011)			✓					✓			
Vahdani et al. (2011)	✓							✓			
Kim (2011)		✓						✓			
Irfan et al. (2012)			✓		✓	✓		✓			
Kim et al. (2012)		✓						✓			
Cirilovic et al. (2013)	✓		✓							✓	✓
Oh et al. (2013)			✓				✓				
Mahamid (2013)			✓				✓				
Choi et al. (2014)		✓						✓			
Du and Bormann (2014)		✓				✓		✓			
Shehab et al. (2014)	✓		✓				✓				
Adel et al. (2016)	✓							✓			✓
Catalina (2016)				✓				✓			
Holmlin (2016)			✓			✓					

	Model Type					Variable Types Used					
	ANN	CBR	Linear	Exponential	Cobb-Douglas	Outputs	Bid Items	Project	Process	Economic	Geographic
Hyari et al. (2016)	✓							✓			
Membah (2016)			✓					✓			
Chan et al. (2017)		✓				✓		✓			
Wang et al. (2017)	✓		✓			✓					
Elmousalami et al. (2018)	✓		✓	✓	✓			✓			
Juszczyk1 (2018)	✓							✓			
This dissertation			✓	✓	✓	✓					
Number of papers and dissertations (40 max.)	16	8	19	4	5	16	5	28	1	2	3

In addition to summarizing the types of function discussed in the literature, Table 2-6 identifies the types of variables used as predictors of project costs. It lists 5 types of variables:

- Outputs: Features of the facility that the users have requested or would recognize as being of value.
- Bid items: Items for which the constructors receive payment.
- Project characteristics: Project-specific factors, other than outputs and bid items, that must be considered by the designers and constructors of the facility.
- Process: Assessments by an expert team on factors relating to the process used in preparing the estimate.
- Economic: Characteristics of the current economic situation in the country or region.
- Geographic: Physical characteristics of the region.

Table 2-7 provides examples of the five variable types that were used in the papers listed in Table 2-6.

The literature indicates that each of these types of variables has an impact on project costs. Future research could help in determining which type of variable has the greatest impact on costs and which variables would best be used in developing conceptual cost estimates.

This dissertation focuses on outputs. In the pedestrian access facility case studies, it uses as its variables a count of wheelchair ramps, linear feet of sidewalk, and a count of audible traffic signals. Each of these variables is requested by the facility users. Pedestrian access projects build these items only in locations where they have been requested by users. The focus on outputs has three advantages:

- It makes manifest the nexus between the customers' desired features and the cost of those features. When, for instance, users and representatives want wheelchair ramps, the parametric function would provide them with a cost of those ramps.

- It adjusts for changes in scope. If, for instance, additional wheelchair ramps were to be included in the scope of a project, the cost estimate could be changed quickly.

- It accommodates the combination of projects of different types. This overcomes one of the challenges with Caltrans former PYPSCAN system which had separate formulae for 119 project types. By focusing on outputs rather than project types, the methods proposed in this dissertation accommodate different combinations of outputs. For example, at the time of writing Caltrans is implementing a "transportation asset management program" (Caltrans 2018:1). This responds to requirements in the 2012 Federal surface transportation law, Public Law 112-141, nicknamed MAP-21 "Moving Ahead for Progress in the 21st Century" (US Congress 2012). It provides for projects of different types on the same section of highway to be combined into single projects. For instance, wheelchair ramps may be included in a pavement rehabilitation project. The output-based algorithms readily combine the pavement and pedestrian access outputs.

Table 2-7 Examples of the variables used in the papers listed in Table 2-6

Outputs	Bid items	Project Characteristics	Process	Economic	Geographic
• building area • floor area • heavy manufacturing • high or low building • multi-use or single-user building • number of apartments • number of elevators • number of floors	• cubic meters of asphalt concrete • cubic meters of base • cubic meters of concrete • cubic meters of earthwork • kilograms of steel / tons of reinforcing bars	• average daily traffic • earthwork • electrical work • electro-mechanical work • geo-technical work • structural work • height of overburden • height of piers	• process design • team experience • time allowed	• fuel consumption • Gross National Income • number of bidders • number of local bidders • oil prices • bidding and labor climate	• climate • earthquake impact • geology • region • terrain

Outputs	Bid items	Project Characteristics	Process	Economic	Geographic
• single or double track railroad • size of parking area • specially engineered building • stack-up building	• square meters of formwork	• interior decoration • length • length of structures • location • number of piles • number of spans • plumbing work • project duration • site area • sub-structure • super-structure • terrain type			

While the desired facilities are well known in the case of pedestrian access projects - wheelchair ramps, sidewalk, and audible traffic signals - such a clear nexus may not be available on other types of projects. On pavement rehabilitation, for instance, there are goals of achieving both a smoother ride and a more durable pavement. Smoothness is readily measured through the International Roughness Index (IRI), but durability is less easy to measure (see the discussion of performance specifications in Section 2.9.2). In some cases, bid items may be good proxies for outputs. On the pavement projects, for instance, cubic meters of asphalt concrete may be a reasonable proxy for pavement durability even though this variable may not be at the forefront of the users' minds. The usefulness of such proxies is a topic for future research on projects other than pedestrian access facilities.

2.11.2 Identification of gaps in conceptual and feasibility cost estimating knowledge

This dissertation addresses knowledge gaps in two areas: 1. Conceptual and feasibility estimating, and 2. Risk strategy and alternative contracting approaches.

In the area of conceptual and feasibility estimating, this dissertation:

1. Adds to the literature on the common exponential parametric and Cobb-Douglas exponential functions. Such exponential functions are most consistent with the accepted Wright and Henderson curves (Wright 1936, Henderson 1968 – see Section 2.6.1). They have been advocated by Wallace (1978), Hamaker (1987), Delionback, (1987), and Akeel (1989), but

the data in Table 2-6 indicated that they have been used far less frequently than the simple linear parametric.

2. Specifically focuses on using the desired outputs as the variables in the two exponential functions. This emphasises the role of the project customer as the target audience of conceptual and feasibility estimating and aims to provide a tool that will inform customers of the specific expected costs of their desired outcomes.

In the area of risk strategy and alternative contracting approaches, the dissertation provides insights into a particular risk approach in which the contractor provides a firm unit-priced bid that has the appearance of design-bid-build but differs in that the contractor provides the design as a part of their unit prices. This dissertation compares and contrasts the costs and outcomes of a set of these contracts with a set of contracts in which the client provided the contractors with detailed plans and accepted the risk. In doing so, this dissertation expands the knowledge base on risk approaches to include this particular type of contract.

2.11.3 Managing project costs

Both target costs and PBCM provide examples of the use of cost estimates as tools for project management in addition to their use as an aide to decisions about whether to proceed past the next stage gate. By providing the project team with an estimate and setting that estimate as a target, both target costs and PBCM can assist in providing an incentive for the team to complete a project within budget.

2.11.4 Correlation between forms of specification and contracting approaches

Section 2.9 on forms of specification and Section 2.10 on contracting approaches provide a likely correlation between forms of specification, on the one hand, and contracting approaches, on the other, thus:

- Prescriptive specifications, where they occur, are expected to be more likely in design-bid-build contracts than design-build contracts.

- Performance specifications, may occur in both design-bid-build and design-build contracts.

- Warranty type 1 (3-5 years) specifications, where they occur, are more likely in design-bid-build contracts than design-build contracts. (Design-build contracts would use longer warranties).

- Warranty type 2 (5-10 years) specifications, may occur in both design-bid-build and design-build contracts.

- Warranty type 3 (20-30 years) specifications, are more likely in design-build-maintain contracts than design-bid-build.

This leads to a correlation table of the form in Table 2-8.

Table 2-8 Most likely contracting approach for different forms of specification

Type of specification	Design-bid-build	Design-build
Prescriptive	✓	
Performance	✓	✓
Warranty type 1 (3-5 years)	✓	
Warranty type 2 (5-10 years)	✓	
Warranty type 3 (20-30 years)		✓

This dissertation discusses projects to build roadway pedestrian access facilities, primarily wheelchair ramps. The author read the specifications for these projects and found that none of them include requirements for the use of specific methods. They are therefore not prescriptive specifications. There do, however, include requirements for the concrete to satisfy breaking-strength requirements for minor concrete. This concrete is normally sourced from a ready-mix supplier and that supplier is responsible for ensuring the concrete meets specifications.

On these pedestrian access facilities, performance consists primarily of conforming to specified dimensions and maximum slopes. It is therefore possible to test the conformance, through measurement, immediately after the facility is built. There is no need to test for long-term durability using elaborate testing methods of the type described in the section on performance specifications.

In addition, pedestrian access facilities are also not normally the subject of long-term warranties and maintenance clauses of the type discussed in the section on warranties.

The case studies discussed in the following chapters, 3, 4, and 5, identify a difference in the amount of detail included in the plans for two sets of pedestrian access facility projects. Both sets of projects use a design-bid-build method, but one set of projects includes far more detail in the plans that the amount of detail in the other set of projects. Section 5.3.2 argues that the plans with greater detail are overdesigned. In closing, it should be noted that over- or under-design bears no relationship to prescriptive versus performance specifications; the two sets projects in the case studies use the same specifications. Some might argue that the more detailed plans require a higher level of performance, but it will be seen that is not the case because both sets of projects specify the same materials, tests, and tolerances (Section 5.2.3 discusses tolerances in greater detail).

3 Case study 1: Pedestrian access facilities on California State Highways

This case study, Chapter 3, considers alternative models for project cost estimating at the early conceptual or feasibility stage using data from pedestrian access projects on California State highways, developed by the California Department of Transportation (Caltrans). The chapter consists of Section 3.1, introduction: why this focus?; Section 3.2, data obtained; Section 3.3, model development without inflation adjustment; Section 3.4, inflation adjustment methods; Section 3.5, results with inflation adjustment; Section 3.6, analysis; and Section 3.7, identification of a preferred alternative using Choosing By Advantages.

3.1 Introduction: why this focus?

3.1.1 Evaluation of cost estimates

The final cost of any given project remains unknown until the project is complete and all the project records closed. The final cost is the cost recorded in the organization's accounting system when the project records are closed. Until that time, the project includes some elements whose cost is unknown. This creates a challenge for those who must develop budgets and arrange project funding.

As an example of this problem, Caltrans, the California Transportation Commission (CTC), the California State Transportation Agency (CalSTA) and the California Legislature have all expressed concerns about the accuracy of cost estimates on California's state highway projects. At the request of CalSTA, the CTC convened a task force in 2016 that found that, "while the current process is better than it was in 2013-14 and Caltrans appears to continue its commitment in developing the best possible estimates for annual workload, it is evident that there is a limit to the accuracy of the estimates given the vast number of variables involved in the forecast." (CTC 2016)

The Task force recommended that, "assigning the Commission responsibility to allocate Caltrans COS [Capital Outlay Support] resources by project component would provide a means to hold Caltrans accountable for its budget estimates." (CTC 2016)

In response to these recommendations, the Legislature voted additional resources to the CTC in the 2017-2018 Fiscal Year to "review Capital Outlay Support projects" (California Legislature 2017:2), and added a provision to state law that gives the CTC phase-by-phase approval authority over Caltrans COS resources on projects (California Legislature 2017:1).

Despite these Legislative actions, Caltrans and the CTC remain the same people with the tools that they had before. None of the Legislative actions addresses the concerns about estimate accuracy expressed by the CTC (2016). To improve estimate accuracy, Caltrans and the CTC would need better tools and processes for making cost estimates. This dissertation aims to make a contribution toward that end.

This dissertation examines the use of two parametric exponential functions, the common exponential and the modified Cobb-Douglas exponential as an estimating tool at the conceptual estimate stage (i.e., for AACE Class 4 and 5 estimates) and compares them to the linear parametric function. This provides a “best fit” parametric model to identify the most likely cost of a project that produces specific desired outputs. It is the first stage in a multi-stage plan to develop a conceptual and feasibility estimating system, using Caltrans data to provide a proof-of-concept that could later be adopted by other agencies that, like Caltrans, own large amounts of infrastructure of a given type and therefore manage large portfolios of projects that are similar to each other in nature. The stages of the plan consist of:

- Stage 1: Develop an algorithm for the “best fit” (i.e., most likely) cost of a given type of project that is commonplace in the organization, based on the historic costs of that type of project (provided that the organization has a large set of historic data).

- Stage 2: Develop a probability density function to address the variability in the project cost data from Stage 1. The intent is that this would enable the organization to determine upper and lower confidence limits of a given project cost estimate for any desired probability. This could be expressed as a statement such as, “Based on historic practices and experience, there is a 60 percent certainty that the actual cost will be less than or equal to this estimate.”

- Stage 3: Expanding Stages 1 and 2 to a wider variety of commonplace projects in the original target organization (in this case, Caltrans), and to commonplace projects in other interested organizations.

3.1.2 Legal context of pedestrian access facilities

This chapter applies the three conceptual estimating functions to one ubiquitous type of project, pedestrian access facilities. These projects result, directly and indirectly, from the Americans with Disabilities Act (ADA) that Congress passed in 1990. They result directly from ADA in that they respond to provisions in the ADA law and, indirectly, from a heightened awareness of pedestrian access issues and social pressures to address those issues.

ADA includes provisions that require public entities to make their facilities accessible to people with disabilities. For highway agencies, the principal barriers to accessibility are found in pedestrian facilities. The expected response to ADA on highways is to provide three principal forms of pedestrian facility:

1. Wheelchair ramps at street corners to allow people in wheelchairs to cross streets at designated pedestrian crossings.

2. Wheelchair-accessible sidewalks.

3. Audible signals at signalized intersections to inform visually impaired people when a pedestrian signal is in their favor.

In August 2006, Californians for Disabilities Rights, Inc. (CDR) introduced a class action lawsuit in Federal Court alleging that Caltrans was failing in its duty to comply with the ADA. The case was settled out of court through a Settlement Agreement that was filed in Federal Court on December 22, 2009 and approved on January 25, 2010 (CDR 2010). The principal financial terms of the agreement state that the State of California will allocate $1.1 billion to ADA pedestrian access facilities over thirty years, as follows:

1. For five years from 2010-11 to 2014-15: $25 million per year.
2. For ten years from 2015-16 to 2024-25: $35 million per year.
3. For ten years from 2025-26 to 2034-35: $40 million per year.
4. For five years from 2035-36 to 2039-40: $45 million per year.

A carry-over provision requires that unexpended money from one year must be carried forward to the following year so that the $1.1 billion is maintained. The agreement also requires that Caltrans prepare an annual progress report and provide the funding for an annual independent compliance review.

The CDR settlement agreement provides the foundation for a case study that has several characteristics that provide a good foundation for research:

1. It ensures that Caltrans will produce a steady high-volume flow of projects that produce small units of output, namely wheelchair ramps, sidewalks, and audible traffic signals.
2. This flow will continue for a considerable time (30 years), permitting longitudinal study of the cost and time to develop the outputs, and of the impacts of process changes during those 30 years.
3. The projects are categorically exempt from environmental laws and require limited external approvals. As a result, the cost and time of development is a function mainly of the processes and efficiency of the Caltrans effort, rather than a function of external constraints. The principal external constraint on most pedestrian access projects comes from the need to obtain rights of entry from adjoining property owners, particularly where sidewalks run along the boundary of the Caltrans right of way.

These characteristics lend themselves to the use of pedestrian access facility projects to test ideas for continuous improvement following the Deming-Shewhart plan-do-check-act cycle (Deming 1986).

3.2 **Data obtained**

This study began as an examination of Caltrans data. The author requested, and Caltrans provided, a data set of 171,790 individual expenditures on pedestrian access facility projects between July 1, 1998 through August 27, 2012. Examples of individual expenditures on these projects include timesheets, travel expense claims, consultant invoices, contractor payments, indirect cost assessments, and other similar details.

The cost data for Caltrans projects included details by project phase, with separate data for preliminary engineering (engineering work that occurs prior to the award of a construction contract), right-of-way operations, construction engineering, construction capital, and right-of-way capital.

These expenditures spread across 319 projects. The author found that most of these projects had not yet reached construction and that the data included construction-phase expenditures on 171 of the 319 projects.

A search of Caltrans records produced as-built plans for 39 of the 171 projects. Those 39 projects constructed 976 wheelchair ramps, 1,462 meters (4,797 feet) of new sidewalk, and 4 audible traffic signals.

The data for these 39 projects is summarized in Appendix A. Each number in that appendix is a summation of many individual expenditure records or plan-sheet details. Each expenditure record included the date on which the expenditure was incurred, a fact that is relevant to the discussion of inflation in section 3.4.

The fields listed in Appendix A are:

- Project number: A seven-character number that consists of the two-character district number and five-character project code assigned by the district. Caltrans has 12 regional districts, numbered 01 through 12. The five-character code must have a number 0 through 4 as its first character and may have alphabetic characters as the second and fifth characters. The third and fourth characters must be numbers. This coding scheme has been replaced in the new Caltrans accounting system, e-FIS, but it remains in use because it is required by the legacy Project Information and System Analysis system (PISA) that Caltrans uses to record its Class 2 cost estimates, to manage the construction bidding process, and for construction contract administration.

- Phase K, 0, 1, 2, 3, 4, and 9 costs: The costs incurred for project initiation documents; permits and environmental studies; plans, specifications, and estimates; right-of-way support; construction engineering; construction capital; and right-of-way capital, all discussed in Section 2.3.1.

- Phase 5 costs: Prior to the adoption of Caltrans new accounting system, e-FIS, Caltrans used Phase 5 to record construction capital costs on minor projects. In the e-FIS system, minor projects use the "Phase 4" code just as major projects do. Section 10105 of the PCC defines minor projects as projects with construction costs of less than $250,000 plus an inflation factor over the 2010 base year. The Department of Finance announces the inflation factor and adjusts the minor contract limit at two-year intervals. Construction work on minor projects can be awarded using a slightly simpler bidding process than that for major projects.

- Phase 8 costs: Prior to the adoption of Caltrans new accounting system, e-FIS, Caltrans used Phase 8 to record payments to local government agencies. In the e-FIS system, these payments now use the "Phase 4" code. There is one such payment in the data shown in Appendix A, for a payment of $84,480 to the City of Santa Barbara.

- R/W hours: The number of hours billed to Phase 2, right-of-way support, by Caltrans employees. These hours consist mainly of work by Caltrans right-of-way agents. As noted in Section 2.3.1, this work may be performed only by government employees and cannot be contracted out.

- Count of ramps, linear feet of sidewalk, and count of signals: The author obtained these numbers by reviewing the as-built plans for each of the projects. This involved counting the ramps and signals and reading the beginning and end points of each section of sidewalk. Sidewalls were normally 1.22 m (4-feet) wide.

The total cost of the 39 projects, by phase, is summarized in Table 3-1.

Table 3-1 Cost of the 39 projects listed in Appendix A, by phase

Phase	Total cost of 39 projects	Percent of total
Phase K (PID)	\$24.68	0.0%
Phase 0 (PA&ED)	\$4,451,907.54	16.6%
Phase 1 (PS&E)	\$8,910,498.57	33.3%
Phase 2 (right-of-way operations)	\$896,147.84	3.4%
Phase 3 (construction engineering)	\$4,161,533.83	15.5%
Phases 4 and 5 (construction capital)	\$7,926,097.68	29.6%
Phase 8 (payments to local government agencies)	\$84,480.00	0.3%
Phase 9 (right-of-way capital)	\$352,974.82	1.3%
TOTAL	\$26,783,664.96	100.0%

3.3 Model development without inflation adjustment

This section describes the development of parametric estimating models for the 39 projects discussed in Section 3.2.

3.3.1 Three alternative parametric models

The literature review has identified three alternative forms of parametric model for performing conceptual and feasibility estimates. These are:

1. The common exponential function (from Section 2.6.4):

$$\text{Cost} = a + gX_1^b + hX_2^c + iX_3^d + jX_4^e + kX_5^f \quad \text{(equation 8)}$$

2. The Cobb-Douglas exponential function (from Section 2.6.6):

$$\text{Cost} = a + bX_1^c.X_2^d.X_3^e.X_4^f.X_5^g \quad \text{(equation 11)}$$

3. The linear parametric function (from Section 2.6.2):

$$\text{Cost} = a + \sum_{i=1}^{i=n} b_i X_i \quad \text{(equation 7)}$$

In the particular case of the present wheelchair ramp projects, with five variables, the linear parametric model can be rewritten as:

$$\text{Cost} = a + gX_1 + hX_2 + iX_3 + jX_4 + kX_5 \qquad \text{(Equation 13)}$$

Where a, g, h, i, j, k, X_1, X_2, X_3, X_4 and X_5 are as in equation 8 (see Section 2.6.2).

3.3.2 Code development

In order to test the three parametric models, the author wrote a series of MATLAB multiple regression analysis scripts. These appear in Appendices C to E.

Each script uses MATLAB's native fminsearch function that finds the minimum value of a function when varying a single unknown constant and keeping all other unknown constants constant. After initializing the constants described in each equation (equations 7, 10, and 11), the script rotates through the constants, adjusting each one in turn, until no further adjustment can reduce the total expression.

Appendix C provides the script for the common exponential model (equation 7), Appendix D for the Cobb-Douglas exponential model (equation 11), and Appendix E for the linear model (equation 13).

The common exponential converged far more slowly than the Cobb-Douglas. To check the status of the convergence and satisfy himself that the function was converging, the author added an extra subroutine, regressionErr, to the code for the common exponential model.

The linear parametric model is a special case of the common exponential with the exponential constants fixed at 1.0 and not being permitted to change. This permitted the use of the regressionFit and regressionErr subroutines that the author had already written and avoided the need to write another subroutine.

3.3.3 Original results without inflation adjustment and with unconstrained variables

Through successive approximations using MATLAB, the following best-fit common exponential function was developed, using the pedestrian access facility outputs for the 39 Caltrans projects:

$$\text{Cost} = -14{,}331{,}186.62 + 14{,}435{,}034.43X_1^{0.007108} + 19{,}468.64X_2^{0.4643} - 0.002579X_3^{24.25} + 314X_4^{0.6403} + 22{,}423X_5^{0.4394} \text{ (Equation 14)}$$

This function has a correlation coefficient $r = 0.75$ and a coefficient of determination $r^2 = 0.55$. It therefore accounts for 55 percent of the variation in costs. This regression function converged very slowly: the values in equation 14 were obtained after 16,000,000 successive rounds of approximations. In a "round of approximations" each constant is minimized once. As equation 14 (and equation 8) has 11 constants, that means that 176,000,000 calls of the fminsearch function were required to produce equation 14 (11 constants x 16,000,000 rounds).

Using the same approach, the modified Cobb-Douglas exponential function converged after only 4,291 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

$\text{Cost} = 232{,}940 + 62{,}711X_1^{0.2928}.X_2^{0.1429}.X_3^{0.3760}.X_4^{0.0172}.X_5^{0.1791}$ (Equation 15)

This function has a correlation coefficient $r = 0.74$ and a coefficient of determination $r^2 = 0.54$. It therefore accounts for 54 percent of the variation in cost. While this correlation is slightly lower than the correlation obtained with the common exponential function, the Cobb-Douglas exponential function converged much more quickly. Moreover, it provided an intuitively satisfying result. It indicates a fixed processing cost per-project of $232,940 regardless of project size, the sum of the exponential factors is 1.01, which is close to Cobb and Douglas' preferred 1.00; and all the factors are positive.

In contrast, the common exponential function produced some negative numbers. Such a result is intuitively incorrect – an increased scope should not produce a decrease in cost.

3.3.4 Results without adjustment for inflation but with constrained variables

To avoid the intuitively incorrect results, the author constrained the code to require that all constraints be positive and that exponents be between 0 and 1. This modifies equation 15 to become:

$\text{Cost} = 161{,}051.25X_1^{0.\ 29082} + 17{,}681.15X_2^{0.\ 4856} + 111{,}653.07X_3^{0.0} + 442.50X_4^{0.\ 6187} +$
$21{,}141.52X_5^{0\ 4388}$ (Equation 16)

This function has a correlation coefficient $r = 0.74$ and a coefficient of determination $r^2 = 0.55$. It therefore accounts for 55 percent of the variation in costs and is not significantly different from the unconstrained result obtained in equation 14. Rather than 176,000,000 rounds of approximation, however it required only 1,483 rounds of approximations.

Equation 16 finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. The data set, shown in Appendix A, includes 4 audible traffic signals on 3 projects (i.e., one project has 2 signals). This null finding creates a zero-intercept fixed cost even though there appeared to be no fixed cost in equation 16. Equation 16 can be rewritten as:

$\text{Cost} = 111{,}653.07 + 161{,}051.25X_1^{0.\ 2908} + 17{,}681.15X_2^{0.\ 4856} + 442.50X_4^{0.\ 6187} +$
$21{,}141.52X_5^{0.4388}$ (Equation 17)

With constrained constants the modified Cobb-Douglas exponential function converged after 3,788 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

$\text{Cost} = 232{,}939.36 + 62{,}711.61X_1^{0.2928}.X_2^{0.\ 1429}.X_3^{0.\ 3760}.X_4^{0.\ 01717}.X_5^{0\ 1791}$ (Equation 18)

This function is essentially unchanged from equation 15 and has a correlation coefficient $r = 0.74$ and a coefficient of determination $r^2 = 0.54$. It therefore accounts for 54 percent of the variation in cost.

With constrained constants, as for equations 16 and 17, the linear parametric model converged after only 40 iterations. It had been constrained to ensure that all the constants remained positive, and this constraint appears to have reduced the numbers of iterations considerably. The resulting best-fit linear function, using the pedestrian access facility outputs for the 39 Caltrans projects was:

$$\text{Cost} = 452{,}719.84 + 2{,}264.77X_1 + 376.79X_2 + 0.X_3 + 7.51X_4 + 171.73X_5 \quad \text{(Equation 19)}$$

This equation, as with equation 16, indicates that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. This function has a correlation coefficient $r = 0.68$ and a coefficient of determination $r^2 = 0.46$. It therefore accounts for 46 percent of the variation in cost. The linear form therefore provides a poorer correlation with the data than the common exponential or the Cobb-Douglas. This fits with the expectations in the literature review, Section 2.6.1, where it was postulated that an exponential function would provide a better fit than the linear, based on the Wright and Henderson curves.

3.4 **Inflation adjustment methods**

As noted in Section 3.2, the cost data received from Caltrans included all expenditures on pedestrian access facility projects from July 1, 1998 to August 27, 2012. Section 3.3 analyzed the data on the 39 short-listed projects without adjusting for inflation. It seems likely that inflation would occur during this time period and the analysis in this section shows that inflation did occur.

To adjust for inflation requires a method. This Section 3.4 discusses how to make the adjustment, and the following Section 3.5 makes the adjustment to the expenditure data in Appendix A.

3.4.1 Identification of expenditure dates for use in inflation adjustment

Equations 14 to 19 all provide parametric estimates of the project cost derived from a set of the actual costs of 39 projects. Those actual costs are not adjusted for inflation. An alternative approach would be to base the parameters on inflation-adjusted costs. That would permit users to estimate future costs assuming that the inflation rate remains constant.

As noted in Section 3.2, each of the expenditure records from Caltrans included the date on which the expenditure was recorded. The earliest and latest dates on which each phase received charges indicate the time period during which work was performed on that phase. Caltrans staff record their time weekly before the Tuesday following the week on which they worked. The standing instruction is for employees to submit time as at the end of the day on Friday so that supervisors can approve that time on the following Monday. If an employee and supervisor were to coordinate their actions they could, nevertheless, beat the Tuesday deadline by submitting and approving time on Monday evening. Caltrans batch-processes the timesheet data each Tuesday, running the hours through the Caltrans Staff Central personnel system to obtain dollar costs and loading both hours and dollars into eFIS. The expenditure dates for the support phases therefore reflect the actual dates on which work was performed with a margin of error of up to 8 days after the event. (Work performed on a Monday is recorded in eFIS on the following Tuesday).

The process for construction capital (Phase 4) is different from that for the support phases. Caltrans staff enter their monthly estimates for each construction contract by the 15th calendar day of each month. The expenditure dates for Phase 4 therefore reflect the actual dates on which work was performed with a margin of error of up to 1 month and 15 days after the event (the cost of work done on the 1st day of the calendar month is entered into eFIS on the 15th day of the next month).

The 8-day and 1-month-and-15-day margins are not significant relative to the process for making inflation adjustments, however, since both margins are considerably smaller than the time periods used for inflation adjustment. Caltrans calculates its index for construction cost (Phase 4) inflation each quarter (see Section 3.4.2) and inflation of support costs is dependent upon multi-year collective bargaining agreements (see Section 3.4.3).

Using the dates recorded for each expenditure, Appendix F shows the last day on which an expenditure was recorded for each project phase.

After identifying the last day of each phase, the author considered two approaches to inflation adjustment. The first is the use of the California Highway Construction Cost Index, and the second is a consideration of the per-hour labor costs. Sections 3.4.2 and 3.4.3 describe and consider each of these approaches.

3.4.2 California Highway Construction Cost Index (CHCCI)

Caltrans collects data on the bids received on construction contracts and publishes a quarterly California Highway Construction Cost Index (CHCCI). This index reflects the bid prices that Caltrans has received during the quarter for items such as cubic yards of concrete, tons of steel, tons of asphalt, cubic yards of aggregate, linear feet of guardrail and many other similar items. The CHCCI reflects the fluctuations in the economy, and also differences from one quarter to the next in the nature of the contracts that Caltrans awards. In one quarter, Caltrans may award many large pavement rehabilitation contracts in urban areas, but only a few small pavement rehabilitation contracts in rural areas in the next quarter. Such changes in size and location may affect the bid prices, and therefore change the CHCCI, without a significant change in the broader economy.

Figure 3-1 charts the CHCCI numbers for the second quarter of 2000 to the third quarter 2012, along with a linear regression trend line for those numbers. This figure illustrates the large fluctuations that occur in CHCCI data from one quarter to the next. The linear regression line has a slope of 4.0 percent per annum relative to a January 1, 2012 base date for inflation adjustment chosen by the author. The linear regression line has an index value of 307.01 on January 1, 2012.

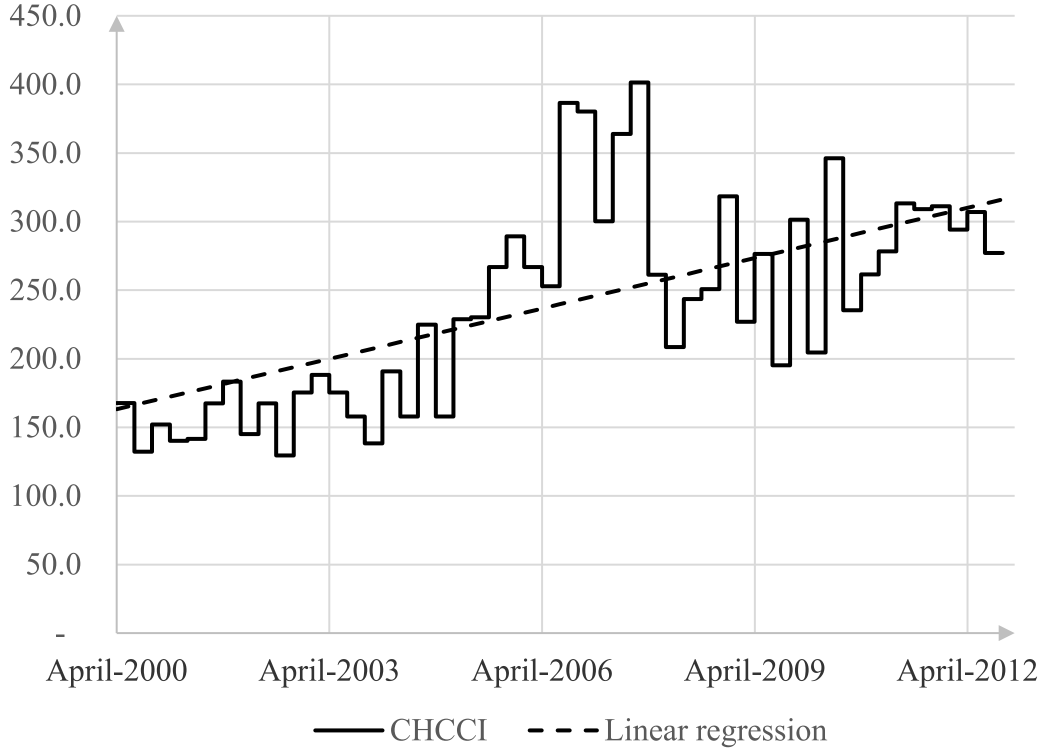


Figure 3-1 CHCCI data and linear regression

3.4.3 Per-hour labor costs

The CHCCI is based upon construction bid items. The construction contracts that result from those bids are funded through the construction capital phases (project Phases 4 and 5). The CHCCI therefore refers only to construction capital costs and not to support costs (project Phases 0, 1, 2, and 3).

In Caltrans, support costs consist mainly of state employee labor costs. These labor costs are not determined by bid prices and do not fluctuate with the CHCCI. Instead, they are determined mainly by collective bargaining agreements between the State and its various labor unions.

The bargaining agreements drive the cost inflation over time. Within the timeframe of each agreement, however, several factors affect labor costs. One of these is the mix of employee classes that work on a project. Each organizational unit that performs work on a project normally consists of a supervisor and several rank-and-file employees all of whom are in the same bargaining unit (e.g., engineering supervisors supervise units in which most employees are rank-and-file engineers). Supervisors are in a different employee class than rank-and-file employees, and most bargaining units have several rank-and-file classes (e.g., Transportation Engineer Range A, Range B, Range C, and Range D). Each class has a fixed per-hour rate. If a supervisor spends more time on one project than another, the average hourly cost of the unit's work on that project will be higher than the average hourly cost on the other project. The same will be true if higher-priced rank-and-file classes do more work on one project than another.

In addition to the classes used, the labor type may affect the labor cost. The State of California has three labor types: regular time, overtime, and temporary help. Regular time refers to state employees working the normal 40 hours per week, overtime refers to them working hours in addition to 40 hours in a week, and temporary help refers mainly to retired employees who return to work part-time. Each of these labor types has a different per-hour rate for each class. Regular time is the most expensive because it includes contributions to the pension fund; the health, dental, and vision plans; and an indirect cost assessment (discussed later in this section). Overtime normally pays time-and-a-half but does not include contributions to the pension fund; the health, dental, and vision plans; or the indirect cost assessment. This makes overtime less costly than regular time. Temporary help is less costly per hour than regular time because it does not include the pension, health, dental, and vision plan contributions.

Appendix G provides the following four items of data for each of the support phases on the projects listed in Appendix A:

- The state employee labor cost to the project phase.
- The state employee labor expressed as a percentage of the total cost of the phase listed in Appendix A.
- The number of hours that state employees charged to the phase.
- The average labor cost per hour for the phase (i.e., labor cost / hours).

When totalled for all 39 projects listed, the labor cost accounts for 66 percent of the costs of Phase 0, 70 percent of the Phase 1 costs, 70 percent of the Phase 2 costs, and 69 percent of the Phase 3 costs. Labor costs therefore make up most of the costs of the four support phases.

Most of the remaining 30 percent to 34 percent of the project costs consists of the indirect cost assessment. Like other government and non-profit organizations in the US that receive federal funding, Caltrans adds an indirect cost assessment to the direct costs that it charges to projects. This indirect cost assessment is sometimes referred to as “overhead” and is governed by the rules in Title 2 of the Code of Federal Regulations, part 230 (OMB 2005). Caltrans develops an indirect cost rate at regular intervals, normally annually, and receives approval for the rate from the FHWA. Figure 3-2 displays the indirect cost rate for the time period of the projects in Appendix F. Caltrans assesses this rate on regular and temporary help labor cost (i.e., not on overtime), and the rate averaged 41 percent during the period time period of the projects in Appendix F.

If the labor cost in Appendix G is, say, 70 percent of the total phase cost, and the indirect cost rate is, say, 40 percent, then the cost attributable to labor is 70% x 140% = 98% of the total phase

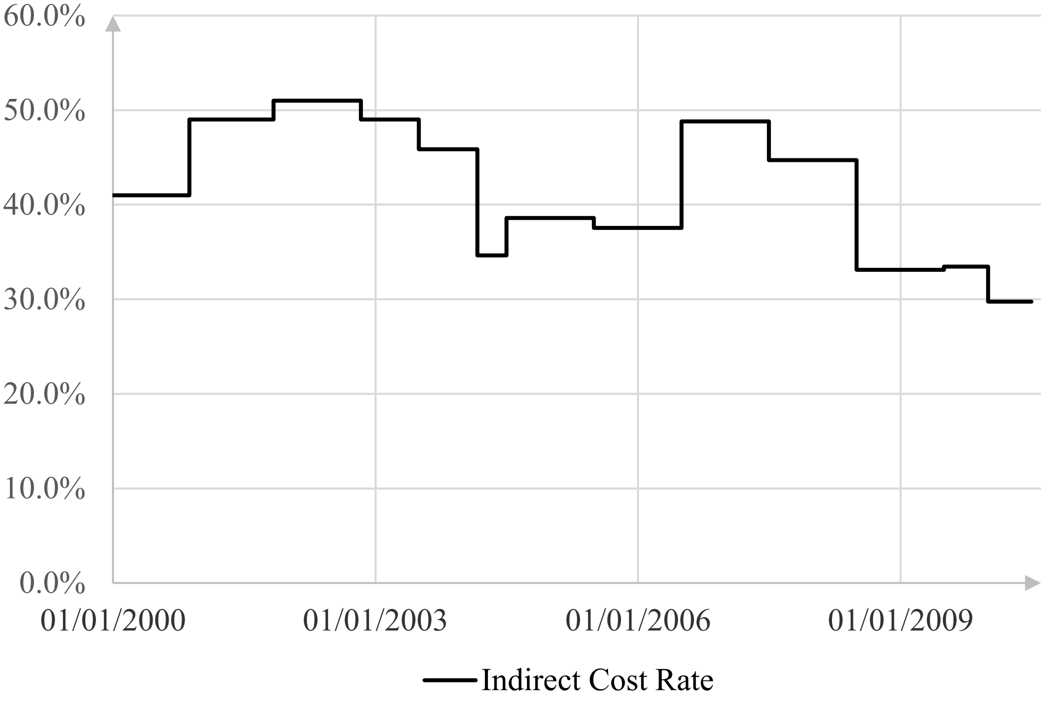


Figure 3-2 Caltrans indirect cost rates assessed on project labor

cost. Examination of the percentages in Appendix G combined with the percentages in Figure 3-2, indicates that state employee labor costs, including their related indirect costs, account for almost all of the costs of the four support phases. On the 39 projects in this study, state employee labor and their related indirect costs account for 95.5 percent of the support costs, consultants account for 4.0 percent, and state employee travel expenses account for the remaining 0.5 percent.

The average hourly labor cost of the four support cost phases, from Appendix G, are:

- Phase 0: $50.18 / hour
- Phase 1: $57.00 / hour
- Phase 2: $43.45 / hour
- Phase 3: $53.15 / hour

Plotting the labor costs per hour costs from Appendix G against the dates in Appendix F produces the labor cost per hour cost lines in Figure 3-3. The labor costs per hour on Phases 0, 1, and 3 overlap each other and do not appear to have any significant difference when considered over time. On Phase 2, however, the labor costs per hour began as lower than the other three support phases prior to 2004, rose to overlap the labor costs per hour of the other three phases, and then became lower than the labor costs per hour of the other three support phases from 2009 onward. This is consistent with the average costs listed above, in which the Phase 2 average ($43.45 / hour) is $6.73 lower than the next-lowest average ($50.18 / hour for Phase 0).

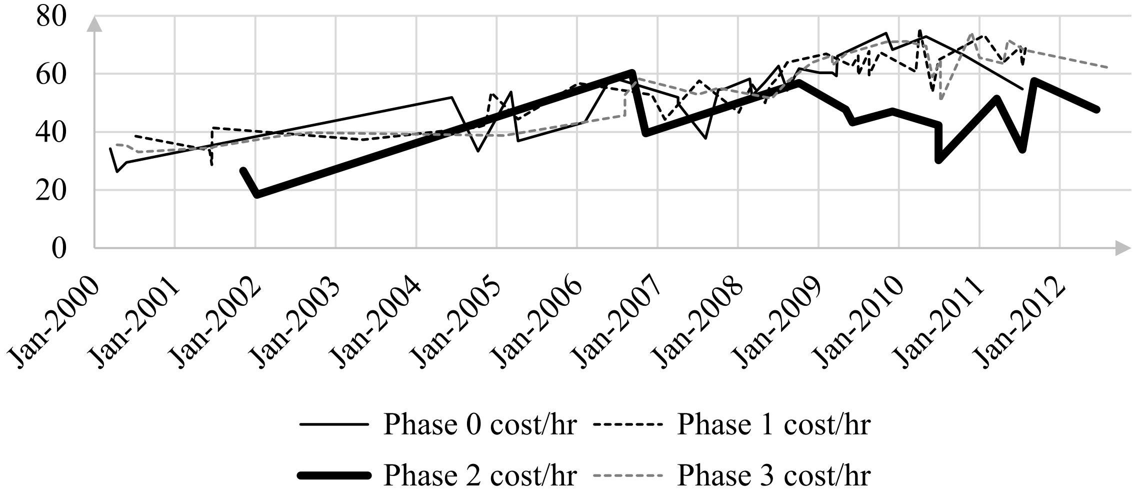


Figure 3-3 Average labor costs per hour by phase of the projects in Appendix A, plotted against the last day on which expenditures were incurred on each project phase

As noted, collective bargaining agreements are the principal drivers of labor cost increases. It is to be expected that there would not be a significant difference between the labor costs on Phases 0, 1, and 3 because the work on those phases is performed mainly by state employees in the engineers bargaining unit, Unit 9, represented by Professional Engineers in California Government (PECG). Work on Phase 2 is performed mainly by land surveyors, who are in Unit 9, and by right-of-way agents, who are in the administrators bargaining unit, Unit 1, represented by Service Employees International Union (SEIU), Local 1000. Comparing rank-and-file salary ranges in Unit 9 to rank-and-file salary ranges in Unit 1, the ranges in Unit 9 are higher. This difference also holds for the salary ranges of supervisors in the two bargaining units. Working on the assumption that the labor costs for employees charging Phases 0, 1, and 3 can be considered together, but that labor costs for Phase 2 should be considered separately, the author developed the chart in Figure 3-4.

3.4.4 Final adjustment

The author chose January 1, 2012, as the base date for inflation adjustment. This date falls toward the end of the dates shown in Appendix F and is therefore closest to the dates of any

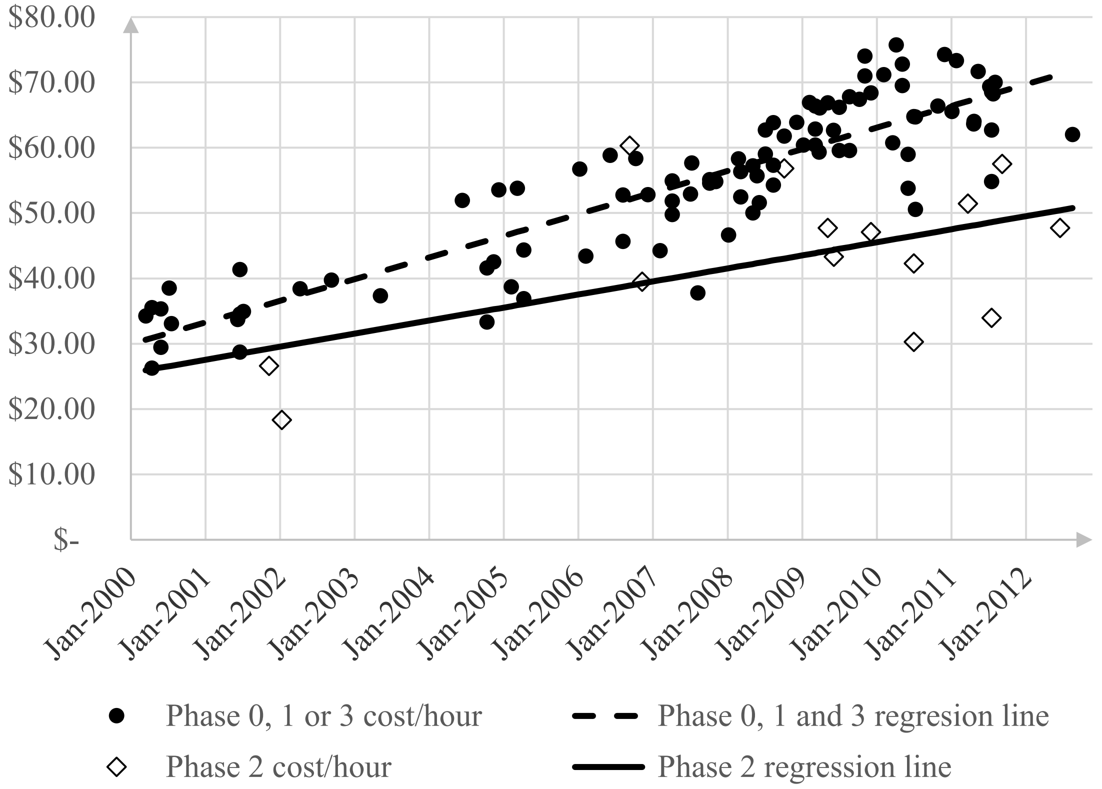


Figure 3-4 Linear regression lines for the per-hour labor costs of the 4 support phases of the projects in Appendix A.

future cost estimates that may be performed. For the calculations in Section 3.5, all costs were brought forward to that date using the chosen inflation-adjustment methods.

Section 3.5 considers two alternative approaches for adjusting for construction cost inflation. One approach, in Section 3.5.2 uses the actual quarterly CHCCI numbers. The other, in Sections 3.5.1 and 3.5.3, attempts to "smooth" the variation in the CHCCI by using the linear regression trend that appears in Figure 3-3.

The author applied the CHCCI numbers and the CHCCI linear regression to the construction capital (Phase 4 and 5) to the obtain the inflation-adjusted costs listed in Appendix H. The bases for the inflation adjustment are:

- Phase K (PID): The data includes only one $24.68 charge in Phase K. With only one charge, it is not possible to create a regression line to adjust for inflation similar to those illustrated in Figure 3-4. Due to its tiny cost relative to the cost of the 39-project portfolio, amounting to less than one-millionth of the total cost of the 39 projects (see Table 3-1), inflation on this small amount is unlikely to have a measurable impact on the parametric functions. The author therefore chose not to attempt to make an inflation adjustment on this $24.68 charge.

- Phases 0 (PA&ED), 1 (PS&E), and 3 (construction engineering): Inflation adjusted using the Phase 0, 1 and 2 regression line in Figure 3-4 at the actual end-date of the phase from Appendix F. The regression line has a slope of 4.7 percent relative to the January 1, 2012 base factor, which is has a value of $69.63 per hour.

- Phases 2 (right-of-way operations): Inflation adjusted using the Phase 2 regression line in Figure 3-4 at the actual end-date of the phase from Appendix F. The regression line has a slope of 4.0 percent relative to the January 1, 2012 base factor, which is has a value of $49.47 per hour.

- Phases 4 and 5 (construction capital): Inflation adjusted using two alternative approaches:

  - The actual CHCCI number at the end-date of Phase 1, when the construction contract is awarded and the PS&E phase is closed. This date normally falls shortly after the date on which the successful contractor submitted its bid.

  - The "smoothed" CHCCI number using the linear regression line in Figure 3-1, measured at the end-date of Phase 1.

- Phase 8 (payments to local agencies) is unchanged from Appendix A. As noted in Section 3.2, the data includes only one Phase 8 charge, a payment of $84,480 to the City of Santa Barbara. With only one charge, it is not possible to create a regression line to adjust for inflation similar to those illustrated in Figure 3-4. Although this charge amounts to 0.3 percent of the total cost of the 39 projects (see Table 3-1), and inflation on this charge could have a slight impact on the parametric functions, the author chose not to attempt to make an inflation adjustment on this charge. To develop an inflation adjustment formula would require an extensive amount of research into the purpose of the charge through an examination of the cooperative agreement between Caltrans and the City of Santa Barbara. (Contracts between the State of California and its local government agencies are called "cooperative agreements.") If one were to develop an inflation adjustment formula for this charge it would not be generalizable to future agreements because cooperative agreements address a vast array of services that require payments from the state government to local agencies and from local agencies to the state government. Each agreement would need to be considered on its own merits.

- Phase 9 (right-of-way capital). Phase 9 records payments to property owners and utilities and related expenses. It accounts for only 1.3 percent of the total cost of the 39 projects in Appendix A.

  Acquisition of property accounts for 49 percent of the dollar value of the charges to Phase 9 on these 39 projects. This acquisition consists of 230 individual payments to property owners. Of these 230 individual payments, 172 are payments of $250.00 apiece, and another 24 payments are payment of $500.00 apiece. These are typical token payments to the owners of adjoining properties for right-of-entry as symbolic acknowledgements of the inconvenience that the owners experience. They are not inflation-adjusted and are not the product of a real property appraisal.

Expert witnesses, appraisals, and legal recording and reporting fees account for another 36 percent of the dollar value of the charges to Phase 9 on the 39 projects, for amounts totaling \$127,663.17. These expenses were all accumulated on one project, 05-0J970, where 1 or more property owners sued Caltrans for "inverse condemnation," claiming harm to their property. Payments for acquisition of property on this project amount to \$14,400.00. The legal fees are therefore far greater than the payments received by the property owners on this project.

Utility relocation payments account for a further 11 percent of the dollar value of the charges to Phase 9 on the 39 projects.

Title and escrow fees account for the remaining 4 percent of the dollar value of the charges to Phase 9 on the 39 projects.

To develop an inflation adjustment for Phase 9 of this set of 39 projects, one would need a property cost inflation index for the non-token property acquisition costs, a legal cost inflation index, and one or more utility cost inflation indices for different types of utilities. Given the small contribution of Phase 9 to the total cost of this set of 39 projects, the author did not deem the effort of researching and developing such indices to be worthwhile.

3.5 Results with inflation adjustment

In Section 3.3.4, the author developed parametric models from the raw, uninflated, data provided in Appendix A. In this section, the author develops revised models using the inflation-adjusted data in Appendix H.

3.5.1 Results with linear capital inflation

Appendix H provides data for forms of inflation-adjusted construction capital costs, linear and CHCCI. This Section develops models using the linear form of the construction capital inflation adjustment. Through 1,251 rounds of approximations using MATLAB, the following best-fit common exponential function was developed, using the pedestrian access facility outputs for the 39 Caltrans projects:

$\text{Cost} = 135{,}312.73X_1^{0.4019} + 30{,}649.59X_2^{0.4089} + 173{,}250.36X_3^{0.00} + 158.33X_4^{0.6814} + 22{,}595.99X_5^{0.47}$ (Equation 20)

This function has a correlation coefficient $r = 0.80$ and a coefficient of determination $r^2 = 0.63$. It therefore accounts for 63 percent of the variation in costs.

Equation 20, as with equation 16, finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. That finding, however, creates a zero-intercept fixed cost even though there appeared to be no fixed cost in equation 20. Equation 20 can be rewritten as:

$\text{Cost} = 173{,}250.36 + 135{,}312.73X_1^{0.4019} + 30{,}649.59X_2^{0.4089} + 158.33X_4^{0.6814} + 22{,}595.99X_5^{0.47}$ (Equation 21)

Using the same approach, the modified Cobb-Douglas exponential function converged after 3,672 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

$\text{Cost} = 288{,}981.67 + 50{,}956.8X_1^{0.3844}.X_2^{0.1306}.X_3^{0.5061}.X_4^{0.00061}.X_5^{0.2085}$ (Equation 22)

This function has a correlation coefficient $r = 0.79$ and a coefficient of determination $r^2 = 0.63$. It therefore accounts for 63 percent of the variation in cost.

Following the same approach as the first two models, the linear parametric model converged after only 39 iterations. It had been constrained to ensure that all the constants remained positive, and this constraint appears to have reduced the numbers of iterations considerably. The resulting best-fit linear function, using the pedestrian access facility outputs for the 39 Caltrans projects was:

$\text{Cost} = 489{,}337.85 + 4{,}646.14X_1 + 374.19X_2 + 0.X_3 + 7.04X_4 + 226.25X_5$ (Equation 23)

This equation indicates that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. This function has a correlation coefficient $r = 0.74$ and a coefficient of determination $r^2 = 0.55$. It therefore accounts for 55 percent of the variation in cost. The linear form therefore provides a poorer correlation with the data than the common exponential or the Cobb-Douglas. This is congruent with the expectations in the literature review, Section 2.6.1, where it was postulated that an exponential function would provide a better fit than the linear, based on the Wright and Henderson curves.

3.5.2 Results with CHCCI inflation

Appendix H provides data for forms of inflation-adjusted construction capital costs, linear and CHCCI. Section 3.5.1 develops models using the linear form of the construction capital inflation adjustment. This section develops models using the CHCCI form of the construction capital inflation adjustment. Through 2,641 rounds of approximations using MATLAB, the following best-fit common exponential function was developed, using the pedestrian access facility outputs for the 39 Caltrans projects:

$\text{Cost} = 117{,}197.77 + 53{,}407.03X_1^{0.\ 6407} + 31{,}746.02X_2^{0\ 4089} + 179{,}421.54X_3^{0.0} + 37.27X_4^{0.\ 7817} + 14{,}225.85X_5^{0.\ 542}$ (Equation 24)

This function has a correlation coefficient $r = 0.85$ and a coefficient of determination $r^2 = 0.72$. It therefore accounts for 72 percent of the variation in costs.

Just as in equations 15 and 19, equation 24 finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. That finding, however, increases the zero-intercept fixed cost in equation 24. Equation 24 can be rewritten as:

$\text{Cost} = 296{,}619.31 + 53{,}407.03X_1^{0.6407} + 31{,}746.02X_2^{0.4089} + 37.27X_4^{0.7817} + 14{,}225.85X_5^{0.542}$
(Equation 25)

Using the same approach, the modified Cobb-Douglas exponential function converged after only 2,548 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

$\text{Cost} = 361{,}693.76 + 31{,}381.50X_1^{0.5182}.X_2^{0.1345}.X_3^{0.6184}.X_4^{0.0}.X_5^{0.2104}$ (Equation 26)

This function has a correlation coefficient $r = 0.84$ and a coefficient of determination $r^2 = 0.70$. It therefore accounts for 70 percent of the variation in cost.

Equation 26 finds that X_4, the right-of-way capital cost, has no effect on project cost, which is an intuitively unsatisfactory conclusion. That finding, however, simplifies equation 26, which can be rewritten as:

$\text{Cost} = 361{,}693.76 + 31{,}381.50X_1^{0.5182}.X_2^{0.1345}.X_3^{0.6184}.X_5^{0.2104}$ (Equation 27)

Following the same approach as the first two models, the linear parametric model converged after only 38 iterations. It had been constrained to ensure that all the constants remained positive, and this constraint appears to have reduced the numbers of iterations considerably. The resulting best-fit linear function, using the pedestrian access facility outputs for the 39 Caltrans projects was:

$\text{Cost} = 462{,}522.95 + 7{,}275.28X_1 + 395.96X_2 + 4{,}752.52X_3 + 5.95X_4 + 276.33X_5$ (Equation 28)

This function has a correlation coefficient $r = 0.82$ and a coefficient of determination $r^2 = 0.67$. It therefore accounts for 67 percent of the variation in cost. The linear form therefore provides a poorer correlation with the data than the common exponential or the Cobb-Douglas. This fits with the expectations in the literature review, Section 2.6.1, where it was postulated that an exponential function would provide a better fit than the linear, based on the Wright and Henderson curves.

3.5.3 Results with linear inflation adjustment ignoring right of way

As discussed in Sections 2.3.1 and 3.4.4, some of the costs of projects refer to right-of-way operations (Phase 2) and right-of-way capital (Phase 9). These phases produce rights of entry into property and relocations of utilities, outcomes which may be independent of the production of the project construction outputs (wheelchair ramps, sidewalk and audible signals). To test their possible independence, the author re-ran the linear inflation-adjusted data that he used in Section 3.5.1, but excluded the data for Phases 2 and 9. Through 1,826 rounds of approximations using MATLAB, the following best-fit common exponential function was developed, using the pedestrian access facility outputs for the 39 Caltrans projects:

$\text{Cost} = 356{,}431.65 + 28{,}964.72X_1^{0.7767} + 74{,}639.85X_2^{0.3024} + 82{,}663.75X_3^{0.00}$ (Equation 29)

This function has a correlation coefficient $r = 0.60$ and a coefficient of determination $r^2 = 0.35$. It therefore accounts for 35 percent of the variation in costs.

Just as in equations 15, 19, and 23, equation 29 finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. That finding, however, increases the zero-intercept fixed cost in equation 29. Equation 29 can be rewritten as:

$\text{Cost} = 439{,}095.40 + 28{,}964.72X_1^{0.7767} + 74{,}639.85X_2^{0.3024}$ (Equation 30)

Using the same approach, the modified Cobb-Douglas exponential function converged after 434 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

$\text{Cost} = 436{,}689.96 + 8{,}691.05X_1.X_2^{0.2837}.X_3$ (Equation 31)

This function has a correlation coefficient $r = 0.66$ and a coefficient of determination $r^2 = 0.44$. It therefore accounts for 44 percent of the variation in cost.

Following the same approach as the first two models, the linear parametric model converged after only 39 iterations. It had been constrained to ensure that all the constants remained positive, and this constraint appears to have reduced the numbers of iterations considerably. The resulting best-fit linear function, using the pedestrian access facility outputs for the 39 Caltrans projects was:

$\text{Cost} = 515{,}649.41 + 8{,}684.17X_1 + 438.21X_2 + 0.X_3$ (Equation 32)

This equation indicates that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. This function has a correlation coefficient $r = 0.55$ and a coefficient of determination $r^2 = 0.31$. It therefore accounts for 31 percent of the variation in cost. The linear form therefore provides a poorer correlation with the data than the common exponential or the Cobb-Douglas. This fits with the expectations in the literature review, Section 2.6.1, where it was postulated that an exponential function would provide a better fit than the linear, based on the Wright and Henderson curves.

3.6 **Analysis**

3.6.1 Summary of the coefficients of determination

Table 3-2 summarizes the coefficients of determination of the 12 alternative conceptual cost estimating models, displayed in a 4-by-3 matrix. The 12 alternatives consist of 4 variations of the input data by 3 parametric model types.

Table 3-2 Coefficients of determination of the 12 alternatives

Input data	Common exponential	Cobb-Douglas exponential	Linear
Actual costs.	$r^2 = 0.55$ (equation 17)	$r^2 = 0.54$ (equation 18)	$r^2 = 0.46$ (equation 19)
Inflation-adjusted costs using linear regression of CHCCI to estimate construction cost inflation.	$r^2 = 0.63$ (equation 21)	$r^2 = 0.63$ (equation 22)	$r^2 = 0.55$ (equation 23)
Inflation-adjusted costs using raw CHCCI to estimate construction cost inflation.	$r^2 = 0.72$ (equation 25)	$r^2 = 0.70$ (equation 27)	$r^2 = 0.67$ (equation 28)
Inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.	$r^2 = 0.35$ (equation 30)	$r^2 = 0.44$ (equation 31)	$r^2 = 0.31$ (equation 32)

3.6.2 Null variables

Table 3-3 lists the null variables in the 12 alternative conceptual cost estimating models displayed, like Table 3-2, in a 4-by-3 matrix.

Table 3-3 Null variables for the 12 alternatives

Input data	Common exponential	Cobb-Douglas exponential	Linear
Actual costs.	X_3, the number of audible traffic signals (equation 17)	No null factors (equation 18)	No null factors (equation 19)
Inflation-adjusted costs using linear regression of CHCCI to estimate construction cost inflation.	X3, the number of audible traffic signals (equation 21)	No null factors (equation 22)	No null factors (equation 23)
Inflation-adjusted costs using raw CHCCI to estimate construction cost inflation.	X3, the number of audible traffic signals (equation 25)	X4, right-of-way capital (equation 27)	No null factors (equation 28)
Inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.	X3, the number of audible traffic signals (equation 30)	No null factors (equation 31)	X3, the number of audible traffic signals (equation 32)

3.6.3 Summary of fixed costs

Table 3-4 summarizes the fixed costs of the 12 alternative conceptual cost estimating models displayed, like Tables 3-2 and 3-3, in a 4-by-3 matrix.

Table 3-4 Fixed costs for the 12 alternatives

Input data	Common exponential	Cobb-Douglas exponential	Linear
Actual costs.	$111,653.07 (equation 17)	$232,939.36 (equation 18)	$452,719.84 (equation 19)
Inflation-adjusted costs using linear regression of CHCCI to estimate construction cost inflation.	$173,250.36 (equation 21)	$288,981.67 (equation 22)	$489,337.85 (equation 23)
Inflation-adjusted costs using raw CHCCI to estimate construction cost inflation.	$296,619.31 (equation 25)	$361,693.76 (equation 27)	$462,522.95 (equation 28)
Inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.	$439,095.40 (equation 30)	$436,689.96 (equation 31)	$515,649.41 (equation 32)

3.7 Identification of a preferred alternative using Choosing By Advantages, including mathematical fit among the advantages

This dissertation has identified 12 alternative conceptual cost estimating models, displayed in a 4-by-3 matrix in Tables 3-2, 3-3, and 3-4. These 12 alternatives are:

1. Common exponential model based on the actual costs (equation 17).

2. Cobb-Douglas exponential model based on the actual costs (equation 18).

3. Linear model based on the actual costs (equation 19).

4. Common exponential model based on inflation-adjusted costs with a linear construction cost inflation (equation 21).

5. Cobb-Douglas exponential model based on inflation-adjusted costs with a linear construction cost inflation (equation 22).

6. Linear model based on inflation-adjusted costs with a linear construction cost inflation (equation 23).

7. Common exponential model based on inflation-adjusted costs with the raw CHCCI construction cost inflation (equation 25).

8. Cobb-Douglas exponential model based on inflation-adjusted costs with the raw CHCCI construction cost inflation (equation 27).

9. Linear model based on inflation-adjusted costs with the raw CHCCI construction cost inflation (equation 28).

10. Common exponential model based on inflation-adjusted costs excluding right-of-way with a linear construction cost inflation (equation 30).

11. Cobb-Douglas exponential model based on inflation-adjusted costs excluding right-of-way with a linear construction cost inflation (equation 31).

12. Linear model based on inflation-adjusted costs excluding right-of-way with a linear construction cost inflation (equation 32).

The author's objective is to determine which of these 12 models provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects. The definition of the preferred tool is decided by 4 factors discussed in Section 3.7.2 below. To make this determination, the author uses the Choosing By Advantages (CBA) method which follows these steps (Suhr 1999, Arroyo 2014):

1. Identify alternatives; 2. Define factors; 3. Define "must" and "want" criteria for each factor, 4. Summarize the attributes of each alternative, 5. Decide the advantages of each alternative, and 6. Decide the importance of each advantage.

The discussion below considers each of the 6 steps, referring to the CBA table in Appendix I.

3.7.1 Identify alternatives

The 12 alternatives are listed above.

3.7.2 Define factors

The author has selected four factors to consider in choosing which of the 12 models provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects. These are:

1. Coefficient of determination: The coefficients of determination (Table 3-2) indicate the degree to which the model accounts for the variation in the cost data, and measure the mathematical fit of the models to the underlying data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient represents a better mathematical fit and is therefore better.

2. Ability to project into the future: A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have the irregular variations that appear in Figure 3-1. Ability to project into the future is better than non-ability.

3. Number of null variables: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such "null variables" appear in Table 3-3. It would be better to have no null variables than to have null variables.

4. Fixed costs: As discussed in relation to Figure 2-9, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. Fixed costs imply that certain processes are repeated on every project and that the costs of those processes are incurred regardless of the size of the project. Verification of these fixed costs would require a detailed study of the work that occurs on the projects.

3.7.3 Define "must" and "want" criteria for each factor

As noted in Section 3.7.2:

1. Coefficient of determination: A higher coefficient of determination indicates a better mathematical fit is therefore a better mathematical model.

2. Availability of future data: Availability of future data is better than non-availability.

3. Number of null variables: It would be better to have no null variables than to have null variables.

4. Fixed cost: It would be better for the variables to account for the variations in cost than to assume a large fixed cost.

Each of these is therefore a "want" criterion. It could be argued that availability of future data and the absence of null variables are both "must" criteria. However, 3 the 12 alternatives use the raw CHCCI data which cannot reliably be projected into the future and an additional 4 alternatives have null variables. To set these factors as "must" would therefore immediately eliminate 7 of the 12 alternatives. The author decided not to set them as "must" criteria and to continue the analysis with all 12 alternatives.

3.7.4 Summarize the attributes of each alternative

Suhr defines an attribute as "a characteristic, quality, or consequence of one alternative" (Suhr 2008:1) His CBA method continues, "Underline the least preferred attribute in each factor" and "Circle the most important advantage in each factor (If there are two that are the same, circle only one.)" (Suhr 2008:2, page 80).

The attributes of each alternative appear in Appendix I, with the least preferred attribute for each factor underlined and the most preferred circled. If more than one attribute is equally the least or most preferred, only the first is underlined or circled, in accordance with Suhr's method. They are:

1. Coefficient of determination varies from a high of 0.72 for the common exponential model based on inflation-adjusted costs with the raw CHCCI construction cost inflation (Alternative 7, equation 25) to a low of 0.31 for the linear model based on inflation-adjusted costs excluding right-of-way with a linear construction cost inflation (Alternative 12, equation 32, see Table 3-2).

2. Availability of future data: Alternatives 7 to 9 use the raw CHCCI inflation factors and cannot be projected into the future because the CHCCI has irregular variations.

3. Number of null variables: 6 alternatives have null variables (see Table 3-3).

4. Fixed cost: Fixed costs vary from a low of $111,653.07 for the common exponential model based on the actual costs (Alternative 1, equation 17) to a high of $515,649.41 for the linear model based on inflation-adjusted costs excluding right-of-way with a linear construction cost inflation (Alternative 12, equation 32, see Table 3-4).

3.7.5 Decide the advantages of each alternative

Suhr (2008:1) defines an advantage as "a difference between the attributes of two alternatives." He says "Decisions must be based on the importance of advantages," and "Decisions about the importance must be anchored in the relevant facts" (Suhr 2008:1). With regard to procedures, Suhr (2008:2) says "We select the paramount advantage, and we assign an importance score" and "There is no such thing as zero advantage. Therefore, where there is no advantage, leave a blank space." (Suhr 2008:2, page 153).

1. Coefficient of determination: The author decided that factor 1, the coefficient of determination which measures the mathematical fit, is the paramount advantage and assigned Alternative 7 (equation 25), which has the highest coefficient (0.72) the highest importance of advantage score, 100. Alternative 12 (equation 32), with the lowest coefficient (0.31) has no advantage in accordance with Suhr's method and has a blank importance of advantage in Appendix I. The author assigned an importance of advantage of between 0 and 100 to the remaining alternatives based on the differences between their coefficients and anchored to the magnitude of their coefficients, in proportion to their r^2 score. Suhr (2008:2) says that 4 considerations determine the importance of advantages: "1. The purpose and circumstances of the decision. 2. The needs and preferences of the stakeholders. 3. The magnitude of the advantages. 4. The magnitude of the associated attributes."

2. Availability of future data: 9 of the 12 alternatives can be projected into the future. The author assigned an importance of 30 to each on those 9 alternatives. The remaining 3 alternatives use the raw CHCCI data and have no advantage. Those 3 alternatives have a blank importance of advantage in Appendix I.

3. Number of null variables: As this is, in effect, a "must," the author assigned an importance of 20 to each of the 6 alternatives that have no null variables. The remaining 6 alternatives have null variables and therefore no advantage. Those 6 alternatives have a blank importance of advantage in Appendix I.

4. Fixed cost: The author assigned an importance of 10 to Alternative 1 (equation 17), which has the lowest fixed cost. Alternative 12 (equation 32) has the highest fixed cost and therefore no advantage. It has a blank importance of advantage in Appendix I. The author assigned an importance of advantage of between 0 and 10 to the remaining alternatives based on the differences between their coefficients and anchored to the magnitude of their fixed cost, in inverse proportion to their fixed costs.

3.7.6 Decide the importance of each advantage

The data in Appendix I is summarized in Table 3-5. The Cobb-Douglas exponential model based on inflation-adjusted costs with a linear construction cost inflation (Alternative 5, equation 22) has the highest sum of importances and is the preferred alternative. It should be noted, however, that a common exponential (Alternative 4, equation 21) would have had the highest sum of importances by a small margin if the common exponential function had not consistently found that the X_3 variable, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. It is possible that the finding might not have persisted with a larger data set. These findings are discussed further in Section 5.1.

Table 3-5 Summary of Appendix I (Choosing By Advantages table for 12 alternatives)

Alternative	1	2	3	4	5	6	7	8	9	10	11	12
Factor 1: Coefficient of Determination	0.55	0.54	0.46	0.63	0.63	0.55	0.72	0.7	0.67	0.35	0.44	0.31
Importance of Advantage	58	56	36	78	78	58	100	95	87	9	31	-
Factor 2: Data available?	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Importance of Advantage	30	30	30	30	30	30	-	-	-	30	30	30
Factor 3: Number of nulls	1	-	-	1	-	-	1	1	-	1	-	1
Importance of Advantage	-	20	20	-	20	20	-	-	20	-	20	-
Factor 4: Zero Intercept	$111,653.07	$232,939.36	$452,719.84	$173,250.36	$288,981.67	$489,337.85	$296,619.31	$361,693.76	$462,522.95	$439,095.40	$436,689.96	$515,649.41
Importance of Advantage	10	7	2	8	6	1	5	4	1	2	2	-
Sum of Importances	98	113	88	116	134	109	105	99	108	41	83	30
Rank	8	3	9	2	1	4	6	7	5	11	10	12

4 Case Study 2: Comparison with Local Agency projects and processes

This second case study, Chapter 4, focuses of pedestrian access projects as Chapter 3 did, but on a different set of those projects. It compares the computed costs using the preferred alternative in Chapter 3 to projects in 4 cities in the San Francisco Bay Area. The chapter consists of Section 4.1, data obtained; Section 4.2, cost comparison: actual versus computed costs for city versus Caltrans projects; Section 4.3, time comparison: project delivery timelines for city versus Caltrans projects; and Section 4.4, summary. Some of this data has been reported and discussed previously in Blampied and Tommelein (2016).

4.1 Data obtained

In addition to obtaining the California Department of Transportation (Caltrans) project data described in Chapter 3, the author also contacted the 10 largest cities in the San Francisco Bay Area to request pedestrian access project information. He received final cost data for 10 pedestrian access projects that had been completed by 4 cities. These projects had constructed 776 wheelchair ramps, 4,170 meters (13,682 feet) of new sidewalk, and one audible traffic signal alert. Appendix B shows the data for these projects. Although the cities are not required to use Caltrans project phases, the author assigned their available data to the Caltrans data fields used previously in Appendix A.

4.2 Cost comparison: actual versus computed costs for city versus Caltrans projects

4.2.1 Using the preferred function (equation 22)

Using data from both Caltrans and the 4 Bay Area cities, Figure 4-1 illustrates the outcome of a comparison of the inflation-adjusted actual project cost on the horizontal axis against the computed costs, using the preferred modified Cobb-Douglas exponential function (equation 22), on the vertical axis. (The identification of the preferred function is discussed in Section 3.7.) Figure 4-1 plots the 39 Caltrans projects and the 10 projects for which the cities had provided data. The data shows that, in all but one case, the inflation-adjusted cost of the city projects was significantly less than the expected cost computed with equation 22.

The total computed cost of the 10 city projects, using the preferred inflation-adjusted modified Cobb-Douglas exponential function (equation 22), was $7,951,281. The total inflation-adjusted actual cost of these projects was $3,202,437, or 40 percent of the computed cost. Thus, on average, the 10 city projects were completed for 40 percent of what those projects would be expected to cost if they had been Caltrans projects. This was true despite the fact that the city projects were built according to Caltrans standard plans.

Nine of the 10 city projects had actual inflation-adjusted costs that were less than the expected cost computed with equation 22. This fact and a visual inspection of Figure 4-1 both indicate that the city project costs are not part of the Caltrans project cost population. In simple terms, if there is an equal probability that an actual cost will be greater or less than the computed cost, then there is a probability of 11/1024 = 1 percent that 9 or more of 10 successive projects will have an actual cost that is less than the computed cost. This is the case here, and we know therefore that there is probability of at least 99 percent that the city project costs are not part of the Caltrans project cost population.

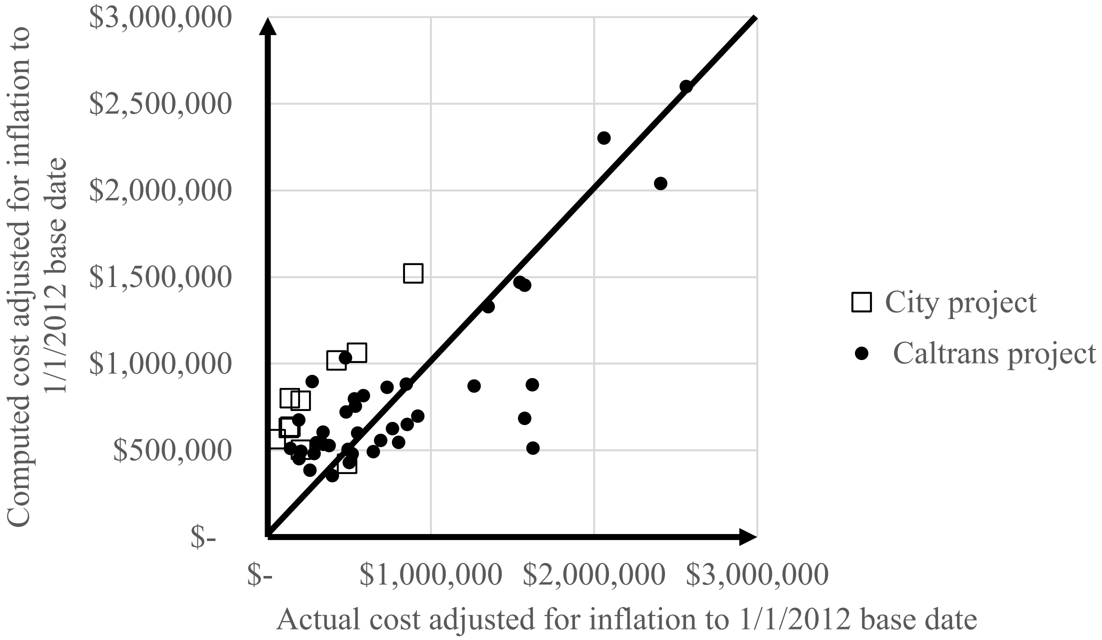


Figure 4-1 Actual versus computed project costs (Cobb-Douglas exponential, using equation 22) for full project costs adjusted for inflation to 1/1/2012 base date

With a more rigorous statistical analysis, the Student's t-statistic for the actual inflation-adjusted costs versus the expected cost computed with equation 22 for the 10 city projects is 3.561. A t-statistic greater than 2.878 indicates a 99.5 percent confidence level that that the two populations (inflation-adjusted costs of city projects versus the expected cost of those projects computed with equation 22) are different.

Having established that there are significant cost differences between the city and Caltrans projects, the author sought reasons for these differences. One possible explanation is the fact that the city project costs (see Appendix B) consist of construction capital costs only, and include no preliminary engineering or construction engineering costs. The next section examines this possible explanation.

4.2.2 Construction-capital-only computation functions with linear capital inflation

The author ran the three parametric functions again, with the costs confined to construction capital only (Caltrans phases 4 and 5). All other costs were excluded from the calculation. Through 332 rounds of approximations using MATLAB, the following best-fit common exponential function was developed for inflation-adjusted construction capital only, using the outputs for the 39 Caltrans projects:

Cost = $83297.68 + 4{,}410.45X_1 + 20{,}771.26X_2^{0.3224} + 0.X_3$ (Equation 33)

This function has a correlation coefficient $r = 0.75$ and a coefficient of determination $r^2 = 0.57$. It therefore accounts for 57 percent of the variation in costs.

Equation 33, as with earlier equation 16, finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. Equation 33 can be rewritten as:

Cost = $83{,}297.68 + 4{,}410.45X_1 + 20{,}771.26X_2^{0.3224}$ (Equation 34)

Using the same approach, the modified Cobb-Douglas exponential function converged after only 234 rounds of approximations to produce the following best-fit function for the same 39 Caltrans projects:

Cost = $94{,}960.59 + 4139.09X_1.X_2^{0.1879}.X_3^{0.0}$ (Equation 35)

This function has a correlation coefficient $r = 0.74$ and a coefficient of determination $r^2 = 0.55$. It therefore accounts for 55 percent of the variation in cost.

Equation 35, as with earlier equations, finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. Equation 35 can be rewritten as:

Cost = $94{,}960.59 + 4139.09X_1.X_2^{0.1879}$ (Equation 36)

Following the same approach as the first two models, the linear parametric model converged after only 22 iterations. It had been constrained to ensure that all the constants remained positive, and this constraint appears to have reduced the numbers of iterations considerably. The resulting best-fit linear function, using the pedestrian access facility outputs for the 39 Caltrans projects was:

Cost = $107{,}613.15 + 4222.10X_1 + 129.95X_2 + 0.X_3$ (Equation 37)

This equation indicates that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. This function has a correlation coefficient $r = 0.72$ and a coefficient of determination $r^2 = 0.52$. It therefore accounts for 52 percent of the variation in cost.

Equation 37, as with earlier equations, finds that X_3, the number of audible traffic signals, has no effect on project cost, which is an intuitively unsatisfactory conclusion. Equation 37 can therefore be rewritten as:

Cost = $107{,}613.15 + 4222.10X_1 + 129.95X_2$ (Equation 38)

Further analysis in the next section considers equations 33 and 35, the 2 construction-capital-only models with the highest coefficients of determination.

4.2.3 Analysis for construction capital costs only

Adjusting for inflation using the 4 percent-per annum formula from Figure 3-1, and applying equations 33 and 35 to the city data produces the data in Table 4-1.

Table 4-1 Actual, inflation-adjusted, and computed costs of city projects

Project	Bid date	Actual cost	Inflation-adjusted actual cost to 1/1/2012 base date	Computed Cobb-Douglas exponential for full project (equation 20)	Computed common exponential for capital only (equation 33)	Computed Cobb-Douglas exponential for capital only (equation 35)
Berkeley 08-10329	2/28/2008	$ 172,065	$ 203,172	$ 503,319	$ 264,126	$ 268,802
Berkeley 10-10465	2/25/2010	$ 119,846	$ 129,376	$ 629,132	$ 295,763	$ 367,736
Berkeley 10-10472	2/25/2010	$ 128,958	$ 139,212	$ 636,617	$ 327,174	$ 315,094
Berkeley 11-10558	2/24/2011	$ 194,668	$ 201,507	$ 786,706	$ 489,823	$ 829,356
Berkeley 12-10642	2/23/2012	$ 136,623	$ 135,837	$ 801,964	$ 483,806	$ 836,999
Oakland C428014	9/10/2015	$ 626,755	$ 546,379	$ 1,063,448	$ 716,079	$ 1,299,633
San Jose 7361	8/1/2013	$ 50,917	$ 47,896	$ 565,415	$ 244,959	$ 266,670
San Jose 7483	3/27/2014	$ 970,921	$ 891,530	$ 1,522,157	$ 1,785,589	$ 5,572,818
Sunnyvale PW13-19	8/14/2013	$ 517,747	$ 486,378	$ 423,319	$ 100,939	$ 115,656
Sunnyvale PW14-02	10/30/2013	$ 451,850	$ 421,149	$ 1,019,204	$ 890,133	$ 1,918,970

Figure 4-2 charts the data for equations 33 and 35 from Table 4-1 along with the data for the same equations for the 39 Caltrans projects. Although Figure 4-2 is confined to capital construction costs only, it still exhibits the features observed in Figure 4-1. The computed costs for 9 of the 10 city projects are again less than expected. Using the simple method offered in

Section 4.2.1, there is a probability of 11/1024 = 1 percent that the city project costs are part of the Caltrans project cost population.

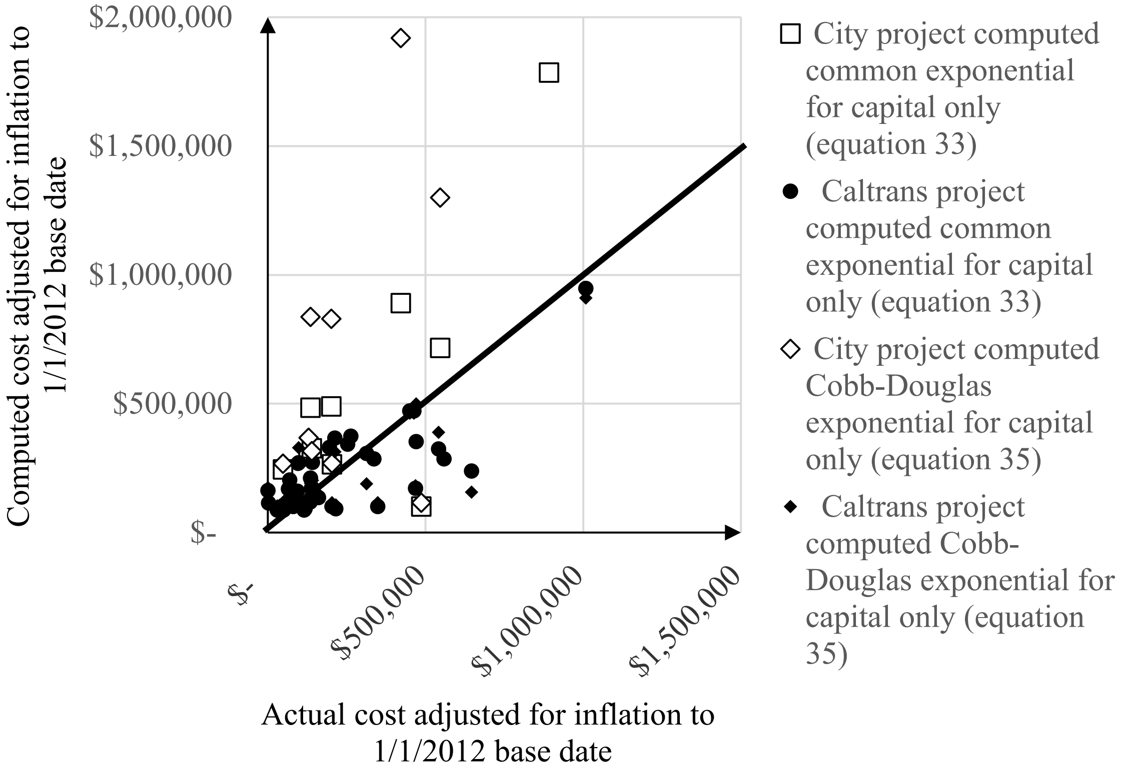


Figure 4-2 Actual versus computed project costs for construction capital only adjusted for inflation to 1/1/2012 base date

With a more rigorous statistical analysis, the Student's t-statistic for the actual inflation-adjusted construction capital costs versus the expected construction capital cost computed with equations 33 and 35 for the 10 city projects is 1.361 for the common exponential (equation 34) and 1.632 for the Cobb-Douglas exponential (equation 36). A t-statistic greater than 1.330 indicates a 90 percent confidence level that that the two populations (inflation-adjusted capital costs of city projects versus the expected capital cost of those projects computed with equations 33 and 35) are different. This certainty is not as great as that for the total project cost found in Section 4.2.1, but it is significant nevertheless, and the fact that the city project costs (see Appendix B) consist of construction capital costs only, and include no preliminary engineering or construction engineering costs, is not a probable explanation for the difference in cost between the city and Caltrans projects. An explanation for the difference in costs needs to be sought elsewhere.

4.2.4 <u>Further consideration of cost comparisons</u>

Both Caltrans and the city projects used a design-bid-bid process in which the agency developed a set of bid documents, received bids from contractors, and awarded the contract to the qualified contractor that submitted the lowest bid. Despite the apparent similarity of the city and Caltrans processes, the cities received bids on pedestrian access facility contracts that were significantly lower in dollar magnitude than the bids received by Caltrans for similar contracts. To understand how this might be, the author engaged in a review of both the city and the Caltrans bid documents, and also interviewed contractors who had submitted bids to both cities and Caltrans. As this review covered both the Caltrans projects discussed in Chapter 3 and the city projects discussed in this Chapter, a comparison of the Caltrans and city contracting approaches is provided in Section 5.3 as part of the cross-case discussion.

4.3 Time comparison: project delivery timelines for city versus Caltrans projects

Discussions of project timelines with staff in each of the cities that provided data revealed that the cities each prepare and award an annual contract for pedestrian access facilities. Their bid documents included Caltrans Standard Plans but provided no project-specific designs (Berkeley 2014, Oakland 2015, San Jose 2014, Sunnyvale 2014). With this annual contract process, a city project takes a year or less from start to finish, with very little of the project lifespan being dedicated to design.

In contrast, Caltrans projects unfold under a very different timeline. They are funded from the State Highway Operation and Protection Program (SHOPP), which has minor and major project components. Minor projects are defined as those having a construction cost of less than $1,250,000 (Caltrans 2018:3). The California Transportation Commission (CTC) allocates funds for minor projects each year, normally in June, and they must be ready for construction within a year. These minor projects therefore typically have a lifespan of up to 2 years: 1 year for preliminary engineering and a second year for construction.

Projects over $1,000,000 are in the major project portion of the SHOPP. This is a program of projects that are to be awarded within the next 4 years. During each year, the CTC allocates funds for projects in the last of the 4 years. This allows Caltrans 4 years to get them ready for construction. The major projects therefore typically have a lifespan of 5 years or more: 4 years for preliminary engineering, and a year or more for construction.

These processes and anecdotal evidence indicate that Caltrans pedestrian access projects take considerably longer to complete than city pedestrian access projects (5 or more years versus up to 2 years). As a result, Caltrans is less able than cities to respond quickly to citizen complaints about accessibility. Cities can respond within a year, and one city studied can respond almost immediately.

4.4 Summary

Through a comparison between a set of 10 pedestrian access projects completed by cities in the San Francisco Bay Area versus a set of 39 pedestrian access projects completed by Caltrans, this chapter has established that the cities completed projects to produce these facilities, using the same standard plans as Caltrans, both for a significantly lower cost than the cost incurred by Caltrans and in a shorter time than the time taken by Caltrans. While this chapter did not establish reasons for these differences, potential reasons will be considered in Section 5.3 as part of the cross-case analysis.

5 Discussion

This discussion, Chapter 5, reviews the case studies from Chapters 3 and 4 in the light of the literature review in Chapter 2. It considers the equations developed in Chapters 3 and 4 and their related observations and discusses possible underlying causes for the data and observations. It also proposes possible applications of this research in the management of highway project portfolios. Chapter 5 consists of Section 5.1, cost modelling; Section 5.2, pedestrian access standards and regulations in California; Section 5.3, role of contracting approaches by Caltrans and cities; and Section 5.4 project portfolio management.

5.1 Cost modeling

5.1.1 Three parametric functions

As a contribution to the understanding of estimating methods, the author considered three forms of parametric models that might be used to develop conceptual (AACE: Class 5) and feasibility (AACE: Class 4) estimates. These models are a linear function, a common exponential function, and a Cobb-Douglas exponential function. The author develops best-fit versions of the three functions for a set of 39 projects for the construction of wheelchair ramps and related pedestrian accessibility features on streets and highways and evaluates the models using the Choosing By-Advantages (CBA) method.

The CBA analysis finds that the Cobb-Douglas exponential model based on inflation-adjusted costs with a linear construction cost inflation (alternative 5, equation 22) has the highest sum of importances and is the preferred alternative. The analysis also revealed that a common exponential would have been preferred had it not consistently found that one of the variables has no effect on project cost.

The preference for exponential functions is consistent with the theoretical discussion of productivity, based upon the work of Wright (1936), Henderson (1968), and Hax and Majluf (1982), who postulated that an exponential function would provide a better fit than a linear function (see Section 2.6.1). As the theoretical discussion would predict, the 2 exponential functions both provide higher coefficients of determination than the linear parametric function (coefficients of determination are summarized in Appendix I and Table 3-2).

The author does not, however, have a theoretical basis for establishing a preference between the common exponential and the Cobb-Douglas exponential functions. In the common exponential form only a portion of the function changes with changes in a variable, whereas with the Cobb-Douglas form the entire function changes. The common exponential is therefore built on an assumption that each variable is independent while the modified Cobb-Douglas exponential is built on an assumption that there is an interdependence between the variables. Arguments can be made for both assumptions. Bearing in mind that the variables in the case studies are the outputs of the projects, the common exponential form would assume that each output is produced independently, with its own equipment, labor, and materials. The addition of a new output would therefore in effect be to add a new sub-project with its own resources. The Cobb-Douglas form, by contrast, assumes that outputs share resources and that the addition of new outputs adds less to the cost of the project than would be the case if the outputs were produced independently.

Both arguments can be correct in different situations. In some cases, new outputs are so different from the existing outputs that they require their own resources. In other cases, the new outputs can share some of the existing resources. The decision regarding dependence or independence has to be made on a case by case basis. The best solution is may be a hybrid of equations 8 and 11, the two exponential functions, that would be similar to equation 39:

$\text{Cost} = a + bX_1^c.X_2^d.X_3^e.X_4^f.X_5^g + hX_6^i.X_7^j.X_8^k.X_9^l.X_{10}^m$ (Equation 39)

where X_1 through X_5 are variables that share one set of resources, X_6 through X_{10} are variables that share a separate set of resources, and a through m are constants, with a being positive and b through m all being greater than 0 and less than 1. This example assumes that there are two sets of resources. It would be expanded when there are multiple sets of resources.

5.1.2 Unexplained variation

The preferred alternative, the Cobb-Douglas exponential model based on inflation-adjusted costs with a linear construction cost inflation (alternative 5, equation 22), has a coefficient of determination, r^2, of 0.63 (see Appendix I and Table 3-2). This leaves unexplained the remaining 0.37 (37 percent) of the variation in the data. Addressing that unexplained variation poses a problem.

One possible approach to addressing the unexplained variation is to ascribe it to random factors that can be addressed through statistical analysis. This is AACE's approach, illustrated in Figure 5-1. AACE says that Class 5 estimates should typically have an 80 percent confidence level of being with a range from +100 percent to -50 percent (AACE 2016). AASHTO, as previously noted, uses a similar approach, but uses a range of +200 percent to -50 percent (AASHTO 2013). The 37 percent unexplained variation would fall into a combination of the +100 percent to -50 percent (or AASHTO's +200 percent to -50 percent) range and the 20 percent of projects for which the actual cost falls outside the AACE range.

An alternative approach to addressing the unexplained variation is to search for additional variables that might explain the variation. The current research has used only outputs as variables, a choice that is discussed in Section 2.11.1. That section includes a synopsis of the variable types used in previous papers on conceptual cost estimating. It points out that other authors have developed conceptual cost estimating models based on non-output variables which include bid items, project characteristics, and economic and geographic factors. Those variables may explain some of the unexplained 37 percent variation in the data. Additional research using non-output variables in addition to output variables would probably increase the coefficient of determination of a selected parametric model and therefore explain a larger percentage of the variation. One should, however, bear in mind the admonition given by Gardner et al. (2016) who studied the correlation of project costs to 29 project characteristics on State Highway pavement preservation projects in Montana. They found that the coefficient of determination did not increase significantly when they considered more than the 8 highest-impact project characteristics. They also found that the additional effort required to search for and assemble data on the ninth and subsequent project characteristics outweighed the value of the slight increase in the coefficient of determination. They therefore advised agencies to perform the research needed to identify their highest-impact variables and then to maintain future data only on those variables, thereby avoiding the costly effort needed to assemble hard-to-find data on low-impact variables.

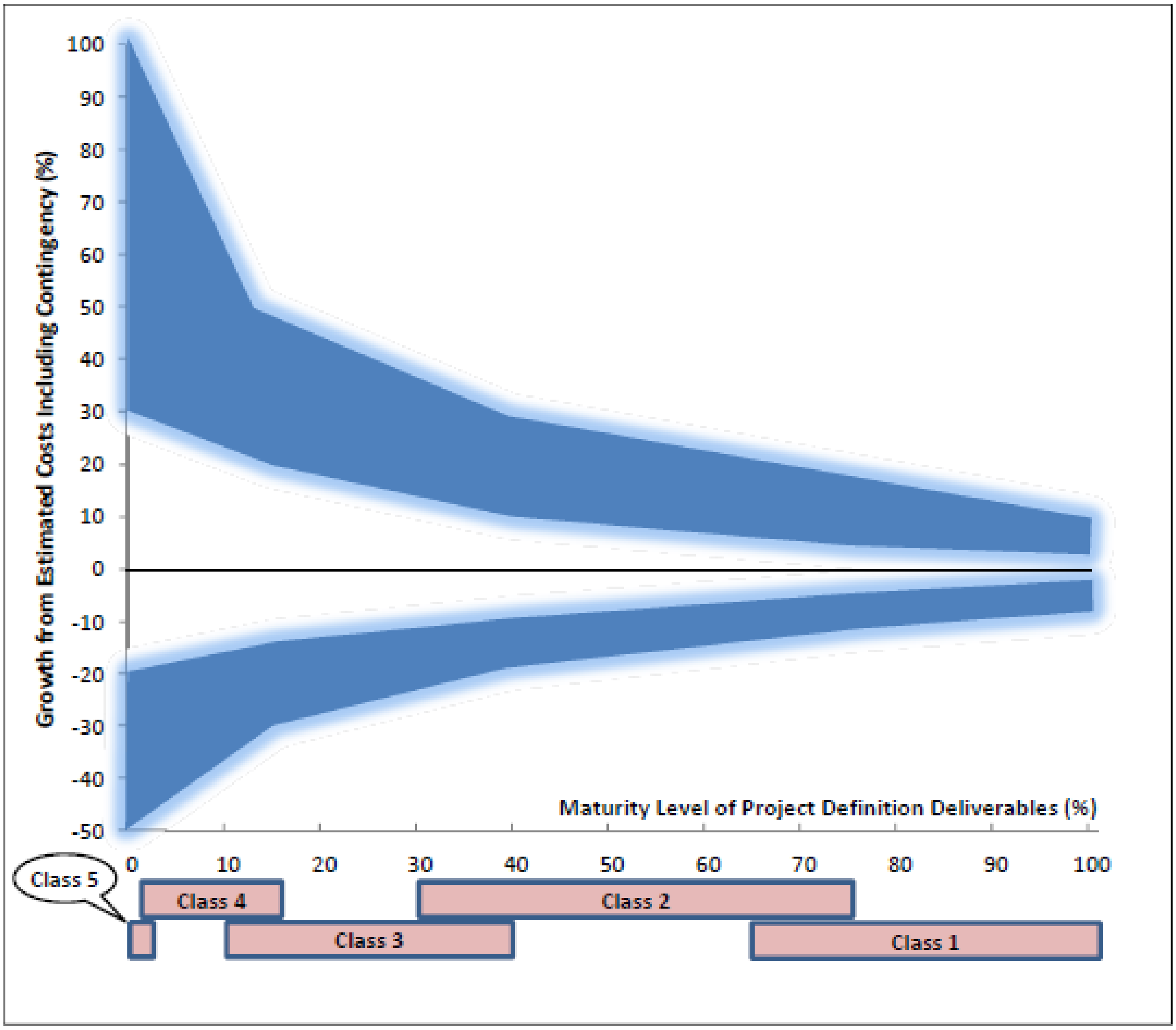


Figure 5-1 AACE classes of estimates and their variances (Figure 1, AACE 2016)

The finding by Gardner et al. (2016) is not surprising. One would expect to find only small marginal changes in the coefficient of determination as one adds further low-impact variables to a parametric model. At some point, the addition of further low-impact variables would produce no change in the coefficient of determination, and some sources of variance should be expected to be unique to individual projects and therefore not possible to model through parametric analysis.

5.1.3 Null variables

Six of the 12 parametric models have null variables. This suggests that the addition of many instances of that variable to a project will make no impact on the project cost. (see Appendix I and Table 3-3). Null variables occur on all 4 of the common exponential models, 1 of the 4 Cobb-Douglas models, and 1 of the 4 linear models. While the constraints used in the MATLAB code for this dissertation are such that they allow null variables to occur (see Appendices C, D and E), AACE (2011) addresses this problem by simply requiring that variables be non-null. For instance, this dissertation requires that exponents must lie in the range from 0 to 1 even though 0 would create a null condition, AACE states that "the value of the exponent typically lies between 0.5 and 0.85." A 0.5 to 0.85 constraint would preclude the null condition, but it has no basis in theory. The exponents found in this dissertation were seldom in the range from 0.5 to 0.85 (see equations 16, 17, 20, 21, 24, 26, 29, and 30). In addition, an 0.5 to 0.85 constraint would be incompatible with the original Cobb-Douglas requirement that the exponents total 1.0 (Douglas 1976).

Further research and analysis are needed to address the problem of null variables and to consider their real or potential effect on project costs.

5.1.4 Fixed costs

Section 2.6.1 introduces the concept of fixed costs. It defines fixed coats as costs that are incurred in a project or production system irrespective of the quantity of outputs produced. The sources of fixed costs are found in the discussion of transaction costs in Section 2.1.2, even though that section does not make specific reference to "fixed costs." Typical fixed costs include the costs of setting up projects in the accounting system, obtaining budget authorizations, printing bid documents, advertising projects for bid, opening bids, preparing monthly reports, and archiving project documents. These are all transaction costs, and they frequently vary very little with the size of the project. They are also all costs of performing standard processes.

The "best fit" models found fixed costs on pedestrian access projects that range from \$111,653.07 to \$515,649.41 (Section 3.6.3 and Table 3-4). The models, however, do not identify the specific processes on which those fixed costs were incurred. That would require a more detailed consideration of common processes that occur across all projects.

Fixed costs can be avoided by altering the processes. This often involves risk-taking because the processes involve time-consuming and costly steps adopted by the implementing agency to avoid risks. Such risk-avoidance efforts may be justified on large projects, where the fixed costs are a small part of the overall project cost, but they may be unnecessarily cautious on small projects where there is little risk of significant losses. The State of California does, for instance, have simplified bidding procedures for minor contracts (referenced in Section 3.2) and very small contracts can be awarded without any bidding at all.

To reduce fixed costs, one needs to know what processes incur the costs, understand the purposes of those processes, and develop alternative processes that can achieve those purposes at a lower cost. Such a reduction therefore requires 3 steps:

1. An analysis of the costs across projects to identify which process incur the costs and the degree of significance of those costs.

2. Studies of the most significant processes to identify their purposes, how they avoid risks, and the value added at each process step. This is a potential application of Lean six sigma programs such as that which the California state government has initiated across many departments, including Caltrans (Dunning 2016, Tusup 2017). Lean focuses on the elimination of waste, which includes the elimination of unnecessary work (Ohno 1988:1 and 1988:2).

3. The adoption of alternative processes by the agency's management. In the case of government agencies such as Caltrans, this step might require legislation.

5.1.5 Inflation and market conditions

Section 3.4 describes the methods used in this dissertation to address inflation. The methods are illustrated in Figures 3-1 and 3-4. Capital construction costs were adjusted for inflation by using the California Highway Construction Cost Index (CHCCI) and by using a linear regression of the CHCCI readings, both illustrated in Figure 3-1. The costs of permits and environmental studies (Phase 0); plans, specifications, and estimates (Phase 1); right-of-way operations (Phase 2); and construction engineering (Phase 3) were adjusted for inflation by using linear regressions of labor costs per hour, illustrated in Figure 3-4.

The linear regression lines have slopes of 4.0 percent for CHCCI, 4.0 percent for right-of-way operations (Phase 2), and 4.7 percent for the combined Phases 0, 1, and 3. All of these percentages are measured relative to a January 1, 2012 base.

The linear regression line was chosen for simplicity although it deviates from normal practice when calculating inflation, which would base each year's inflation of the prior year's base, i.e., the normal practice would assume an exponential growth in costs rather than linear growth.

Whether one uses a linear inflation adjustment or an exponential inflation adjustment, however, the observed data exhibits a variation above and below the regression line, as illustrated in Figures 3-1 and 3-4. Actual observed CHCCI data a given points in time, illustrated in Figure 3-1, can be considerably higher and lower than the regression line. In the 2-year period following April 2006, for instance, the CHCCI rises to its highest peak value in the figure and then plunges in two quarters to a value that is only slightly more than half of the peak value. This plunge is from the second quarter report on 2007, when the CHCCCI stood at 401.4 to the fourth quarter of 2007, when the CHCCI was 208.5.

The CHCCI is an index of the state highway construction market in California. There are many other market indices, most notably stock market indices. Like the CHCCI, those indices normally exhibit a long-term upward trend with many short-term fluctuations and occasional plunges. Stock market plunges include the plunge from October 2007 to March 2009, the downturn from March to October 2002, the plunge from August to November 1987, and the plunge from September to November 1929. Much research is conducted on the behavior of stock market indices, and there are daily items about them on the business pages of newspapers. Given the amount of analysis being done elsewhere without much success in making predictions, it is unlikely that a project cost estimator or researcher would be able to accurately predict fluctuations in the CHCCI. Indeed, if one were able to make accurate predictions about the behavior of a market index, one could make a fortune on Wall Street and one's skills would be wasted in project cost estimating.

It appears that the best that one could hope for in the way of inflation adjustment when preparing conceptual and feasibility estimates (Class 5 and 4 estimates) is to use a linear or exponential regression adjustment that reflects the long-term inflationary trend. At the conceptual and feasibility stages, the largest project expenditures lie far in the future, sometimes several years in the future. When preparing control and bid/tender estimates (Class 2 and 1), by contrast, the estimated expenditures will be incurred only a few months into the future. On Class 2 and 1 estimates, therefore, it would be appropriate to consider current market conditions and to attempt to adjust the estimates to allow for expected near-term fluctuations.

5.2 Pedestrian access standards and regulations in California

This dissertation considers pedestrian access facilities, which consist mainly of a simple product of construction: wheelchair ramps at pedestrian crossings, colloquially referred to as "curb cuts" (Figure 5-2). These are the depressions in sidewalks that allow wheelchair riders to move from raised sidewalks into and across streets. Their engineering is simple. Structurally, they are made from an unreinforced concrete slab with a minimum thickness of 3.5 inches (about 90 mm). This thickness is not determined through structural design calculations, but rather responds empirically to experience of ground movement (e.g., due to the growth of tree roots). Ramps and their adjacent sidewalks must resist movement of the underlying ground with a minimum of cracking. Loading is not a significant factor because they carry minimal dynamic loads (people on foot, or a person in a wheelchair, etc.).

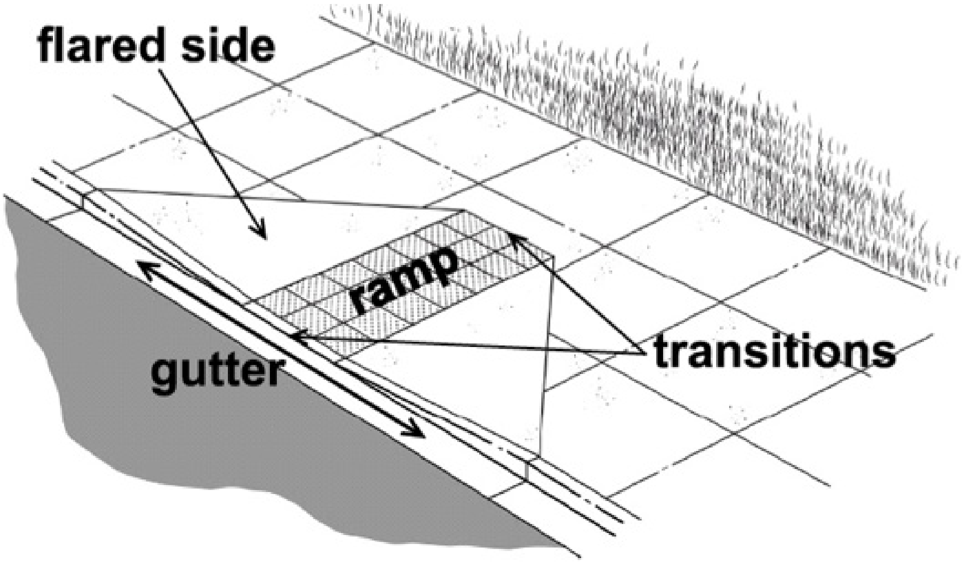


Figure 5-2 Wheelchair ramp (USDOJ 2007)

Guided by federal law and regulations, the California State Architect establishes standards for pedestrian access facilities on public roads, which are owned and maintained by Caltrans, 58 counties and 482 cities (League of California Cities 2015). The entire land area of California is divided into the 58 counties, and cities are self-governing areas within counties. Each city is fully contained within a single county. "Unincorporated" areas (i.e., areas that are not part of any city) exist in 57 of the 58 counties. Under the Americans with Disabilities Act (ADA) each of these 541 agencies (482 cities, 58 counties, and 1 state) is required to facilitate the movement of wheelchair riders by building ramps and maintaining sidewalks on the roads within their jurisdiction (US Congress 1990). Many also have to provide audible traffic signals to assist blind pedestrians. These three elements, (1) ramps, (2) sidewalks, and (3) signals, constitute the principal elements of pedestrian access facility infrastructure on roads.

5.2.1 Federal Policy

The three pedestrian access facility elements identified above have acquired increased significance since 2013. The ADA requires facilities that are altered to be upgraded to current standards for pedestrian access, but until 2013 pavement resurfacing was considered to be a maintenance activity rather than an alteration. Resurfacing was therefore considered to be exempt from the ADA upgrade requirement. This changed in July 2013 with the issuance of the *Department of Justice/Department of Transportation Joint Technical Assistance on the Title II of the Americans with Disabilities Act Requirements to Provide Curb Ramps when Streets, Roads, or Highways are Altered through Resurfacing* (FHWA 2013), which clarified that road resurfacing projects are alterations. It placed an increased significance on wheelchair ramps on road projects throughout the US and US Territories. Because resurfacing is now defined as an alteration, pedestrian facilities must be upgraded whenever roads are resurfaced.

This decision impacts both road programs and pedestrian access. Roads generally go for many decades without being upgraded or altered in their outward appearance. They cannot, however, go without pavement rehabilitation. Without regular rehabilitation, pavement disintegrates due to the effects of traffic and other forces. The earlier interpretation of the ADA, that pavement rehabilitation did not require pedestrian access facility upgrades, meant that some road sections might not see pedestrian access facility improvements for many decades. In contrast, the revised interpretation means that every road in the US must receive pedestrian access facility improvements within a short period of time from 2013, certainly within three decades.

5.2.2 Standards

Table 5-1 lists the minimum standards for wheelchair ramps in California (Caltrans 2013:1). A ramp is considered to be non-compliant if any of these standards is not met. Exceptions are permitted only if compliance is technically infeasible or structurally impractical.

These standards can be traced back through from a cascading set of documents that have become enforceable by law as a result of their adoption by the US Department of Justice in 1994 (USDOJ 1994). The first standard, which had no force of law, was American National Standard A117.1 *Buildings and Facilities - Providing Accessibility and Usability for Physically Handicapped People*. It was first published in 1960 and was most recently revised in 1986

(ANSI 1986). The US Access Board added additional detail to Standard A117.1 to produce the *ADA Accessibility Guidelines* in 1991 and the US Department of Justice adopted this in 1994 as the legally enforceable standard for publicly owned facilities (USDOJ 1994). The US Access Board most recently revised the *ADA Accessibility Guidelines* in 2004 (US Access Board 2004).

Table 5-1 Wheelchair ramp standards (Swanson 2012, modified by Value Management Strategies 2014)

Feature	Standard (as specified, in US customary units)	SI equivalent, where applicable
Width of Ramp	48-inch min.	1.22 m
X-slope of Ramp	2 percent max.	
Flare Slope	10 percent max.	
Gutter Slope	5 percent max.	
Gutter Lip	0 inch (Flush)	0 mm
Top Landing Slope on perpendicular ramps	2.0 percent max.	
Slope of Ramp	8.3 percent max.	
Top Landing Length	48-inch min.	1.22 m
Top Landing X-Slope	2 percent max.	
Gutter X-slope	2 percent max.	
Truncated Domes	36-inch deep x ramp width	915 mm

Various agencies have also added supplemental guidance to the *ADA Accessibility Guidelines.* In the California context, the State Architect has primary responsibility for setting ADA standards for state and local agencies. For federally funded or federally owned state highways, county roads, and city streets, these agencies must also be cognizant of the FHWA guidance in *Designing Sidewalks and Trails for Access* (Axelson et al. 1999).

Dimensional Tolerances in Construction and for Surface Accessibility (Ballast 2011) is another item of supplemental guidance, in this case non-governmental guidance for the American Institute of Architects, the Construction Specifications Institute, and other building-related and privately owned facility developers. Ballast adds a discussion of tolerances, which are not discussed in the governmental regulations. The following section considers the issue of tolerances.

5.2.3 Tolerances

The two 48-inch width and length tolerances in Table 5-1 are one-sided tolerances. That is, any dimension in excess of 48 inches is permitted, but any dimension that is fractionally smaller is a failure.

The slope tolerances provide for both positive and negative slopes. The ramp may slope upwards from the gutter to the sidewalk with a slope of no more than 8.3 percent (1-inch rise to 1-foot run), or downwards to the sidewalk with the same maximum slope. In most cases, the sidewalk is at a higher elevation than the gutter, but in some locations the opposite is true. The rule is that wheelchair riders should not be required to climb at gradients greater than 8.3 percent. Every slope downward for one rider is a slope upward for a rider traveling in the opposite direction.

The 8.3 percent US maximum reflects a path-dependence on the long-standing US customary units, using exact US customary units for both the rise and the run, i.e. 1-inch rise to a 1-foot run. The International Standard for kerb ramps, by contrast, uses SI units and does not follow this 1-to-12 ratio. Instead, the International Standard uses kerb ramp slopes that vary with the height of the kerb: 1 in 8 (12.5 percent) for kerb heights up to 75 mm, 1 in 9 (11.1 percent) for kerb heights up to 110 mm, 1 in 10 (10.0 percent) for kerb heights up to 150 mm, and 1 in 11 (9.1 percent) for kerb heights up to 180 mm. For kerbs of height greater than 180 mm, the International Standard requires that kerb ramp slopes meet the requirements for indoor ramps, whose maximum slopes vary from 1 in 12 for rises of up to 210 mm to 1 in 20 for rises of 500 mm or more (ISO 2011:2). The International Standard reflects a combination of the ability of a hand-driven wheelchair rider to climb for a sustained period and an avoidance of the toppling sensation caused by steep ramps. For a long ramp with a 1 in 20 slope the focus is on the ability of the rider: the International Standard reflects a belief that the rider can continue wheeling for a long distance or can stop and rest without danger of rolling backwards. For a short ramp with a rise of no more than 75 mm and a 1 in 8 slope (which translates to a length of no more than 600 mm) the focus is on toppling rather than ability: the International Standard reflects a belief that the wheelchair rider can climb a ramp at this slope without toppling backwards or forwards. As shown in Figure 5-3, this requires that the center of gravity of the loaded wheelchair must fall between the points of contact (POC) of the front and rear wheels.

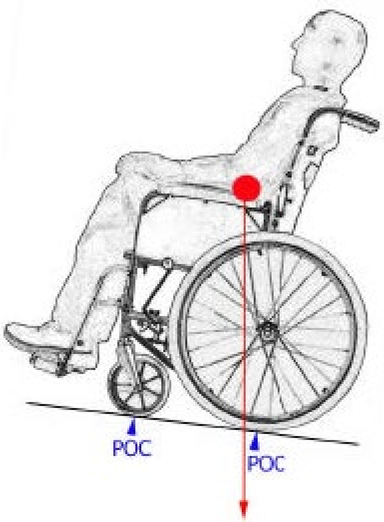


Figure 5-3 Wheelchair stability condition when climbing a ramp (MHRA 2004)

The cross-slope maxima of 2 percent refer to the left-to-right slope under the wheelchair, that must not exceed 2 percent from the vertical to save the rider from having the sensation, or real possibility, of toppling sideways. This 2 percent rule applies equally to a left-leaning and right-leaning slope.

The Settlement Agreement discussed in Section 3.1.2 requires an annual independent review of Caltrans compliance with that agreement. The independent review for 2012 included an examination of 91 recently completed Caltrans wheelchair ramps and found that 39 of them did not comply with one or more of the standards. This is a 43 percent failure rate (Swanson 2012).

Caltrans commissioned a review of the independent reviewer's work, and found that reviewer had used outdated standards and had reported on ramps that were not part of recently completed projects. After adjusting for these errors, the failure rate was reduced to 13 percent (Value Management Strategies 2014).

To address the problems identified by the 2012 and subsequent reviews, Caltrans issued revised standard plans in 2016. These new plans adopt slopes and dimensions that are more stringent than those required by the State Architect (CSA 2018). The 8.3 percent maximum slopes have been changed to 7.5 percent, the 2 percent maxima to 1.5 percent, the 10 percent maxima to 9 percent, and the 48-inch minima to 50 inches. In addition, Caltrans has also addressed the non-compliance issue by issuing new design and construction bulletins (Caltrans 2013:1 and 2014) and by introducing a Standard Special Provision requiring the contractor to survey each site before construction to "verify that forms and site constraints will allow the design dimensioning and slope requirements to be achieved" and then to survey each facility again after construction to "verify that design dimensioning and slope requirements were achieved." If the contractor encounters "site conditions that will not accommodate the design details" then the contractor is promised compensation for making changes (Caltrans 2013:2).

Caltrans revised maxima are consistent with Ballast (2011), who recommends that exterior accessible ramps to buildings be designed with a 7.5 percent maximum longitudinal slope with a tolerance of 0.8 percent. As a maximum cross slope, Ballast advocates 1.5 percent with a tolerance of 0.5 percent.

The revised standards introduce a buffer between the regulated requirements and the new standard. By introducing the buffer, Caltrans and Ballast add a level of protection against any errors by designers or contractors. An unintended failure to meet the new 7.5 percent and 1.5 percent standards of may still meet the regulated maxima of 8 percent and 2 percent. In adding this buffer, however, Caltrans and Ballast imposes limits on its designers and contractors that could cause an increase in exception requests. Solutions that meet the regulatory requirements might not satisfy the new standards.

The tighter standards also lead to increased costs. If a 7.5 percent solution has a lower construction cost than an 8.3 percent solution in a particular case, it could be adopted in the event that an 8.3 percent maximum is specified. In all other cases, it is more expensive. Ballast (2011) says that decreasing the longitudinal slope from 8 percent to 7.5 percent will not lengthen the ramp excessively. While that may be true in buildings, where the surfaces at both ends of the ramp are normally level or near-level, it is less likely to be true on roads because sidewalks follow the gradients of their associated roads, which need to have a slope to ensure that rain and snowmelt will drain away. While AASHTO recommends a maximum gradient of 15 percent for roads in urban areas (AASHTO 1984), the steepest road in the US is said to have a gradient of 37 percent (Batz 2005). Such steep roads exceed the maximum toppling slope for wheelchairs, and are clearly impassable to wheelchairs. Nevertheless, the difference between 7.5 percent and 8.3 percent can make a significant difference to the length of wheelchair ramps on many roads.

The use by Caltrans of a buffer is a risk avoidance strategy, to avoid non-conformance and protect Caltrans from adverse sanctions by regulators. It is not the only solution, however. An alternative approach is to transfer the risk. Caltrans could decrease its involvement in design and require the contractor to both design and construct the wheelchair ramps to the governing 8.3 percent standard, with a requirement for the contractor, rather than Caltrans, to warrant that the ramp satisfies this standard.

5.3 Role of contracting approaches by Caltrans and cities

5.3.1 Contracting law and practices

In California public agencies, pedestrian access facility projects are delivered through a design-bid-build process because Caltrans, the counties, and cities must comply with the California Public Contract Code (PCC). However, different PCC sections apply to different agencies. Relevant quotes from these codes are:

- For Caltrans: PCC 10120 (introduced in 1876 and most recently revised in 1981). “Before entering into any contract for a project, the department shall prepare full, complete, and accurate plans and specifications and estimates of cost, giving such directions as will enable any competent mechanic or other builder to carry them out.”

- For counties: PCC 20124 (introduced in 1883 and most recently revised in 1982). “The board of supervisors shall adopt plans, specifications, strain sheets, and working details for the work.”

- For cities: PCC 20162 (introduced in 1883 and most recently revised in 1982). “When the expenditure required for a public project exceeds five thousand dollars ($5,000), it shall be contracted for and let to the lowest responsible bidder after notice.”

The code applicable to Caltrans is the most specific of the three and has been interpreted strictly. The code that applies to the cities is the least specific and has been interpreted flexibly. This becomes apparent when one examines the bid documents and payment methods of the various agencies, as the author did as part of his case study data analysis. In addition to the Caltrans bid documents, the author examined bid documents by 1 county and 4 cities, tabulated in Table 5-2. Caltrans prepares detailed plans for its pedestrian access facility projects whereas cities merely list their locations, if noted at all. Table 5-2 shows the information provided to bidders by the subject agencies.

As indicated in Table 5-2, public agencies differ from one another with respect to the type and quantity of information provided to bidders on pedestrian access facility projects. Caltrans provides detailed plans and pays for wheelchair ramps per volume of concrete, whereas counties provide plans and pay per volume of concrete or by the upper surface area. Both approaches require a considerable amount of preparatory and follow-up measurement work. For Caltrans and counties to prepare their detailed plans, they must send out a survey crew to create a map of each location and then employ a designer to design each ramp. The designer must also calculate the surface area of each ramp and, if a cubic measure is required, multiply by the expected concrete thickness. The minimum permitted thickness, as noted, is 3.5 inches (about 90 mm). After the ramp is built, the government's inspector must measure the ramp and determine its area for payment.

Table 5-2 Information provided to bidders, and units of payment used, on pedestrian access projects

Agency	Provides a location plan	Provides a plan for each ramp	Lists locations in the contract text, but provides no plans	Unit of payment for ramps
Caltrans	Yes	Yes	No	Cubic Yard
Sonoma County	Yes	Yes	No	Cubic Yard / Square Yard
City of Berkeley	No	No	Yes	Each
City of Oakland	No	No	No	Each
City of San Jose	No	No	Yes	Each
City of Sunnyvale	No	No	Yes	Each

Caltrans did not always design wheelchair ramps in this amount of detail. In 1985, the author prepared plans for several streets in Downey indicating wheelchair ramp locations in no greater detail than that used by the cities of Berkeley, San Jose, and Sunnyvale (Blampied et al. 1985). Caltrans used these plans for a period of time in the mid-1980s as a statewide model in training engineers on how to prepare plans. Given the current level of detail, Caltrans has increased its level of effort on wheelchair ramp design considerably since 1985.

By contrast, the cities provide no drawings to bidders and offer limited location information, if any. Three of the four cities listed in Table 5-2 provide bidders with lists of locations at which the ramps are to be constructed. The fourth city merely states the number of locations, selects locations after the contract has been awarded, and then provides the successful contractor with the list.

It is possible that the differences in practice between Caltrans and the cities may stem from a path-dependent divergence in which Caltrans and the cities have each followed their own paths since the Legislature enacted the separate laws that govern their contracting practices (PCC 10120 introduced in 1876; and PCC 20162 introduced in 1883). Alternatively, the difference may have its origins in a critical juncture that occurred for cities in the wake of Proposition 13 a tax-cutting measure that voters approved on June 7, 1978 and that took effect July 1, 1978. Proposition 13 reduced the cities' property tax revenues by more than half (Reid 1988) and consequently led to a significant reduction in city staff. The author was told about some of these effects in 1982 when he was employed in the City Engineer's office of the City of Torrance to fill a recently vacated position. His colleagues were survivors of major layoffs in the city engineer's staff in the immediate aftermath of Proposition 13, and they spoke frequently about that time.

The author postulates a possible argument against attributing the cities' choice to use such minimal designs to the effects of Proposition 13, however. This argument is based on the fact that pedestrian access projects of city streets are not dependent on the property taxes that Proposition 13 cut so severely. Instead, city street rehabilitation is funded from a portion of California's excise tax on gasoline. This portion of the gasoline tax is determined by a formula that is contained in Sections 7360 and 7361.1 of the Revenue and Taxation Code and Section 2103 (a) (3) (C) (i) of the Streets and Highways Code and, although this formula has changed over time, it has provided an apportionment to each city since before passage of Proposition 13 in 1978.

Whatever the cause, it is a fact that cities provide less data to contractors during the bidding stage than Caltrans does and yet receive bids for construction capital (Caltrans Phase 4) that are lower in price to those received by Caltrans (discussed in Section 4.2.3). The difference between the Caltrans and city documents reflects a difference in the risk approach of the agencies. In the Caltrans project set, the public agency performs detailed design and accepts responsibility for compliance with the standards. If the contractor builds the facilities in accordance with the design plans and the work is accepted by the agency's inspectors, the contractor escapes any further liability for compliance. In the event of non-compliance, Caltrans carries the risks and would have to pay for the correcting the non-compliant features.

In the City project set, the public agencies perform minimal design. They place the onus of both performing the design and complying with the state-mandated standards upon the construction contractor. In the event of non-compliance, it is the contractor that carries the risks and would have to pay for the correcting the non-compliant features.

The result runs counter to designer expectations in a design-bid-build environment. The normal intent of providing more detailed designs in design-bid-build is to establish a "level playing field" so that all contractors will have the same understanding and will bid on the same scope of work. The designer's justification for increasing design detail, then, is that increased detail decreases the contractor's uncertainty and ensures that bidding will be more competitive. If design detail is missing, designers assume that contractors will add a risk factor to their bids and that bid prices will be higher. Adding detail to the design is intended to decrease overall risk to the agency: the agency assumes greater risk by inserting the detail – design errors rest with the client rather than the contractor - but that risk is expected to be more than offset by lower contractor prices.

Contrary to these expectations, contractors who bid on both sets of projects submitted lower bids on the less detailed city projects than their bids on the more detailed Caltrans projects. Interviews with these contractors did not produce an explanation for, or even an awareness of, the pattern identified in the data. That pattern may, however, have an explanation in the consideration of overdesign that follows.

5.3.2 Overdesign

The cities' contracting approach is a form of design-build by low bid. The cities require contractors to submit bids for work in which the contractor will design and construct the pedestrian facilities, and bid that work on a unit-priced low-bid basis. The contracts are, therefore, design-build contracts that have the appearance of design-bid-build because they are awarded on a "lowest qualified bidder" basis rather than through the qualification-based selection and negotiations that are the standard selection method for design-build.

A fallacy in the design-bid-build process is referring to the plans that accompany the bid documents as the "final design." Pietroforte (1997) points out that design is not complete until construction is complete. No matter how detailed the design may be at bid time, it continues to be refined or altered in construction. To go out for bid, the designer should produce a product that indicates the desired performance, that is biddable and buildable, and that will promote fair competition among bidders.

In the case of a cities' wheelchair ramp bid documents, these criteria are met by establishing the desired performance as that which will meet the standards set by regulators. Many configurations at any given street corner could satisfy these standards. In the cities' case, the mere provision of the Standard Plans and a location is sufficient to obtain competitive bids, and there is no need for additional design prior to bid.

In the Caltrans case, the law requires a bid package that can be executed by a "competent mechanic." On large projects, this concept of a competent mechanic has been understood to include the ability to design and execute complex engineering feats. Certainly, a "competent mechanic" ought to be able to design a wheelchair ramp, as that does not entail any complex engineering calculations. In fact, such ramps are routinely designed and built by contractors who do not have a professional engineering registration.

The author discussed the projects with contractors who had submitted bids to both cities and Caltrans, and it appears that the lower prices on city projects result from the contractors' belief that they can provide wheelchair ramp designs that meet the customer's standard-plan requirements at a lower cost than the client-provided designs. It appears that the contractors, as the last designers, are in a position to envisage a design in the field that satisfies the requirements of the standard plans at a lower cost than the cost of the design envisaged by the designers in their offices.

This "design-build by low bid" contracting approach has limitations. It works only if the client has clearly defined requirements and is willing to accept any solution that meets those requirements. Such is apparently the case on the wheelchair ramps on city streets. It would not be the case if the client had aesthetic concerns that could not easily be communicated other than through project-specific plans. The "design-build by low bid" contracting approach for wheelchair ramps might not work, for instance, if the wheelchair ramps are part of a "complete streets" design that must consider other factors in addition to pedestrian accessibility (Smart Growth America 2018). This would also not be a good approach for a wheelchair ramp that provides access to a building if the ramp must blend-in with the building architecture.

This is another potential place for applying the Lean six-sigma program introduced in Section 5.1.4. The fact that the cities can develop pedestrian access projects with so much less work than the work performed by Caltrans suggests that there is an opportunity to increase output while at the same time lowering the costs of pedestrian access projects. This could be done by developing a Caltrans-specific version of the cities' approach and testing it on a few projects, following the Deming-Shewhart "plan-do-check-act" approach (Deming 1986). Given the nature of the 30-year Caltrans ADA commitment, involving many thousands of wheelchair ramps and related facilities, an experiment based on this research could potentially lead to both a large saving in cost and earlier completion of pedestrian access improvements that have been requested by the public.

5.4 **Project portfolio management**

5.4.1 Portfolio management reprise

Section 2.1.4 introduces the concept of a project portfolio, and Section 3.1.1 describes the responsibilities of Caltrans and the California Transportation Commission (CTC) in respectively developing and reviewing cost estimates for state highway projects. Section 3.1.1 also introduces the need for cost estimating tools. As a first step towards the development of those tools, this dissertation has developed "best fit" parametric estimating tools for a small subset of state highway projects. These estimating tools can be scaled-up to a larger set of projects in the manner described later in Section 6.4.1. While that would provide a "best fit" conceptual cost estimate for each project it would not address the variation discussed in Section 5.1.2. To address that variation, one needs further research or probability density functions.

5.4.2 Probability density functions

As previously discussed in Section 5.1.2, with particular reference to Figure 5-1, the "best fit" leaves unexplained 37 percent of the variation in the project costs used in this research. Section 6.4.4 will propose further research to understand possible causes of that variance, and Section 6.4.5 will propose research on probability density functions (PDF).

Figure 5-4 provides an illustrative example of the use of a PDF in a simple case in which there is only one output. In the research on pedestrian access facilities, there are three outputs (wheelchair ramps, sidewalk, and audible traffic signals), and many more outputs are possible, but one can represent only one output in a 2-dimensional diagram, and one output is sufficient for the Figure 5-4 illustration.

Figure 5-4 is a modified version of Figure 2-9 with $0 < c < 1$, which illustrated the exponential form of the cost production function. The pertinent modification from Figure 2-9 is that Figure 5-

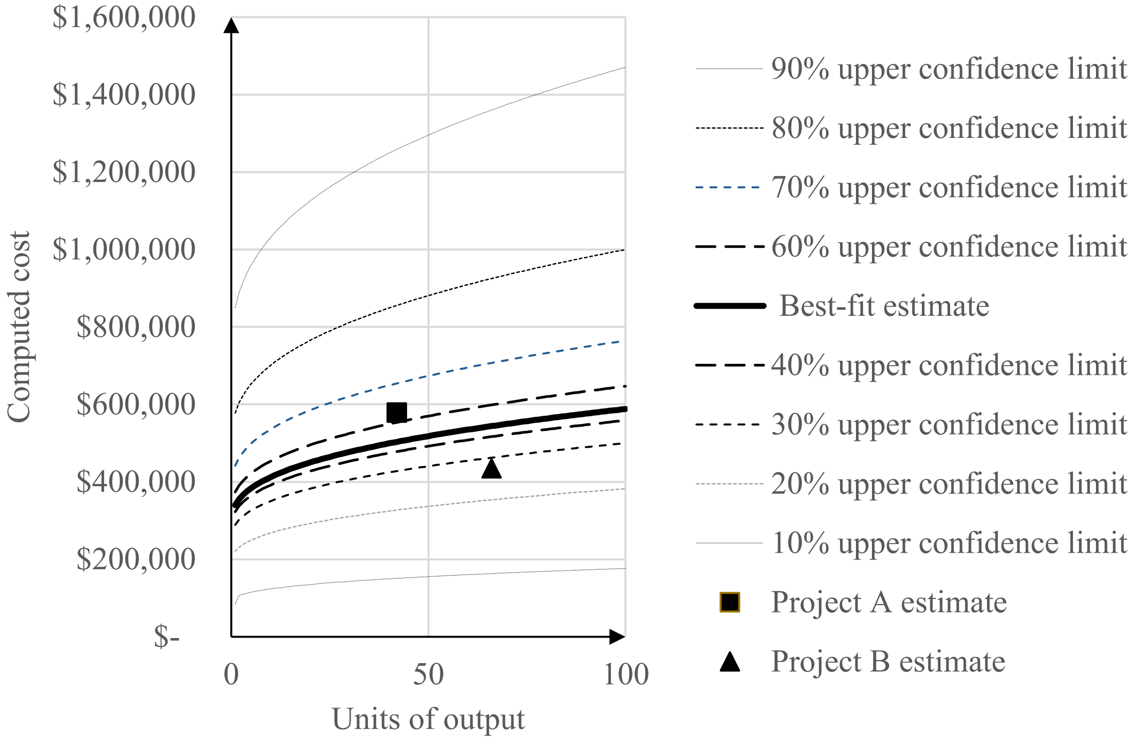


Figure 5-4 Illustrative example of the use of a probability density function

4 adds cost probabilities at various confidence levels. The "best fit" estimate from the parametric cost estimates matches the $0 < c < 1$ cost function illustrated in Figure 2-9 and provides, on the vertical axis, the expected computed average cost of projects that produce a given number of units, entered on the horizontal axis.

Above and below the "best fit" computed cost, the PDF provides lines for different upper confidence levels. At the 10 percent upper confidence limit line, for instance, there is a 10 percent confidence that the cost will be below that limit line and a 90 percent confidence that the cost will be above the limit line. At the 90 percent upper confidence limit line, the reverse is true - there is a 90 percent confidence that the cost will be below that limit line and a 10 percent confidence that the cost will be above the limit line.

Such a PDF function could be used by project portfolio owners such as Caltrans and the CTC to evaluate cost estimates that are submitted by project teams. In the example shown in Figure 5-4, the team for Project A has submitted an estimate that is higher than average, being slightly above the 60-percent upper confidence limit. The team for Project B has submitted an estimate that is lower than average, being slightly below the 30-percent upper confidence limit.

The estimates for Projects A and B are not necessarily wrong. Almost 40 percent of historic projects with outputs similar to those of Project A have cost more than the Project A estimate, and almost 30 percent of projects with outputs similar to those of Project B have cost less than the Project B estimate. The PDF provides a tool that the project team and, to a lesser extent, review agencies such as the CTC can use to evaluate the team's estimates. There may good reasons why the estimate for a given project is above or below the historic average, and it is incumbent upon the team to both consider and provide those reasons.

A project-by-project review by review agencies is an excessive effort. For such agencies, a portfolio-level review is more appropriate. The next section considers this form of review.

5.4.3 Portfolio-level review

As noted in the discussion of Figure 5-4, 10 percent of projects will have costs above the 90-percent upper confidence limit if the costs of future projects follow the patterns of past projects. California's 2018 State Highway Operation and Protection Program (SHOPP) consist of 1,073 projects with a total 4-year programmed budget of more than \$14 billion (Caltrans 2018:2). If future projects were to follow the patterns of past projects, more than 100 of those projects can be expected to have costs the exceed the 90 percent upper confidence limit illustrated in Figure 5-4.

In reviewing estimates for a project portfolio such as the SHOPP, it would therefore be unreasonable for a review agency to reject a given estimate based solely upon its place in the PDF. The review agency would need additional data and would need to spend time considering that data. In the worst case, the review agency could second-guess reasonable decisions taken by the project team.

Instead of examining individual projects, the appropriate action for a review agency would be to consider the entire portfolio. In a portfolio some projects can be expected to have estimates above the "best fit" line and others below that line, and these surpluses and deficits can be expected to cancel each other. Across more than 1,000 projects in the SHOPP, for instance, the aggregate of the estimates by the project teams should be close to the aggregate of the "best fit" computed conceptual estimates.

In statistical terms, and considering again the combined standard deviation of independent variables (equation 3), the PDF spread of the portfolio aggregate should vary approximately with the square root of the number of projects. That is, the PDF spread of a 900-project portfolio will be approximately one 30th of the sum of the spreads of the individual PDFs. Using the Student's t-test, as used in Section 4.2.1, it can be determined with confidence whether or not the projects teams' estimates on the portfolio are significantly different from the "best fit" computed conceptual estimates. The analysis in Section 4.2.1 established significant differences with a portfolio of only 10 projects. With more than 1,000 projects, the confidence would be greatly enhanced and would lead to a tool for managing project costs.

5.4.4 Managing project costs

Section 2.8 has described the use of cost estimates in target costing, a process which engages the estimator in the execution of the projects and steers the design and construction toward the target costs. The approved portfolio of projects after the review described in Section 5.4.3 would have two key characteristics for project cost management:

1. The aggregate programmed estimate of the portfolio would be close to the cost that would be realized if the implementing agency were to continue its past project delivery practices.

2. Each project in the portfolio would have an estimate that is developed by its respective project team and each team would be aware of the degree of divergence from the "best fit" estimate. Because of their involvement in developing and justifying the estimate there is an enhanced probability that each project team would have a sense of ownership of the estimate and a commitment to completing the project within its estimated cost.

These two conditions create a situation in which teams can "steer" the direct costs of each project to completion within the "direct cost" portion of the programmed amount. The direct cost of a project is the sum of the direct costs of the individual activities on that project, and the direct cost of each activity consists of the costs of the labor, equipment rental, permanent equipment and materials charged to that activity (as discussed in Section 2.4.3). Each of these direct costs results from the actions of project team members:

- Project team members perform the labor for which labor charges are incurred.

- Project team members operate the equipment for which rental charges are incurred.

- Project team members incorporate permanent equipment and materials into the product of the project.

It is the role of the project team members, then, to be cognizant of the direct costs and to "steer" these direct costs toward completion within the "direct cost" portion of the programmed amount. They cannot, however, be held accountable for:

- Indirect costs, sometimes referred to as "overhead" (see discussion in Section 3.4.3)

- Limitations on their productivity that are imposed by processes mandated by the agency's executive management or legislative bodies.

The indirect costs are normally included in the overall project estimate as a multiplier of the some or all of the estimated of direct costs (see Section 3.4.3), and the limitations on productivity form part of the project team's assumptions when preparing an estimate.

In a large portfolio such as the 1,073-project SHOPP it is inevitable that some projects will overrun their programmed amount. As teams become invested in their estimates, however, it is likely that they would steer most projects to completion within the programmed amount. When the "best fit" model and the PDFs are recalculated with updated datasets that include the recently completed projects, the "best fit" estimated costs would decrease. The distribution of the PDF confidence limits would also probably become narrower as teams work to avoid costs that are in the upper ranges of the PDF. Overall, there would be a greater degree of control of project costs instilled from the bottom by the project teams.

6 Conclusions

Chapter 6 concludes this dissertation and is organized as follows: Section 6.1 answers the research questions; Section 6.2 presents the research findings; Section 6.3 lists the contributions to knowledge; Section 6.4 proposes questions for further research; and Section 6.5 provides final remarks.

6.1 Research questions and answers

6.1.1 Cost estimating

As noted in Section 1.3, the aim of this research was to contribute to the body of knowledge of project management by answering 3 interrelated principal research questions:

Question 1: What are the available parametric cost estimating methods for conceptual and feasibility cost estimating in public highway project portfolios?

Answer 1: This dissertation has examined the literature on parametric cost estimating methods and found that the literature refers to 3 variations of parametric estimate, all of which are variations of equation 6. The first variation sets $c = 1$, and this dissertation refers to this variation as the "linear parametric function." As noted in Section 2.6.7, Hamaker (1987) refers to it as a "linear curve" and takes the form of equation 7.

The second and third variations set $0 < c < 1$. Wallace (1978) and Akeel (1989) refer to the second variation as the "additive" exponential parametric function, while Hamaker (1987) calls it a "power curve," and this dissertation refers to it as the "common exponential parametric function." It takes the form of equation 8.

The third variation goes by several names in the literature. Wallace (1978) and Akeel (1989) refer to this variation as the "multiplicational" exponential parametric function, Kouskoulas (1984) refers to it as the "multiplicative" exponential parametric function, and Hamaker (1987) calls it a "logarithmic curve." Many other writers cited in Section 2.6.6 refer to it as the "modified Cobb-Douglas exponential parametric function," and this dissertation uses the "Cobb-Douglas" name. The third variation takes the form of equation 11. As in equation 8, equation 11 is written for a case with 5 variables and it can be expanded indefinitely if there are more variables.

Question 2: How do the available parametric cost estimating methods compare in their mathematical best fit, what are their relative advantages and, based upon the importances of advantages, which is preferable?

Answer 2: When applied to a data set of 39 pedestrian access facility projects, the two exponential models both provide greater coefficients of determination than linear parametric models. This is consistent with the expected result from Section 2.6.1 which postulated an exponential relationship.

The analysis in Chapter 3 found no differences in coefficients of determination between the common exponential and the modified Cobb-Douglas exponential. A further analysis, using Choosing By Advantages, found that Cobb-Douglas was the author's preferred alternative according the preferences used in Section 3.7 together with their supporting logic. This finding rested mainly on the fact that it did not result in null variables. A larger sample, with more instances of each type of variable, would likely result in no null variables and thereby eliminate the influence of the nullness upon the choice of the preferred alternative.

Section 5.1.1 discusses the fact that equation 8 is built on an assumption that each output is produced by separate resources and equation 11 is built on an assumption that outputs are produced by shared resources. Section 5.1.1 therefore proposes the development a hybrid of equations 8 and 11 that would be similar to equation 39.

Question 3: How might the preferred method be used for portfolio-wide validation of cost estimates in a large project portfolio?

Answer 3: The concept of project portfolios and, in particular, public agency project portfolios, is introduced in Section 2.1.4. Its application in this research is discussed in Section 3.1.1 as part of a 3-stage plan for a project cost estimating system. This dissertation addresses Stage 1. Section 5.4.2 describes the planned Stage 2, the development of probability density functions, while Section 5.4.3 describes Stage 3, the expansion to a full portfolio.

This dissertation has tested parametric estimating functions on a small portfolio of 39 projects with an aggregate cost of $26.8 million which have been completed as part of the Caltrans State Highway Operation and Protection Program (SHOPP). In a typical year, Caltrans completes about 250 SHOPP projects with an aggregate cost of about $3 billion (Caltrans 2018:2). Stage 3 would expand the data set from the initial 39 projects to include data on several thousand SHOPP projects with an aggregate cost in the tens of billions of dollars.

The 2018 SHOPP implements the Caltrans "transportation asset management program", or TAMP (Caltrans 2018:1). The TAMP responds to requirements in the 2012 Federal surface transportation law (US Congress 2012) which mandates that every state in the US both prepare an initial asset management plan by April 30, 2018, and revise that plan at least every 4 years (FHWA 2016).

In the California context, the TAMP provides for projects of different types on the same section of highway to be combined into single projects. These combinations depart from the previous Caltrans project types. Section 2.6.5 describes how Caltrans categorized projects into 119 unique project types in 1992. Additional project types have since been introduced, although the formal 1992 categorization has been abandoned. As an example of the combination of project types, the TAMP may combine a wheelchair ramp project into a pavement rehabilitation project. This research has used output-based algorithms which overcome the limitations of the large number of project types and would, for instance, readily combine the pavement and pedestrian access outputs.

Through the proposed expansion to encompass the SHOPP, this research provides a possible path to address some of the challenges in the Caltrans TAMP. It also provides a path that could be adopted by other US states in their versions of the TAMP.

Perhaps most significantly, the 3-stage plan can provide a tool for setting targets, as described in Section 5.4.4, to assist project teams in steering project costs following the successful models described in Section 2.8.

6.1.2 Risk strategy and alternative contracting approaches

While the principal aim of this research was to compare parametric estimating models, when differences between the costs and durations of sets of projects were observed, the author identified a secondary thread. This secondary thread asked what the root causes are of significant differences between agencies in the cost and duration of pedestrian access facility projects developed in compliance with similar procurement statutes.

The author found that comparable physical outcomes (the pedestrian access facilities) were produced at considerably lower cost in the city projects and in much shorter time with minimal city-provided design as compared to the California Department of Transportation (Caltrans) projects that have detailed designs. This was true even when considering only the construction capital costs and discounting the pre-construction and construction engineering costs. That is, the construction contractors submitted lower bids when the client agency provided them with less detailed designs upon which to bid than with more detailed designs.

In this research, the designers' assumption that increased design detail will result in lower bid prices proved to be incorrect. In fact, when contractors received more detailed information, they submitted higher bids. As a result, the client both increased its risk by accepting responsibility for any design errors introduced by the additional detail, and failed to achieve the expected cost savings.

The data suggests that there is an opportunity to increase output and lower the costs of pedestrian access projects (and perhaps other types of highway projects as well) by decreasing the Caltrans design effort and transferring more of the design effort and consequent risk to the contractors. This opportunity could be tested through experiments on a few pedestrian access facility installations.

6.2 Research findings

6.2.1 Cost estimating

The author finds that the Cobb-Douglas exponential function and the common exponential function produce equally acceptable cost estimates but that, in the case examined, the Cobb-Douglas function is preferable primarily because it produced no null variables. Whether or not this finding will hold with a larger data set has yet to be determined. Second, this research revealed that comparable physical outcomes (the pedestrian facilities) were produced at considerably lower cost and in much quicker time when agencies used minimal, rather than detailed, design.

This finding contributes not only to the prediction of project costs on large programs of similar projects but also to an understanding of how differences in statutory language and in risk strategy can lead to differences in the cost of public projects.

Through a consideration of the literature and an analysis of the cases, the author has developed 2 models, the common exponential and the modified Cobb-Douglas exponential, that appear to have a foundation in the literature and fit the case study data. (With further research, the author hopes to refine and improve these models.) This finding provides a first step toward the development of a system for evaluating cost estimates on large portfolios of highway rehabilitation projects, and the author hopes to carry out further research with the intent of refining and improving the models.

In the Caltrans case, the author hopes that such research, as expanded into the future, will assist Caltrans and the CTC to manage California's State Highway asset preservation program by:

1. Enabling Caltrans and the CTC to evaluate whether Caltrans cost estimates are reasonable. This includes determining both where a given estimate is reasonable, and whether the collective estimates of the entire portfolio is reasonable.

2. Enabling Caltrans and the CTC to determine whether efficiency measures have succeeded. To demonstrate that an innovation has achieved an efficiency, one must know both the actual cost after the innovation and what the cost would have been without the innovation. While the cost after the innovation would be readily available from the actual costs incurred, it is more difficult to determine what the cost would have been without the innovation. As the algorithms would be based on historic costs, it would be possible to state with a given statistical degree of certainty, whether a project with the innovation has been completed at a lower (or higher) cost than that project would have cost using Caltrans pre-innovation methods.

3. Incentivizing Caltrans project teams to improve upon past performance. The cost estimating models would provide Caltrans employees with an expected cost using their historic delivery methods. Given that information, it is possible (and likely) that Caltrans teams would rise to the challenge and work to complete their projects at lower-than expected costs.

6.2.2 Benchmarking

The author tested the preferred estimating model on a set of projects obtained from cities in the San Francisco Bay Area. Upon finding that the costs of this second set of projects differed significantly from the cost of the Caltrans projects, the author conducted further research, examining both Caltrans and city bid documents, talking to Caltrans and city personnel, and talking to contractors who had submitted bids on both Caltrans and city projects.

As part of the Caltrans Lean six-sigma program, discussed in Sections 5.1.4 and 5.3.2, it would be appropriate for Caltrans employees at the rank-and-file and first-line supervisor level, as well as executives to engage in similar benchmarking activities. This would include reviewing work done by cities, counties, consulting firms, and contractors that is similar to work done by Caltrans employees; learning from those outside agencies and firms; and applying those lessons to Caltrans work. Such learning could be accomplished by reviewing the online products of the outside agencies and firms, talking to people in those agencies and firms, and by participating in professional gathering such as meetings of the American Society of Civil Engineers and the Project Management Institute.

6.3 Contributions to knowledge

Table 6-1 lists the contributions to knowledge from each chapter of this dissertation.

Table 6-1 Contributions to knowledge

Section	Contribution
2.1.1	Unveils the previously little-known history of design-bid-build in California government, preceding by 40 years Miller’s date for the origins of this contracting approach, and provides a context to the 1916 adoption of design-bid-build by the US federal government.
2.1.4	Provides an overview of the literature on project portfolios and reveals a possible critical juncture in which 2 sentences in a document in 2000 may have triggered an explosion of academic articles, growing to 131 articles in the year 2017.
2.2.1	Identifies and documents the relationship between the AACE and AASHTO estimate classes.
2.2.2	Provides narrative definitions of the estimate classes.
2.3.1	Identifies and documents the relationship between the 5 AACE estimate classes and the Caltrans project phases.
2.3.2	Identifies and documents the relationship between the 5 AACE classes of estimate and the Highways England project stages.
2.3.3	Describes 2 specific instances of analogous conceptual estimating on multi-billion-dollar projects in California.
2.4	Illustrates the relationship between the PMI estimating method categories and AACE estimating methods and provides a description of the various estimating methods.
2.5 and 2.11.1	Provides an overview of the literature on conceptual and feasibility estimating methods.
2.6.1	Provides a theoretical discussion of the relationship between the Wright Curve and exponential parametric estimating.
2.6.5	Documents the PYPSCAN estimating system formerly used by Caltrans.
2.6.6	Provides a discussion of the modified Cobb-Douglas function as an alternative parametric estimating method for conceptual and feasibility estimates.
2.8 and 2.11.3	Describes the potential use of parametric conceptual cost estimates as a starting point for target costing and project cost management.
2.9	Provides a literature review of forms of specification: prescriptive, performance, and warranty specifications.
2.10	Provides a literature review of contracting approaches: design-bid-build and design-build.

Section	Contribution
2.11.2	Provides a case for developing conceptual and feasibility cost estimates based on outputs rather than other factors such as project characteristics, geographic factors, and economic factors.
2.11.4	Discusses the correlation between forms of specification and contracting approaches.
3.3	Provides MATLAB scripts for developing conceptual and feasibility estimates based on outputs.
3.3.3 and 3.5	Provides 12 alternative parametric models for developing conceptual and feasibility estimates for pedestrian access facility projects on California State Highways.
3.4	Discusses inflation adjustment methods for state highway projects in California.
3.7	Finds that exponential parametric cost estimating models, such as the common exponential and modified Cobb-Douglas exponential, provide greater coefficients of determination than linear parametric models and preferable models to the linear parametric.
4.2	Finds that cost differences for similar projects correlate strongly to the procurement approach and risk strategy which, in turn, is rooted in historic differences in the statutory language that controls the procurement and the path-dependent changes that different agencies have made.
4.2	Finds that increased design effort in the project sets used for this research resulted in increased bid prices, opposite to the effect intended by designers, and that the more effective pre-bid design in this case is a minimal design (as discussed in Chapter 5).
4.3	Finds that increased design effort in the project sets used for this research also resulted in considerable project delay, reinforcing the conclusion that the more effective pre-bid design in this case is a minimal design.

6.4 Questions for further research

During the course of this research, the author has identified several areas for further research. While these were alluded to in Chapter 5, they are discussed in greater depth in this section. These areas include, but are not limited to:

6.4.1 Expansion of the exponential models to a broader range of projects

Chapter 3 has described the application of an exponential parametric estimating models to one ubiquitous type of project, pedestrian access facilities. This was a “proof of concept” to test the various models. These models could be applied to projects with outputs that are not limited to the pedestrian access project outputs and could encompass the totality of an agency’s asset preservation projects as discussed in Section 2.11.1. This would require the development of a database of completed asset preservation projects that combines the actual expenditures, dates of expenditures, and outputs for each project. The expenditures are available in the Caltrans accounting system, but outputs might be more difficult to obtain. The Caltrans Division of System Information maintained a database of outputs in the past, but that database may no longer be up to date. In the worst case, outputs can be obtained from the project plans as was done for the 39 projects in the pedestrian access project data set. Such further research could assist agencies in preparing cost estimates, aid in evaluating cost estimates, and provide a tool for assessing the overall reasonableness of an agency's asset preservation portfolio.

6.4.2 Comparison of exponential models with artificial neural networks (ANN) and case-based reasoning (CBR)

This research has considered three types of parametric models – linear, the common exponential, and the modified Cobb-Douglas exponential. The literature review found that most research on conceptual cost estimating models since 2004 has been on artificial neural networks (ANN) and case-based reasoning (CBR), or comparisons between ANNs and linear parametric models (Figure 2-7). This dissertation has not considered ANNs and CBR, and further research could consider them. That research would compare ANNs and CBR with common exponential and modified Cobb-Douglas exponential models.

6.4.3 Phase and specialty-level estimates and estimates of hours rather than dollars

This research has modelled total project costs, with all the project phases considered together. Further research could develop separate models for each phase of projects, for capital and support separately, for pre-construction work separately from construction-phase work, and for right of way. Models could also be developed for support work in hours, rather than dollars, and for each element a standard Work Breakdown Structure. While such additional models, at a more granular level, would be expected to be have larger variances that the total-project models used in this research, they would have potential use to an agency in evaluating the granular costs estimates prepared by agency staff, especially when considered in conjunction with probability density functions (as discussed in Section 5.4.2).

6.4.4 Comparison of variable types for conceptual cost estimating

This research has used project outputs as the input variables for the conceptual cost estimating models. Papers discussed in the literature review considered other variables such as bid items, project characteristics, and economic and geographic factors. Gardner et al. (2016) performed research of the variables that had the largest impact on the variation in data on highway pavement preservation projects. The research in this dissertation might be enhanced by considering a wider range of variables and following Gardner's example ranking the impact of the variables and using only the highest-impact variables.

6.4.5 Quantification of variability (probability density functions and upper and lower confidence limits)

As noted in Section 5.1.2, even the author's preferred alternative among the models considered in this research leaves unexplained 37 percent of the variation in the data. Addressing that unexplained variation remains a problem. AACE indicates that Class 5 estimates should typically have an 80 percent confidence level of being with a range from +100 percent to -50 percent (AACE 2016) and AASHTO gives this range as +200 percent to -50 percent (AASHTO 2013). Figure 5-1 illustrates this expectation for the AACE ranges. Further research, discussed in Section 5.4.2, could focus on the variability of the data with the objective of creating probability density tools to address the variability in project cost data. It would provide upper and lower confidence limits to enable and agency to make statements such as, “Based on historic practices and experience, there is a 60 percent certainty that the actual cost will be less than or equal to this estimate.” While this is similar in form to AACE’s 80 percent, that 80 percent number is based on the professional opinion of the AACE members who prepared the AACE guidance (AACE 2016) and not on statistical analysis as proposed here.

6.4.6 Minimal design of pedestrian access facility projects

As indicated in Sections 5.3.2 and 6.1.2, there is an opportunity to increase output and lower the costs of pedestrian access projects by decreasing the Caltrans design effort and transferring more of the design effort and consequent risk to the contractors. This could be tested through an experimental use of an alternative contracting approach, similar to that used by Bay Area cities, on pedestrian access facility installations.

6.4.7 Benchmarking, alternative design detail, and specifications

The author found opportunities for cost savings and improved delivery of services to the public by comparing the Caltrans processes with those of San Francisco Bay Area cities for one type of project. As part of the Caltrans Lean six-sigma improvement program, introduced in Sections 5.1.4 and 5.3.2, Caltrans could do additional benchmarking with public and private agencies that do work similar to Caltrans. Such benchmarking could lead to experimental applications of alternative processes in Caltrans.

Just as benchmarking could help Caltrans, it could help all organizations. Every organization has room for improvement and such improvement can be facilitated by learning from other organizations. In a famous example, Toyota’s adoption of just-in-time production was inspired by observations of supermarkets in the US (Ohno 1988:1). Inspirations for improvement can come from many sources.

6.5 Final remarks

By considering and analysing data on 39 pedestrian access facility projects on California State Highways (Chapter 3) and 9 similar projects on city streets in the San Francisco Bay Area (Chapter 4), the author has developed twelve alternative models for conceptual and feasibility cost estimating and found a preference for a modified Cobb-Douglas exponential. This study has also led serendipitously to finding an opportunity for cost and schedule savings on pedestrian access facility projects.

This research is generalizable – the conceptual and feasibility cost estimating models could be applied to any set of projects on which costs and outputs are known, and the benchmarking concept of comparing between organizations can be applied between any two organizations that perform similar types of work.

Through ongoing research and testing, the author hopes to refine and improve the models using larger datasets and to pursue additional opportunities for benchmarking between organizations that manage large portfolios of highway projects. It is anticipated that the application of such cost estimating models and benchmarking strategies would result in project cost savings, earlier project delivery, and (most importantly) improved employee morale.

7 References

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8 Appendix A: Data for Caltrans projects

Project Number	Phase K	Phase 0	Phase 1	Phase 2	Phase 3
020E850	$ -	$ 111,408.40	$ 106,162.51	$ 32,645.51	$ 102,172.78
022C310	$ -	$ 16,961.14	$ 45,688.24	$ 8,788.46	$ 21,593.46
0233660	$ -	$ -	$ 34,349.97	$ 11,554.44	$ 18,289.50
024C460	$ -	$ 22,031.28	$ 95,972.22	$ 3,229.40	$ 17,196.00
024C890	$ -	$ 47,425.61	$ 146,621.03	$ 33,711.78	$ 71,663.01
033E250	$ -	$ 164,292.69	$ 373,585.63	$ 50,833.42	$ 389,237.16
034296X	$ 24.68	$ 156,837.92	$ 209,998.07	$ 173,548.59	$ 244,877.80
040F280	$ -	$ -	$ 199,243.20	$ -	$ 38,263.47
0425206	$ -	$ -	$ -	$ -	$ -
043A990	$ -	$ 497,589.58	$ 417,904.95	$ 63,290.80	$ 172,815.24
050E500	$ -	$ -	$ 70,449.64	$ -	$ 23,089.82
050F300	$ -	$ -	$ 236,343.87	$ -	$ 86,687.48
050J24X	$ -	$ -	$ 213,369.79	$ -	$ 51,350.05
050J690	$ -	$ 50,225.75	$ 96,475.88	$ 24,368.21	$ 66,678.93
050J970	$ -	$ 392,398.61	$ 511,010.84	$ 88,135.22	$ 274,049.19
050N850	$ -	$ 222,988.73	$ 428,780.67	$ 41,301.47	$ 344,030.47
060G930	$ -	$ 385,013.20	$ 457,501.13	$ -	$ 178,641.00
0638690	$ -	$ -	$ -	$ -	$ 39,377.61
0638980	$ -	$ -	$ -	$ -	$ 24,306.98
0640940	$ -	$ 253,571.78	$ 296,915.91	$ -	$ 232,884.00
0640960	$ -	$ 174,870.74	$ 33,060.81	$ -	$ 60,636.66
064099X	$ -	$ 51,781.93	$ 61,123.51	$ -	$ 81,601.03
0642440	$ -	$ -	$ -	$ -	$ 16,987.27
074S860	$ -	$ 63,129.01	$ 216,706.26	$ -	$ 68,019.28
080A320	$ -	$ 149,002.29	$ 160,553.97	$ 4,969.60	$ 112,180.99
080A410	$ -	$ 255,856.08	$ 572,395.97	$ -	$ 142,918.45
080A580	$ -	$ 58,822.20	$ 69,769.10	$ -	$ 28,596.81
080C650	$ -	$ 33,583.31	$ 196,288.56	$ -	$ 20,860.02
080E500	$ -	$ 181,226.25	$ 1,103,637.16	$ 125,959.60	$ 266,942.44
080F000	$ -	$ 9,233.64	$ 123,739.40	$ -	$ 24,323.20
080F130	$ -	$ 126,971.90	$ 181,684.63	$ -	$ 48,057.39
080F380	$ -	$ 171,839.98	$ 64,113.99	$ -	$ 93,580.27
080F390	$ -	$ 119,159.07	$ 288,564.99	$ -	$ 191,374.74
080H540	$ -	$ 87,630.19	$ 57,152.28	$ -	$ 68,584.57
084583X	$ -	$ 192,066.93	$ 560,095.01	$ 1,812.52	$ 195,371.89
1046362	$ -	$ -	$ 180,919.97	$ -	$ 48,369.21
1129560	$ -	$ 224,918.47	$ 287,669.32	$ 206,385.82	$ 58,972.00
1129670	$ -	$ 112,261.10	$ 554,081.83	$ 25,613.00	$ 16,754.00
120J480	$ -	$ 118,809.76	$ 258,568.26	$ -	$ 220,199.66

Project Number	Phase 4	Phase 5	Phase 8	Phase 9
020E850	$ 134,598.20	$ -	$ -	$ 4,000.00
022C310	$ -	$ 57,218.06	$ -	$ 650.00
0233660	$ -	$ 80,812.26	$ -	$ 4,000.38
024C460	$ -	$ 43,545.80	$ -	$ -
024C890	$ 130,422.82	$ -	$ -	$ 1,500.00
033E250	$ 450,381.20	$ -	$ -	$ 9,500.00
034296X	$ 886,834.11	$ -	$ -	$ 47,524.00
040F280	$ -	$ 99,515.94	$ -	$ -
0425206	$ 613,117.41	$ -	$ -	$ -
043A990	$ 732.00			$ 13,666.00
050E500	$ -	$ 24,845.98	$ -	$ -
050F300	$ 197,876.68	$ -	$ -	$ -
050J24X	$ -	$ 99,955.00	$ 84,480.00	$ 864.00
050J690	$ 187,102.92	$ -	$ -	$ 2,450.00
050J970	$ 462,314.26	$ -	$ -	$ 147,188.49
050N850	$ 464,513.42	$ -	$ -	$ 40,996.95
060G930	$ 556,236.62	$ -	$ -	$ -
0638690	$ 219,205.09	$ -	$ -	$ -
0638980	$ 120,122.02	$ -	$ -	$ -
0640940	$ 413,214.62	$ -	$ -	$ 10,000.00
0640960	$ 292,066.64	$ -	$ -	$ -
064099X	$ 171,467.98	$ -	$ -	$ -
0642440	$ 231,986.29	$ -	$ -	$ -
074S860	$ 93,600.00	$ -	$ -	$ -
080A320	$ 148,876.86	$ -	$ -	$ -
080A410	$ -	$ 80,403.00	$ -	$ -
080A580	$ -	$ 40,690.06	$ -	$ -
080C650	$ -	$ 39,684.58	$ -	$ -
080E500	$ 525,954.19	$ -	$ -	$ 30,710.00
080F000	$ -	$ 49,559.77	$ -	$ -
080F130	$ -	$ 77,915.90	$ -	$ -
080F380	$ -	$ 116,423.06	$ -	$ -
080F390	$ 139,029.94	$ -	$ -	$ -
080H540	$ -	$ 69,079.49	$ -	$ -
084583X	$ 307,388.45	$ -	$ -	$ -
1046362	$ 88,203.16	$ -	$ -	$ -
1129560	$ 2,087.00	$ -	$ -	$ 39,925.00
1129670	$ 785.00	$ -	$ -	$ -
120J480	$ 208,331.90	$ -	$ -	$ -

Project Number	R/W hours	Ramps	Sidewalk (feet)	Signals
020E850	532	12	-	0
022C310	161	1	207	0
0233660	481	21	-	0
024C460	41	4	-	0
024C890	483	8	-	0
033E250	872	88	-	0
034296X	5033	196	-	0
040F280	0	1	-	0
0425206	0	4	350	0
043A990	924	4	-	0
050E500	61	1	-	1
050F300	377	2	-	0
050J24X	72	2	-	0
050J690	294	4	-	0
050J970	2128	35	202	0
050N850	447	20	-	0
060G930	0	46	-	0
0638690	0	59	-	0
0638980	0	20	-	0
0640940	818	88	-	0
0640960	17	46	-	0
064099X	42	56	-	0
0642440	0	66	-	0
074S860	0	42	-	0
080A320	76	12	-	0
080A410	116	5	21	1
080A580	5	1	-	0
080C650	61	5	-	0
080E500	1633	22	400	0
080F000	2	4	40	0
080F130	0	13	-	0
080F380	34	9	90	0
080F390	0	7	546	0
080H540	22	4	-	2
084583X	851	5	1,153	0
1046362	75	26	50	0
1129560	2722	7	-	0
1129670	491	18	-	0
120J480	0	12	1,737	0

9 Appendix B: Data for city projects

Project Number	Phase K	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4
Berkeley 08-10329	$ -	$ -	$ -	$ -	$ -	$ 172,064.70
Berkeley 10-10465	$ -	$ -	$ -	$ -	$ -	$ 119,846.25
Berkeley 10-10472	$ -	$ -	$ -	$ -	$ -	$ 128,957.75
Berkeley 11-10558	$ -	$ -	$ -	$ -	$ -	$ 194,668.00
Berkeley 12-10642	$ -	$ -	$ -	$ -	$ -	$ 136,622.75
Oakland C428014	$ -	$ -	$ -	$ -	$ -	$ 626,755.00
San Jose 7361	$ -	$ -	$ -	$ -	$ -	$ 50,917.00
San Jose 7483	$ -	$ -	$ -	$ -	$ -	$ 970,921.00
Sunnyvale PW13-19	$ -	$ -	$ -	$ -	$ -	$ 517,747.00
Sunnyvale PW14-02	$ -	$ -	$ -	$ -	$ -	$ 451,850.00
					TOTAL	$ 3,370,349.45

Project Number	Phase 5	Phase 8	Phase 9	R/W hours	Ramps	Side-walk (feet)	Signals
Berkeley 08-10329	$ -	$ -	$ -	0.0	41	-	0
Berkeley 10-10465	$ -	$ -	$ -	0.0	25	140	0
Berkeley 10-10472	$ -	$ -	$ -	0.0	14	840	0
Berkeley 11-10558	$ -	$ -	$ -	0.0	69	140	0
Berkeley 12-10642	$ -	$ -	$ -	0.0	64	220	0
Oakland C428014	$ -	$ -	$ -	0.0	50	10,583	0
San Jose 7361	$ -	$ -	$ -	0.0	17	84	0
San Jose 7483	$ -	$ -	$ -	0.0	337	1,425	0
Sunnyvale PW13-19	$ -	$ -	$ -	0.0	4	-	1
Sunnyvale PW14-02	$ -	$ -	$ -	0.0	155	250	0
				TOTALS	776	13,682	1

10 Appendix C: Common exponential MATLAB code

10.1 Primary code

```
format long
db = xlsread('data_4_MATLAB.xls');
paed = db(:,1);
pse= db(:,2);
rwo = db(:,3);
ce = db(:,4);
maj = db(:,5);
min = db(:,6);
phase8 = db(:,7);
rwc = db(:,8);
pid = db(:,9);
rwhrs = db(:,10);
ramps = db(:,11);
sw = db(:,12);
sig = db(:,13);
engr = paed + pse + ce;
cos = engr + rwo + phase8;
con = maj + min;
cap = con + rwc;
proj = cos + cap;
tot = proj + pid;
a =  0;
b1 = 1;
b2 = 1;
b3 = 1;
b4 = 1;
b5 = 1;
c1 = 1;
c2 = 1;
c3 = 1;
c4 = 1;
c5 = 1;
count = 0;
model2 = 1e14;
test = model2;
abstest = abs(test);
lowtest = abstest;
while (test > 0)&& (count < 100000)
a = fminsearch (@(a) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), a);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
```

```
if a < 0
   a = 0
end
b1 = fminsearch (@(b1) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b1);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b1 < 0
   b1 = 0
end
c1 = fminsearch (@(c1) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), c1);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if c1 < 0
   c1 = 0
end
if c1 > 1
   c1 = 1
end
b2 = fminsearch (@(b2) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b2);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b2 < 0
   b2 = 0
end
c2 = fminsearch (@(c2) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), c2);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if c2 < 0
   c2 = 0
end
if c2 > 1
   c2 = 1
end
b3 = fminsearch (@(b3) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b3);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b3 < 0
   b3 = 0
end
c3 = fminsearch (@(c3) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), c3);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if c3 < 0
   c3 = 0
end
if c3 > 1
```

```
   c3 = 1
end
b4 = fminsearch (@(b4) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b4);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b4 < 0
   b4 = 0
end
c4 = fminsearch (@(c4) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), c4);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if c4 < 0
   c4 = 0
end
if c4 > 1
   c4 = 1
end
b5 = fminsearch (@(b5) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b5);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b5 < 0
   b5 = 0
end
c5 = fminsearch (@(c5) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), c5);
if c5 < 0
   c5 = 0
end
if c5 > 1
   c5 = 1
end
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot)
model1 = model2;
model2 = minErr;
test = model1 - model2;
abstest = abs(test);
if abstest < lowtest
   lowtest = abstest
end
test = lowtest;
count = count +1;
end
minErr
count
test
lowtest
```

```
a
b1
b2
b3
b4
b5
c1
c2
c3
c4
c5
```

10.2 **First subroutine code (“regressionFit”)**

```
function out = regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5,
tot)
model = a +
b1.*((ramps).^c1)+b2.*((sw).^c2)+b3.*((sig).^c3)+b4.*((rwc).^c4)+b5.*((rwhrs).^c5);
err = (tot - model).^2;
out = sum(err);
end
```

10.3 **Second subroutine code (“regressionErr”)**

```
function out = regresionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5,
tot)
model = a +
b1.*((ramps).^c1)+b2.*((sw).^c2)+b3.*((sig).^c3)+b4.*((rwc).^c4)+b5.*((rwhrs).^c5);
err = (tot - model).^2;
out = sum(err);
end
```

11 Appendix D: Cobb-Douglas MATLAB code

11.1 Primary code

```
format long
db = xlsread('data_4_MATLAB.xls');
paed = db(:,1);
pse= db(:,2);
rwo = db(:,3);
ce = db(:,4);
maj = db(:,5);
min = db(:,6);
phase8 = db(:,7);
rwc = db(:,8);
pid = db(:,9);
rwhrs = db(:,10);
ramps = db(:,11);
sw = db(:,12);
sig = db(:,13);
engr = paed + pse + ce;
cos = engr + rwo + phase8;
con = maj + min;
cap = con + rwc;
proj = cos + cap;
tot = proj + pid;
a = 0;
b = 0;
c1 = 0;
c2 = 0;
c3 = 0;
c4 = 0;
c5 = 0;
count = 0;
model2 = 1e14;
test = model2;
   while test > 0
b = fminsearch (@(b) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot), b);
c1 = fminsearch (@(c1) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot),
c1);
if c1 < 0
   c1 = 0
end
if c1 > 1
   c1 = 1
end
```

```
c2 = fminsearch (@(c2) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot),
c2);
if c2 < 0
   c2 = 0
end
if c2 > 1
   c2 = 1
end
c3 = fminsearch (@(c3) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot),
c3);
if c3 < 0
   c3 = 0
end
if c3 > 1
   c3 = 1
end
c4 = fminsearch (@(c4) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot),
c4);
if c4 < 0
   c4 = 0
end
if c4 > 1
   c4 = 1
end
c5 = fminsearch (@(c5) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot),
c5);
if c5 < 0
   c5 = 0
end
if c5 > 1
   c5 = 1
end
a = fminsearch (@(a) cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot), a);
if a < 0
   a = 0
end
minErr = cobbDougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot)
model1 = model2;
model2 = minErr;
test = model1 - model2
count = count +1
   end
minErr
count
test
a
```

```
b
c1
c2
c3
c4
c5
```

11.2 **Subroutine code ("cobbDougFit")**

```
function out = cobbdougFit(a, b, ramps, c1, sw, c2, sig, c3, rwc, c4, rwhrs, c5, tot)
model = a + b.*((ramps + 1).^c1).*((sw + 1).^c2).*((sig + 1).^c3).*((rwc + 1).^c4).*((rwhrs + 1).^c5);
err = (tot - model).^2;
out = sum(err);
end
```

12 Appendix E: Linear parametric MATLAB code

```
format long
db = xlsread('data_4_MATLAB.xls');
paed = db(:,1);
pse= db(:,2);
rwo = db(:,3);
ce = db(:,4);
maj = db(:,5);
min = db(:,6);
phase8 = db(:,7);
rwc = db(:,8);
pid = db(:,9);
rwhrs = db(:,10);
ramps = db(:,11);
sw = db(:,12);
sig = db(:,13);
engr = paed + pse + ce;
cos = engr + rwo + phase8;
con = maj + min;
cap = con + rwc;
proj = cos + cap;
tot = proj + pid;
a =  0;
b1 = 1;
b2 = 1;
b3 = 1;
b4 = 1;
b5 = 1;
c1 = 1;
c2 = 1;
c3 = 1;
c4 = 1;
c5 = 1;
count = 0;
model2 = 1e14;
test = model2;
abstest = abs(test);
lowtest = abstest;
while (test > 0) && (count < 100000)
a = fminsearch (@(a) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), a);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if a < 0
   a = 0
```

```
end
b1 = fminsearch (@(b1) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b1);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b1 < 0
   b1 = 0
end
b2 = fminsearch (@(b2) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b2);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b2 < 0
   b2 = 0
end
b3 = fminsearch (@(b3) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b3);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b3 < 0
   b3 = 0
end
b4 = fminsearch (@(b4) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b4);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b4 < 0
   b4 = 0
end
b5 = fminsearch (@(b5) regressionFit(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5,
rwhrs, c5, tot), b5);
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot);
if b5 < 0
   b5 = 0
end
minErr = regressionErr(a, b1, ramps, c1, b2, sw, c2, b3, sig, c3, b4, rwc, c4, b5, rwhrs, c5, tot)
model1 = model2;
model2 = minErr;
test = model1 - model2;
abstest = abs(test);
if abstest < lowtest
   lowtest = abstest
end
test = lowtest;
count = count +1;
end
minErr
count
test
lowtest
```

a
b1
b2
b3
b4
b5
c1
c2
c3
c4
c5

13 Appendix F: Date of the last recorded charge to each project phase in Appendix A

Project Number	Phase K	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4
020E850		1/12/2009	8/26/2009	12/10/2009	8/1/2011	5/17/2010
022C310		6/9/2006	7/15/2007	11/13/2006	4/10/2007	
0233660			6/8/2001	1/10/2002	4/13/2000	
024C460		3/11/2009	10/14/2009	10/10/2008	2/10/2010	
024C890		2/29/2008	2/11/2009	5/11/2009	6/10/2010	6/18/2010
033E250		10/10/2008	7/7/2009	7/8/2010	5/19/2011	8/15/2011
034296X	10/7/1998	3/13/2000	6/19/2001	11/8/2001	9/11/2002	1/24/2002
040F280			8/18/2008		3/11/2009	
0425206					7/9/2007	
043A990		11/10/2009	7/15/2011	6/25/2012	8/22/2012	
050E500			1/11/2008		3/20/2012	
050F300			10/12/2004		8/11/2006	10/4/2005
050J24X			3/11/2008		1/10/2011	8/15/2011
050J690		6/14/2004	12/10/2004	9/12/2006	8/11/2006	
050J970		4/9/2007	7/8/2010	7/8/2010	7/16/2010	10/24/2011
050N850		3/11/2008	4/29/2011	3/30/2011	4/28/2011	2/11/2000
060G930		12/10/2009	8/10/2011		7/31/2012	12/20/2007
0638690					5/26/2000	4/23/2001
0638980					7/18/2000	
0640940		10/12/2004	11/15/2004		6/9/2008	12/15/2000
0640960		5/26/2000	7/7/2000		7/6/2001	8/21/2001
064099X		4/13/2000	6/18/2001		4/10/2002	
0642440					6/18/2001	8/24/2009
074S860		7/9/2008	8/26/2009		11/10/2009	2/16/2006
080A320		4/11/2005	4/11/2005	7/24/2006	7/8/2007	
080A410		8/13/2007	5/9/2008		5/12/2010	8/15/2011
080A580		2/10/2006	2/9/2007		10/10/2007	
080C650		4/10/2007	12/11/2006		8/18/2008	
080E500		7/24/2011	7/7/2009	6/11/2009	8/25/2012	
080F000		3/11/2005	1/11/2006		10/12/2006	2/17/2009
080F130		8/18/2008	6/9/2009		5/11/2009	
080F380		10/10/2007	5/29/2008		3/11/2009	7/17/2001
080F390		5/9/2008	3/26/2010		12/5/2010	6/23/2010
080H540		11/9/2007	7/9/2008		12/10/2008	
084583X		3/30/2009	6/10/2010	4/9/2004	7/16/2010	
1046362			5/8/2003		2/8/2005	
1129560		11/2/2010	2/1/2011	9/15/2011	11/1/2011	
1129670		5/12/2010	7/24/2011	7/24/2011	7/5/2012	
120J480		4/3/2009	4/13/2010		7/25/2011	

Project Number	Phase 5	Phase 8	Phase 9
020E850			10/28/2009
022C310	1/16/2007		2/7/2006
0233660	8/11/1999		12/24/1998
024C460	9/28/2009		
024C890			3/28/2008
033E250			5/18/2010
034296X			6/30/2000
040F280	11/4/2008		
0425206	3/13/2006		
043A990		8/31/2007	10/17/2011
050E500	5/4/2006		
050F300			11/5/2004
050J24X			6/23/2010
050J690			
050J970			
050N850			
060G930			9/4/2002
0638690			
0638980			
0640940			
0640960			
064099X			
0642440			
074S860			
080A320	8/30/2006		
080A410			7/18/2008
080A580	8/5/2005		
080C650	10/30/2008		
080E500	12/29/2006		
080F000			
080F130	1/30/2008		
080F380			
080F390			
080H540			
084583X	11/6/2000		
1046362			
1129560			
1129670			
120J480			

14 Appendix G: Support cost data for the projects in Appendix A

Project Number	Phase 0 Labor	Phase 0 Labor % of Phase 0 total	Phase 0 Labor hours	Phase 0 Labor cost/ hour
020E850	$ 73,884.08	66%	1,223.0	$ 60.41
022C310	$ 12,061.80	71%	205.0	$ 58.84
0233660	$ -		-	
024C460	$ 15,219.03	69%	252.0	$ 60.39
024C890	$ 29,324.60	62%	503.0	$ 58.30
033E250	$ 112,750.76	69%	1,825.0	$ 61.78
034296X	$ 99,938.97	64%	2,917.0	$ 34.26
040F280	$ -		-	
0425206	$ -		-	
043A990	$ 358,238.16	72%	4,840.0	$ 74.02
050E500	$ -		-	
050F300	$ -		-	
050J24X	$ -		-	
050J690	$ 34,589.87	69%	666.0	$ 51.94
050J970	$ 272,672.85	69%	5,260.0	$ 51.84
050N850	$ 154,344.32	69%	2,942.0	$ 52.46
060G930	$ 239,711.66	62%	3,506.0	$ 68.37
0638690	$ -		-	
0638980	$ -		-	
0640940	$ 184,961.79	73%	5,550.0	$ 33.33
0640960	$ 133,585.11	76%	4,532.0	$ 29.48
064099X	$ 40,346.08	78%	1,535.0	$ 26.28
0642440	$ -		-	
074S860	$ 43,509.15	69%	694.0	$ 62.69
080A320	$ 104,080.03	70%	2,821.0	$ 36.89
080A410	$ 182,882.30	71%	4,838.0	$ 37.80
080A580	$ 40,513.13	69%	933.0	$ 43.42
080C650	$ 23,685.68	71%	476.0	$ 49.76
080E500	$ 114,000.89	63%	2,080.0	$ 54.81
080F000	$ 6,615.95	72%	123.0	$ 53.79
080F130	$ 84,732.71	67%	1,561.0	$ 54.28
080F380	$ 121,385.48	71%	2,225.0	$ 54.56
080F390	$ 22,261.53	19%	389.0	$ 57.23
080H540	$ 59,835.55	68%	1,091.0	$ 54.84
084583X	$ 57,945.10	30%	977.0	$ 59.31
1046362	$ -		-	
1129560	$ 166,307.88	74%	2,505.0	$ 66.39
1129670	$ 84,300.29	75%	1,158.0	$ 72.80
120J480	$ 75,296.19	63%	1,139.0	$ 66.11
TOTAL	**$ 2,948,980.94**	**66%**	**58,766.0**	**$ 50.18**

Project Number	Phase 1 Labor	Phase 1 Labor % of Phase 1total	Phase 1 Labor hours	Phase 1 Labor cost/ hour
020E850	$ 83,167.59	78%	1,227.0	$ 67.78
022C310	$ 31,939.71	70%	554.0	$ 57.65
0233660	$ 25,250.70	74%	749.0	$ 33.71
024C460	$ 69,157.62	72%	1,026.0	$ 67.41
024C890	$ 102,134.33	70%	1,526.0	$ 66.93
033E250	$ 273,572.00	73%	4,132.0	$ 66.21
034296X	$ 155,986.43	74%	3,770.0	$ 41.38
040F280	$ 137,362.16	69%	2,151.0	$ 63.86
0425206	$ -		-	
043A990	$ 311,780.48	75%	4,496.0	$ 69.35
050E500	$ 51,287.61	73%	1,099.0	$ 46.67
050F300	$ 161,284.04	68%	3,875.0	$ 41.62
050J24X	$ 150,151.55	70%	2,664.0	$ 56.36
050J690	$ 69,757.89	72%	1,303.0	$ 53.54
050J970	$ 380,688.14	74%	5,879.0	$ 64.75
050N850	$ 310,822.70	72%	4,853.0	$ 64.05
060G930	$ 342,097.86	75%	4,887.0	$ 70.00
0638690	$ -		-	
0638980	$ -		-	
0640940	$ 204,117.28	69%	4,800.0	$ 42.52
0640960	$ 25,276.32	76%	656.0	$ 38.53
064099X	$ 46,631.21	76%	1,625.0	$ 28.70
0642440	$ -		-	
074S860	$ 164,805.77	76%	2,767.0	$ 59.56
080A320	$ 115,458.40	72%	2,603.0	$ 44.36
080A410	$ 392,823.76	69%	7,854.0	$ 50.02
080A580	$ 49,399.05	71%	1,116.0	$ 44.26
080C650	$ 141,388.55	72%	2,677.0	$ 52.82
080E500	$ 754,306.54	68%	12,664.0	$ 59.56
080F000	$ 89,360.91	72%	1,575.0	$ 56.74
080F130	$ 120,004.75	66%	1,915.0	$ 62.67
080F380	$ 46,277.26	72%	831.0	$ 55.69
080F390	$ 108,297.82	38%	1,783.0	$ 60.74
080H540	$ 36,968.49	65%	626.0	$ 59.06
084583X	$ 366,747.49	65%	6,817.0	$ 53.80
1046362	$ 126,069.69	70%	3,375.0	$ 37.35
1129560	$ 218,571.86	76%	2,980.0	$ 73.35
1129670	$ 416,752.47	75%	6,646.0	$ 62.71
120J480	$ 194,206.86	75%	2,564.0	$ 75.74
TOTAL	**$ 6,273,905.29**	**70%**	**$ 110,065.0**	**$ 57.00**

Project Number	Phase 2 Labor	% of Phase 2 total	Phase 2 Labor hours	Phase 2 Labor cost/ hour
020E850	$ 25,044.37	77%	536.0	$ 46.72
022C310	$ 6,356.93	72%	127.0	$ 50.05
0233660	$ 8,824.56	76%	253.0	$ 34.88
024C460	$ 2,330.02	72%	46.0	$ 50.65
024C890	$ 23,052.99	68%	506.0	$ 45.56
033E250	$ 36,891.50	73%	966.0	$ 38.19
034296X	$ 133,853.68	77%	4,440.0	$ 30.15
040F280	$ -		-	
0425206	$ -		-	
043A990	$ 44,080.30	70%	950.0	$ 46.40
050E500	$ -		-	
050F300	$ -		-	
050J24X	$ -		-	
050J690	$ 17,729.27	73%	328.0	$ 54.05
050J970	$ 64,413.07	73%	1,253.0	$ 51.41
050N850	$ 22,985.67	56%	457.0	$ 50.30
060G930	$ -		-	
0638690	$ -		-	
0638980	$ -		-	
0640940	$ -		-	
0640960	$ -		-	
064099X	$ -		-	
0642440	$ -		-	
074S860	$ -		-	
080A320	$ 120.74	2%	4.0	$ 30.19
080A410	$ -		-	
080A580	$ -		-	
080C650	$ -		-	
080E500	$ 70,745.61	56%	1,315.0	$ 53.80
080F000	$ -		-	
080F130	$ -		-	
080F380	$ -		-	
080F390	$ -		-	
080H540	$ -		-	
084583X	$ 1,294.42	71%	35.0	$ 36.98
1046362	$ -		-	
1129560	$ 156,611.52	76%	2,788.0	$ 56.17
1129670	$ 16,671.00	65%	517.0	$ 32.25
120J480	$ -		-	
TOTAL	**$ 631,005.65**	**70%**	**$ 14,521.0**	**$ 43.45**

Project Number	Phase 3 Labor	Labor % of Phase 3 total	Phase 3 Labor hours	Phase 3 Labor cost/ hour
020E850	$ 54,032.32	53%	792.0	$ 68.22
022C310	$ 14,495.13	67%	264.0	$ 54.91
0233660	$ 7,962.59	44%	224.0	$ 35.55
024C460	$ 12,883.79	75%	181.0	$ 71.18
024C890	$ 50,835.54	71%	862.0	$ 58.97
033E250	$ 294,464.66	76%	4108.0	$ 71.68
034296X	$ 169,285.36	69%	4260.0	$ 39.74
040F280	$ 28,743.59	75%	433.0	$ 66.38
0425206	$ -		0.0	
043A990	$ 102,466.91	59%	3444.0	$ 29.75
050E500	$ 14,628.90	63%	391.0	$ 37.41
050F300	$ 65,842.88	76%	1442.0	$ 45.66
050J24X	$ 37,440.39	73%	571.0	$ 65.57
050J690	$ 46,761.47	70%	886.0	$ 52.78
050J970	$ 201,725.43	74%	3116.0	$ 64.74
050N850	$ 228,512.18	66%	3591.0	$ 63.63
060G930	$ 114,078.00	64%	3106.0	$ 36.73
0638690	$ 28,571.06	73%	809.0	$ 35.32
0638980	$ 15,518.29	64%	469.0	$ 33.09
0640940	$ 163,766.62	70%	3175.0	$ 51.58
0640960	$ 37,022.49	61%	1059.0	$ 34.96
064099X	$ 60,166.47	74%	1566.0	$ 38.42
0642440	$ 9,886.09	58%	286.0	$ 34.57
074S860	$ 51,046.42	75%	719.0	$ 71.00
080A320	$ 59,916.46	53%	1132.0	$ 52.93
080A410	$ 105,714.22	74%	1521.0	$ 69.50
080A580	$ 20,671.28	72%	375.0	$ 55.12
080C650	$ 12,609.94	60%	220.0	$ 57.32
080E500	$ 199,359.45	75%	3213.0	$ 62.05
080F000	$ 17,792.81	73%	305.0	$ 58.34
080F130	$ 36,100.81	75%	540.0	$ 66.85
080F380	$ 17,478.77	19%	278.0	$ 62.87
080F390	$ 140,988.67	74%	1898.0	$ 74.28
080H540	$ 47,480.31	69%	743.0	$ 63.90
084583X	$ 145,578.16	75%	2878.0	$ 50.58
1046362	$ 41,347.17	85%	1068.0	$ 38.71
1129560	$ 34,592.00	59%	1350.0	$ 25.62
1129670	$ 12,244.00	73%	271.0	$ 45.18
120J480	$ 168,444.20	76%	2457.0	$ 68.56
TOTAL	**$ 2,870,454.83**	**69%**	**$ 54,003.0**	**$ 53.15**

15 Appendix H: Appendix A costs after inflation adjustment to January 1, 2012 base date

Project Number	Phase K unchanged	Phase 0	Phase 1	Phase 2	Phase 3
020E850	$ -	$ 129,682.46	$ 119,489.82	$ 35,598.97	$ 104,246.15
022C310	$ -	$ 23,049.68	$ 57,981.53	$ 11,080.60	$ 27,844.57
0233660	$ -	$ -	$ 68,927.14	$ 19,319.10	$ 41,227.46
024C460	$ -	$ 25,421.91	$ 107,251.35	$ 3,711.80	$ 18,890.39
024C890	$ -	$ 57,995.39	$ 169,899.67	$ 37,728.52	$ 77,397.95
033E250	$ -	$ 194,000.66	$ 423,583.22	$ 54,066.40	$ 401,072.29
034296X	$ 24.68	$ 356,778.70	$ 420,179.52	$ 293,586.20	$ 438,731.76
040F280	$ -	$ -	$ 237,200.79	$ -	$ 44,152.24
0425206	$ -	$ -	$ -	$ -	$ -
043A990	$ -	$ 553,896.22	$ 427,348.95	$ 62,085.27	$ 167,713.61
050E500	$ -	$ -	$ 86,827.13	$ -	$ 22,855.11
050F300	$ -	$ -	$ 359,619.75	$ -	$ 116,508.99
050J24X	$ -	$ -	$ 260,468.20	$ -	$ 53,841.74
050J690	$ -	$ 78,281.34	$ 145,103.87	$ 30,991.01	$ 89,617.26
050J970	$ -	$ 506,079.32	$ 549,744.12	$ 93,740.58	$ 294,491.93
050N850	$ -	$ 272,210.39	$ 443,004.94	$ 42,603.44	$ 355,491.00
060G930	$ -	$ 426,728.35	$ 466,228.55	$ -	$ 173,849.91
0638690	$ -	$ -	$ -	$ -	$ 87,658.91
0638980	$ -	$ -	$ -	$ -	$ 53,292.66
0640940	$ -	$ 385,833.65	$ 448,767.85	$ -	$ 280,286.85
0640960	$ -	$ 389,281.60	$ 72,713.26	$ -	$ 120,792.16
064099X	$ -	$ 116,724.76	$ 122,332.21	$ -	$ 151,638.10
0642440	$ -	$ -	$ -	$ -	$ 33,998.22
074S860	$ -	$ 75,623.78	$ 243,910.90	$ -	$ 75,716.26
080A320	$ -	$ 218,884.78	$ 235,854.23	$ 6,364.89	$ 142,530.01
080A410	$ -	$ 323,152.99	$ 692,263.01	$ -	$ 154,986.74
080A580	$ -	$ 81,654.16	$ 90,880.67	$ -	$ 35,777.82
080C650	$ -	$ 43,305.38	$ 258,308.25	$ -	$ 24,834.04
080E500	$ -	$ 185,100.23	$ 1,251,338.75	$ 140,430.09	$ 258,964.10
080F000	$ -	$ 13,645.02	$ 172,704.05	$ -	$ 32,340.35
080F130	$ -	$ 151,161.17	$ 206,853.46	$ -	$ 54,950.65
080F380	$ -	$ 214,991.12	$ 77,297.23	$ -	$ 107,982.33
080F390	$ -	$ 144,112.50	$ 315,019.15	$ -	$ 201,650.40
080H540	$ -	$ 109,102.88	$ 68,464.11	$ -	$ 80,234.98
084583X	$ -	$ 220,996.29	$ 604,917.44	$ 2,632.37	$ 209,945.68
1046362	$ -	$ -	$ 307,051.05	$ -	$ 71,905.84
1129560	$ -	$ 238,071.34	$ 300,726.29	$ 208,874.60	$ 59,443.37
1129670	$ -	$ 121,740.63	$ 565,926.15	$ 26,076.18	$ 16,358.47
120J480	$ -	$ 136,623.30	$ 281,553.27	$ -	$ 224,876.90

Project Number	Phase 4 using CHCCI	Phase 5 using CHCCI	Phase 4 using linear regression	Phase 5 using linear regression
020E850	$ 131,364.99	$ -	$ 138,313.62	$ -
022C310	$ -	$ 64,438.23	$ -	$ 69,607.55
0233660	$ -	$ 167,879.48	$ -	$ 139,603.86
024C460	$ -	$ 62,607.20	$ -	$ 47,762.56
024C890	$ 138,752.90	$ -	$ 134,873.47	$ -
033E250	$ 439,562.49	$ -	$ 463,559.13	$ -
034296X	$ 1,842,310.18	$ -	$ 1,008,308.49	$ -
040F280	$ -	$ 91,939.73	$ -	$ 114,959.44
0425206	$ 690,484.75	$ -	$ 646,237.94	$ -
043A990	$ 328,154.07	$ -	$ 349,028.49	$ -
050E500	$ -	$ 32,211.08	$ -	$ 29,520.46
050F300	$ 254,291.85	$ -	$ 215,683.36	$ -
050J24X	$ -	$ 120,701.00	$ -	$ 117,843.59
050J690	$ 240,446.46	$ -	$ 203,530.29	$ -
050J970	$ 520,024.59	$ -	$ 470,294.68	$ -
050N850	$ 442,161.09	$ -	$ 468,133.54	$ -
060G930	$ 525,767.99	$ -	$ 558,755.69	$ -
0638690	$ 384,733.71	$ -	$ 252,730.34	$ -
0638980	$ 267,083.09	$ -	$ 138,229.05	$ -
0640940	$ 531,023.21	$ -	$ 449,877.32	$ -
0640960	$ 649,390.20	$ -	$ 336,225.61	$ -
064099X	$ 356,207.78	$ -	$ 194,961.80	$ -
0642440	$ 481,928.58	$ -	$ 263,772.07	$ -
074S860	$ 91,351.61	$ -	$ 96,183.72	$ -
080A320	$ 164,143.99	$ -	$ 161,277.94	$ -
080A410	$ -	$ 94,303.61	$ -	$ 94,078.30
080A580	$ -	$ 32,891.97	$ -	$ 50,547.59
080C650	$ -	$ 38,899.09	$ -	$ 49,702.81
080E500	$ 513,320.12	$ -	$ 541,343.35	$ -
080F000	$ -	$ 57,668.12	$ -	$ 65,040.09
080F130	$ -	$ 117,356.59	$ -	$ 86,780.09
080F380	$ -	$ 136,551.07	$ -	$ 135,877.80
080F390	$ 118,165.41	$ -	$ 141,899.87	$ -
080H540	$ -	$ 63,820.42	$ -	$ 80,204.11
084583X	$ 384,118.04	$ -	$ 312,973.65	$ -
1046362	$ 164,214.19	$ -	$ 97,887.51	$ -
1129560	$ 1,958.98	$ -	$ 2,109.05	$ -
1129670	$ 742.00	$ -	$ 788.98	$ -
120J480	$ 260,335.22	$ -	$ 212,510.16	$ -

Project Number	Phase 8 unchanged	Phase 9 unchanged
020E850	$ -	$ 4,000.00
022C310	$ -	$ 650.00
0233660	$ -	$ 4,000.38
024C460	$ -	$ -
024C890	$ -	$ 1,500.00
033E250	$ -	$ 9,500.00
034296X	$ -	$ 47,524.00
040F280	$ -	$ -
0425206	$ -	$ -
043A990		$ 13,666.00
050E500	$ -	$ -
050F300	$ -	$ -
050J24X	$ 84,480.00	$ 864.00
050J690	$ -	$ 2,450.00
050J970	$ -	$ 147,188.49
050N850	$ -	$ 40,996.95
060G930	$ -	$ -
0638690	$ -	$ -
0638980	$ -	$ -
0640940	$ -	$ 10,000.00
0640960	$ -	$ -
064099X	$ -	$ -
0642440	$ -	$ -
074S860	$ -	$ -
080A320	$ -	$ -
080A410	$ -	$ -
080A580	$ -	$ -
080C650	$ -	$ -
080E500	$ -	$ 30,710.00
080F000	$ -	$ -
080F130	$ -	$ -
080F380	$ -	$ -
080F390	$ -	$ -
080H540	$ -	$ -
084583X	$ -	$ -
1046362	$ -	$ -
1129560	$ -	$ 39,925.00
1129670	$ -	$ -
120J480	$ -	$ -

16 Appendix I: Choosing By Advantages and best fit table for 12 alternatives

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 1: Common exponential		Alternative 2: Cobb-Douglas expone	
	Using actual costs without inflation adjustment.		Using actual costs without inflation adjustment.	
	Equation 17, Section 3.3.4		Equation 18, Section 3.3.4	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.55		Attribute: 0.54	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 58	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 56
FACTOR 2: Ability to project into the future.	Attribute: Available		Attribute: Available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: Ability to project into the future.	Importance of Advantage: 30	Advantage: Ability to project into the future.	Importance of Advantage: 30
FACTOR 3: Number of null variables	Attribute: 1 null variable		Attribute: no null variables	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such "null variables" appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: None	Importance of Advantage:	Advantage: Every variable affects the outcome.	Importance of Advantage: 20
FACTOR 4: Fixed costs	Attribute: $111,653.07		Attribute: $232,939.36	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: This alternative has the lowest fixed cost.	Importance of Advantage: 10	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 7
TOTAL IMPORTANCE OF ADVANTAGES:		98		113
RANK AMONG 12 ALTERNATIVES:		8		3

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 3: Linear parametric		Alternative 4: Common exponential	
	Using actual costs without inflation adjustment.		Using inflation-adjusted costs. Adjustment by linear regression of CHCCI to estimate construction cost inflation.	
	Equation 19, Section 3.3.4		Equation 21, Section 3.5.1	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.46		Attribute: 0.63	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 36	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 78
FACTOR 2: Ability to project into the future.	Attribute: Available		Attribute: Available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: Ability to project into the future.	Importance of Advantage: 30	Advantage: Ability to project into the future.	Importance of Advantage: 30
FACTOR 3: Number of null variables	Attribute: no null variables		Attribute: 1 null variable	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such "null variables" appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: Every variable affects the outcome.	Importance of Advantage: 20	Advantage: None	Importance of Advantage:
FACTOR 4: Fixed costs	Attribute: $452,719.84		Attribute: $173,250.36	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 2	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 8
TOTAL IMPORTANCE OF ADVANTAGES:		88		116
RANK AMONG 12 ALTERNATIVES:		9		2

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 5: Cobb-Douglas expone		Alternative 6: Linear exponential	
	Using inflation-adjusted costs. Adjustment by linear regression of CHCCI to estimate construction cost inflation.		Using inflation-adjusted costs. Adjustment by linear regression of CHCCI to estimate construction cost inflation.	
	Equation 22, Section 3.5.1		Equation 23, Section 3.5.1	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.63		Attribute: 0.55	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 78	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 58
FACTOR 2: Ability to project into the future.	Attribute: Available		Attribute: Available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: Ability to project into the future.	Importance of Advantage: 30	Advantage: Ability to project into the future.	Importance of Advantage: 30
FACTOR 3: Number of null variables	Attribute: no null variables		Attribute: no null variables	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such "null variables" appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: Every variable affects the outcome.	Importance of Advantage: 20	Advantage: Every variable affects the outcome.	Importance of Advantage: 20
FACTOR 4: Fixed costs	Attribute: $288,981.67		Attribute: $489,337.85	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 6	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 1
TOTAL IMPORTANCE OF ADVANTAGES:		134		109
RANK AMONG 12 ALTERNATIVES:		1		4

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 7: Common exponential		Alternative 8: Cobb-Douglas expone	
	Using inflation-adjusted costs and using raw CHCCI to estimate construction cost inflation.		Using inflation-adjusted costs and using raw CHCCI to estimate construction cost inflation.	
	Equation 25, Section 3.5.2		Equation 27, Section 3.5.2	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.72		Attribute: 0.70	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: The highest coefficient.	Importance of Advantage: 100	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 95
FACTOR 2: Ability to project into the future.	<u>Attribute: Not available</u>		Attribute: Not available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: None	Importance of Advantage:	Advantage: None	Importance of Advantage:
FACTOR 3: Number of null variables	Attribute: 1 null variable		Attribute: 1 null variable	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such “null variables” appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: None	Importance of Advantage:	Advantage: None	Importance of Advantage:
FACTOR 4: Fixed costs	Attribute: $296,619.31		Attribute: $361,693.76	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 5	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 4
TOTAL IMPORTANCE OF ADVANTAGES:		105		99
RANK AMONG 12 ALTERNATIVES:		6		7

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 9: Linear exponential		Alternative 10: Common exponential	
	Using inflation-adjusted costs and using raw CHCCI to estimate construction cost inflation.		Using inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.	
	Equation 28, Section 3.5.2		Equation 30, Section 3.5.3	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.67		Attribute: 0.35	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 87	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 11
FACTOR 2: Ability to project into the future.	Attribute: Not available		Attribute: Available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: None	Importance of Advantage:	Advantage: Ability to project into the future.	Importance of Advantage: 30
FACTOR 3: Number of null variables	Attribute: no null variables		Attribute: 1 null variable	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such “null variables” appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: Every variable affects the outcome.	Importance of Advantage: 20	Advantage: None	Importance of Advantage:
FACTOR 4: Fixed costs	Attribute: $462,522.95		Attribute: $439,095.40	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 1	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 2
TOTAL IMPORTANCE OF ADVANTAGES:		108		41
RANK AMONG 12 ALTERNATIVES:		5		11

Decision to be made:	Which model provides the preferred tool for predicting the cost of a future pedestrian access project on California State Highways based on the data for the 39 projects?			
	Alternative 11: Cobb-Douglas expon		Alternative 12: Linear exponential	
	Using inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.		Using inflation-adjusted costs excluding right of way, using linear regression of CHCCI to estimate construction cost inflation.	
	Equation 31, Section 3.5.3		Equation 32, Section 3.5.3	
FACTOR 1: Coefficient of determination ("best fit" mesure)	Attribute: 0.44		Attribute: 0.31	
Criterion: The coefficients of determination appear in Table 3-2. They indicate the degree to which the model accounts for the variation in the cost data. The coefficient of determination is a number between 0 and 1, and the higher the coefficient, the greater the amount of variation accounted for by the model. A higher coefficient is therefore better.	Advantage: Intermediate between the highest coefficient (Alternative 7) = 0.72 and lowest cofficient (Alternative 12) = 0.31	Importance of Advantage: 31	Advantage: None. This alternative has the lowest coefficient.	Importance of Advantage:
FACTOR 2: Ability to project into the future.	Attribute: Available		Attribute: Available	
Criterion: This factor refers to the ability to project the data into the future. A linear regression line can be extended into the future. Other factors, most notably the CHCCI, cannot be projected into the future because they have irregular variations such as the variation of the CHCCI line in Figure 3-3. Availability of future data is better than non-availability.	Advantage: Ability to project into the future.	Importance of Advantage: 30	Advantage: Ability to project into the future.	Importance of Advantage: 30
FACTOR 3: Number of null variables	Attribute: no null variables		Attribute: 1 null variable	
Criterion: If a model finds that a variable has no effect, that would suggest that the addition of many instances of that variable to a project will make no impact on the project cost. Such "null variables" appear in Table 3-3. It would be better to have no null variables than to have null variables.	Advantage: Every variable affects the outcome.	Importance of Advantage: 20	Advantage: None	Importance of Advantage:
FACTOR 4: Fixed costs	Attribute: $436,689.96		Attribute: $515,649.41	
Criterion: As discussed in relation to Figure 2-7, it is expected that each project will have some unavoidable fixed costs that do not vary with the project scope. It would be more desirable, and therefore better, for the variables to account for the variations in cost than to assume a large fixed cost. A lower fixed cost is better.	Advantage: Intermediate between lowest fixed cost (Alternative 1) = $111,653.07 and highest fixed cost (Alternative 12) = $515,649.41	Importance of Advantage: 2	Advantage: None. This alternative has the highest fixed cost.	Importance of Advantage:
TOTAL IMPORTANCE OF ADVANTAGES:		83		30
RANK AMONG 12 ALTERNATIVES:		10		12