SHOPP Pilot Project

Phase 1: A Framework for Project Prioritization

June 17, 2015

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DISCLAIMER STATEMENT

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Executive Summary

This report documents the work of a team of Caltrans engineers in developing and applying a Multi-Objective Decision Analysis (MODA) framework to prioritize projects within the State Highway Operation and Protection Program (SHOPP). Under the sponsorship of Caltrans Executive Management, the team pursued an extensive scope of work from July 2014 through March 2015. As decision analysis is a highly specialized area of study, the team initially consulted with top decision analysis experts as well as the literature to help identify best practices in project prioritization. With input from Caltrans subject matter experts, a preliminary decision analysis framework has been developed that facilitates the calculation of project "value" using available project-specific data. A prototype tool was implemented in *Microsoft Excel* to carry out calculations, test the framework, and demonstrate to sponsors the potential benefits of a MODA-based project prioritization approach.

Given the constrained timeline and recently acquired knowledge of the team, the project prioritization framework and *Microsoft Excel* tool should be considered a "proof of concept" rather than a comprehensive and rigorous calculation framework ready for operational implementation. Despite this limitation, a number of important conclusions can be drawn from this pilot effort. A MODA-based approach will bring more transparency to the project prioritization process, provide a quantitative basis for decision-making, and provide a mechanism to communicate the alignment of project priorities with strategic objectives. Furthermore, in contrast to the existing SHOPP project prioritization process where funding decisions are based by program, a MODA-based approach ranks projects based on objective value with direct consideration of cost.

The next phase will consist of outreach to department stakeholders and external partners for feedback and recommendations. The outreach will be in the form of presentations and facilitated discussions on the overall Caltrans Asset Management Program, the SHOPP Pilot Project and decision making framework, and future SHOPP business process improvements. A report will document the outcomes of this outreach effort.

Moving forward in subsequent phases, a major effort will need to be pursued to fully develop the work that has been started with this pilot project. The compilation of more comprehensive data sets will drive the development of more focused calculations to better reflect project value. Changes in business processes, policies, and tools in the SHOPP will need to follow to support this paradigm shift. A research project will be initiated to identify shortcomings and change and/or improve the decision analysis framework. An expanded analysis of the 2016 SHOPP using the pilot project framework will provide an opportunity to more fully evaluate the effectiveness of the approach.

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1. Introduction

The Caltrans Improvement Project (CIP),[1] initiated in 2014 with the California State Transportation Agency (CalSTA), identified that an improved and transparent process for project selection within the State Highway Operation and Protection Program (SHOPP) was required as a key component of transportation asset management. The SHOPP[2] is a $2.3 billion annual program of projects to maintain and preserve infrastructure investments on the State Highway System. Capital improvements programmed in the SHOPP are limited to maintenance, safety, and rehabilitation of state highways and bridges that do not add new traffic capacity.

In 2009 a project prioritization process was implemented statewide for all SHOPP projects. Under this process, the priorities of each of the 31 SHOPP programs were ranked, and project funding decisions were made based on association of projects to these programs. For instance, a project to improve the resilience of a bridge at a water crossing against foundation failures from scour would be associated to a specific program, in this example, "201.111 Bridge Scour Mitigation." The rank of the program would determine if this project would be funded. For purposes of project development, a target level of funding was determined for each program within the SHOPP. Projects were prioritized within each program and put forward for the project development process. Although this program-level approach establishes a logical project prioritization framework, it does not adequately account for the array of benefits that the project delivers, the diversity of improvements across multiple infrastructure assets, and those benefits relative to the cost of the project. As a result, current funding decision outcomes can result in a biased portfolio with concentrations of projects focused on a particular program or asset type.

The goal of this pilot project is to develop a more objective and transparent methodology for the prioritization of SHOPP projects based on best practices and decision-making sciences. A core team, consisting of four Caltrans engineers, with various backgrounds and diverse expertise, was formed to carry out the pilot project. In addition, Executive Management and SHOPP Program Managers were engaged for input throughout the project.

An initial literature review by the team indicates that there are various competing methodologies for decision-making and project prioritization. There are also a variety of different decision-making software tools available with costs ranging from free to over $1 million annually. Recognizing the limited experience in decision analysis theory of the team members, two well-regarded experts in the field of decision analysis were brought onboard in September 2014 to provide knowledge transfer and initial guidance. Dr. Ralph Keeney conducted interviews with Caltrans Executive Managers over the course of a day and delivered a report compiling observations, findings, and recommendations. In an independent effort, Dr. Lee Merkhofer organized a one-day workshop that included Caltrans Executives,

[1] http://www.dot.ca.gov/CIP/
[2] http://www.dot.ca.gov/hq/transprog/shopp.htm

SHOPP Division Chiefs, and SHOPP Program Managers. The workshop had both an educational and a framework development components.

Guided by the findings and recommendations from the two consultants, the team pursued the development of a Multi-Objective Decision Analysis (MODA) approach for project prioritization. The appeal of MODA is that data from which decisions are made can be linked to the Department's Mission, Vision, and Goals, and therefore, can be used to prioritize projects. The team, through a series of meetings with SHOPP Program Managers and subject matter experts, developed a draft Objectives Hierarchy, serving as a blueprint for how the data can be used to score projects and shows the strategic alignment of the data with the Department's mission. The calculation of a project's value is carried out within a Value Function, comprised of sub-models. These sub-models are tied to specific objectives within the hierarchy, and the data feeds into those sub-models in calculations used to score projects.

A prototype SHOPP Project Prioritization Tool was produced in December 2014, implemented in *Microsoft Excel*. The tool applies a MODA-based value function and facilitates the evaluation and prioritization of SHOPP projects. In summary, the tool:

- Communicates project priorities in the context of the Department's goals, formalized in a hierarchy of fundamental objectives and a value function.
- Assigns the value that each project is expected to deliver, identifying those projects providing the best "bang-for-the buck."
- Calculates the overall value of project portfolios, given variations in funding levels, and goal weights.
- Facilitates the assessment of "what if" scenarios (e.g., budget changes) and provides justification for additional funding requests.
- Evaluates various scenarios where specific projects are forced to be included (or excluded) in the portfolio.
- Compares project priorities developed using the new process against existing processes.

2. Background

As a result of a recent extensive review by external partners and stakeholders, Caltrans is expediting the implementation of an Transportation Asset Management Plan (TAMP) to improve system planning, management, operations, and preservation with a "fix-it-first" policy. Beginning with the 2016 SHOPP, new processes are anticipated to be in place that will improve the project selection process for greater transparency and alignment with current goals and objectives. This pilot project is a major step in guiding investments as a key element in the plan, allowing decision makers to achieve the greatest "bang for the buck."

2.1. SSTI and the Initiation of the Caltrans Improvement Project

In 2013, the State Smart Transportation Initiative (SSTI)[3] at the University of Wisconsin, under a contract through the California State Transportation Agency (CalSTA), performed an assessment of the performance of the California Department of Transportation (Caltrans). The SSTI report, published on January 30, 2014, contained many recommendations for improvements to Caltrans business processes.[4] Among these was a specific recommendation for implementing asset management practices. The report states:

> *"Caltrans should modernize its stewardship effort through asset management. Establishment of an asset management system, which will provide more efficient use of scarce system preservation dollars, is one of the goals of the department's own program review."*

Based on the recommendations from the SSTI report, Caltrans initiated the Caltrans Improvement Project (CIP) and formed five workgroups to address these recommendations. CIP Workgroup No. 2, Smart Investment and Resource Alignment, comprised of Caltrans executive management as well as external partners, was tasked with looking at "smart investment and resource alignment." Among many tasks, the workgroup's workplan states in regard to asset management:

> *"This workgroup's task will expedite the implementation of an asset management plan for Caltrans to improve system planning, management, operations and preservation with a "fix it first" policy. It will address recommendations #2 (better matching investments to policy goals in the mission and vision), #4 (aligning resources with goals) and #7 (focusing on freight) from the SSTI report."*

Under the sponsorship and guidance of the CIP Workgroup 2, the SHOPP Pilot Project was pursued as one of the first steps toward Caltrans modernizing "its stewardship effort…" and "better matching investments to policy goals in the mission and vision." Although just a piece of the big picture for asset

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[3] http://www.ssti.us/

[4] The California Department of Transportation: SSTI Assessment and Recommendations, http://www.dot.ca.gov/CIP/docs/SSTIReport.pdf

management, the SHOPP Pilot Project will develop a decision-making framework for project selection that will eventually identify portfolios of projects that will increase utilization and investment of taxpayer's funding and Caltrans' resources.

2.2. Relation to Department's Asset Management Efforts

Moving Ahead for Progress in the 21st Century,[5] defines asset management as "a strategic and systematic process of operating, maintaining, and improving physical assets. Its focus is on engineering and economic analysis, based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve a desired and sustainable state of good repair over the lifecycle of the assets at minimum practicable cost." To comply with State and Federal codes, the Department is developing a Transportation Asset Management Plan (TAMP) to be implemented in the coming years.

2.2.1. Senate Bill 486 (SB 486)

On September 30, 2014, the Governor signed into law Senate Bill (SB) 486[6] requiring the Department, in consultation with the California Transportation Commission (Commission), to prepare a robust TAMP to guide the development of the State Highway Operation and Protection Program (SHOPP). This requires the Commission to adopt related targets and performance measures that reflect state policy goals and objectives. The statute allows for the Department to prepare the TAMP in phases.

The health and condition of the system, as documented by the TAMP, will determine an effective way of applying the State's limited financial resources. The legislation authorizes the Commission to decline adoption of SHOPP programming document if it is not sufficiently consistent with the TAMP. It allows the creation of the plan in phases: (1) the first phase to be implemented for the 2016 SHOPP; and (2) the final phase, a complete TAMP, applied against the 2020 SHOPP. It calls for the Commission to adopt targets and performance measures that reflect State transportation goals and objectives. The Department will need to develop a performance report through the Commission to increase the transparency and accountability of the SHOPP.

This SHOPP Pilot Project is intended to help meet the initial requirements of the first phase. Once the ultimate mature tool is developed, together with other Caltrans management systems, it will assist in a transparent project selection process and optimize the use of the State's transportation dollars.

2.2.2. Moving Ahead for Progress in the 21st Century

The transportation reauthorization bill, Moving Ahead for Progress in the 21st Century (MAP-21), signed in July 2012, established federal regulation governing asset management requirements for all National Highway System (NHS) roads and bridges. It requires that each state department of transportation

[5] http://www.fmcsa.dot.gov/mission/policy/map-21-moving-ahead-progress-21st-century-act
[6] http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB486

(DOT) develop a risk-based asset management plan for the NHS to improve or preserve the condition of assets and the performance of the system. The plan is to include asset summary listings and conditions; plan objectives and measures; and financial and investment strategies. Aside from pavement and bridges, as called for in MAP-21, Caltrans will add culverts and intelligent transportation system (ITS) elements in this initial implementation of asset management. This will be a strategic and systematic process of operating, maintaining, and improving physical assets with a focus on engineering and economic analysis.

2.2.3. The Transportation Asset Management Plan

In order to meet the requirements of MAP-21 and SB 486, as well as address concerns raised by the SSTI report, a comprehensive Transportation Asset Management Plan (TAMP) is needed. An initial development effort of the TAMP can be traced back to October 2012 and the Caltrans Program Review. This process resulted in the preparation of the document, "Workplan for Developing a Transportation Asset Management Plan (TAMP) v.2a" in October 2013. The Caltrans Executive Board identified the four assets for initial focus (i.e., pavement, bridges, culvert, and ITS elements) as well as the six teams to carry out the work (i.e., Data, Asset Analysis, Financial, Local Engagement, Risk, and Organization).

2.3. Existing SHOPP Project Prioritization Process

The purpose of the SHOPP is to maintain and preserve the State Highway System (SHS) and its supporting infrastructure. Projects in the SHOPP are limited to capital improvements relative to maintenance, safety, and rehabilitation of State highways and bridges — capital improvements that do not add capacity to the system. The current SHOPP is comprised of over 31 programs all competing for limited funding, as shown in Table 2-1. These programs can be correlated to one of nine categories. Three categories are considered non-discretionary; that is, projects in these categories must be funded. The remaining six categories are comprised of programs that fall under a discretionary category. In the annual funding cycle, projects are organized in rank order based on the program to which it is associated. Projects are funded in a top-down manner, based on program, until available funding is exhausted.

Table 2-1 – SHOPP Program Priorities

	Program Code	Program Priority	Program	Major Damage Restoration	Collision Reduction	Mandates & Storm Water	Bridge Preservation	Roadway Preservation	Mobility Improvements	Roadside Preservation	Facility Improvements
Non-Discretionary	**201.130**	1	Emergency Damage Repair	●							
	201.010	1	Safety Improvements		●						
	201.131	1	Permanent Restoration	●							
	201.361	1	ADA Access Improvements			●					
	201.378	1	ADA Pedestrian Infrastructure			●					
	201.235	1	Roadside Safety Improvements		●						
	201.119	1	Bridge Preventive Maintenance			●					
	201.321	1	Weigh Stations & WIM Facilities			●					
Discretionary	**201.015**	2	Collision Severity Reduction		●						
	201.111	3	Bridge Scour Mitigation				●				
	201.113	4	Bridge Seismic Restoration				●				
	201.110	5	Bridge Rehabilitation				●				
	201.120	6	Roadway Rehabilitation (3R)					●			
	201.121	6	Roadway Preservation (CAPM)					●			
	201.122	6	Roadway Rehabilitation (2R)					●			
	201.151	7	Drainage System Restoration					●			
	201.112	8	Bridge Rail Replacement/Upgrade				●				
	201.335	9	Storm Water			●					
	201.315	10	Transportation Management Systems						●		
	201.322	11	Trans Permit Requirements for Bridges				●				
	201.150	12	Roadway Protective Betterment					●			
	201.310	13	Operational Improvements						●		
	201.240	14	Roadside Protection and Restoration							●	
	201.250	15	Safety Roadside Rest Area Rehabilitation							●	
	201.210	16	Roadside Rehabilitation							●	
	201.170	17	Signs and Lighting Rehabilitation							●	
	201.160	18	Relinquishments			●					
	201.325	19	Railroad at-grade Crossing			●					
	201.330	20	Hazardous Waste Mitigation			●					
	201.352	21	Maintenance Facilities								●
	201.351	22	Equipment Facilities								●
	201.353	23	Office Buildings								●
	201.260	25	New Safety Roadside Rest Areas							●	

SHOPP program priorities were established in 2009 through a ranking exercise, formalized in a decision document[7] approved through Caltrans Executive Management. The program prioritization process was carried out with a group of 50 representatives from all 12 Caltrans Districts and SHOPP Managers. Participants were asked to compare each of the 31 programs against each other and assess the relative importance of one program over another on a 3-point scale (1 = slightly more important, 2 = somewhat more important, 3 = significantly more important). The judgments were captured using a spreadsheet, as shown in Figure 2-1. The results of these pairwise comparisons by individuals were used in a series of calculations to produce program priorities. Additional calculations were then performed to determine the overall priorities established of the group.

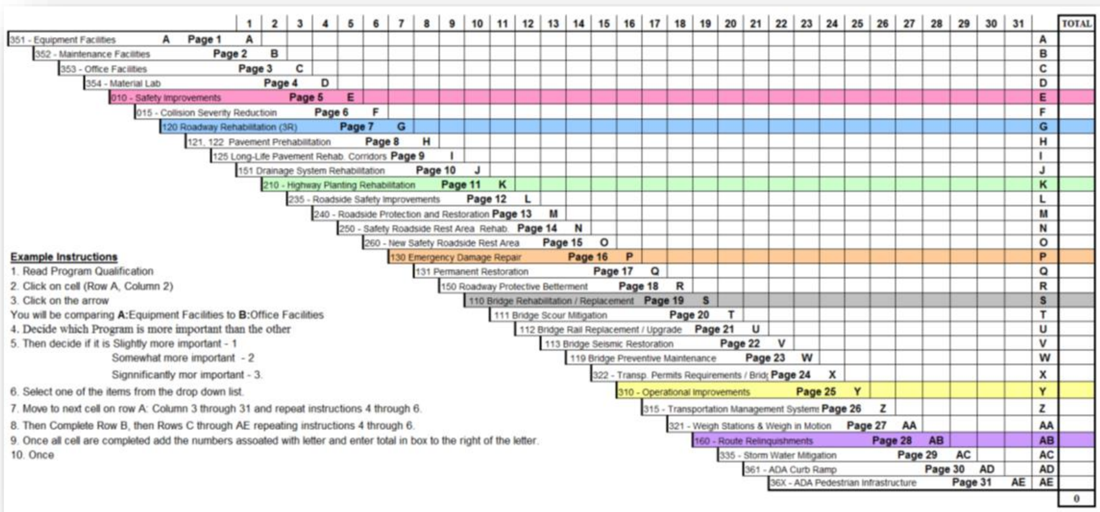

Figure 2-1 – Priority Matrix Worksheet used to Establish SHOPP Program Priorities

Over the next several SHOPP cycles, the priorities have been updated to match funding and changes to the Department's Strategic Goals for the SHOPP. However, the basic premise of the prioritization approach has remained the same.

[7] "SHOPP Decision Document 2009-3, SHOPP Priority" (internal documentation)

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3. Strategy for Change

Under the sponsorship of Executive Management, a team was established and a workplan set into motion to pursue the development of a new SHOPP project prioritization framework. This strategy involved getting a small team of Caltrans engineers to become more knowledgeable in decision analysis theory in order to effectively evaluate alternatives and/or develop new processes.

3.1. Formation of the Core Team

In July 2014, the Executive Board Committee on Asset Management (EBCAM) directed the formation of a team of four Senior Transportation Engineers from three headquarters divisions – Division of Programming; Division of Research, Innovation and System Information; and the Director's Office of Strategic Management. This team, referred to as the "Core Team," was tasked with researching decision-making methodologies, software tool alternatives, and developing a pilot project prioritization framework for the SHOPP.

The Core Team initially identified the need for both leadership and technical expertise. As shown in Figure 3-1, Executive Management provided leadership and guidance. Subject Matter Experts (SMEs) were engaged to build and refine the decision-making framework as well as provided key technical information. This information was used to develop the value function to calculate the project benefit. More detailed information on the scoring method of the value function is presented later in the report.

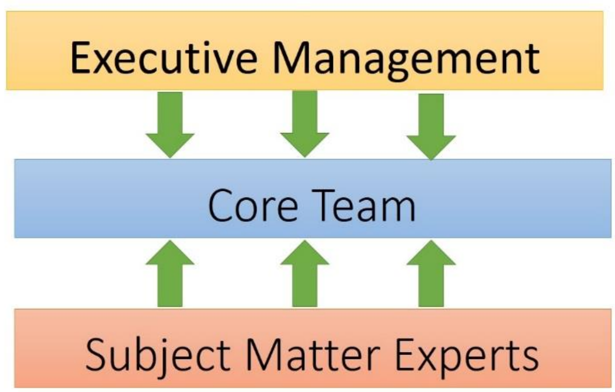

Figure 3-1 - Core Team Engagement

3.2. Research on Decision Analysis Methods and Tools

The Core Team recognized early on in the project that there was a need to become more knowledgeable on the fundamental principles of decision analysis and project prioritization. Given the short time frame for the pilot project, a short literature search was conducted. In addition, the team also evaluated a number of commercial and open source decision-making tools.

3.2.1. Decision Analysis and Project Prioritization

Decision analysis encompasses the methods and tools to systematically consider key aspects of a decision-making problem, guides the selection of the best alternative, and establishes a logical and transparent framework that provides insight on how decisions are made. Decision analysis is a discipline that combines elements of operations research, management science, and systems analysis. The goal of the decision-making process is to provide the decision maker with a logical and defensible framework that can help articulate how choices and priorities were made. Project prioritization is a specific implementation of decision analysis based on the same fundamental principles. Where in decision analysis the goal is to determine the single best alternative, project prioritization aims to identify an optimized portfolio of projects from a pool of projects.

3.2.2. Literature Search

A cursory literature search was conducted in the early weeks of the project to identify documents and tutorials that would help get the team up to speed and conversant in project prioritization and decision analysis methods. Online publications and articles served as a primary resource. An internet search on the topic of "project prioritization" led to a series of informative online articles by business consultant Lee Merkhofer which described overarching project prioritization principles and practical applications through examples. This, in turn, led to other online articles, tutorials, and presentations on the subject published by a wide variety of entities – university researchers discussing the merits of various methods and mathematical models, commercial software companies in the business of developing tools, businesses that have applied various decision-making methods and tools in practice, and governmental agencies and partners that have established processes based on decision analysis theory. A partial listing of online articles is presented in Table 3-1.

Table 3-1 - References

Title	Description	Website
"Project Prioritization and Project Portfolio Management" (2014) Lee Merkhofer Consulting	This is a series of papers that explains project prioritization principles.	http://www.prioritysystem.com/papers.html
"Decision Analysis: An Overview" (1982) INFORMS, Operations Research, Vol. 30, No. 5., Ralph L. Keeney	This article presents an overview of decision analysis and provides additional sources for its foundations, procedures, history, and applications.	http://web.stanford.edu/class/cee115/wiki/uploads/Main/Schedule/OverviewDA.pdf
"Multiple-Objective Decision Analysis Involving Multiple Stakeholders" (2009) INFORMS, Tutorials in Operations Research, Robin Keller	This is a high-level tutorial that explains decision-making frameworks, development of objectives hierarchies, and case studies to illustrate application of the Multi-Objective Decision Analysis (MODA) methodology.	http://faculty.sites.uci.edu/lrkeller/files/2011/06/multiple-objective-decision-analysis-involving-ultiple-stakeholders.pdf

Title	Description	Website
"Multi-Criteria Analysis: A Manual" (2009) Department for Communities and Local Government, UK	This manual provides guidance for government officials and other practitioners on how to undertake and make the best use of multi-criteria analysis for the appraisal of options for policy and other decisions.	https://www.gov.uk/government/publications/multi-criteria-analysis-manual-for-making-government-policy
"Application of the Analytic Hierarchy Process in Road Asset Management: User Manual" (2007) Austroads, Association of Australian and New Zealand Road Transport and Traffic Authorities	This manual provides guidance for the application of the analytic hierarchy process (AHP) as a decision support tool in road asset management.	https://www.onlinepublications.austroads.com.au/items/AP-T84-07
"States' Approaches to Transportation Project Prioritization: Linking Policy, Planning and Programming" (2007) Metropolitan Planning Council	This document addresses the question of how Illinois should prioritize its transportation project investments. Included in the document is a synthesis of project prioritization practices of several state DOTs.	http://www.metroplanning.org/uploads/cms/documents/NationalPractices.pdf
"Project Prioritization Process Guidebook for Large Urban Areas" (2014) Mid-Region Council of Governments, New Mexico	This manual describes a project prioritization method used by a Metropolitan Planning Organization in New Mexico.	http://www.mrcog-nm.gov/transportation/metro-planning/project-prioritization-process
"Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance" (2015) **NCHRP Report 806** National Cooperative Highway Research Program	This guidance includes discussion of analytical tools to support decision-making and is supplemented by a prototypical spreadsheet-based implementation of the guide's analysis framework.	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_806.pdf

Publications by state and local transportation agencies on project prioritization methods were of particular interest to the team.

3.2.3. The Need for Decision Analysis and Project Prioritization Methods

Project prioritization can be considered a "knapsack problem," a term used in mathematics and computer sciences to describe an optimization problem. In the knapsack analogy, items are selected based on specific volumes and values and are to be packed in a knapsack with a limited volume capacity (Figure 3-2).

Figure 3-2- Knapsack Problem

The knapsack problem closely parallels the project prioritization task in that a set of the highest priority projects must be determined from a pool of projects given a budget constraint. Each project is unique and produces some level of benefit (or value) based on a defined set of parameters and value judgments. Decision makers strive to select a portfolio of projects that provide the greatest overall benefit within the resource limits.

Unfortunately, the mathematical solution to the knapsack problem is not trivial, and approximate solutions are frequently used in practice. Decision analysis methods and tools are used to arrive at approximate solutions.

3.2.4. Methods for Decision Analysis

Various project prioritization and decision analysis methods were evaluated for applicability to SHOPP project prioritization. The methods considered all fall under a general class known collectively as Multi-Criteria Decision Analysis (MCDA) or Multi-Criteria Decision Methods (MCDM). Although methods differed in the details and implementation, for the most part each had elements that involved the identification of criteria or objectives, assignment of criteria or objective weights or importance, scoring, ranking, analysis, and portfolio optimization.

Within MCDA, two major types of analysis methods were identified in the literature – Multi-Attribute Decision Analysis (MADA), and Multi-Objective Decision Analysis (MODA). A paper published by the

National Institute of Standards and Technology (NIST)[8] suggests that MODA methods are best suited to the task of resource allocation problems, as is the case for SHOPP project prioritization. Used in conjunction with these methods, a suite of additional decision-making methods are available. A partial listing is presented in Table 3-2.

Table 3-2 - MCDA Methods

Partial Listing of Methods Used in Multi-Criteria Decision Analysis (MCDA)	
Aggregated Indices Randomization Method (AIRM) Analytic Hierarchy Process (AHP) Analytic Network Process (ANP) Best Worst Method (BWM) Characteristic Objects METhod (COMET) Data Envelopment Analysis Decision EXpert (DEX) Disaggregation – Aggregation Approaches (UTA, UTAII, UTADIS) Dominance-based Rough Set Approach (DRSA) ELECTRE (Outranking) Evidential Reasoning Approach (ER) Goal Programming Grey Relational Analysis (GRA) Inner Product of Vectors (IPV) Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	Multi-Attribute Global Inference of Quality (MAGIQ) Multi-Attribute Utility Theory (MAUT) Multi-Attribute Value Theory (MAVT) New Approach to Appraisal (NATA) Nonstructural Fuzzy Decision Support System (NSFDSS) Potentially all Pairwise Rankings of all Possible Alternatives (PAPRIKA) PROMETHEE (Outranking) Superiority and Inferiority Ranking Method (SIR method) Technique for the Order of Prioritisation by Similarity to Ideal Solution (TOPSIS) Value Analysis (VA) Value Engineering (VE) VIKOR Method Fuzzy VIKOR Method Weighted Product Model (WPM) Weighted Sum Model (WSM)

A comprehensive evaluation of all possible supporting methods was not possible within the scope of the SHOPP Pilot Project. The Core Team focused primarily on what appeared to be the most commonly cited and implemented suite of methods within a Multi-Objective Decision Analysis (MODA) framework: Multi-Attribute Utility Theory (MAUT), Multi-Attribute Value Theory (MAVT), and the Analytic Hierarchy Process (AHP).

3.2.4.1. Multi-Attribute Value Theory (MAVT)

Multi-Attribute Utility Theory (MAUT) and Multi-Attribute Value Theory (MAVT) are closely related methods that are used in decision analysis. MAUT uses "utility functions," whereas MAVT uses "value functions." These are technical differences in the methods that are used to address aspects such as the treatment of decision uncertainty. In general, MAVT can be considered a more limited version of MAUT. MAVT implements value functions to transform criteria (e.g., GHG reduction, economic impacts, etc.) into a dimensionless, uniform scale referred to as "value." The aggregated value of the alternative can then be used to prioritize multiple alternatives.

[8] Norris, G. A.; Marshall, H. E., 1995. "Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems," NISTIR 5663; 86 p. September 1995 (http://fire.nist.gov/bfrlpubs/build95/art066.html)

3.2.4.2. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a prioritization technique that can be applied in its entirety to a decision-making or prioritization problem. Furthermore, it can be used as one component within the MAVT method. The AHP technique requires that the analyst elicit from the decision makers their preferences between pairs of criteria. The degree to which one criterion is preferred more than another is quantified, and through this pair-wise comparison approach, a set of criteria weights are established. Alternatives are assessed in a similar manner – pairs of alternatives are evaluated for their relative alignment with each criteria. The resulting pair-wise comparisons of alternatives combined with the weighting are then used to generate a final list of priorities.

3.2.4.3. Multi-Objective Decision Analysis for Project Prioritization

The Core Team pursued a Multi-Objective Decision Analysis (MODA) approach for the SHOPP Pilot Project. Specifically, a MAVT process was used and was carried out in a number of key steps, as shown in Figure 3-3.

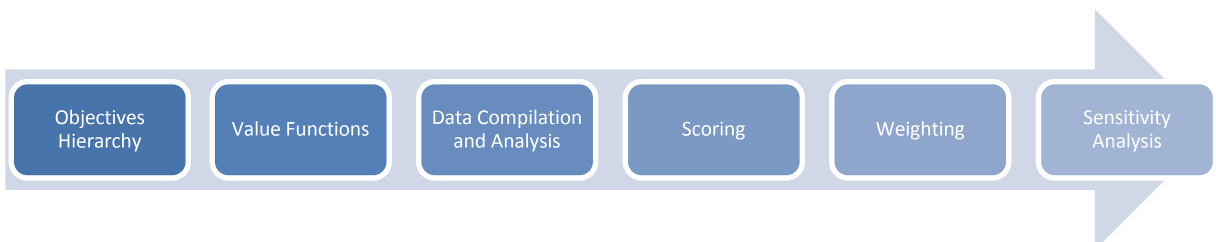

Figure 3-3- MODA/MAVT Process

In this process, an Objectives Hierarchy (Figure 3-4) is developed that ties the decision maker's high level goals to lower level criteria that can be measured. The objectives hierarchy provides a means to deconstruct organizational goals into fundamental objectives. Weights are determined for objectives, and a linear-additive, multi-attribute value function is then used to combine the products of the weighted values to determine the overall value that a project delivers. Portfolios of projects are analyzed for sensitivity to changes in the weighting assignment, which provides insight to the decision-making process.

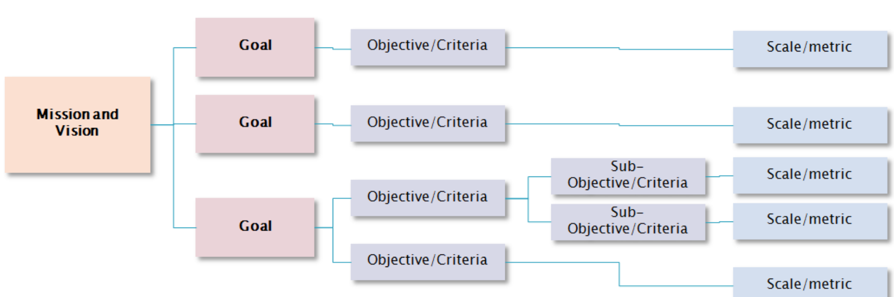

Figure 3-4 – Framework for an Objectives Hierarchy

In the MAVT process, scores are assigned to the lowest level elements in the hierarchy. These scores are then aggregated using the weighting on each score and summing the components. This aggregation provides a structured framework to bring together different considerations and perspectives of the decision makers. Furthermore, these differences can then be isolated, analyzed, and more effectively communicated through this framework.

3.2.5. Software Tools for Project Prioritization

The Core Team informally evaluated a number of software tools for suitability to SHOPP project prioritization. These tools covered a wide range of feature sets, costs, deployment mechanisms, and decision analysis methods. While many of the commercial tools were packaged as web applications, open source and freely available tools were commonly packaged as standalone workstation applications or *Microsoft Excel* spreadsheets.

Open source and freely available tools were downloaded, installed, and tested to the extent possible. Commercial software tools offering a free trial version (typically 30 days and/or limited to a set of basic features) were also evaluated. A rigorous evaluation protocol was not followed. Rather, the goal was to get a reasonably good overview of the tool's functions and its ability to:

- Manage prioritization of tens to hundreds of projects.
- Establish simple as well as multiple hierarchical criteria/objectives.
- Implement different decision analysis methods and techniques.
- Support individual and group decision analysis processes for weighting and scoring.
- Carry out sensitivity analyses of weighting.
- Report results in graphical and tabular formats.

Several of the software tools evaluated are presented in this section.

3.2.5.1. Open Source Software

Two open source, standalone software tools were identified during the search – *Open Decision Maker*[9] and *Priority Estimation Tool (PriEsT)*.[10] These tools had a number of features in common, including:

- Implements the AHP method for criteria weighting and alternatives scoring.
- Developed as a cross-platform Java application installed on individual computers.
- Supports use of complex hierarchies of criteria.
- Freely available for use under the terms of *GNU General Public License version 3.0 (GPLv3)*.[11]

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[9] http://opendecisionmak.sourceforge.net/
[10] http://sourceforge.net/projects/priority/
[11] http://www.gnu.org/licenses/gpl.html

Both tools proved to be effective in carrying out prioritization problems within an AHP-based framework. Both included numerous features to perform sensitivity analysis (e.g., sliders for weighting), graphical reporting, and flexible means of data import/export (e.g., XML in *PriEsT*, ODBC connectivity in *Open Decision Maker*). Screenshots from these tools are shown in Figure 3-5 and Figure 3-6.

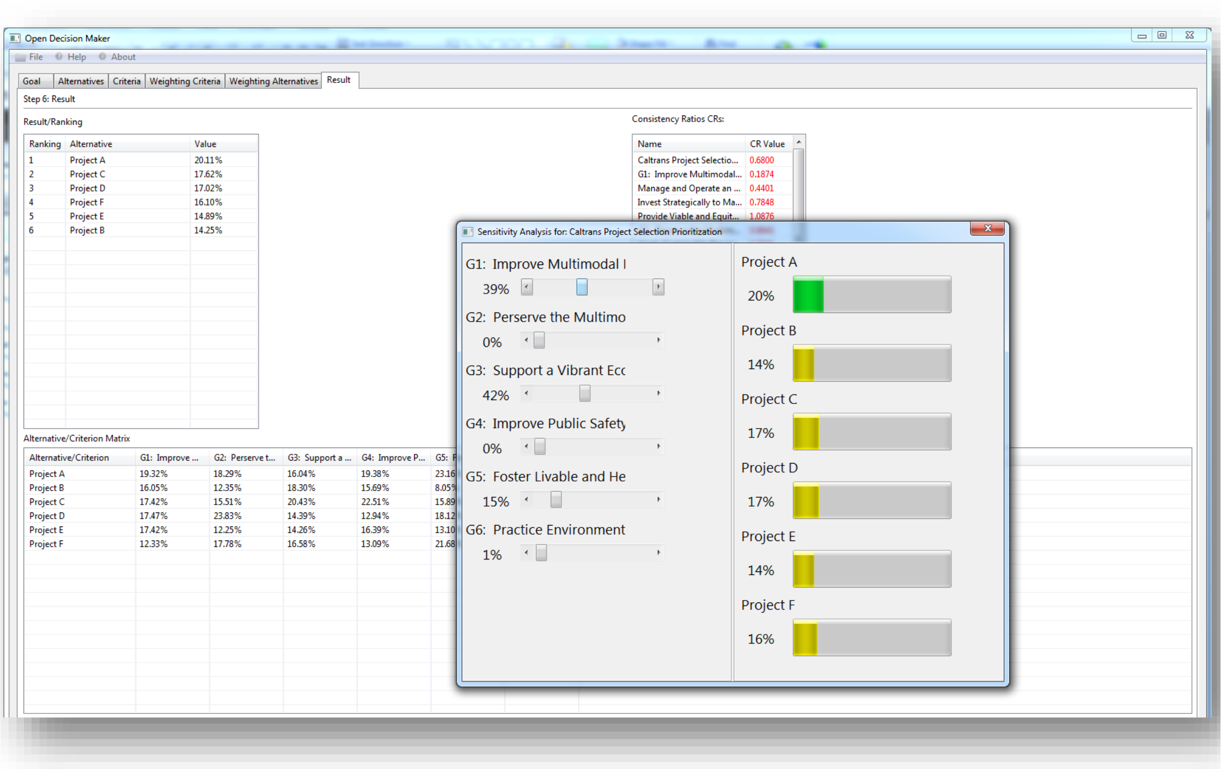

Figure 3-5 - Open Decision Maker

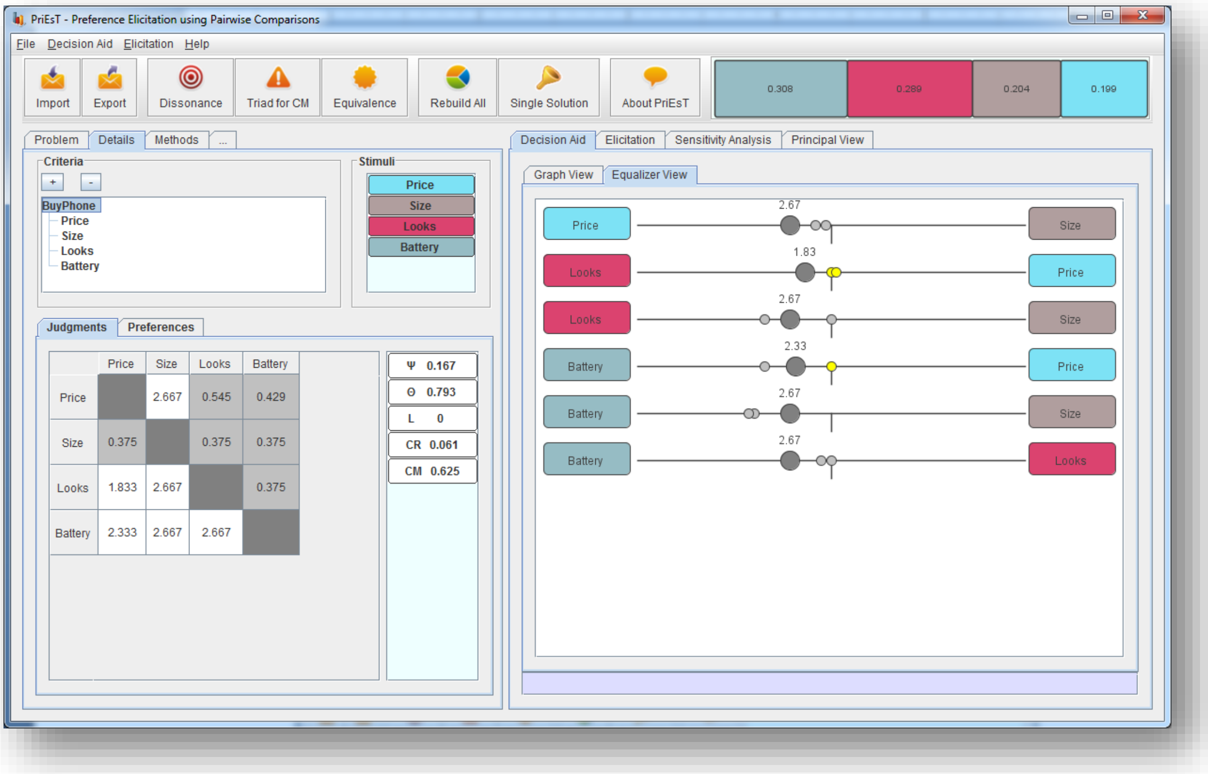

Figure 3-6 - Priority Estimation Tool (PriEsT)

3.2.5.2. Commercial Web-based Software

Several web-based commercial software tools were evaluated, including *Decision Lens*[12] (Figure 3-1), *ExpertChoice Comparion*[13] (Figure 3-8), *MakeItRational*[14] (Figure 3-9), and *TransparentChoice*[15] (Figure 3-10). All of these tools support the following features:

- Group decision-making
- AHP method for criteria weighting and alternatives scoring
- Value-based or direct scoring of alternatives
- Use of complex hierarchies of criteria
- Hosting of the application and the project data by the software vendor as a service
- Client access via web browser interface

[12] http://decisionlens.com/
[13] http://expertchoice.com/comparion/
[14] http://makeitrational.com/
[15] http://www.transparentchoice.com/

Some of the tools provided advanced features to support MAUT/MAVT-based utility and value functions for use in scoring (e.g., *Decision Lens*). Some of the tools provided a business analysis functions to consider alternative budget scenarios, phased portfolio funding, and varying portfolio scenarios (e.g., *Decision Lens, ExpertChoice*). Annual software licensing fees varied widely, ranging from hundreds of dollars to tens of thousands of dollars to over a million dollars.

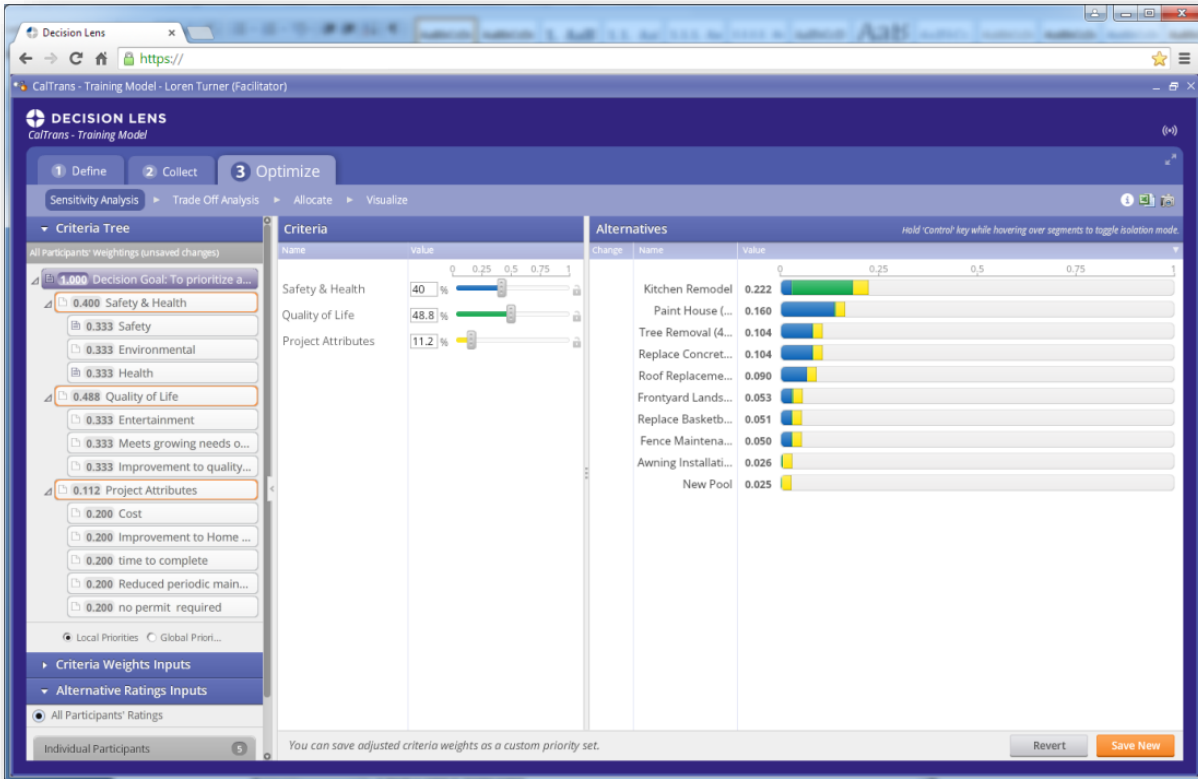

Figure 3-7 – Decision Lens

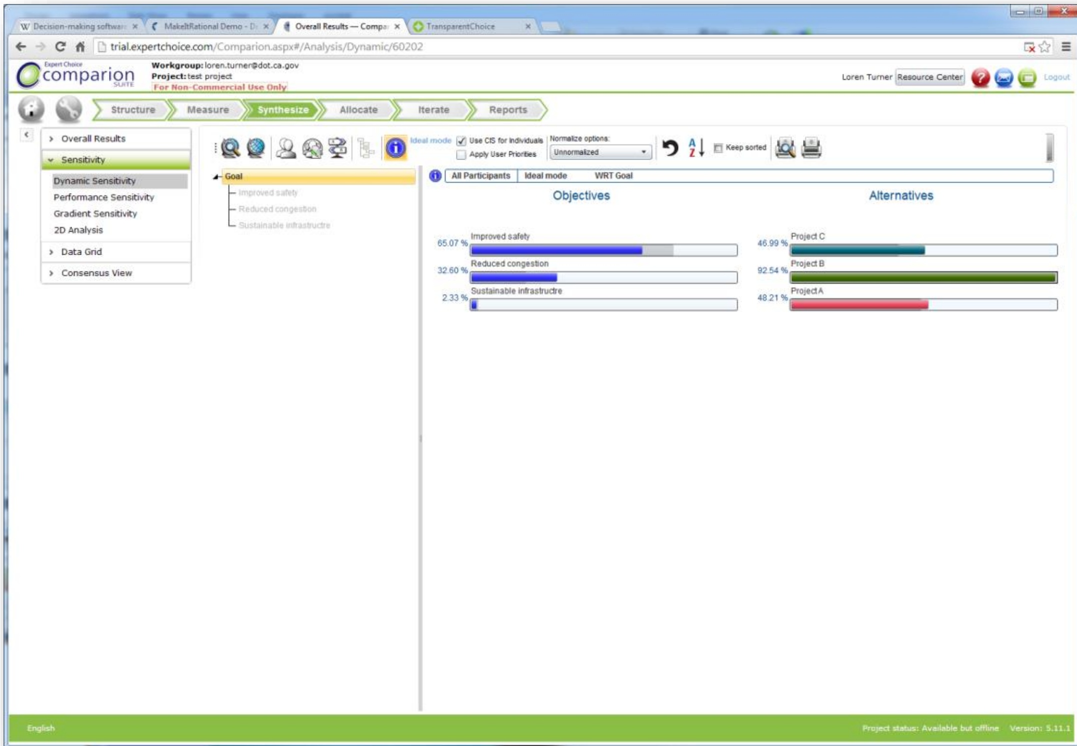

Figure 3-8 – ExpertChoice Comparion

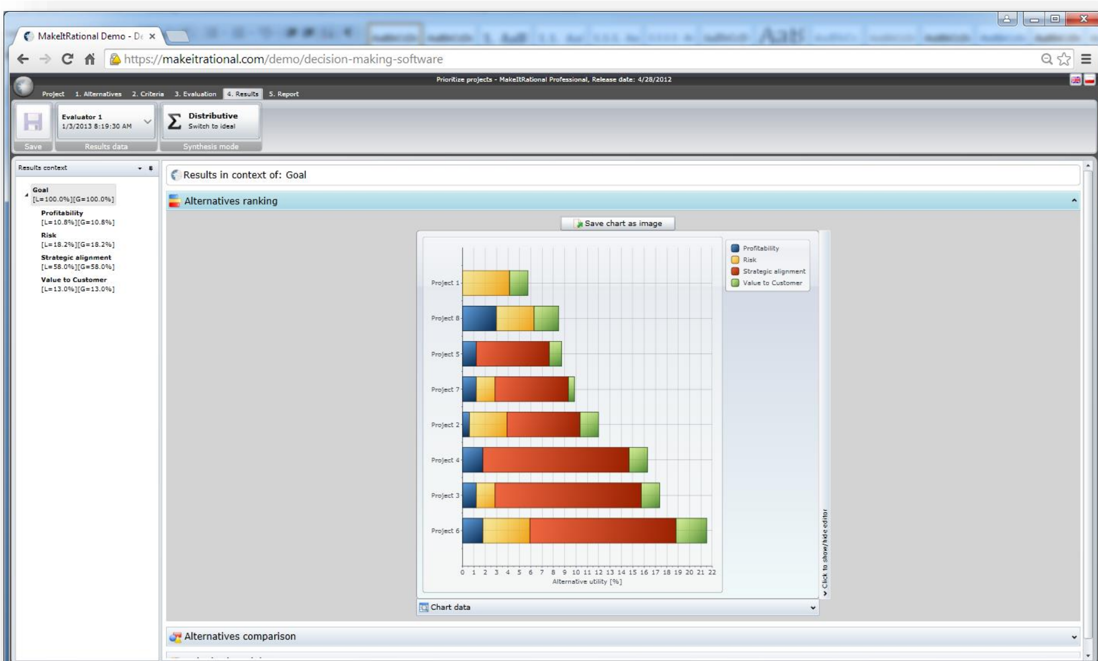

Figure 3-9 – MakeItRational

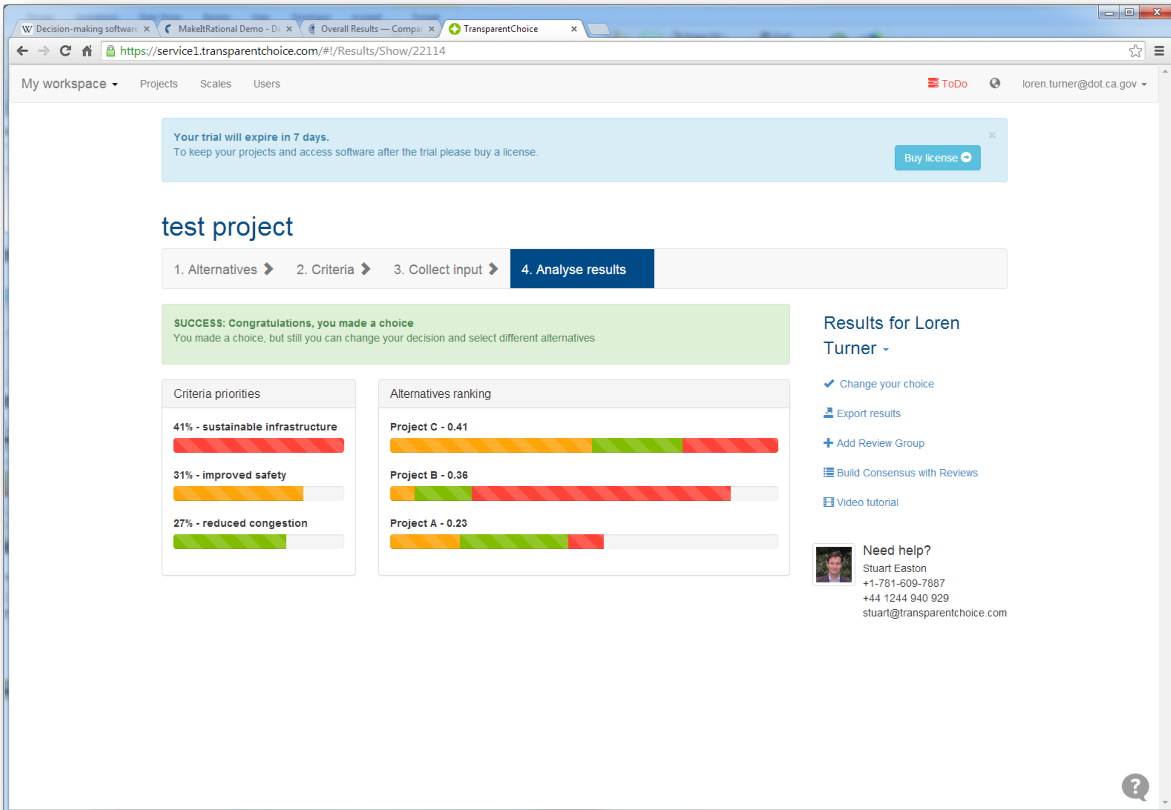

Figure 3-10 - TransparentChoice

3.2.5.3. NCHRP 08-91

A project carried out through the National Cooperative Highway Research Program (NCHRP), titled "Cross-Asset Resource Allocation and the Impact on System Performance (NCHRP 08-91)"[16] produced a *Microsoft Excel* spreadsheet (Figure 3-11) tool to carry out transportation project prioritization. The tool was developed specifically for state transportation agencies and includes a default set of objectives and scoring criteria. The tool implements a MODA approach that allows the use of AHP or direct assignment of criteria weights. The spreadsheet supports scoring of projects using complex mathematical value functions. Tradeoff analysis, alternative portfolio analysis, changes in budget, and resource allocation analysis function are also included.

[16] http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3398

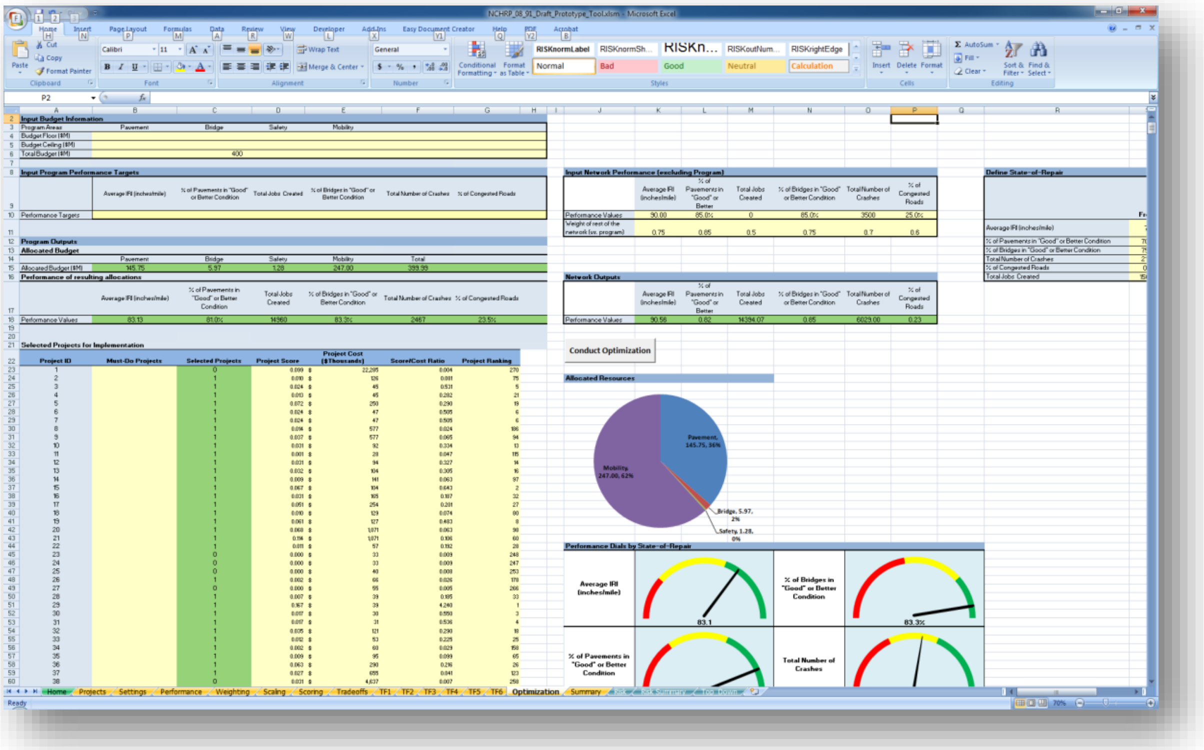

Figure 3-11 - NCHRP Project 08-91 Microsoft Excel-based Tool

3.2.5.4. Limitation of Tools That Only Support AHP

Because some of the tools only allow for alternatives evaluation using AHP, carrying out an analysis of hundreds of alternatives would prove to be onerous. In the application to the SHOPP project prioritization task, pair-wise comparisons of all pairs of projects against all criteria would be required. In order to evaluate *N* number of projects, $(N^2 – N)/2$ judgments from the decision maker are needed for each criterion (e.g., “for criteria X, Project A is strongly favored over Project B”). To quantify this with an example, 400 projects with 10 criteria would require 798,000 separate judgments from a single decision maker. As such, these tools are likely best suited for use in problems where the number of alternatives is limited or for establishing criteria weights.

3.3. SHOPP Pilot Project Workplan Development

The Core Team had originally intended to initiate a parallel research effort, through DRISI, that would be a more long-term, in-depth analysis of decision-making methodologies and tools. It was later determined that the research effort would take place after the SHOPP Pilot Project, as the Core Team would have a better understanding of the needs and scope of the research project. (See Section 7.2 - Recommendations)

One of the first activities of the Core Team was to define the scope of the project and what the expectations were for it. The team recognized that with the six month time frame we were given, there were certain things that could be accomplished, but also things that would need more time and resources. The following items were identified as feasible to accomplish within the given time frame:

- Provide early guidance on application of decision methods and tools.
- Engage subject matter experts in the development of criteria, goals, and metrics.
- Produce a draft set of objectives applicable to the SHOPP project prioritization process.
- Provide insight on pros/cons of leading decision-making methods.
- Inform executive management on the level of effort and resources required to implement future project prioritization processes.
- Raise awareness of major issues and limitations associated with alternative decision-making methods and software.
- Engage the expertise of decision analysis consultant(s).
- Enhance decision-making knowledge for a core group of Caltrans staff.

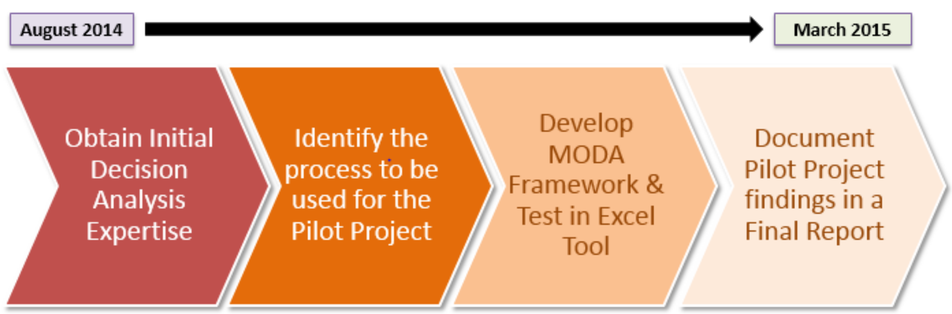

Figure 3-12 - SHOPP Pilot Project Timeline

The team also realized the need to clearly define what would not be done by this project. More importantly, it was necessary to identify that the SHOPP Pilot Project would develop a draft set of criteria, draft decision-making framework, draft *Microsoft Excel* tool, and recommendations for next steps. It is not intended to be a final solution. The following are identified as the activities the project will not accomplish:

- Replace a comprehensive research effort that carefully considers decision-making methods, tools, and applicability to Caltrans-specific use cases.
- Provide a comprehensive data integration solution for transportation asset management.
- Provide an in-depth evaluation of alternative decision-making methods and applicability to Caltrans practices.
- Establish a finalized set of criteria for SHOPP project prioritization.
- Produce a business-ready, fully-integrated decision-making software tool.

3.4. Engaging Decision Analysis Expertise

Prior to a prioritization effort, the Core Team engaged the participation of two nationally recognized experts in the field of decision analysis. Dr. Ralph Keeney and Dr. Lee Merkhofer were independently contracted to facilitate development of preliminary criteria and provide recommendations on appropriate applications of decision-making methodology. The two experts conducted a cursory assessment of Caltrans' SHOPP processes and developed preliminary recommendations for moving forward with the pilot project.

3.4.1. Consultation with Dr. Ralph Keeney

Dr. Ralph Keeney, assisted by Dr. Johannes Siebert, conducted a series of small meetings on September 22, 2014, including an initial meeting with the Core Team and key stakeholders. Three additional meetings were conducted over the course of the day that included members from the Executive Board and the California Transportation Commission. Dr. Keeney's approach was to gather background information about the current SHOPP project prioritization process, interview key executives about overarching priorities and goals for the envisioned process, synthesize findings, and provide direction to Caltrans on moving forward with the development of a process. A final report was produced, documenting observations and recommendations and is included in the Appendix.

3.4.2. Workshop Facilitated by Dr. Lee Merkhofer

Dr. Lee Merkhofer conducted a day-long workshop on September 26, 2014, that included the Core Team and SHOPP Program Managers. Key executives participated during an hour-long session in the afternoon. Dr. Merkhofer's approach was to engage a broad group of stakeholders over the course of the day to raise awareness on the basic principles of decision analysis and project prioritization and begin to develop a generalized framework applicable to the SHOPP process. The workshop resulted in the development of a preliminary objectives hierarchy, a charter, and recommendations, summarized in a series of presentation slides included in the Appendix.

3.4.3. Key Findings and Outcomes

Significant observations and themes, common to both the Keeney and Merkhofer findings, are summarized as follows:

- The existing SHOPP project prioritization criteria (based on program priorities) and the current draft set of criteria under consideration (based on the new Caltrans' mission, vision, goals, objectives, and the draft California Transportation Plan (CTP) 2040)[17] are not consistent with key principles of a Multi-Objective Decision Analysis (MODA) framework.
- The recommended MODA approach differs significantly from the current SHOPP project prioritization processes in the way in which criteria are identified, and in the treatment of

[17] http://www.dot.ca.gov/hq/tpp/californiatransportationplan2040/index.shtml

project value and cost. The concept of "value" is central to the proposed process, requiring that all aspects of the decision-making (e.g., establishing criteria, weighting, etc.) tie back to value.

- A MODA framework makes an important distinction between "means" criteria and "fundamental" criteria. Fundamental criteria represent core organizational values, whereas means criteria describe how to achieve them. (For example, "maximize seat belt use" is a means criteria, whereas "minimize injuries from automobile crashes" is a fundamental criteria.) The draft SHOPP criteria are predominantly means criteria. The use of means criteria in decision-making models leads to mathematical inconsistencies and bias in the results.
- Alternative project prioritization methods that require a comparison of one criterion to another (i.e., using pair-wise comparisons) without consideration of the impact on value can lead to ambiguity in establishing a logical theoretical basis for the prioritization task.
- A criterion's "weight" should not be interpreted as a criterion's "importance" in a MODA framework. Rather, a specific interval of change in one criterion compared with an interval of change in another criterion is used to establish the relative weight between criterion.
- Two alternative straw-man criteria hierarchies have been proposed. Dr. Keeney has proposed a subset of the existing Caltrans goals and objectives. In contrast, Dr. Merkhofer has proposed a different set of top-level criteria and using "cross-walks" to tie the hierarchy back to Caltrans' goals.

3.4.4. Recommendations on Draft Objectives Hierarchies

Dr. Keeney and Dr. Merkhofer offered recommendations for starting points for developing objectives hierarchies. Figure 3-13 and Figure 3-14 represent the team's interpretations of these objectives hierarchies.

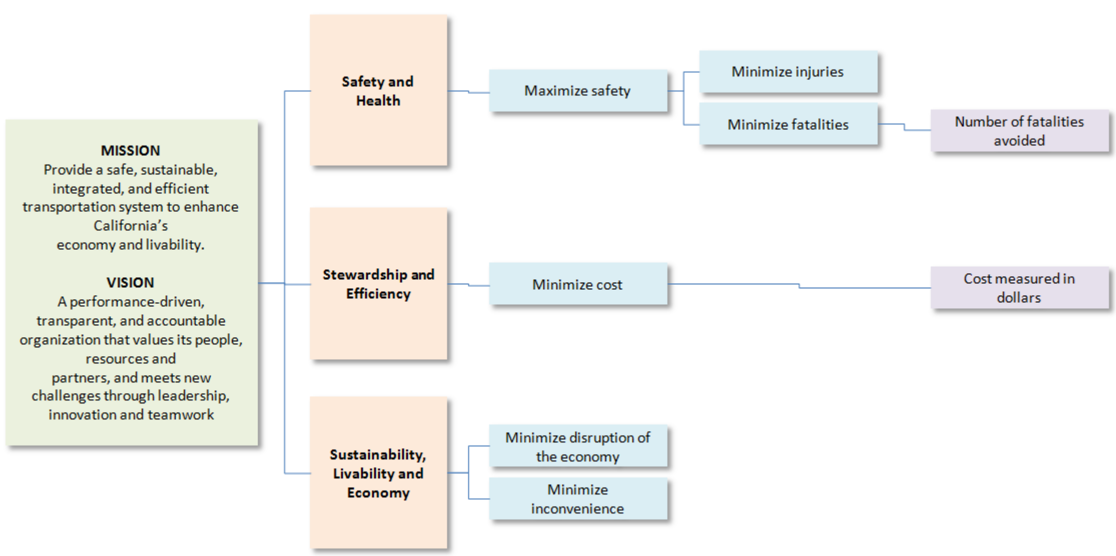

Figure 3-13 –Objectives Hierarchy Based on Dr. Keeney's Recommendations

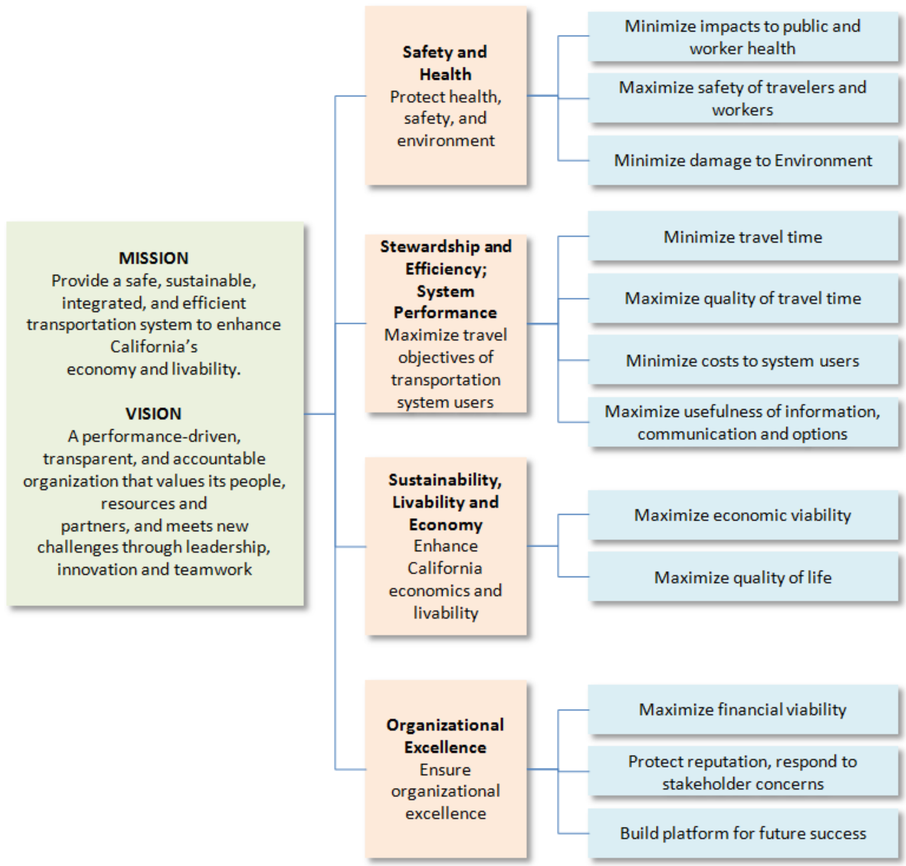

Figure 3-14 – Objectives Hierarchy Adapted from Dr. Merkhofer's Recommendations

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4. Development of a Decision Analysis Framework

The decision analysis framework is comprised of an objectives hierarchy, a value function and its sub-models, and scoring and weighting procedures. Collectively, these components are used to calculate a project's value. The project's value-to-cost ratio is then used to determine its priority relative to other projects. This framework is presented in this section.

4.1. Objectives Hierarchy

The Core Team developed an objectives hierarchy representing the Department's fundamental objectives, sub-objectives, and the relationships to Department values and data sources. The Department's current mission, vision, and goals statement[18] served as the starting point. From this, a set of fundamental objectives and sub-objectives were identified. These objectives were compiled by the Core Team and were based on early guidance provided by two decision analysis experts, Dr. Keeney and Dr. Merkhofer. The Appendix contains initial recommendations from Dr. Keeney in September 2014 and Dr. Merkhofer in October 2014. Based on a subsequent review by Dr. Merkhofer in February 2015 the objectives hierarchy was modified as presented in Figure 4-1.

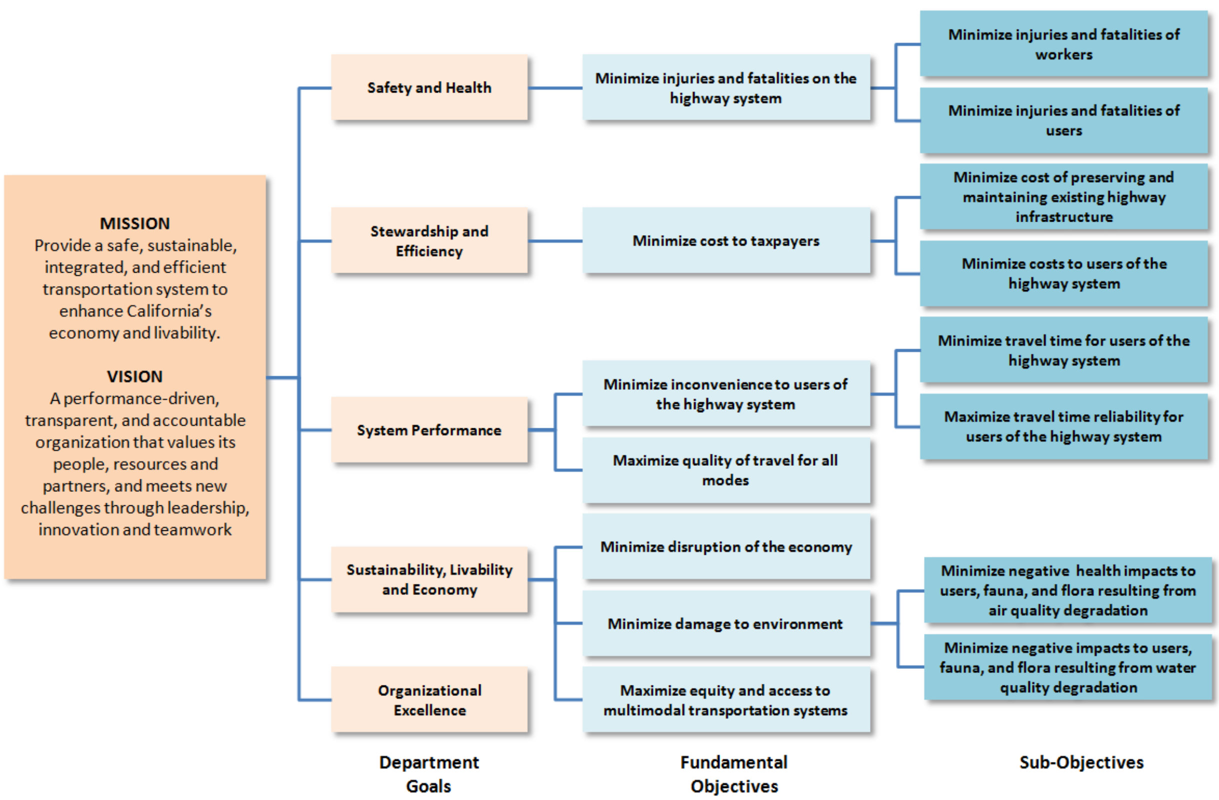


Figure 4-1 - Objectives Hierarchy

[18] http://www.dot.ca.gov/hq/paffairs/about/mission.htm

The generalized objectives hierarchy, shown in Figure 4-1, shows the fundamental objectives and sub-objectives as well as their alignment to the Department's mission, vision, and goals. It is important to note that the Organizational Excellence Goal does not have any fundamental objectives. This was based on recommendations by Dr. Ralph Keeney. His final report states that the Organizational Excellence Goal is "influenced more by the implications of the totality of Caltrans actions than by the selection of specific projects."

4.1.1. Safety and Health Objectives

The Department established the Safety and Health goal that states: "Provide a safe transportation system for workers and users and promote health through active transportation and reduced pollution in communities." Key strategic objectives are as follows:

- Zero Worker Fatalities.
- Reduce user fatalities and injuries by adopting a "Toward Zero Deaths" practice.
- Promote community health through active transportation and reduced pollution in communities.

One fundamental and two sub-objectives were identified, as shown in Figure 4-2.

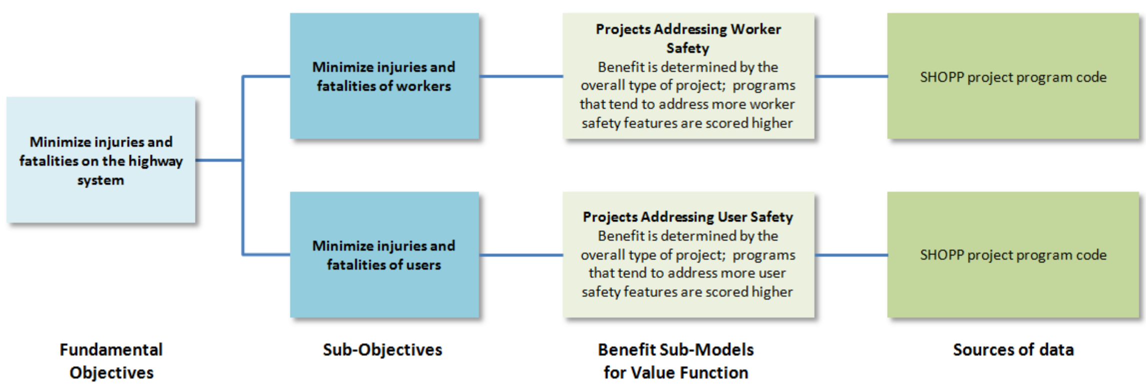


Figure 4-2 - Safety and Health Objectives

4.1.2. Stewardship and Efficiency Objectives

The Department established the Stewardship and Efficiency goal that states: "Money counts. Responsibly manage California's transportation-related assets." Key strategic objectives are as follows:

- Effectively manage transportation assets by implementing the asset management plan, embracing a fix-it-first philosophy.
- Efficiently deliver projects and services on time and on budget.

One fundamental and two sub-objectives were identified, as shown in Figure 4-3:

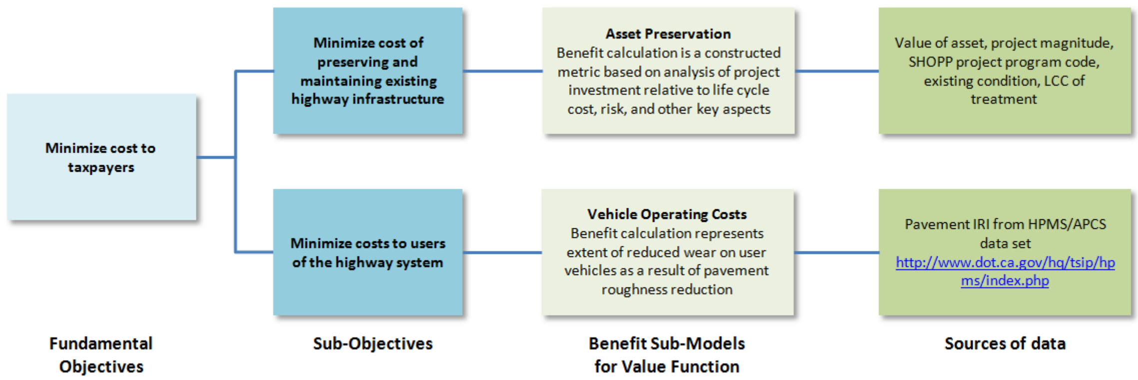


Figure 4-3 - Stewardship and Efficiency Objectives

4.1.3. System Performance Objectives

The Department established the System Performance goal that states: “Utilize leadership, collaboration and strategic partnerships to develop an integrated transportation system that provides reliable and accessible mobility for travelers.” Key strategic objectives are as follows:

- Improve travel time reliability for all modes.
- Reduce peak period travel times and delay for all modes through intelligent transportation systems, operational strategies, demand management, and land use/ transportation integration.
- Improve integration and operation of the transportation system.

Two fundamental and two sub-objectives were identified, as shown in Figure 4-4.

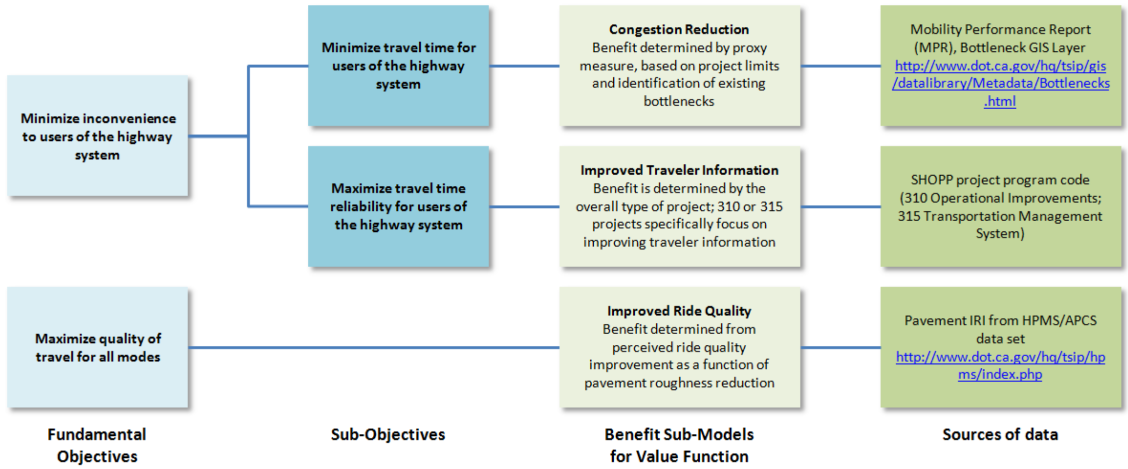


Figure 4-4 - System Performance Objectives

4.1.4. Sustainability, Livability and Economy Objectives

The Department established the Sustainability, Livability and Economy goal to "make long-lasting, smart mobility decisions that improve the environment, support a vibrant economy, and build communities, not sprawl." Key strategic objectives are as follows:

- PEOPLE: Improve the quality of life for all Californians by providing mobility choice, increasing accessibility to all modes of transportation and creating transportation corridors not only for conveyance of people, goods, and services, but also as livable public spaces.
- PLANET: Reduce environmental impacts from the transportation system with emphasis on supporting a statewide reduction of greenhouse gas emissions to achieve 80% below 1990 levels by 2050.
- PROSPERITY: Improve economic prosperity of the State and local communities through a resilient and integrated transportation system.

Three fundamental and two sub-objectives were identified, as shown in Figure 4-5.

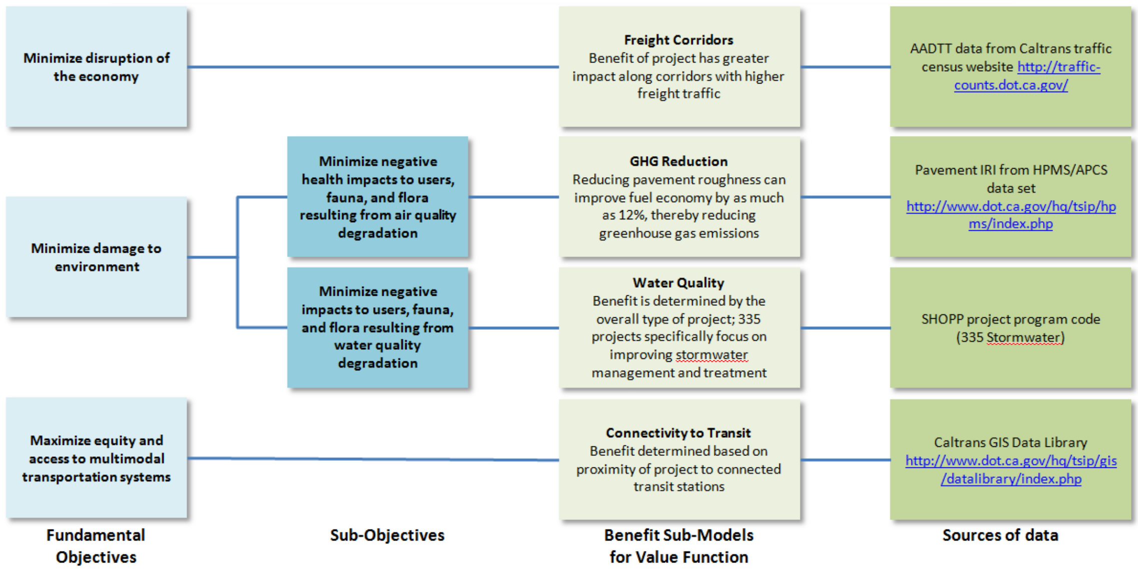


Figure 4-5 - Sustainability, Livability, and Economy Objectives

4.2. Calculation Framework

4.2.1. Value Function

A project's overall value, or benefit, is determined through the aggregation of benefits derived from benefit sub-models associated with each objective. In the calculation framework, shown in Figure 4-6, each objective or sub-objective has a sub-model that is used to determine a score. Those scores are multiplied by a weight, and the sum of the weighted scores are then added to produce the "project value." The project value is divided by the project cost to produce to "project value-to-cost ratio," the key metric used to in project prioritization. Details of scoring and weighting are described in more detail later in this report. (See Section 4.5 Weighting and Scoring)

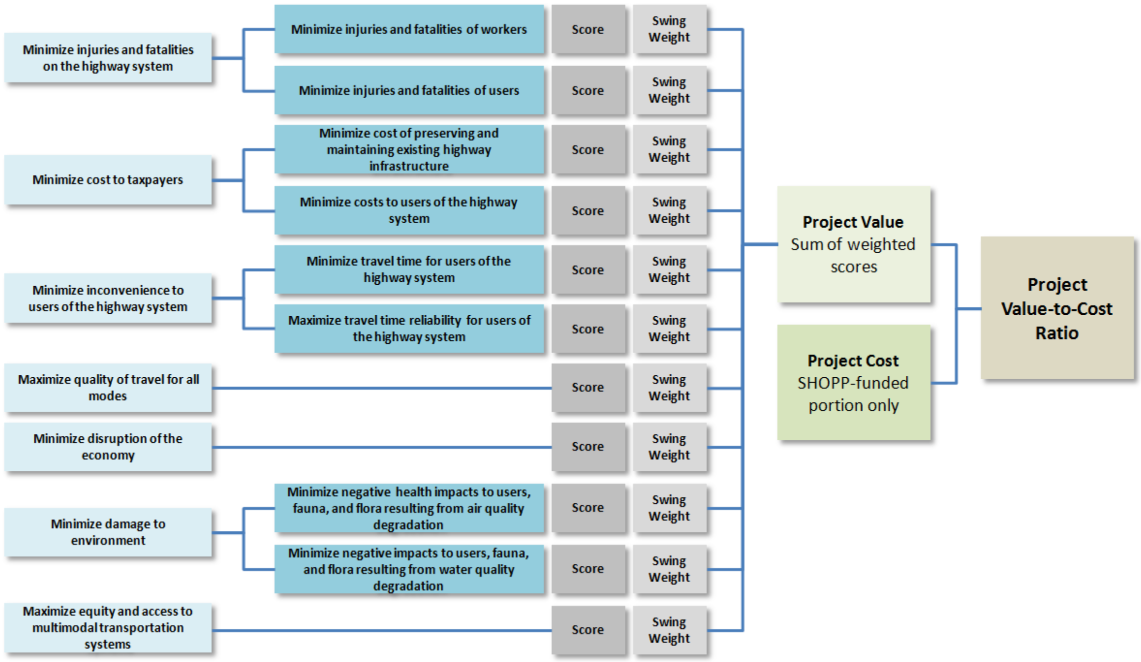


Figure 4-6 - Value Function Calculation Framework

The value function takes the generalized form:

$$Project\ Value = (Score_1)(Weight_1) + (Score_2)(Weight_2) + \dots + (Score_n)(Weight_n)$$

$$Project\ Value\ to\ Cost\ Ratio = \frac{Project\ Value}{Project\ Cost}$$

4.3. Benefit Sub-Models

For each objective or sub-objective, a benefit sub-model is defined. These sub-models use combinations of natural metrics, proxy metrics, and constructed metrics to assign a score of 0-100 for each objective for each SHOPP project. These scores are used within the value function to determine the overall value the project provides. The calculations and data sources for 11 benefit sub-models are presented in this section.

4.3.1. Minimize Injuries and Fatalities of Workers

SHOPP projects can incorporate design features that help to mitigate worker exposure – e.g., installation of guardrails that provide barriers between workers and live traffic, use of lower maintenance landscaping that reduces worker trips to job sites, etc. In a rigorous analysis, this benefit sub-model would capture the degree to which worker safety is improved by the SHOPP project based on the condition of the project site prior to and following the completion of the project. However, due to the limited availability of data on the condition of the existing project site and the proposed project-specific improvements, a rigorous measure of the degree of improvement was not feasible within the scope of the SHOPP Pilot Project.

In the absence of a rigorous analysis, a panel of traffic safety experts was convened to explore an alternative means of assigning value to SHOPP projects based on the effectiveness in reducing worker injuries and fatalities. There was general consensus within the group that some types of SHOPP projects tend to address worker safety more than others. These judgment decisions were translated into a quantitative 0-100 scale, assigning relative value based on SHOPP program codes, as shown in Table 4-1.

Table 4-1 – Assignment of Value to Worker Safety Based on Program Codes

Program Code	Program	Worker Safety Benefit
201.015	Collision Severity Reduction	100
201.111	Bridge Scour Mitigation	0
201.113	Bridge Seismic Restoration	0
201.110	Bridge Rehabilitation	100
201.120	Roadway Rehabilitation (3R)	100
201.121	Roadway Preservation (CAPM)	0
201.122	Roadway Rehabilitation (2R)	50
201.151	Drainage System Restoration	50
201.112	Bridge Rail Replacement/Upgrade	100
201.335	Storm Water	0
201.315	Transportation Management Systems	0
201.322	Trans Permit Requirements for Bridges	0
201.150	Roadway Protective Betterment	50
201.310	Operational Improvements	0
201.240	Roadside Protection and Restoration	0
201.250	Safety Roadside Rest Area Rehabilitation	0
201.210	Roadside Rehabilitation	100
201.170	Signs and Lighting Rehabilitation	100
201.160	Relinquishments	0
201.325	Railroad at-grade Crossing	0
201.330	Hazardous Waste Mitigation	0
201.352	Maintenance Facilities	100
201.351	Equipment Facilities	100
201.353	Office Buildings	100
201.260	New Safety Roadside Rest Areas	0

The calculation to estimate the value provided by the SHOPP project towards worker safety is as follows:

Table 4-2 - Calculation Steps for Minimize Injuries and Fatalities of Workers

Step	Description
1	**Identify the Benefit Associated with Worker Safety** Using the SHOPP project's program code, determine the associated worker safety benefit metric from Table 4-1.
2	**Calculate Scaling Factors** Two separate scaling factors are used that take into consideration (1) exposure to traffic, and (2) size of the project. The combination of these factors is used to scale how much benefit the project contributes to the system relative to other projects. The assumption is that larger projects that expose workers to higher traffic volumes have the greater potential to bring safety benefits. The traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4. The project magnitude scaling factor, $SF_{project\ magnitude}$, is determined from the relative asset worth in dollars. The details of the determination of that factor are contained in Section 4.4. These two scaling factors are weighted based on an assumed contribution to scaling. For the purpose of the SHOPP pilot project, the weights were initially set at 80% for traffic volume exposure and 20% for project magnitude. $$SF_{total} = (0.8)SF_{traffic\ volume} + (0.2)SF_{project\ magnitude}$$
3	**Scoring** The combined scaling factor and the safety benefit score is used to calculate a final score, as follows: $$Benefit = (SF_{total}) \times (Worker\ Safety\ Benefit)$$

The benefit sub-model used for the SHOPP pilot project carries significant limitations in that it does not adequately account for the specific types or scope of improvements in the projects. The calculation relies on inference of relative levels of benefit between project categories based on judgment and experience from prior projects.

An improvement to the calculation would be to use the "Safety Review" as a means to capture specific safety related details about the project. The Safety Review is a formal process mandated by policy in the

Highway Design Manual, 6th Edition, Section 110.8, "Safety Reviews."[19] The policy states that "all projects must be reviewed by the District Safety Review Committee prior to approval of the appropriate project initiation document" and that "safety concepts that are identified during these safety reviews which directly limit the exposure of employees to vehicular and bicycle traffic shall be incorporated into the project unless deletion is approved by the District Director." The Safety Review includes qualitative and/or quantitative safety considerations of items, such as:

- Exposure of employees to vehicular and bicycle traffic
- Traffic control plans
- Transportation Management Plans
- Traversability of roadsides
- Elimination or other appropriate treatment of fixed objects
- Susceptibility to wrong-way moves
- Safety of construction and maintenance personnel
- Sight distance
- ADA design
- Guardrail
- Run off road concerns
- Superelevation, etc.
- Roadside management and maintenance reduction
- Access to facilities from off of the freeway
- Maintenance vehicle pull-out locations

[19] http://www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp0100.pdf

4.3.2. Minimize Injuries and Fatalities of Users

Similar to the sub-model for worker safety, this sub-model is intended to capture the degree to which the safety of the travelling public is improved by the SHOPP project. Many projects incorporate design features that reduce the incidence of traffic collisions as well as mitigate the severity of injuries when they do occur. These include relatively modest improvements (e.g., the installation of rumble strips, lighting, traffic signals, etc.) or more extensive work (e.g., new truck climbing lanes on two-lane highways).

Under current federal requirements, a significant portion of the SHOPP funding is mandated to be used on safety projects through the Federal Highway Administration's (FHWA) Highway Safety Improvement Program (HSIP).[20] Under the HSIP rules "safety projects" conform to specific criteria and are characterized by the Traffic Safety Index (SI),[21] a calculated value that factors in historic accident data at the site and anticipated reduction in accidents, their severity, and costs as a result of the project's improvements. Projects having an SI value greater than 200 are automatically funded through the SHOPP 201.010 Program.

There are SHOPP projects that directly address safety of the travelling public; however, they do not meet the minimum criteria of having a SI>200 per HSIP. These projects are referred to as "Collision Severity Reduction Improvements" projects and fall under the SHOPP 201.015 Program. Types of work can include, new or upgraded guardrails and crash cushions, school zone signals, or rumble strips.

Due to the limited availability of data on the condition of the existing project site and the proposed project-specific improvements, a rigorous measure of the degree of improvement was not feasible within the scope of the SHOPP Pilot Project. In the absence of this data, a proxy measure is used – a qualitative assessment by Safety Subject Matter Experts to estimate the probability to which a project, within each program, would contribute user safety improvements to the system. This assessment was conducted in a consensus forum by the Safety Subject Matter Experts on February 12, 2015.

[20] http://safety.fhwa.dot.gov/hsip/

[21] http://www.dot.ca.gov/hq/LocalPrograms/HSIP/HSIPSIcalc&Instructions.pdf

A score is assigned for each SHOPP project based on a qualitative assessment by the Safety Subject Matter Experts, as follows:

Table 4-3– Assignment of Value to User Safety Based on Program Codes

Program Code	Program	User Safety Benefit
201.015	Collision Severity Reduction	100
201.111	Bridge Scour Mitigation*	100
201.113	Bridge Seismic Restoration*	100
201.110	Bridge Rehabilitation	100
201.120	Roadway Rehabilitation (3R)	100
201.121	Roadway Preservation (CAPM)	0
201.122	Roadway Rehabilitation (2R)	50
201.151	Drainage System Restoration	0
201.112	Bridge Rail Replacement/Upgrade	100
201.335	Storm Water	0
201.315	Transportation Management Systems	30
201.322	Trans Permit Requirements for Bridges	0
201.150	Roadway Protective Betterment	50
201.310	Operational Improvements	70
201.240	Roadside Protection and Restoration	0
201.250	Safety Roadside Rest Area Rehabilitation	40
201.210	Roadside Rehabilitation	0
201.170	Signs and Lighting Rehabilitation	50
201.160	Relinquishments	0
201.325	Railroad at-grade Crossing	100
201.330	Hazardous Waste Mitigation	0
201.352	Maintenance Facilities	0
201.351	Equipment Facilities	0
201.353	Office Buildings	0
201.260	New Safety Roadside Rest Areas	70

* These values were initially set to "0" and the analysis results used to derive conclusions presented in this report. These values were changed to "100" during the report review process. However, the impacts on the overall results and findings were not found to be significant.

The calculation to estimate the value provided by the SHOPP project towards user safety is as follows:

Table 4-4 - Calculation Steps

"Minimize Injuries and Fatalities of Users"

Step	Description
1	**Identify the Benefit Associated with User Safety** Using the SHOPP project's program code, determine the associated u safety benefit metric from Table 4-3.
2	**Calculate Scaling Factors** Two separate scaling factors are used that take into consideration (1) exposure to traffic, and (2) size of the project. The combination of these factors is used to scale how much benefit the project contributes to the system relative to other projects. The assumption is that larger projects that expose workers to higher traffic volumes have the greater potential to bring safety benefits. The traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4. The project magnitude scaling factor, $SF_{project\ magnitude}$, is determined from the relative asset worth in dollars. The details of the determination of that factor are contained in Section 4.4. These two scaling factors are weighted based on an assumed contribution to scaling. For the purpose of the SHOPP pilot project, the weights were initially set at 80% for traffic volume exposure and 20% for project magnitude. $SF_{total} = (0.8)SF_{traffic\ volume} + (0.2)SF_{project\ magnitude}$
3	**Scoring** The combined scaling factor and the safety benefit score is used to calculate a final score, as follows: $Benefit = (SF_{total}) \times (User\ Safety\ Benefit)$

This value function sub-model carries significant limitations in that the function is not based on actual safety elements each project contributes. Potential improvements to this value function are as follows:

- Capture the types and scope of anticipated improvements. For example, this could be a checklist that indicates the types of safety improvements included.
- If possible, identify an appropriate measure that would indicate the degree to which safety is improved, collisions are avoided, severity of accidents reduced, etc.

4.3.3. Minimize Cost of Preserving and Maintaining Existing Highway Infrastructure

Preservation of existing highway infrastructure assets is a key principle driving the SHOPP project selection process. As noted in the 2014 SHOPP Report,[22] the SHOPP is a program of projects "that have the purpose of collision reduction, restoring damaged roadways, bridge preservation, roadway preservation, roadside preservation, mobility enhancement, and preservation of other transportation facilities related to the State Highway System."

The intent of this value function is to assign a benefit score based on a project's merit to preserve existing infrastructure assets with cost-effective solutions. This benefit calculation is a constructed metric that attempts to capture the variability of a few components: (A) the degree to which the project reduces the need for future maintenance, (B) the existing condition of the asset, and (C) the consequence to the traveler if the asset fails as a result of deferred maintenance. The primary focus of the benefit calculation is on bridge and pavement assets, as they constitute the vast majority of the built highway infrastructure. However, consideration is given to other key assets, such as culverts and elements of traffic management systems.

For purposes of the SHOPP pilot project, a relatively crude scoring logic was created to quantify the degree to which projects addressed the three components cited earlier. In this calculation framework, each project is evaluated for its effectiveness to address asset preservation goals resulting in a score of 1, 2, or 3, as shown in Table 4-5.

Table 4-5 - Asset Preservation Calculation

	Bridge	**Pavement**	**Other Assets**
(A) Reduced Future Maintenance Intervals	Type of Bridge Project: 3 = Rehab/Replace (110) 2 = Seismic/scour or overhead (113, 111, 322)	Type of Pavement Project: 3 = 3R (120) 2 = 2R (122) 1 = CAPM (121)	Type of Work: 3 = Rehab/Replace (151) 1 = Preservation (315)
(B) Urgency Relative to Existing Asset Condition	NBI Bridge Sufficiency Rating (SR): 3 = SR < 50 replace 2 = 50 < SR < 80 rehab 1 = 80 < SR	Pavement International Roughness Index (IRI): 3 = Poor (IRI > 170) 2 = Acceptable (170 > IRI > 95) 1 = Good (95 > IRI)	For Culvert and TMS Elements: 2 = culvert projects (151) 1 = TMS elements (315), other
(C) Consequence of Asset Failure to Users	The consequence in the event of a failure of the asset is characterized as follows: 3 = High; failure of asset results in highway closure or long detour over extended time period (may include 110, 111, 113, 322). 2 = Medium; failure of asset results in short-term, partial highway capacity loss period (may include 110, 111, 113, 322; all 151). 1 = Low; failure of asset does not significantly impact highway capacity (all 120, 121, 122, 315).		

"Reduced Future Maintenance Intervals" is scored based on the type of work being performed. For example, pavement projects that replace existing pavements with new pavements (i.e., "3R") are

[22] http://www.dot.ca.gov/hq/transprog/SHOPP/2014_SHOPP/2014_SHOPP_as_approved_by_the_CTC.pdf

expected to last longer and require less maintenance resources for a significant time period. However, these more extensive treatments can cost considerably more. The higher score for a "3R" versus a "CAPM" reflects this general logic. The higher score, when combined with other measures in the framework, will ultimately lead to a higher benefit calculation but will be offset by a higher cost.

"Urgency Relative to Existing Asset Condition" reflects the condition of the existing asset and a level of urgency to the work. For bridges, the "sufficiency rating" and corresponding thresholds for bridge replacement and rehabilitation from the FHWA's National Bridge Inventory (NBI)[23] are used. For pavements, the FHWA's Highway Performance Monitoring System (HPMS)[24] thresholds for "poor," "acceptable," and "good" are used.

"Consequence of Asset Failure to Users" attempts to capture risk. If the asset were to experience a failure as a result of deferred maintenance, the impact to the traveling public could span the range from a complete loss of functionality to very little impact. For example, the loss of service for a bridge at a river crossing could result in hundreds of miles in a detour. For the consequence of a bridge detour to be considered "high," the detour length is more than 20 times the length of the bridge. By contrast, the failure of traffic loop detectors might have relatively little impact on travelers.

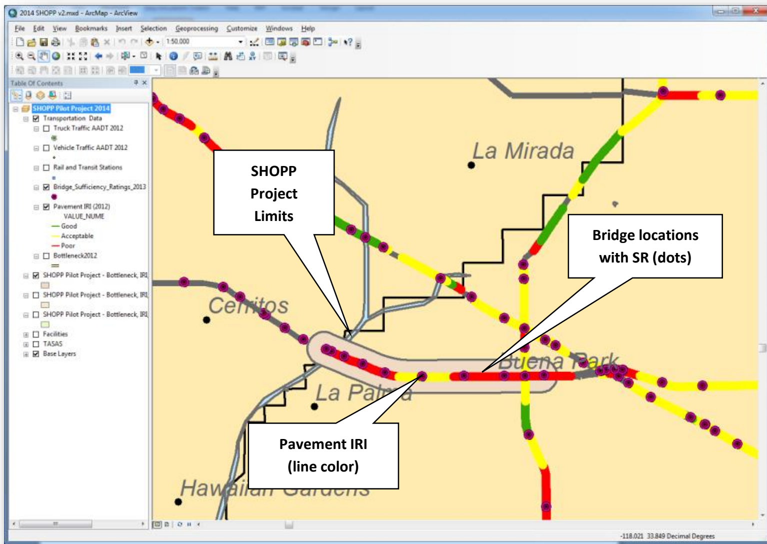
The calculation to estimate the asset preservation benefit provided by the SHOPP project is as follows:

Table 4-6 - Calculation Steps

"Minimize Cost of Preserving and Maintaining Existing Highway Infrastructure"

Step	Description
1	**Calculate Score for "Reduced Future Maintenance Intervals"** Using the SHOPP project's program code, determine the score (1-3) associated with "Reduced Future Maintenance Intervals" from Table 4-5.
2	**Calculate Score for "Urgency Relative to Existing Asset Condition"** Using the SHOPP project's program code, determine the score (1-3) associated with "Urgency Relative to Existing Asset Condition" from Table 4-5. For bridges, obtain the Sufficiency Rating (SR) data from the FHWA's 2014 California NBI data set.[25] For pavements, obtain the International Roughness Index (IRI) data from the Highway Performance Monitoring System (HPMS).[26] Through a geo-spatial analysis, determine the maximum IRI or the minimum SR for bridges within the limits of the SHOPP project.

[23] http://www.fhwa.dot.gov/bridge/nbi.cfm
[24] http://www.fhwa.dot.gov/policyinformation/hpms.cfm
[25] http://www.fhwa.dot.gov/bridge/nbi/disclaim.cfm?nbiYear=2014/delimited&nbiState=CA14
[26] http://www.dot.ca.gov/hq/tsip/hpms/datalibrary.php

<table>
<tr><th>Step</th><th>Description</th></tr>
<tr><td></td><td>


Using GIS to determine IRI and SR parameters for SHOPP projects
</td></tr>
<tr><td>3</td><td>

Calculate Score for “Consequence of Asset Failure to Users”
Using the SHOPP project’s program code, determine the score (1-3) associated with “Consequence of Asset Failure to Users” from Table 4-5.
</td></tr>
<tr><td>4</td><td>

Calculate a Preliminary Weighted Score
Calculate a weighted score from the three scores associated with (A) Reduced Future Maintenance Intervals, (B) Urgency Relative to Existing Asset Condition, and (C) Consequence of Asset Failure to Users. For purposes of the SHOPP Pilot Project, an equal weighting is applied. The calculation of the score (normalized to a 0-100 scale) is as follows:

$$\textit{Weight of A } (W_A) = \textit{Weight of B } (W_B) = \textit{Weight of C } (W_C) = 100$$

$$\textit{Preliminary Weighted Score} = [\ (W_A)\ (Score_A) + (W_B)\ (Score_B) + (W_C)\ (Score_C)\ ] \,/\, 9$$
</td></tr>
<tr><td>5</td><td>

Calculate Scaling Factors
Two separate scaling factors are used that take into consideration (1) exposure to traffic, and (2) size of the project. The combination of these factors is used to scale how much benefit the project contributes to the system relative to other projects. The assumption is that larger projects that expose workers to higher traffic volumes have the greater potential to bring asset preservation benefits.
</td></tr>
</table>

Step	Description
	The traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4. The project magnitude scaling factor, $SF_{project\ magnitude}$, is determined from the relative asset worth in dollars. The details of the determination of that factor are contained in Section 4.4. These two scaling factors are weighted based on an assumed contribution to scaling. For the purpose of the SHOPP Pilot Project, the weights were initially set at 20% for traffic volume exposure and 80% for project magnitude. $SF_{total} = (0.2)SF_{traffic\ volume} + (0.8)SF_{project\ magnitude}$
6	**Scoring** The combined scaling factor and the preliminary weighted score are used to calculate a final score (0-100), as follows: *Benefit = (SF_{total}) x (Preliminary Weighted Score)*

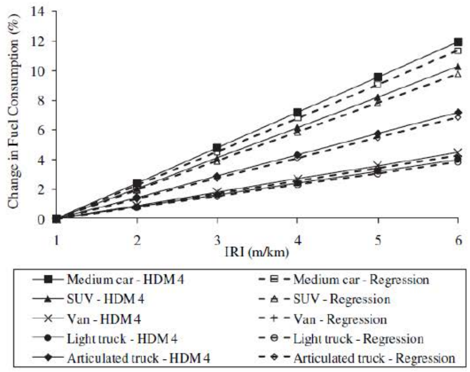
4.3.4. Minimize Costs to Users of the Highway System

Users of the highway system are subject to significant vehicle operating costs, including fuel and oil consumption, tire wear, repair and maintenance, and depreciation. These costs are largely dependent on the vehicle class and are influenced by vehicle technology, pavement-surface type, pavement condition, roadway geometrics, environment, speed of operation, and other factors. SHOPP projects have the capacity to reduce vehicle operating costs in a number of ways – reducing pavement roughness, reducing travel-time delay, etc. However, for purposes of the SHOPP Pilot Project, the benefit sub-model used is built upon the reduction in pavement roughness and the related improvements in fuel economy.

A study conducted through the National Cooperative Highway Research Program (NCHRP), titled "NCHRP 720: Estimating the Effects of Pavement Condition on Vehicle Operating Cost,"[27] described three primary areas of vehicle operating costs tied to pavement roughness: fuel efficiency, tire wear, and vehicle repair and maintenance. Numerous models have been proposed by researchers to quantify these costs. Overall, there is general consensus that fuel consumption related to pavement roughness is the largest component of cost.

[27] http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_720.pdf

The NCHRP 720 study suggests that the change in fuel consumption can be as much as 12% for an IRI reduction from 6 m/km (380 in/mi) to 1 m/km (63.4 in/mi) for some vehicle classes, as shown in Figure 4-7.



(b) Calibrated HDM 4 Model

1 m/km = 63.4 in./mi

Speed	Vehicle Class	Calibrated HDM 4 model						Current HDM 4 model					
		Base (mL/km)	Adjustment factors from the base value					Base (mL/km)	Adjustment factors from the base value				
		IRI (m/km)						IRI (m/km)					
		1	2	3	4	5	6	1	2	3	4	5	6
56 km/h (35 mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13	81.83	1.01	1.03	1.04	1.05	1.06
	Van	76.99	1.01	1.02	1.03	1.04	1.05	94.8	1.01	1.02	1.03	1.04	1.05
	SUV	78.69	1.02	1.05	1.07	1.09	1.12	96	1.01	1.02	1.02	1.03	1.04
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06	159.1	1.01	1.01	1.02	1.02	1.03
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11	425	1.01	1.02	1.03	1.04	1.04
88 km/h (55 mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13	76.60	1.01	1.03	1.04	1.05	1.06
	Van	96.98	1.01	1.02	1.03	1.04	1.05	98.04	1.01	1.02	1.03	1.04	1.05
	SUV	101.29	1.02	1.04	1.07	1.09	1.11	103.12	1.01	1.02	1.02	1.03	1.04
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05	187.06	1.01	1.01	1.02	1.02	1.03
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08	420.09	1.01	1.02	1.03	1.04	1.04
112 km/h (70 mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12	87.64	1.01	1.03	1.04	1.05	1.06
	Van	128.96	1.01	1.02	1.03	1.03	1.04	115	1.01	1.02	1.03	1.04	1.05
	SUV	140.49	1.02	1.04	1.06	1.08	1.10	124	1.01	1.02	1.02	1.03	1.04
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04	250.5	1.01	1.01	1.02	1.02	1.03
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06	584.7	1.01	1.02	1.03	1.04	1.04

$$\text{mpg} = \frac{2352}{\text{mL/km}}$$

Figure 4-7 - Change in Fuel Consumption Based on IRI

Note, for newly rehabilitated pavements, a Federal Highway Administration (FHWA) study showed that "85 percent of the test sections had an IRI value of less than 1.2 m/km (76 in/mi)" after overlay.[28]

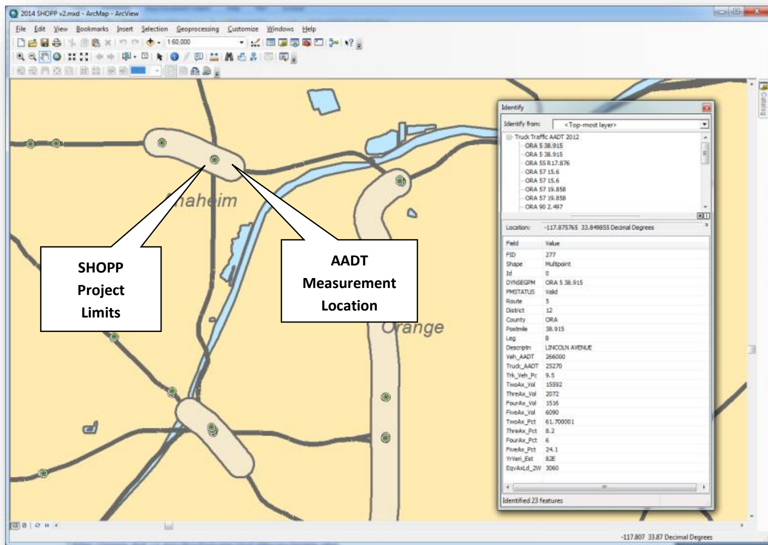
The calculation to estimate the reduction in fuel consumption is as follows:

Table 4-7 - Calculation Steps

"Minimize Costs to Users of the Highway System"

Step	Description
1	**Determine Project Length** Using the SHOPP project's postmile limits, determine the overall length of the project (L) in units of miles. Postmiles limits are converted to a statewide odometer on the Linear Reference System (LRS) in order to carry out this calculation.
2	**Determine Key Traffic Data Parameters** Through a geo-spatial analysis, determine the maximum vehicle (AADT) volume within the limits of the SHOPP project. The *Caltrans GIS Data Library*[29] is a data resource that contains a suite of authoritative Department data sets, including traffic volume data in a geo-spatial file format. This data, combined with the spatial boundaries of the SHOPP project, can be used to determine the maximum values, as shown in the figure below.

[28] FHWA Tech Brief, "Reducing Roughness in Rehabilitated Asphalt Concrete (AC) Pavements," PUBLICATION NO. FHWA-RD-98-149
http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/98149/98149.pdf
[29] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

Step	Description
	 Using GIS to determine AADT parameters for SHOPP projects
3	**Calculate the Annual Vehicle Miles Traveled (VMT_{365}) within the Limits of SHOPP Project** An annual VMT can be calculated as follows: VMT_{365} = *[AADT vehicles/day] x [Project Length, L miles] x [365 days/year]*
4	**Calculate Annual Average Fuel Cost** The annual average fuel cost for all vehicle types attributed to the limits of the SHOPP project is estimated as follows: *Fuel Cost = VMT (miles) x (23.3 miles/gallon)*[30] *x ($3.59/gallon)*[31]
5	**Calculate the Percent Reduction in Fuel Consumption** Determine the maximum IRI value within the limits of the SHOPP project. Calculate the expected reduction in IRI following pavement rehabilitation (ΔIRI) using 76 inches/mile. Calculate the change in fuel consumption due to the IRI change as follows:

[30] http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html

[31] http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_sca_a.htm

Step	Description
	$$Percent\ reduction\ in\ fuel\ consumption = \frac{12\%}{\left(317\ {}^{in}/_{mile}\right)} \Delta IRI - 2.4\%$$
6	**Calculate the Total Reduction in Fuel Costs** Multiply the percent reduction in fuel consumption by the existing fuel consumption cost to get the overall reduction in fuel consumption cost. *Total reduction fuel consumption cost = (% reduction) x (existing fuel consumption cost)*
7	**Scoring** The maximum reduction in fuel consumption cost for all SHOPP projects under consideration is used to determine a normalized benefit score on a scale of 0-100, as follows: *Benefit = 100 x (Total reduction fuel cost) / (Max reduction in fuel cost)*

4.3.5. Minimize Travel Time for Users of the Highway System

SHOPP projects can result in incremental improvements to travel time for users. In particular, areas of high traffic congestion (or “bottleneck” zones) can benefit from certain types of improvements, such as those under Program 201.310, “Operational Improvements,” or Program 201.315, “Transportation Management Systems.” To a lesser degree, reductions in pavement roughness can also contribute to travel time.

The benefit sub-model used for the SHOPP Pilot Project uses a combination of bottleneck zone locations and SHOPP project type to estimate a benefit. Bottleneck locations are identified and documented through the Mobility Performance Report,[32] one of the products of the Mobility Performance Reporting and Analysis Program (MPRAP). Caltrans collects vehicle counts and calculates speeds at all hours of the day and all days of the week in major metropolitan areas throughout California via the Caltrans Performance Measurement System (PeMS). This information helps identify congestion bottlenecks and results in more cost-effective investments to improve the performance of the State Highway System. PeMS defines a bottleneck as “a persistent and significant drop in speed between two locations on a freeway,” where there has been a drop in speed of at least 20 mph between the current detector and the detector immediately downstream. Geo-spatial data on locations of bottlenecks are available

[32] http://www.dot.ca.gov/hq/traffops/sysmgtpl/MPR/index.htm

through the Caltrans GIS Data Library.[33] This data, combined with the spatial boundaries of the SHOPP project, can be used to determine bottleneck locations, as shown in the figure below.

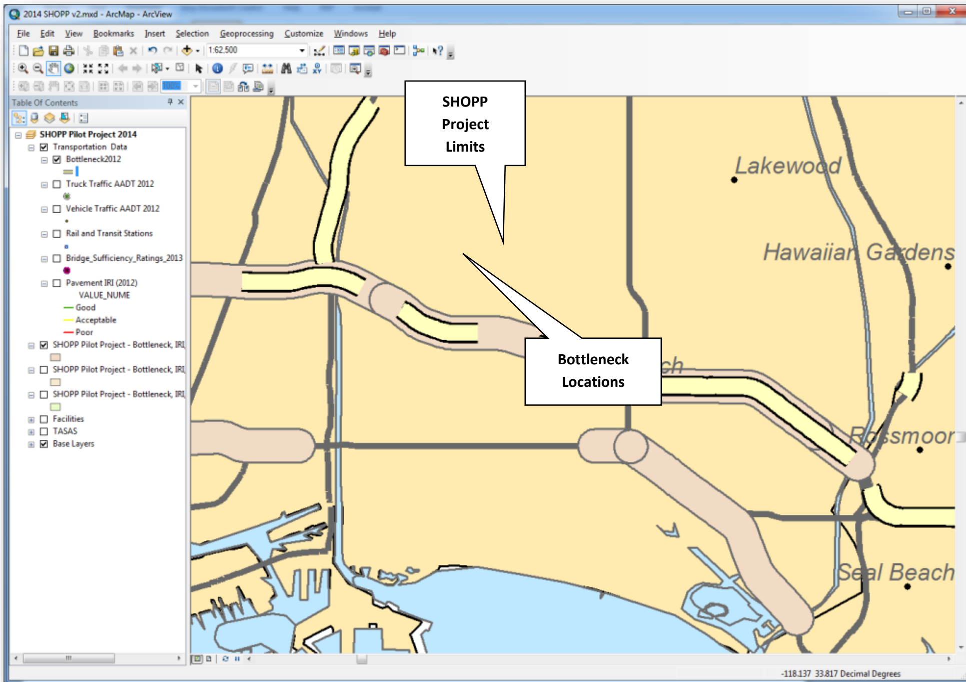


Figure 4-8 - Bottleneck Locations

[33] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

The degree to which a SHOPP project potentially improves travel time depends on the type of work, as defined by the SHOPP program code. For purposes of the pilot project, a crude scoring system was developed with input from Subject Matter Experts (SMEs) from the Division of Traffic Operations. Projects that fall within bottleneck zones are scored as follows:

Table 4-8 – Assignment of Value to Travel Time Reduction Based on Program Codes

Program Code	Program	Travel Time Benefit
201.015	Collision Severity Reduction	60
201.111	Bridge Scour Mitigation	0
201.113	Bridge Seismic Restoration	0
201.110	Bridge Rehabilitation	50
201.120	Roadway Rehabilitation (3R)	70
201.121	Roadway Preservation (CAPM)	70
201.122	Roadway Rehabilitation (2R)	70
201.151	Drainage System Restoration	50
201.112	Bridge Rail Replacement/Upgrade	0
201.335	Storm Water	50
201.315	Transportation Management Systems	90
201.322	Trans Permit Requirements for Bridges	0
201.150	Roadway Protective Betterment	0
201.310	Operational Improvements	100
201.240	Roadside Protection and Restoration	0
201.250	Safety Roadside Rest Area Rehabilitation	0
201.210	Roadside Rehabilitation	0
201.170	Signs and Lighting Rehabilitation	60
201.160	Relinquishments	0
201.325	Railroad at-grade Crossing	50
201.330	Hazardous Waste Mitigation	0
201.352	Maintenance Facilities	0
201.351	Equipment Facilities	0
201.353	Office Buildings	0
201.260	New Safety Roadside Rest Areas	0

Note, projects that don’t fall within bottleneck zones are assigned a score of 0.

The calculation to estimate the value provided by the SHOPP project towards travel time is as follows:

Table 4-9 - Calculation Steps

"Minimize Travel Time for Users of the Highway System"

Step	Description
1	**Identify the Benefit Associated with Minimizing Travel Time** Using the SHOPP project's program code, determine the associated benefit metric from Table 4-8.
2	**Identify Projects Where Bottnecks Exist** Using the bottleneck data from the Mobility Performance Report, determine if a bottleneck exists within the limits of the SHOPP project.
3	**Calculate Scaling Factor** A traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4.
4	**Scoring** The combined scaling factor and the travel time benefit score is used to calculate a final score for projects where a bottleneck is identified, as follows: $Benefit = (SF_{traffic\ volume}) \times (Travel\ Time\ Benefit)$ For projects where no bottleneck exists, a score of 0 is assigned.

4.3.6. Maximize Travel Time Reliability for Users of the Highway System

Users of the highway system can benefit from the reduction in uncertainties in travel time estimates. SHOPP projects have the potential to reduce these uncertainties, primarily through the collection and distribution of traffic information. Two categories of SHOPP projects specifically address this – Program 201.310, "Operational Improvements," or Program 201.315, "Transportation Management Systems." The benefit sub-model adopted for the SHOPP Pilot Project uses these program codes in combination with traffic volumes as a scaling factor.

The calculation to estimate the value provided by the SHOPP project towards travel time reliability is as follows:

Table 4-10 - Calculation Steps

"Maximize Travel Time Reliability for Users of the Highway System"

Step	Description
1	**Identify Projects That Address Travel Time Reliability** Based on the SHOPP program code, identify projects that are associated with Operational Improvements (201.310) or Transportation Management Systems (201.315). Projects in these programs are assigned a preliminary travel time reliability benefit score of 100. All other projects are assigned a score of 0.
2	**Calculate Scaling Factors** Two separate scaling factors are used that take into consideration (1) exposure to traffic, and (2) size of the project. The combination of these factors is used to scale how much benefit the project contributes to the system relative to other projects. The assumption is that larger projects that expose workers to higher traffic volumes have the greater potential to bring travel time benefits. The traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4. The project magnitude scaling factor, $SF_{project\ magnitude}$, is determined from the relative asset worth in dollars. The details of the determination of that factor are contained in Section 4.4. These two scaling factors are weighted based on an assumed contribution to scaling. For the purpose of the SHOPP Pilot Project, the weights were initially set at 80% for traffic volume exposure and 20% for project magnitude. $SF_{total} = (0.8)SF_{traffic\ volume} + (0.2)SF_{project\ magnitude}$
3	**Scoring** The combined scaling factor and the travel time reliability benefit score is used to calculate a final score, as follows: $Benefit = (SF_{total}) \times (Travel\ Time\ Reliability\ Benefit)$

4.3.7. Maximize Quality of Travel for all Modes

In addition to minimizing congestion, travel delays, uncertainties in travel times, and other inconveniences experienced by travelers, maximizing the quality of the travel experience is an important objective. SHOPP projects can contribute to a positive travel experience through a number of types of improvements. For example, smoother riding pavements, welcoming rest areas, enhanced landscaping, informative signage, better lighting, improvements and expansion of bike lanes and other modes of transportation.

The degree to which a SHOPP project potentially improves quality of travel depends on the type of work, as defined by the SHOPP program code. For purposes of the Pilot Project, a relatively crude scoring system was developed, as follows:

Table 4-11 - Assignment of Value of Travel Quality Improvement Based on Program Codes

Program Code	Program	Quality of Travel Benefit
201.015	Collision Severity Reduction	0
201.111	Bridge Scour Mitigation	0
201.113	Bridge Seismic Restoration	0
201.110	Bridge Rehabilitation	10
201.120	Roadway Rehabilitation (3R)	100
201.121	Roadway Preservation (CAPM)	100
201.122	Roadway Rehabilitation (2R)	100
201.151	Drainage System Restoration	0
201.112	Bridge Rail Replacement/Upgrade	0
201.335	Storm Water	0
201.315	Transportation Management Systems	50
201.322	Trans Permit Requirements for Bridges	0
201.150	Roadway Protective Betterment	20
201.310	Operational Improvements	50
201.240	Roadside Protection and Restoration	20
201.250	Safety Roadside Rest Area Rehabilitation	60
201.210	Roadside Rehabilitation	60
201.170	Signs and Lighting Rehabilitation	50
201.160	Relinquishments	0
201.325	Railroad at-grade Crossing	10
201.330	Hazardous Waste Mitigation	0
201.352	Maintenance Facilities	0
201.351	Equipment Facilities	0
201.353	Office Buildings	0
201.260	New Safety Roadside Rest Areas	60

Pavement projects are given the highest possible score as they tend to have the most significant impact of travel quality. A 2002 study by the Washington State Transportation Center (TRAC)[34] suggests that traveler driving behavior is directly influenced by the condition of the pavement as measured the International Roughness Index (IRI), a measure of the roughness of the pavement. The "Caltrans 2013 State of the Pavement Report"[35] documents the condition of pavements statewide and reports them as either "poor" (IRI>170), "acceptable" (95>IRI>170), or "good" (IRI<95). The Washington study provided empirical data to support the FHWA threshold of 170 in/mile as an upper limit for acceptable pavement. An early study by Sayers[36] in 1984 established a relationship between IRI and reduced speeds, as shown in Figure 4-9.

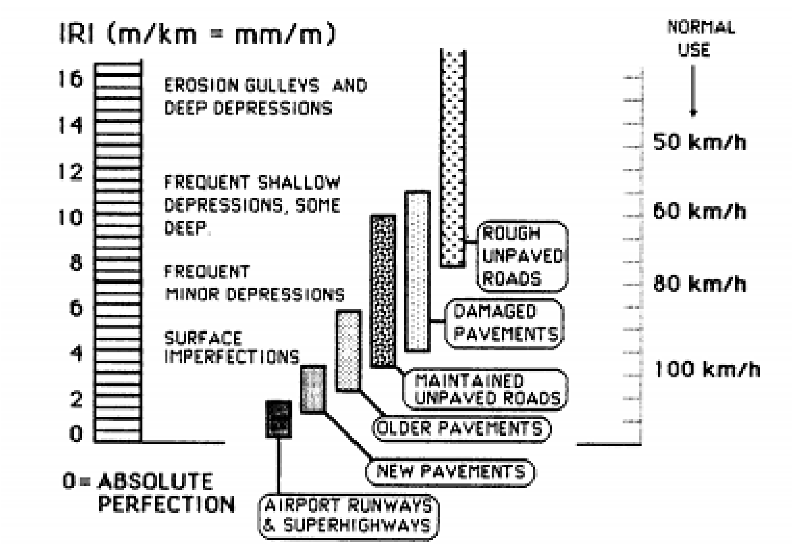


Figure 4-9 - IRI and Reduced Speeds (from Sayer 1984)

Other project types were assigned scores based on judgments by the Core Team.

[34] http://depts.washington.edu/trac/bulkdisk/pdf/538.1.pdf
[35] http://www.dot.ca.gov/hq/maint/Pavement/Pavement_Program/PDF/2013_SOP_FINAL-Dec_2013-1-24-13.pdf
[36] http://deepblue.lib.umich.edu/bitstream/handle/2027.42/3133/72764.pdf

The calculation of the benefit due to travel quality improvements is as follows:

Table 12 – Calculation Steps

"Maximize Quality of Travel for all Modes"

Step	Description
1	**Identify the Benefit Associated with Travel Quality** Using the SHOPP project's program code, determine the associated travel quality benefit metric from Table 4-11.
2	**Calculate Scaling Factor** A traffic volume scaling factor ($SF_{traffic\ volume}$) is calculated from the maximum vehicle (AADT) volume within the limits of the SHOPP project relative to all other SHOPP projects under consideration. The details of the determination of this factor are contained in Section 4.4.
3	**Scoring** The combined scaling factor and the travel quality benefit score is used to calculate a final score, as follows: $Benefit = (SF_{total}) \times (Travel\ Quality\ Benefit)$

4.3.8. Minimize Disruption of the Economy

The full economic impacts of a SHOPP project are complex and difficult to assess. There are short-term impacts realized during construction that affect regional job creation, traffic congestion, and commerce. There are longer-term economic impacts that are possible, such as changes in trucking routes resulting from efficiency improvements to specific corridors. However, these largely depend upon the type of SHOPP project work and can be difficult to quantify. For purposes of the SHOPP Pilot Project, the benefit calculation is intended to represent those realized following the completion of the project, not the economic impacts as a direct result of the construction activity.

The volume of truck traffic on the State Highway System serves as a reasonable proxy to identify freight corridors that support elevated economic activity. These corridors can be identified based on the Annual Average Daily Truck Traffic (AADTT)[37], as shown in Figure 4-10.

[37] http://traffic-counts.dot.ca.gov/

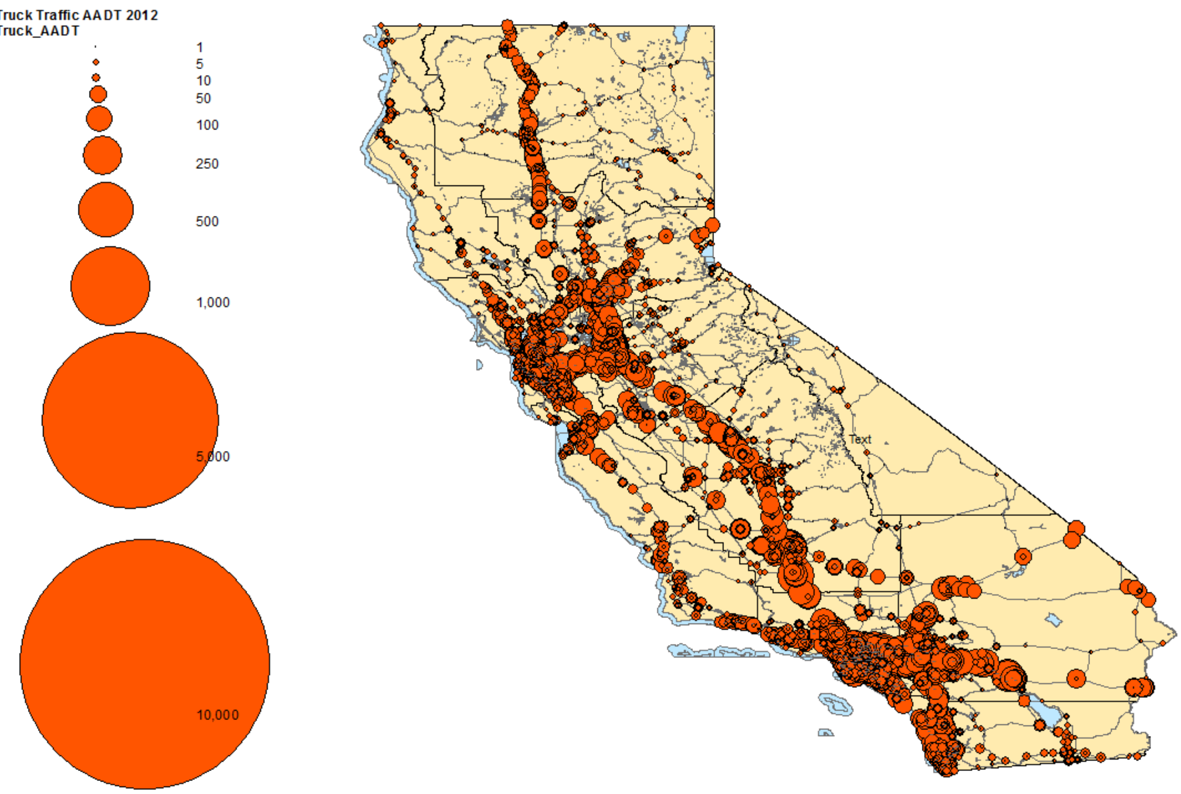


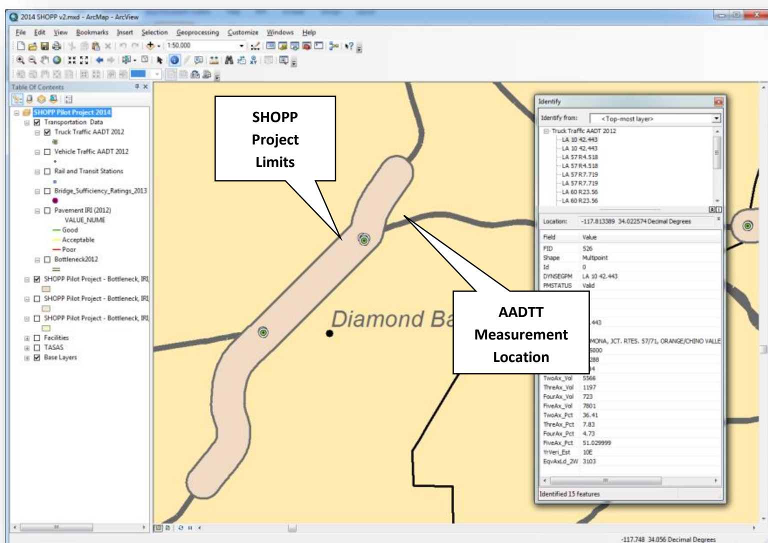
Figure 4-10 - 2012 AADTT Statewide Measurements

The benefit sub-model assigns higher value to SHOPP projects where there are higher volumes of truck traffic. The Core Team recognizes that this approach is an over-simplification of a complex set of variables and carries significant limitations as it does not differentiate projects based on the type of work carried out nor the effectiveness of the work.

The calculation to estimate economic impacts is as follows:

Table 4-13 – Calculation Steps

"Minimize Disruption of the Economy"

Step	Description
1	**Determine Key Traffic Data Parameters** Through a geo-spatial analysis, determine the maximum truck traffic (AADTT) volume within the limits of the SHOPP project. The *Caltrans GIS Data Library*[38] is a data resource that contains a suite of authoritative Department data sets, including traffic volume data in a geo-spatial file format. This data, combined with the spatial boundaries of the SHOPP project, can be used to determine the maximum values, as shown in the figure below.  **Using GIS to determine AADTT parameters for SHOPP projects**
2	**Scoring** The maximum AADTT for all SHOPP projects under consideration is used to determine a normalized benefit score on a scale of 0-100, as follows: *Benefit = 100 x (max AADTT within project limits) / (max AADTT from all SHOPP projects)*

[38] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

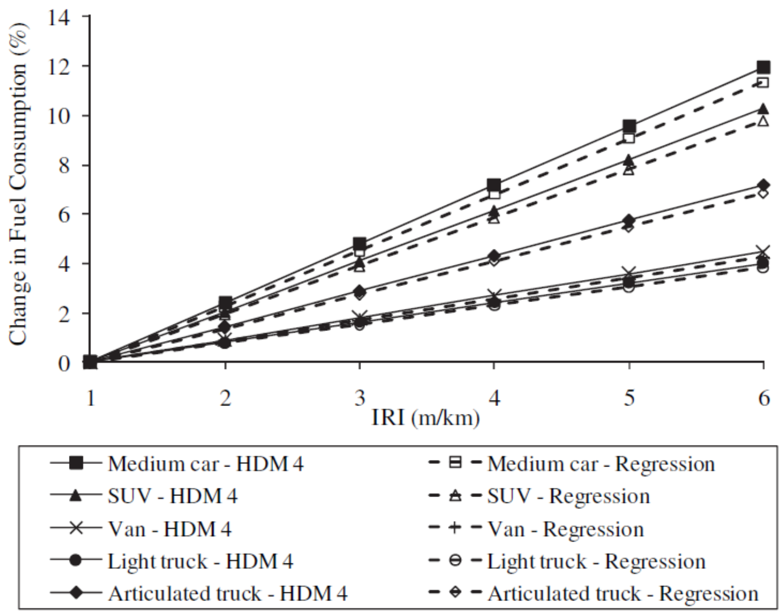
4.3.9. Minimize Negative Health Impacts to Users, Fauna, and Flora Resulting from Air Quality Degradation

Minimizing damage to the environment is achieved through reducing adverse changes to the physical conditions within the area affected by the project, including land, air, water, minerals, flora, fauna, ambient noise, and objects of historic or aesthetic significance. Two components of environmental impacts were identified for the Pilot Project: (1) the reduction of greenhouse gas emissions, and (2) impacts on water quality. This section describes the calculation that is intended to capture the degree to which the SHOPP project will reduce greenhouse gas (GHG) emissions and the subsequent impact on the environment. The benefits represent those realized following the completion of the project, not the environmental impacts as a direct result of the construction activity.

Many types of SHOPP projects can result in tangible reductions in GHG emissions. An April 2013 Caltrans report, "Caltrans Activities to Address Climate Change, Reducing Greenhouse Gas Emissions and Adapting to Impacts,"[39] estimated that a suite of Caltrans activities could reduce GHG by approximately 161,500 tons (0.16 MMT) annually. These activities include changes to materials, concrete, and pavement; roadway lighting; alternative fuels for fleet vehicles; renewable energy; building facility energy and water efficiency; and workplace commute. A 2014 study by the University of California Davis Pavement Research Center (UC-PRC) by Wang, Harvey, and Kendall, "Reducing Greenhouse Gas Emissions Through Strategic Management of Highway Pavement Roughness,"[40] suggests that the cumulative effect of improvement in pavement smoothness on California highways, quantified through the International Roughness Index (IRI), could result in up to 1.38 million metric tons (MMT) of CO_2 emissions reduction. The constitutes about 0.8% of all road traffic emissions and is roughly 10 times the amount reduction from all other Caltrans GHG efforts combined. Considering that on-road vehicle use is responsible for about a quarter of US annual GHG emissions, this reduction is substantial.

GHG emissions are assumed to be directly correlated to a reduction in fuel consumption. A study conducted by the National Cooperative Highway Research Program (NCHRP) in 2012[41] suggests that a strong linear correlation exists between fuel consumption and pavement roughness, measured using the International Roughness Index (IRI). At IRI values near 360 inches/mile (indicating "rough" ride quality) as much as a 12% increase in fuel consumption is possible as compared to an IRI approaching zero ("smooth"), as shown in Figure 4-11.

[39] http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/Caltrans_ClimateChangeRprt-Final_April_2013.pdf
[40] http://iopscience.iop.org/1748-9326/9/3/034007/pdf/1748-9326_9_3_034007.pdf
[41] NCHRP Report 720, "Estimating the Effects of Pavement Condition on Vehicle Operating Costs", 2012. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_720.pdf



(b) Calibrated HDM 4 Model

1 m/km = 63.4 in./mi

Figure 4-11 - IRI and fuel consumption

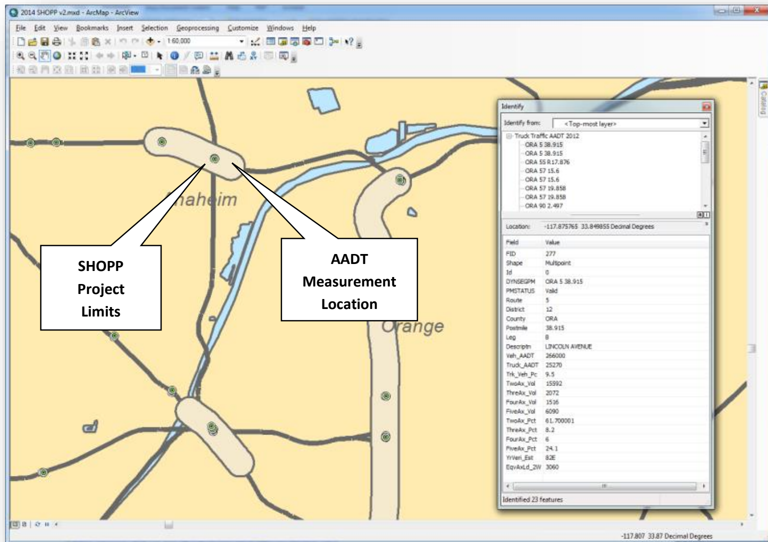
The calculation to estimate the reduction in GHG emissions is as follows:

Table 14 – Calculation Steps

"Minimize Negative Health Impacts to Users, Fauna, and Flora Resulting from Air Quality Degradation"

Step	Description
1	**Determine Project Length** Using the SHOPP project's postmile limits, determine the overall length of the project (L) in units of miles. Postmiles limits are converted to a statewide odometer on the Linear Reference System (LRS) in order to carry out this calculation.
2	**Determine Key Traffic Data Parameters** Through a geo-spatial analysis, determine the maximum vehicle (AADT) volume within the limits of the SHOPP project. The Caltrans GIS Data Library[42] is a data resource that contains a suite of authoritative Department data sets, including traffic volume data in a geo-spatial file format. This data, combined with the spatial boundaries of the SHOPP project, can be used to determine the maximum values, as shown in the figure below.

[42] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

Step	Description
	 Using GIS to determine AADT parameters for SHOPP projects
3	**Calculate the Annual Vehicle Miles Traveled (VMT_{365}) within the Limits of SHOPP Project** An annual VMT can be calculated as follows: $VMT_{365} = [AADT\ vehicles/day] \times [Project\ Length,\ L\ miles] \times [365\ days/year]$
4	**Calculate Current GHG Emissions within the Limits of SHOPP Project** The rate of CO2 emissions can be calculated based on fuel consumption, per the Environmental Protection Agency[43] and US Department of Transportation studies.[44] These studies established the initial National Program fuel economy standards for model years 2012-2016 and a common conversion factor of 8.887×10^{-3} metric tons CO2/gallon of gasoline. Using the 2012 US DOT reported vehicle fleet average of 23.3 mpg,[45] the estimated GHG emissions within the limits of a SHOPP project can be calculated as follows: $Existing\ GHG\ emissions = VMT_{365} \times 1/(23.3\ mpg) \times (8.887 \times 10^{-3}\ metric\ tons\ CO_2/gallon)$

[43] http://www.epa.gov/cleanenergy/energy-resources/refs.html
[44] http://www.gpo.gov/fdsys/pkg/FR-2010-05-07/pdf/2010-8159.pdf
[45] http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html

Step	Description
5	**Calculate the Percent Reduction in GHG Emissions** The calculation of GHG emissions reduced is as follows: • Determine the maximum IRI value within the limits of the SHOPP project. • Calculate the expected reduction in IRI following pavement rehabilitation (ΔIRI). An FHWA study[46] suggests that newly rehabilitated pavements will have an IRI of 76 inches/mile or thereabout. • Calculate change in GHG emissions (or fuel consumption) due to IRI change as follows: $Percent\ reduction\ in\ GHG\ emissions = \frac{12\%}{\left(317\ {}^{in}/_{mile}\right)} \Delta IRI - 2.4\%$
6	**Calculate the Total Reduction in GHG Emissions** Multiply the percent reduction in GHG emissions by the existing GHG emissions to get the overall reduction in GHG emissions (in metric tons). *Total reduction in GHG emissions = (% reduction) x (existing GHG emissions)*
7	**Scoring** The maximum reduction in GHG emissions for all SHOPP projects under consideration is used to determine a normalized benefit score on a scale of 0-100, as follows: *Benefit = 100 x (Total reduction in GHG emissions) / (Max reduction in GHG emissions)*

A more accurate measure of GHG emission reductions resulting from the SHOPP project would require a rigorous study for each project. One would need to assess the baseline emissions state in the region prior to the project and carry out the necessary analyses to identify and evaluate the key factors of the project that would bring about changes to emissions. These factors would likely include many beyond paving rehabilitation alone (e.g., selection of building materials, construction strategy, etc.). For most SHOPP projects, however, the types of analyses required to adequately measure these types of environmental impacts are typically not conducted. At best, the degree of change to the environment can only be inferred from the data available.

[46] http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/98149/98149.pdf

4.3.10. Minimize Negative Health Impacts to Users, Fauna, and Flora Resulting from Water Quality Degradation

Minimizing damage to the environment is achieved through reducing adverse changes to the physical conditions within the area affected by the project, including land, air, water, minerals, flora, fauna, ambient noise, and objects of historic or aesthetic significance. Two components of environmental impacts were identified for the Pilot Project: (1) the reduction of greenhouse gas emissions, and (2) impacts on water quality. This section describes the calculation that is intended to capture the degree to which the SHOPP project will reduce impacts on water quality. The benefits represent those realized following the completion of the project, not the environmental impacts as a direct result of the construction activity.

The existing SHOPP process has a unique program of projects, Storm Water (201.335), specifically targets water quality. The goal of the program is to ensure that Caltrans storm water discharges meet applicable water quality standards and achieve compliance with the federal and state regulatory requirements and other legal mandates by funding stand-alone projects that retrofit the State Highway System to current federal standards over ten years (Fiscal Years 2015/16 through 2024/25). Although storm water projects are in a “discretionary” category, this is a mandated owner operator responsibility.

A second program, Roadside Protection and Restoration (201.240), can have elements that focus on storm water treatment and environmental impacts. However, no projects of this type were evaluated in the pilot project.

Storm water projects are quantified by the area of land treated, in units of acres. This quantification allows for a comparison of the relative benefits of different storm water projects. Projects in the Roadside Protection and Restoration program (201.240) can vary in scope and may or may not result in a reportable treatment area.

The calculation to estimate the value of a SHOPP project's effectiveness in reducing adverse changes to water quality is as follows:

Table 4-15 – Calculation Steps

"Minimize Negative Health Impacts to Users, Fauna, and Flora Resulting from Water Quality Degradation"

Step	Description
1	**Identify Projects That Address Water Quality** Based on the SHOPP program code, identify projects that are associated with Storm Water (201.335) and Roadside Protection and Restoration (201.240).
2	**Determine the Extent of Water Quality Treatment** For each project, obtain the "acres treated" measure.
3	**Scoring** The maximum acres treated for all SHOPP projects under consideration is used to determine a normalized benefit score on a scale of 0-100, as follows: *Benefit = 100 x (acres treated on project) / (max acres treated from all SHOPP projects)*

4.3.11. Maximize Equity and Access to Multimodal Transportation Systems

Caltrans Deputy Directive DD-64-R1, Complete Streets,[47] states: "The Department views all transportation improvements as opportunities to improve safety, access, and mobility for all travelers in California and recognizes bicycle, pedestrian, and transit modes as integral elements of the transportation system." To the extent that SHOPP projects can integrate elements of Complete Streets, a higher value is assigned.

Ideally, quantifiable information from each SHOPP project would be obtained. This includes identification of specific elements tied to Complete Streets, types of improvements, quantities, and an indicator for degree of improvement for inter-operability and usability of all modes of the transportation infrastructure. For the SHOPP Pilot Project, however, this level of data compilation and analysis was not feasible. As such, a proxy for this was used – the proximity of transit stations relative to the limits of the SHOPP project. Projects that have a transit station within the limits are assumed to generate some degree of benefit towards equity and access. This is a significant limitation of the approach, as proximity of transit facilities alone is likely not a strong indicator that a benefit as a result of the SHOPP project

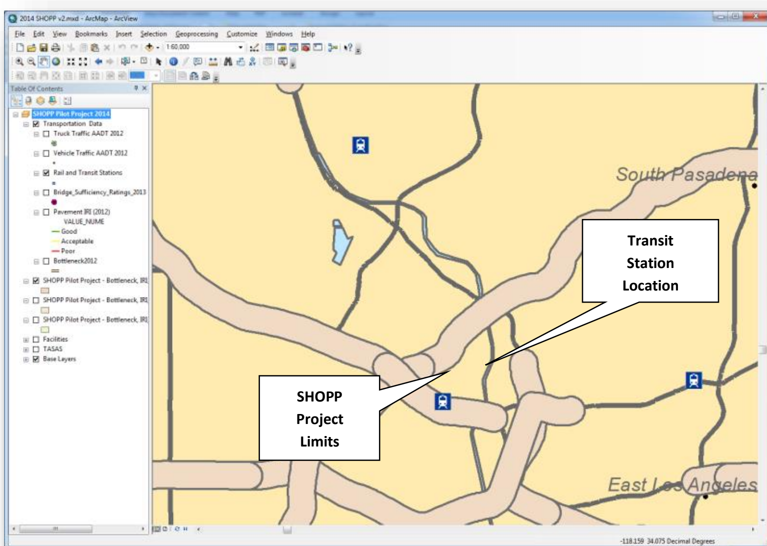
[47] http://www.dot.ca.gov/hq/tpp/offices/ocp/complete_streets_files/dd_64_r1_signed.pdf

was realized. Nevertheless, this is used in the analysis as a placeholder until improvements to the sub-model can be implemented.

The calculation of the value associated with equity and access to multimodal transportation systems is as follows:

Table 4-16 – Calculation Steps

"Maximize Equity and Access to Multimodal Transportation Systems"

Step	Description
1	**Identify Connection Locations for Other Transportation Modes** Obtain locations of stations for rail and other modes as published online by the Office of Data Analysis and GIS through the *Caltrans GIS Data Library.*[48] Passenger and commuter rail stations are available.
2	Through a geo-spatial analysis, identify for each project if one or more transit stations fall within a 0.25 mile buffer of the limits of the SHOPP project.  **Transit station within SHOPP project limits**
3	**Scoring** Projects that have a transit station within the limits are assigned a score of 100. All other projects are assigned a score of 0.

[48] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

4.4. Scaling Factors Used in Benefit Sub-Model Calculations

4.4.1. Project Magnitude Scaling Factor

The Project Magnitude Scaling Factor, $SF_{project\ magnitude}$, is introduced into calculations in order to scale the relative benefit of a particular objective to the overall size of the project using the dollar worth of the asset as the basis. This is needed in order to normalize the benefit to the magnitude of work. In many sub-model calculations, a benefit per unit asset is determined on a 0-100 scale. For example, a benefit is determined per lane-mile for pavement projects, per bridge for bridge projects, etc. A scaling factor is needed in order to scale the benefit relative to the size of the projects. For example, one would need to differentiate the relative benefit from a five-mile pavement project compared to a 50-mile pavement project. In this example, the larger project may result in ten times the benefit. Furthermore, a mechanism is needed when comparing the benefit of projects of different asset types. For example, the relative benefit from asset preservation work realized from 10 miles of pavement improvements compared to two bridge rehabilitations requires some basis.

An asset cost-based approach is proposed in an attempt to capture some aspects of project magnitude. Although crude, the approach serves as a reasonable starting point for the Pilot Project. The calculation steps are described in Table 4-17. This cost based approach is modeled after work developed by Caltrans Structure Maintenance and Investigations.[49]

Table 4-17 - Project Magnitude Scaling Factor

	Bridge	Pavement	Other Assets
Project Size	A_{deck} = combined deck area of all bridges in the project (sqft)	L = total lanes miles of pavement in project (ln-miles)	N = Number of asset locations (ea)
Dollar value of the asset	$V_{bridge} = (A_{deck})(\$300/sqft)$	$V_{pavmt} = (L)(\$1.25mil/ln\text{-}mi)$	$V_{culvert} = (N)(\$400k/ea)$ $V_{TMS} = (N)(\$300k/ea)$
Project Magnitude Scaling Factor	Project Magnitude Scaling Factor, $SF_{project\ magnitude}$, is determined by the dollar value of the asset according to the following calculation: $SF_{project\ magnitude} = (\text{Value of Asset})/\$10mil$ $SF_{project\ magnitude,\ max} = 1.0$		

Three general classes of assets are identified: bridges, pavements, and other asset types. For each asset type an estimated asset cost is calculated. The cost of bridge construction is calculated using the value of $300 per square foot of deck area, an upper-end cost figure typical of cast-in-place, pre-stressed box

[49] http://onlinepubs.trb.org/onlinepubs/circulars/ec128.pdf

girder bridge construction, as published in the Caltrans' Structure Design document, "Comparative Bridge Costs (January 2014)."[50] Pavement construction costs are calculated using an upper-end cost figure of $1.25mil per lane-mile, a cost associated with Portland Cement Concrete slab replacement, as published in the "2013 State of Pavement Report."[51]

For most SHOPP projects, quantities for bridge deck areas and lane-miles of pavement could be readily calculated using data from the 2014 SHOPP program summary documents. For other asset classes, however, only the quantity of "elements" was available. It was not possible within the scope and time constraints of the Pilot Project to determine through a review of each Project Initiation Document (PID) the quantity, type, and cost associated with each element. A more generalized approach was used where an average cost per element was calculated. The resulting element costs within two specific asset types, culverts and traffic management system elements, were highly variable. Additional data and analysis is needed if this is to be used moving forward beyond a pilot effort.

The Project Magnitude Scaling Factor is calculated as a ratio of the dollar cost of the asset divided by $10mil with a maximum value of 1.0. The use of $10mil in the denominator was selected as an approximate order-of-magnitude dollar value based on a cursory review of bridges and pavements within the 2014 SHOPP Pilot Project listing. Although this cost figure is not well founded on rigorous inventory analysis, the resulting scaling factor does succeed in capturing magnitude differences between the most commonly encountered projects.

4.4.2. Traffic Volume Scaling Factor

The Traffic Volume Scaling Factor, $SF_{traffic\ volume}$, is calculated from the maximum Annual Average Daily Traffic (AADT) volume occurring within the limits of the SHOPP project, scaled relative to the maximum AADT for all other SHOPP projects under consideration. The resulting scaling factor reflects the degree to which the traveling public is exposed to the benefit as a result of the SHOPP project work.

$$SF_{traffic\ volume} = (Max\ AADT\ within\ SHOPP\ project\ limits) / (Max\ AADT\ for\ all\ SHOPP\ projects)$$

The maximum AADT within the limits of the SHOPP project is determined through a geospatial analysis within a GIS application. The Caltrans GIS Data Library[52] is the authoritative data resource that contains a suite of Department data sets, including traffic volume data in a geo-spatial file format. AADT data is provided as points of traffic volume measurements. In most instances, multiple AADT measurement points are found within project limits, and the maximum can be determined. In other instances, no AADT measurement points are within the limits. As such, the closest AADT measurement point is used. The figure below illustrates an example of the relationship between the AADT data and the SHOPP project limits.

[50] http://www.dot.ca.gov/hq/esc/estimates/COMP_BR_COSTS_2013-eng.pdf
[51] http://www.dot.ca.gov/hq/maint/Pavement/Pavement_Program/PDF/2013_SOP_FINAL-Dec_2013-1-24-13.pdf
[52] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

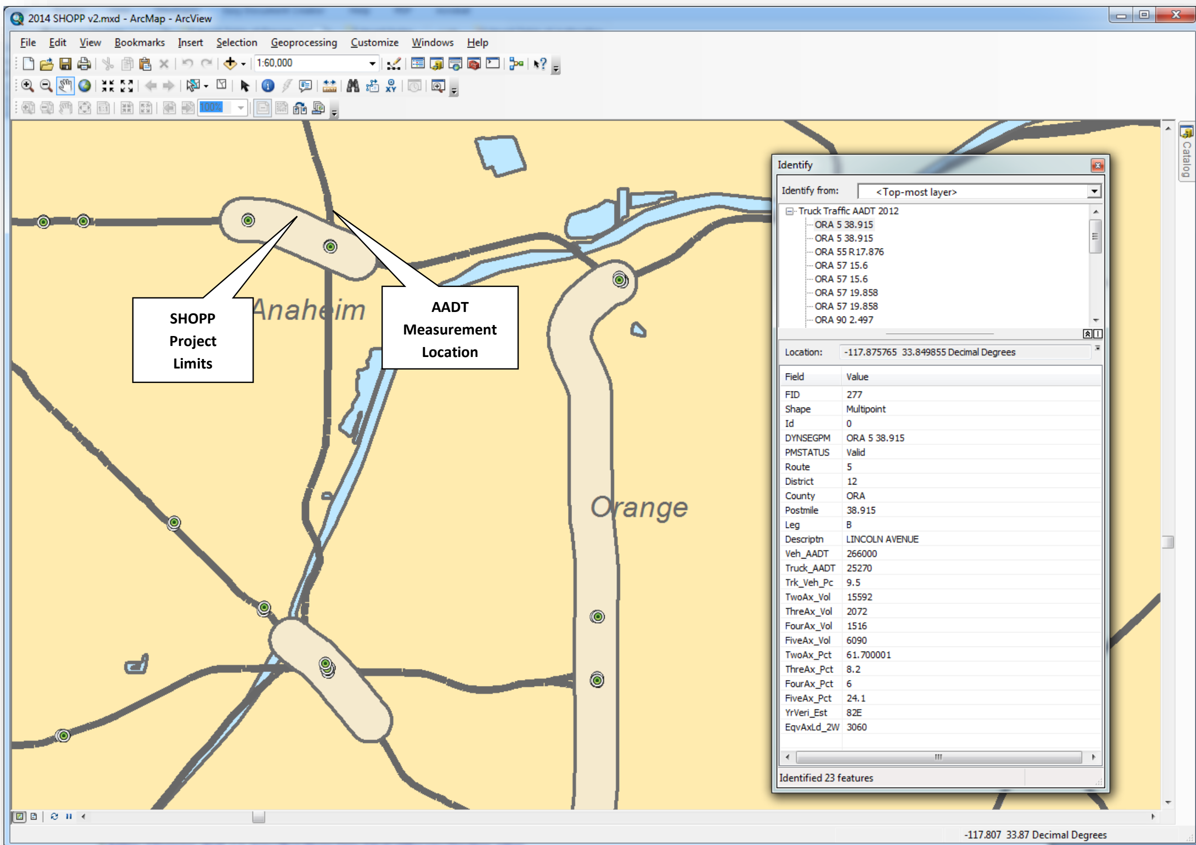


Figure 4-12 - Using GIS to Determine AADT Parameters for SHOPP Projects

4.5. Weighting and Scoring

In a MODA-based approach there are various methods to carry out weighting and scoring that can be implemented to arrive at the calculation of the project value. Having reviewed the literature on this subject, the team adopted methods for both scoring and weighting recommended by the UK Department for Communities and Local Government and published in the document, "Multi-Criteria Analysis: A Manual53." For scoring, the values derived from value function sub-models were normalized on a scale of 0 to 100. A method called "swing weighting" was used for assigning weights to the value function sub-models, and, as with scoring, was also implemented on a scale of 0-100. In many MODA case examples, weighting is primarily used to emphasize the importance a variable adds to a final outcome. Swing weighting, by contrast, not only represents the importance placed on a criterion, it also reflects the variability of the data and impact on the overall score. As stated succinctly in the UK document, "the weight on a criterion reflects both the range of difference of the options, and how much that difference matters."

The Core Team initially attempted to apply a swing weighting approach to the MODA model. However, the degree of variability in the data and the proxies used in the construction of the sub-models made it too difficult to rigorously quantify the change in value, a requirement for swing weighting. Due to this issue, the Core Team was not confident in carrying out the swing weighting approach, and, instead, applied judgment-based weights for preliminary calculations. For future use of this methodology in prioritizing SHOPP projects, there will need to be more effort put toward the swing weighting methodology to ensure confidence in the value function model.

[53] https://www.gov.uk/government/publications/multi-criteria-analysis-manual-for-making-government-policy

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5. Pilot SHOPP Tool Development

The SHOPP Project Prioritization Tool (Figure 5-1) was produced in late 2014 as a result of the work of the Core Team in support of the SHOPP Pilot Project. The prototype tool is implemented in *Microsoft Excel* and facilitates the evaluation and prioritization of SHOPP projects using a Multi-Objective Decision Analysis (MODA) framework. In summary, the tool:

- Communicates project priorities in the context of the Department's goals, formalized in a hierarchy of fundamental objectives and value functions.
- Assigns the value that each project is expected to deliver, thereby identifying those projects providing the best "bang-for-the-buck."
- Calculates the overall value of project portfolios, given variations in funding levels and goal weights.
- Facilitates the assessment of "what if" scenarios (e.g., budget changes), and provides justification for additional funding requests.
- Evaluates various scenarios where specific projects are forced to be included (or excluded) in the portfolio.
- Compares project priorities developed using the new process against the existing processes.

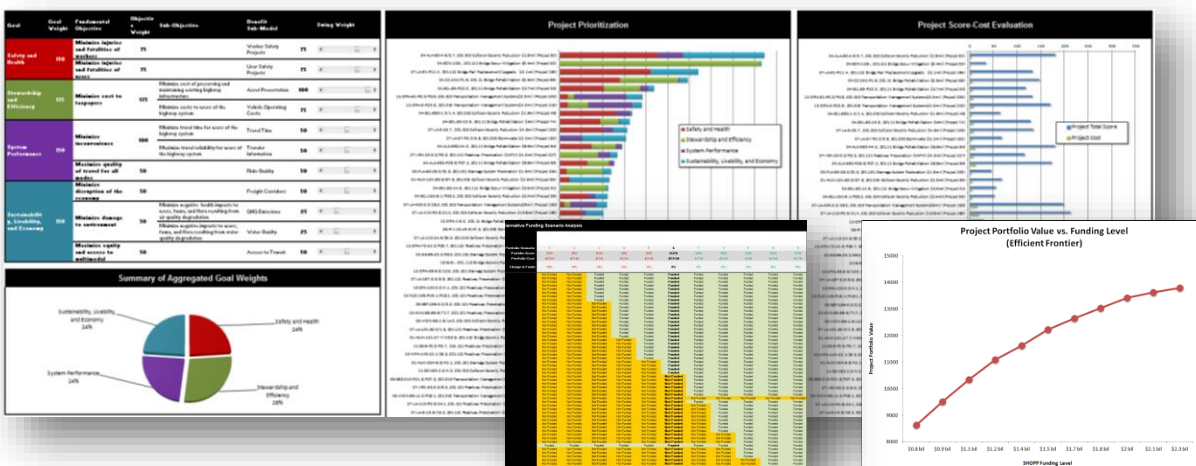


Figure 5-1 – SHOPP Project Prioritization Tool

5.1. Project Data

Two primary sources of data are used by the tool – SHOPP project data and Caltrans GIS Library data. SHOPP project data is provided by the Division of Transportation Planning through the SHOPP Management Office. This data includes location information (i.e. district, county, route, and postmile limits), funding, program coding, and a brief project description. Department GIS data is obtained from the online Caltrans GIS Data Library,[54] maintained by the Division of Research, Innovation, and System Information. Key GIS data sets include Annual Average Daily Traffic (AADT), truck traffic, pavement International Roughness Index (IRI), locations of high traffic congestion (or "bottleneck") zones, bridges, and various other highway fixtures tied to the statewide Linear Reference System (LRS).

By combining the available SHOPP project data and the Caltrans GIS data through the LRS, a suite of data can be attributed to each SHOPP project for further analysis. The geospatial analysis that is required to extract this data is carried out in *ESRI ArcGIS* software (Figure 5-2).

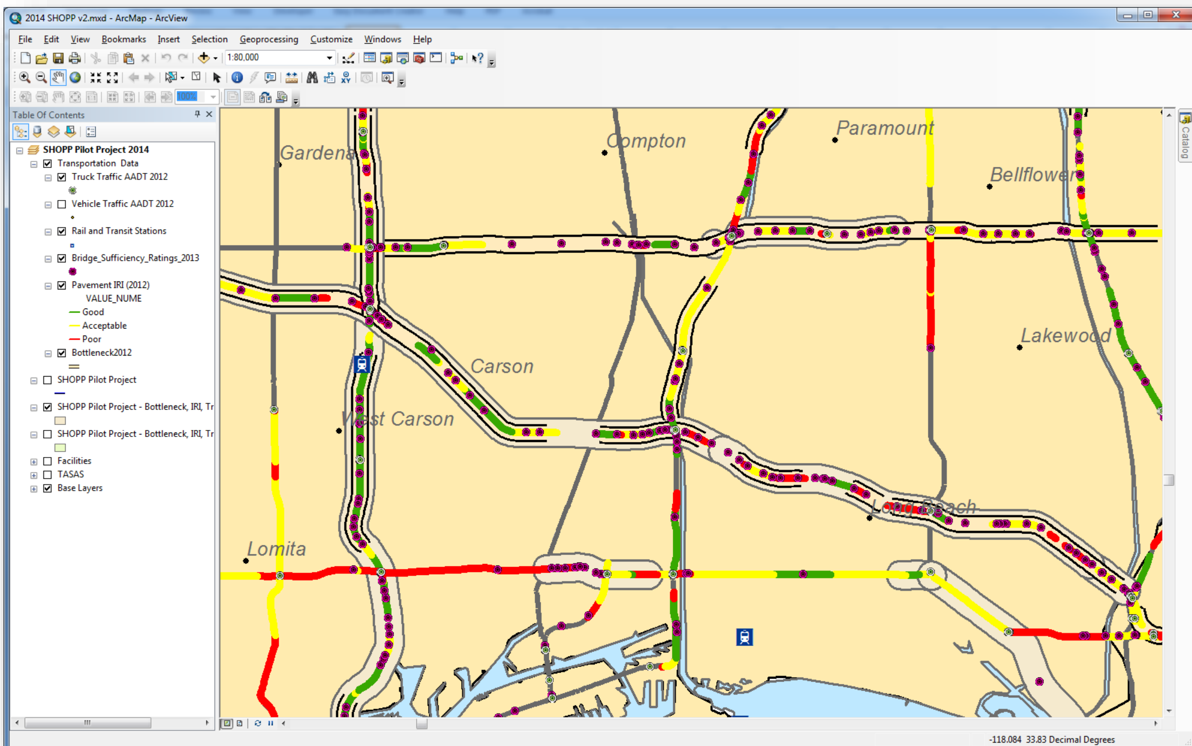
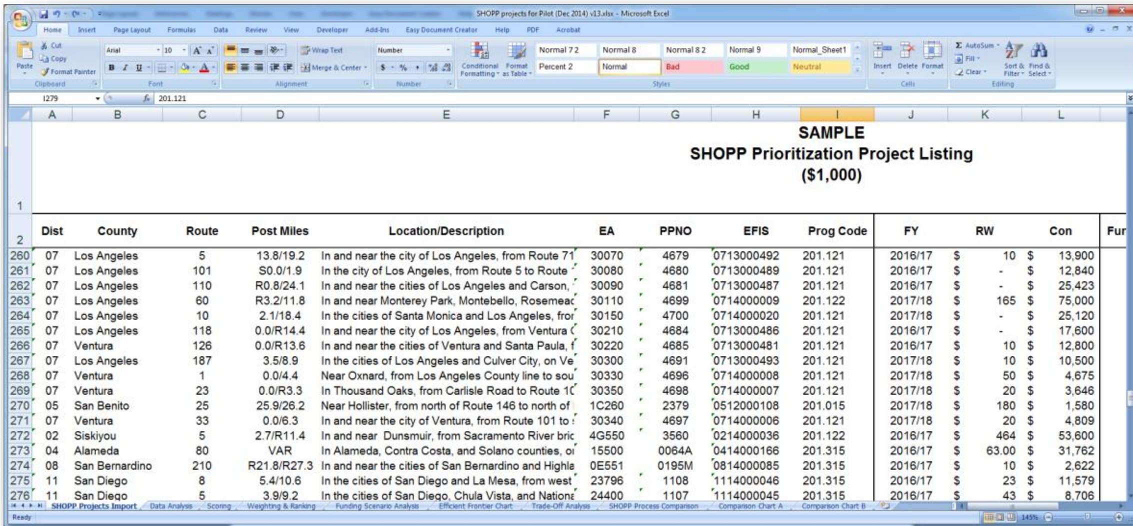


Figure 5-2 – Geo-Spatial Analysis of SHOPP Projects Implemented with Caltrans GIS Data

SHOPP Project data is imported into the tool to the "SHOPP Projects Import" worksheet (Figure 5.3). The format and structure of this worksheet is identical to a file generated by the SHOPP Management Office.

[54] http://www.dot.ca.gov/hq/tsip/gis/datalibrary/index.php

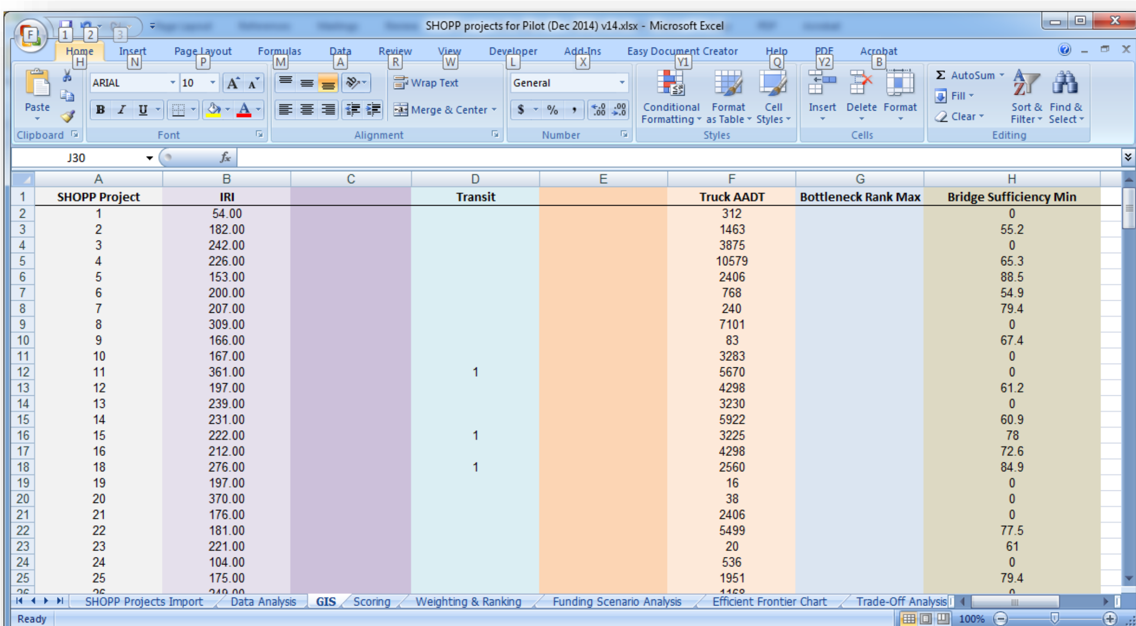


SAMPLE
SHOPP Prioritization Project Listing
($1,000)

Dist	County	Route	Post Miles	Location/Description	EA	PPNO	EFIS	Prog Code	FY	RW	Con
07	Los Angeles	5	13.8/19.2	In and near the city of Los Angeles, from Route 71	30070	4679	0713000492	201.121	2016/17	$ 10	$ 13,900
07	Los Angeles	101	S0.0/1.9	In the city of Los Angeles, from Route 5 to Route	30080	4680	0713000489	201.121	2016/17	$ -	$ 12,840
07	Los Angeles	110	R0.8/24.1	In and near the cities of Los Angeles and Carson,	30090	4681	0713000487	201.121	2016/17	$ -	$ 25,423
07	Los Angeles	60	R3.2/11.8	In and near Monterey Park, Montebello, Rosemeac	30110	4699	0714000009	201.122	2017/18	$ 165	$ 75,000
07	Los Angeles	10	2.1/18.4	In the cities of Santa Monica and Los Angeles, fror	30150	4700	0714000020	201.121	2017/18	$ -	$ 25,120
07	Los Angeles	118	0.0/R14.4	In and near the city of Los Angeles, from Ventura (	30210	4684	0713000486	201.121	2016/17	$ -	$ 17,600
07	Ventura	126	0.0/R13.6	In and near the cities of Ventura and Santa Paula, f	30220	4685	0713000481	201.121	2016/17	$ 10	$ 12,800
07	Los Angeles	187	3.5/8.9	In the cities of Los Angeles and Culver City, on Ve	30300	4691	0713000493	201.121	2017/18	$ 10	$ 10,500
07	Ventura	1	0.0/4.4	Near Oxnard, from Los Angeles County line to sou	30330	4696	0714000008	201.121	2017/18	$ 50	$ 4,675
07	Ventura	23	0.0/R3.3	In Thousand Oaks, from Carlisle Road to Route 1C	30350	4698	0714000007	201.121	2017/18	$ 20	$ 3,646
05	San Benito	25	25.9/26.2	Near Hollister, from north of Route 146 to north of	1C260	2379	0512000108	201.015	2017/18	$ 180	$ 1,580
07	Ventura	33	0.0/6.3	In and near the city of Ventura, from Route 101 to	30340	4697	0714000006	201.121	2017/18	$ 20	$ 4,809
02	Siskiyou	5	2.7/R11.4	In and near Dunsmuir, from Sacramento River bric	4G550	3560	0214000036	201.122	2016/17	$ 464	$ 53,600
04	Alameda	80	VAR	In Alameda, Contra Costa, and Solano counties, oı	15500	0064A	0414000166	201.315	2016/17	$ 63.00	$ 31,762
08	San Bernardino	210	R21.8/R27.3	In and near the cities of San Bernardino and Highla	0E551	0195M	0814000085	201.315	2016/17	$ 10	$ 2,622
11	San Diego	8	5.4/10.6	In the cities of San Diego and La Mesa, from west	23796	1108	1114000046	201.315	2016/17	$ 23	$ 11,579
11	San Diego	5	3.9/9.2	In the cities of San Diego, Chula Vista, and Nationa	24400	1107	1114000045	201.315	2016/17	$ 43	$ 8,706

Figure 5-3 - SHOPP Project Data Import

Results from the ArcGIS analysis are imported into the "GIS" worksheet (Figure 5-4).



SHOPP Project	IRI		Transit		Truck AADT	Bottleneck Rank Max	Bridge Sufficiency Min
1	54.00				312		0
2	182.00				1463		55.2
3	242.00				3875		0
4	226.00				10579		65.3
5	153.00				2406		88.5
6	200.00				768		54.9
7	207.00				240		79.4
8	309.00				7101		0
9	166.00				83		67.4
10	167.00				3283		0
11	361.00		1		5670		0
12	197.00				4298		61.2
13	239.00				3230		0
14	231.00				5922		60.9
15	222.00		1		3225		78
16	212.00				4298		72.6
18	276.00		1		2560		84.9
19	197.00				16		0
20	370.00				38		0
21	176.00				2406		0
22	181.00				5499		77.5
23	221.00				20		61
24	104.00				536		0
25	175.00				1951		79.4

Figure 5-4 - ArcGIS Data Import Worksheet

5.2. Project Scoring

The "Scoring" worksheet (Figure 72) captures the calculations and scores for all projects based on value function sub-models. Intermediate calculations associated with value function sub-models are carried out in separate worksheets associated with each sub-model.

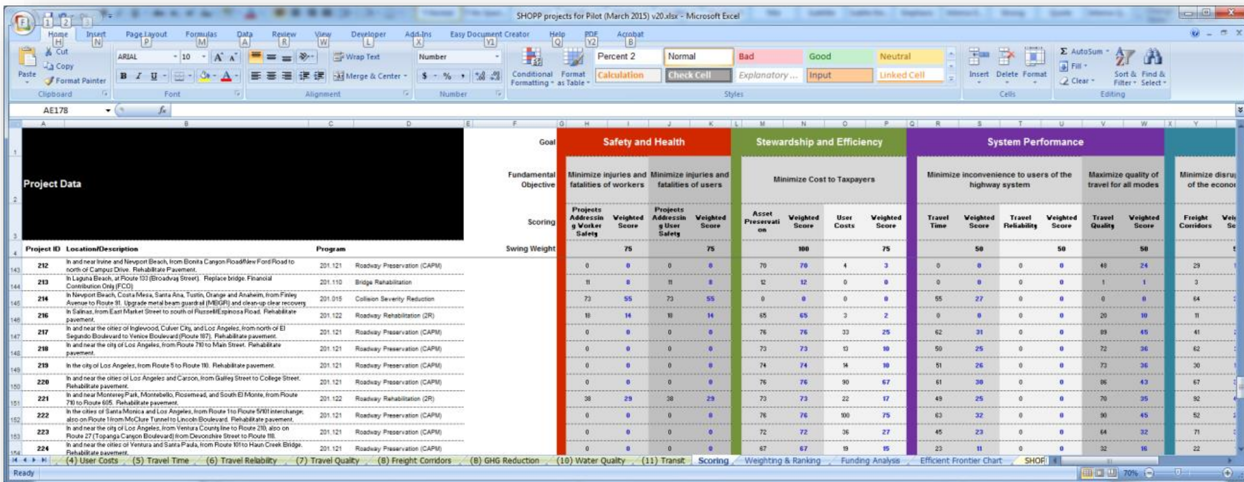
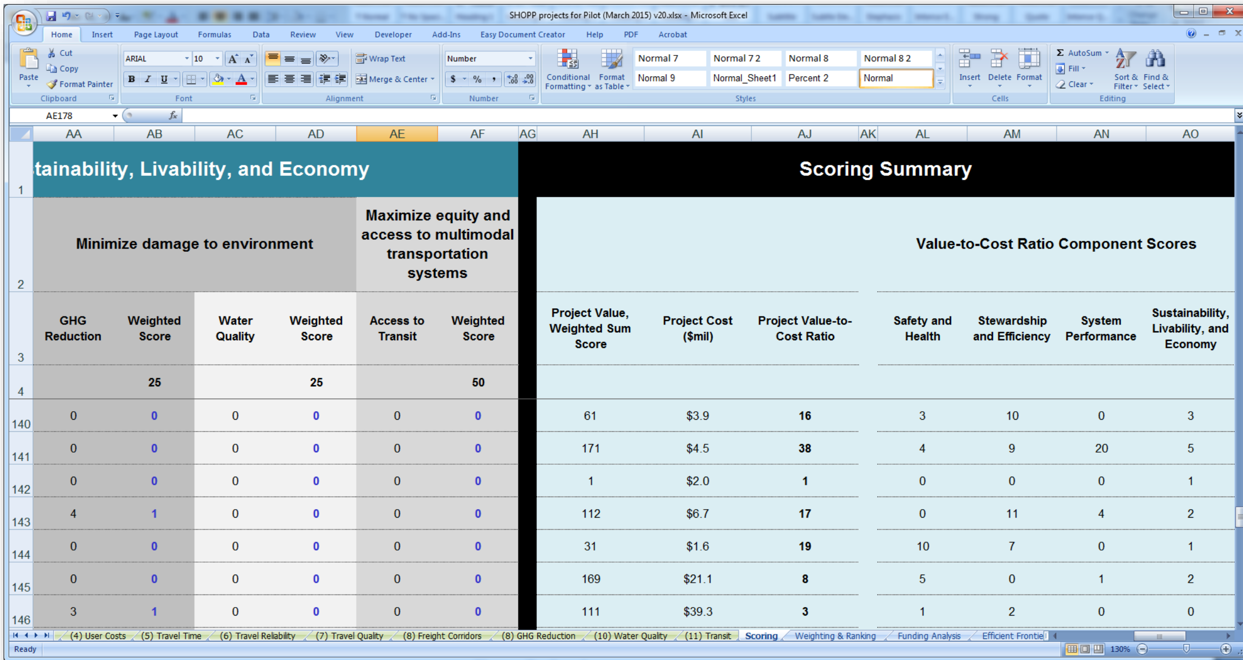


Figure 5-5 - Scoring Worksheet

For the SHOPP Pilot Project, the scoring process is entirely data driven (from the geo-spatial analysis). No manual or subjective assessments of individual projects are required to carry out the portfolio prioritization.

The right-most columns in the "Scoring" worksheet (Figure 5-6) calculates and summarizes the project scores as a product of the weighted sum of the scores from the sub-models. The resulting score, called the Project Value, is divided by the Project Cost to yield the Project Value-to-Cost Ratio. The Value-to-Cost Ratio is used to rank projects in priority order and accounts for the broad range of project costs and scopes.



Row	GHG Reduction	Weighted Score	Water Quality	Weighted Score	Access to Transit	Weighted Score	Project Value, Weighted Sum Score	Project Cost ($mil)	Project Value-to-Cost Ratio	Safety and Health	Stewardship and Efficiency	System Performance	Sustainability, Livability, and Economy
1	tainability, Livability, and Economy						Scoring Summary						
2	Minimize damage to environment				Maximize equity and access to multimodal transportation systems		Value-to-Cost Ratio Component Scores						
4		25		25		50							
140	0	0	0	0	0	0	61	$3.9	16	3	10	0	3
141	0	0	0	0	0	0	171	$4.5	38	4	9	20	5
142	0	0	0	0	0	0	1	$2.0	1	0	0	0	1
143	4	1	0	0	0	0	112	$6.7	17	0	11	4	2
144	0	0	0	0	0	0	31	$1.6	19	10	7	0	1
145	0	0	0	0	0	0	169	$21.1	8	5	0	1	2
146	3	1	0	0	0	0	111	$39.3	3	1	2	0	0

Figure 5-6 - Scoring Summary

5.3. Weighting and Ranking Projects

The “Weighting and Ranking” worksheet is the primary input and reporting interfaces in the tool (Figure 5-7). The four panels in this worksheet convey the primary results of the prioritization process – the weights applied to the objectives, the aggregation of weights relative to Department goals, project priorities, and project valuation. Discussion of each panel is presented in this section.

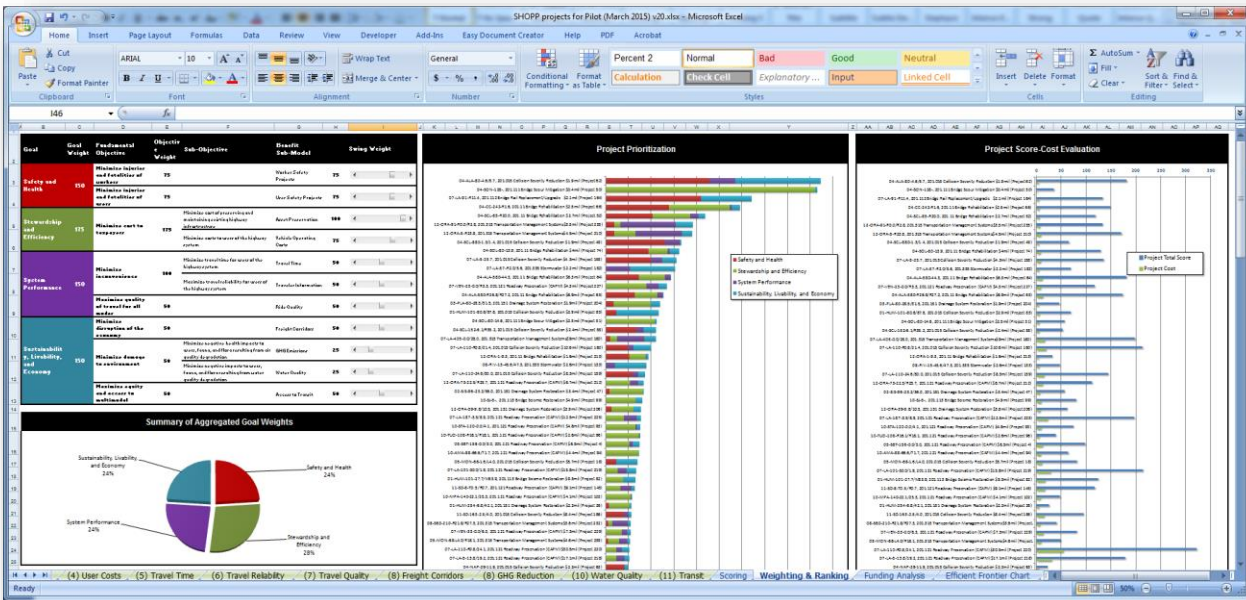
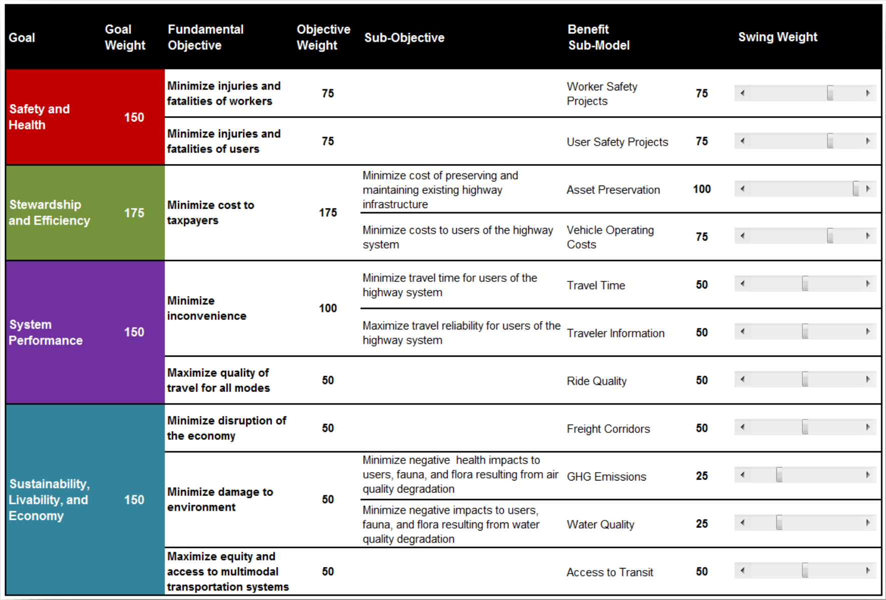


Figure 5-7 - Weighting and Ranking Projects

5.3.1. Setting Weights

The left and center panels provide a means to set weights associated with each sub-model and review how those weights are aggregated in the objectives hierarchy. Weights can be set by manually entering values (0-100) in the “Swing Weight” column, or by moving the horizontal sliders. Weights are only assigned to sub-models in a “bottom up” approach. The sub-model weights are summed for each objective, and the objective weights are summed for each goal. As the swing weights are adjusted, the objective and goal weights are recalculated. An explanation of the weighting process can be found in Section 4.5Weighting and Scoring. The goal weights are presented in the table in numeric form as well as in a pie chart in a lower panel as percentages (Figure 5-8 and Figure 5-9).



Goal	Goal Weight	Fundamental Objective	Objective Weight	Sub-Objective	Benefit Sub-Model	Swing Weight
Safety and Health	150	Minimize injuries and fatalities of workers	75		Worker Safety Projects	75
		Minimize injuries and fatalities of users	75		User Safety Projects	75
Stewardship and Efficiency	175	Minimize cost to taxpayers	175	Minimize cost of preserving and maintaining existing highway infrastructure	Asset Preservation	100
				Minimize costs to users of the highway system	Vehicle Operating Costs	75
System Performance	150	Minimize inconvenience	100	Minimize travel time for users of the highway system	Travel Time	50
				Maximize travel reliability for users of the highway system	Traveler Information	50
		Maximize quality of travel for all modes	50		Ride Quality	50
Sustainability, Livability, and Economy	150	Minimize disruption of the economy	50		Freight Corridors	50
		Minimize damage to environment	50	Minimize negative health impacts to users, fauna, and flora resulting from air quality degradation	GHG Emissions	25
				Minimize negative impacts to users, fauna, and flora resulting from water quality degradation	Water Quality	25
		Maximize equity and access to multimodal transportation systems	50		Access to Transit	50

Figure 5-8 – Adjusting Weights

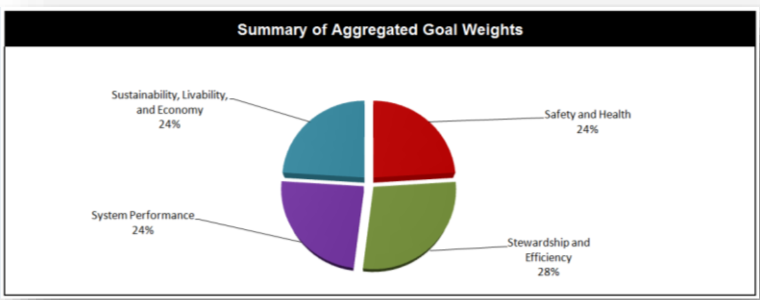


Figure 5-9 – Alignment with Department Goals

5.3.2. Evaluate Project Priorities

The center panel (Figure 5-10) presents the full list of projects, listed in rank order. Ordering of projects changes automatically as the swing weights for the value functions are adjusted. The relative contributions of each Department goal are represented as a proportion of the bar charts, symbolized using the color convention throughout the tool. The length of each bar represents the overall “value” of the project, which, in the context of this tool, is the overall project score divided by the project cost. Projects that provide more value (i.e., higher ratio of score-to-cost) rank higher.

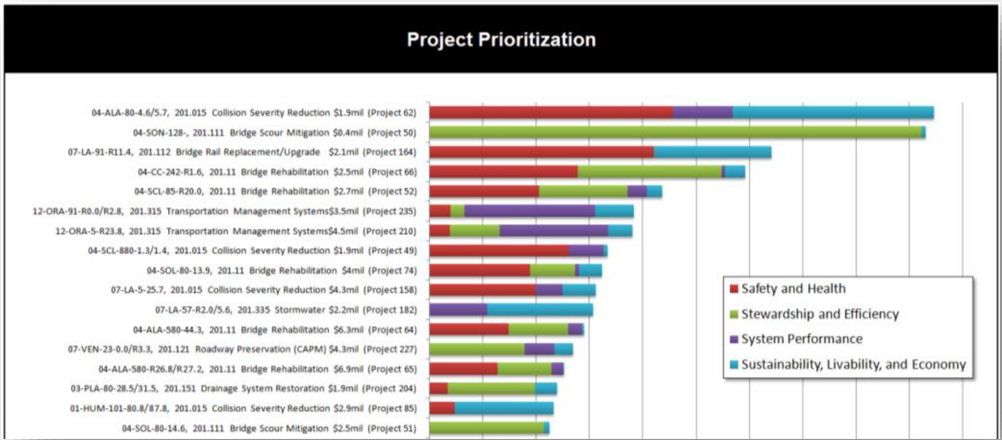


Figure 5-10 - Project Prioritization Panel

5.4. Project Score and Cost

The right-most panel (Figure 5-11) presents the projects in the same priority order, however, it displays the project cost and the project score using a Two-axis bar chart. The ratio of the score-to-cost establishes the rank of the project. The graphical presentation of the two numbers in this chart helps in understanding how priorities are determined. Although the data presented in the chart is expressed quantitatively (blue corresponding the project score and green corresponding to project cost), the chart's strength is in the visualization of the relative size of the score (blue) and cost (green) bars. For instance, projects ranked higher of the list will have scores (blue) that exceed the costs (green). Lower ranking projects will show the reverse, where costs (green) will exceed the value (blue). The overall ranking of high and low cost projects can be quickly identified. Likewise, the distribution of high and low scoring projects can be assessed.

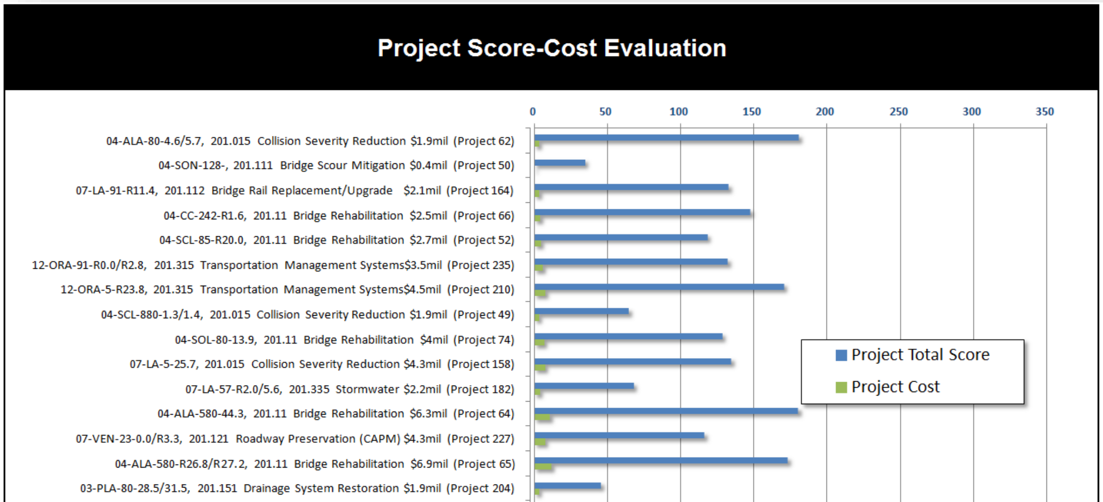
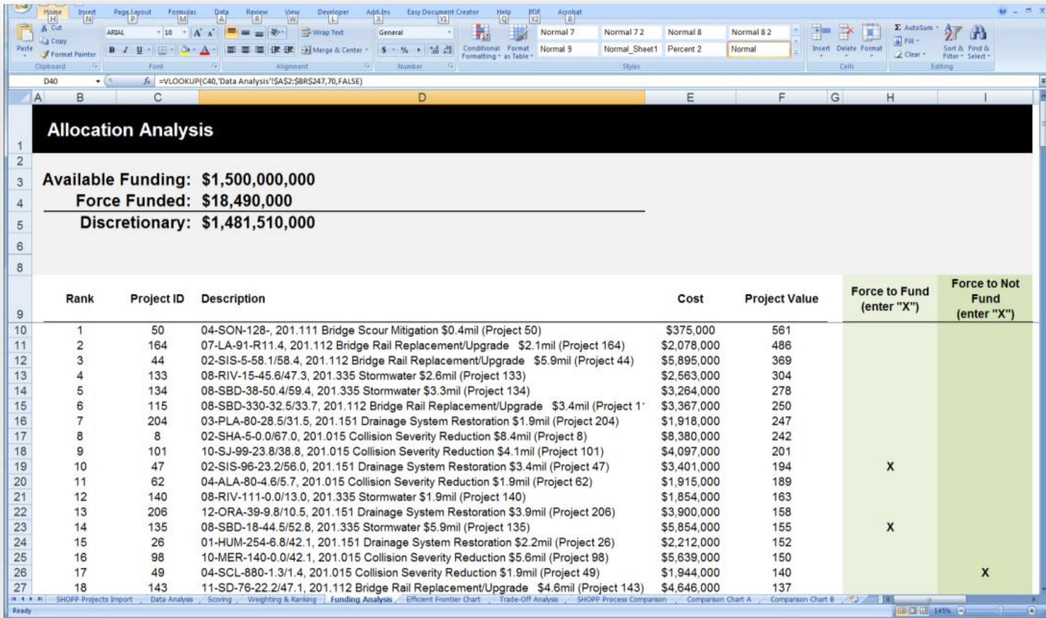


Figure 5-11 - Project Score-Cost Evaluation

5.5. Funding Analysis

The "Funding Analysis" worksheet carries over project priorities from the prior worksheet and facilitates the analysis of various funding scenarios.

Individual projects can be forced to be funded (or not funded) regardless of their ranking in the overall prioritization (Figure 5-12). The analysis accounts for these over-ride choices and redistributes the remaining discretionary funds to the remaining portfolio. A separate series of columns to the right (Figure 5-12) display the cut-off of funded and unfunded projects.



Allocation Analysis

Available Funding: $1,500,000,000
Force Funded: $18,490,000
Discretionary: $1,481,510,000

Rank	Project ID	Description	Cost	Project Value	Force to Fund (enter "X")	Force to Not Fund (enter "X")
1	50	04-SON-128-, 201.111 Bridge Scour Mitigation $0.4mil (Project 50)	$375,000	561		
2	164	07-LA-91-R11.4, 201.112 Bridge Rail Replacement/Upgrade $2.1mil (Project 164)	$2,078,000	486		
3	44	02-SIS-5-58.1/58.4, 201.112 Bridge Rail Replacement/Upgrade $5.9mil (Project 44)	$5,895,000	369		
4	133	08-RIV-15-45.6/47.3, 201.335 Stormwater $2.6mil (Project 133)	$2,563,000	304		
5	134	08-SBD-38-50.4/59.4, 201.335 Stormwater $3.3mil (Project 134)	$3,264,000	278		
6	115	08-SBD-330-32.5/33.7, 201.112 Bridge Rail Replacement/Upgrade $3.4mil (Project 1	$3,367,000	250		
7	204	03-PLA-80-28.5/31.5, 201.151 Drainage System Restoration $1.9mil (Project 204)	$1,918,000	247		
8	8	02-SHA-5-0.0/67.0, 201.015 Collision Severity Reduction $8.4mil (Project 8)	$8,380,000	242		
9	101	10-SJ-99-23.8/38.8, 201.015 Collision Severity Reduction $4.1mil (Project 101)	$4,097,000	201		
10	47	02-SIS-96-23.2/56.0, 201.151 Drainage System Restoration $3.4mil (Project 47)	$3,401,000	194	X	
11	62	04-ALA-80-4.6/5.7, 201.015 Collision Severity Reduction $1.9mil (Project 62)	$1,915,000	189		
12	140	08-RIV-111-0.0/13.0, 201.335 Stormwater $1.9mil (Project 140)	$1,854,000	163		
13	206	12-ORA-39-9.8/10.5, 201.151 Drainage System Restoration $3.9mil (Project 206)	$3,900,000	158		
14	135	08-SBD-18-44.5/52.8, 201.335 Stormwater $5.9mil (Project 135)	$5,854,000	155	X	
15	26	01-HUM-254-6.8/42.1, 201.151 Drainage System Restoration $2.2mil (Project 26)	$2,212,000	152		
16	98	10-MER-140-0.0/42.1, 201.015 Collision Severity Reduction $5.6mil (Project 98)	$5,639,000	150		
17	49	04-SCL-880-1.3/1.4, 201.015 Collision Severity Reduction $1.9mil (Project 49)	$1,944,000	140		X
18	143	11-SD-76-22.2/47.1, 201.112 Bridge Rail Replacement/Upgrade $4.6mil (Project 143)	$4,646,000	137		

Figure 5-12 - Allocation Analysis

Using the "available funding" number on this worksheet and the selection of force funded (and not funded) projects, a baseline scenario is determined and is presented as "Portfolio Scenario 6" in the right-most columns in the worksheet (Figure 5-13). Alternative funding scenarios in 10% increments and decrements are presented in ten additional scenarios. The table presents a strong visual of the relation of funded (green) to unfunded (orange) projects as the budget changes.

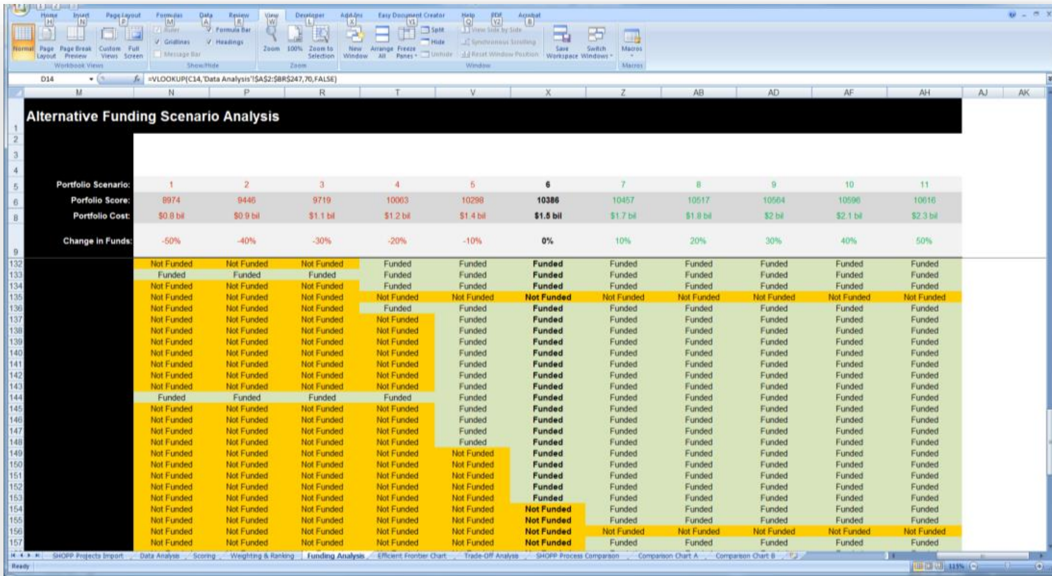


Figure 5-13 - Evaluating Alternative Funding Scenarios

For each portfolio scenario an overall portfolio score is calculated. This is the sum of the scores of all projects funded under each budget scenario. The portfolio score divided by the portfolio cost is considered the "portfolio value" in the context of this tool. When all scenarios are plotted in a chart showing the score vs. cost (Figure 5-14), one can quickly assess the relative increase in portfolio value relative to the increase in portfolio cost.

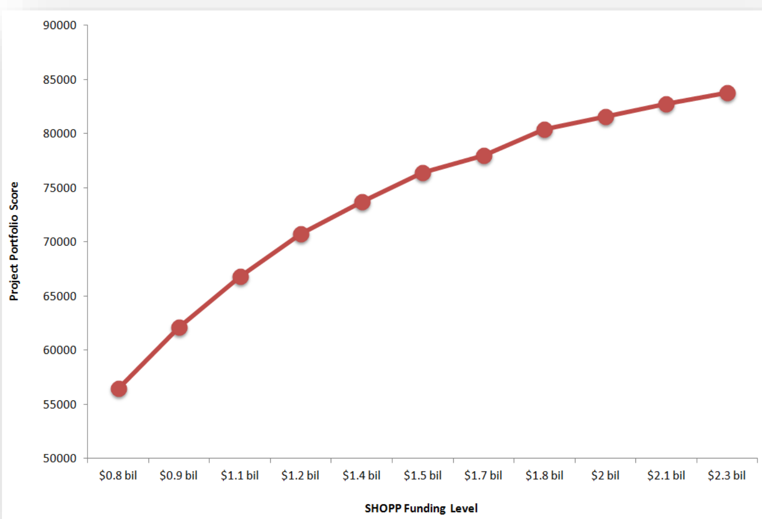


Figure 5-14 - Portfolio Value vs Funding

The “Funding Analysis” worksheet and corresponding plot serve two primary purposes. First, it allows evaluating the inclusion and exclusion of specific projects in order to identify the portfolio of projects that delivers the greatest value given a fixed funding level. Second, it allows evaluation of alternative funding levels in order to evaluate “what-if” scenarios. For example, one could quantitatively show that an increase in funding might yield significant portfolio value.

5.6. Sensitivity Analysis

The Excel tool provides a framework to carry out sensitivity analysis on the results of the project prioritization. In the context of this decision analysis framework, a sensitivity analysis is where one makes changes to the objective weights and observes the resulting changes in project priorities. In the Excel tool, the sliders were implemented as a convenient mechanism to make adjustments dynamically. It can be instructive to the decision makers to see the significance of changes in weights to the priorities. Most of the commercial and open source software tools evaluated provide a similar mechanism to make adjustments. Furthermore, the decision analysis professionals advocate the use of sensitivity analysis as a critical step in understanding the decision outcomes.

6. Analysis of a Sample Portfolio from the 2014 SHOPP

A subset of 2014 SHOPP projects provided two primary benefits: (1) a base set of projects for which calculations could be tested, and (2) a comparison of priorities using both the existing and the newly developed processes. This section describes the set of projects used in the analyses, presents the outcomes of applying the new project prioritization process, and offers a comparison of the priorities generated between the new and the existing processes. An example prioritization exercise was carried out using equal weighting across all objectives to support initial findings and observations documented in this section.

6.1. Sample Set of 2014 New SHOPP Projects

A total of 172 projects from a list of 289 total projects from the 2014 SHOPP were considered for this Pilot Project. The cost for these 172 projects is $2.7 billion. The majority of the 117 excluded projects were non-discretionary, “priority 1” projects. A smaller subset of other projects was excluded due to lack of specific location information. The location of the project was used in many of the value function sub-models to tie in other data sets, e.g., traffic volume, pavement roughness, etc. A summary of the distribution of project types by counts and funding is presented in Figure 6-1 and Figure 6-2. Detailed counts and funding by program code are presented in Table 6-1.

Table 6-1 - Project and Programs Used for the Pilot Project

Program Code	Program Priority	Program	Number of Projects	Total Funding	Percent of Porfolio (by funding)
201.130	1	Emergency Damage Repair	0	*(Non-discretionary projects were not considered for this Pilot Project)*	
201.010	1	Safety Improvements	0		
201.131	1	Permanent Restoration	0		
201.361	1	ADA Access Improvements	0		
201.378	1	ADA Pedestrian Infrastructure	0		
201.235	1	Roadside Safety Improvements	0		
201.119	1	Bridge Preventive Maintenance	0		
201.321	1	Weigh Stations & WIM Facilities	0		
201.015	2	Collision Severity Reduction	27	$216,235,000	8.10%
201.111	3	Bridge Scour Mitigation	8	$45,190,000	1.70%
201.113	4	Bridge Seismic Restoration	6	$118,504,000	4.50%
201.110	5	Bridge Rehabilitation	28	$400,197,000	15.00%
201.120	6	Roadway Rehabilitation (3R)	9	$253,808,525	9.50%
201.121	6	Roadway Preservation (CAPM)	44	$657,537,000	24.70%
201.122	6	Roadway Rehabilitation (2R)	10	$642,388,000	24.10%
201.151	7	Drainage System Restoration	6	$21,371,000	0.80%
201.112	8	Bridge Rail Replacement/Upgrade	9	$43,271,000	1.60%
201.335	9	Storm Water	14	$148,215,000	5.60%
201.315	10	Transportation Management Systems	9	$106,095,000	4.00%
201.322	11	Trans Permit Requirements for Bridges	2	$9,981,000	0.40%
201.150	12	Roadway Protective Betterment	0	*(Projects from these programs were not included in the 2014 SHOPP, and therefore were not considered for this Pilot Project)*	
201.310	13	Operational Improvements	0		
201.240	14	Roadside Protection and Restoration	0		
201.250	15	Safety Roadside Rest Area Rehabilitation	0		
201.210	16	Roadside Rehabilitation	0		
201.170	17	Signs and Lighting Rehabilitation	0		
201.160	18	Relinquishments	0		
201.325	19	Railroad at-grade Crossing	0		
201.330	20	Hazardous Waste Mitigation	0		
201.352	21	Maintenance Facilities	0		
201.351	22	Equipment Facilities	0		
201.353	23	Office Buildings	0		
201.260	25	New Safety Roadside Rest Areas	0		
		TOTAL PROJECTS	**172**	**$2.7mil**	

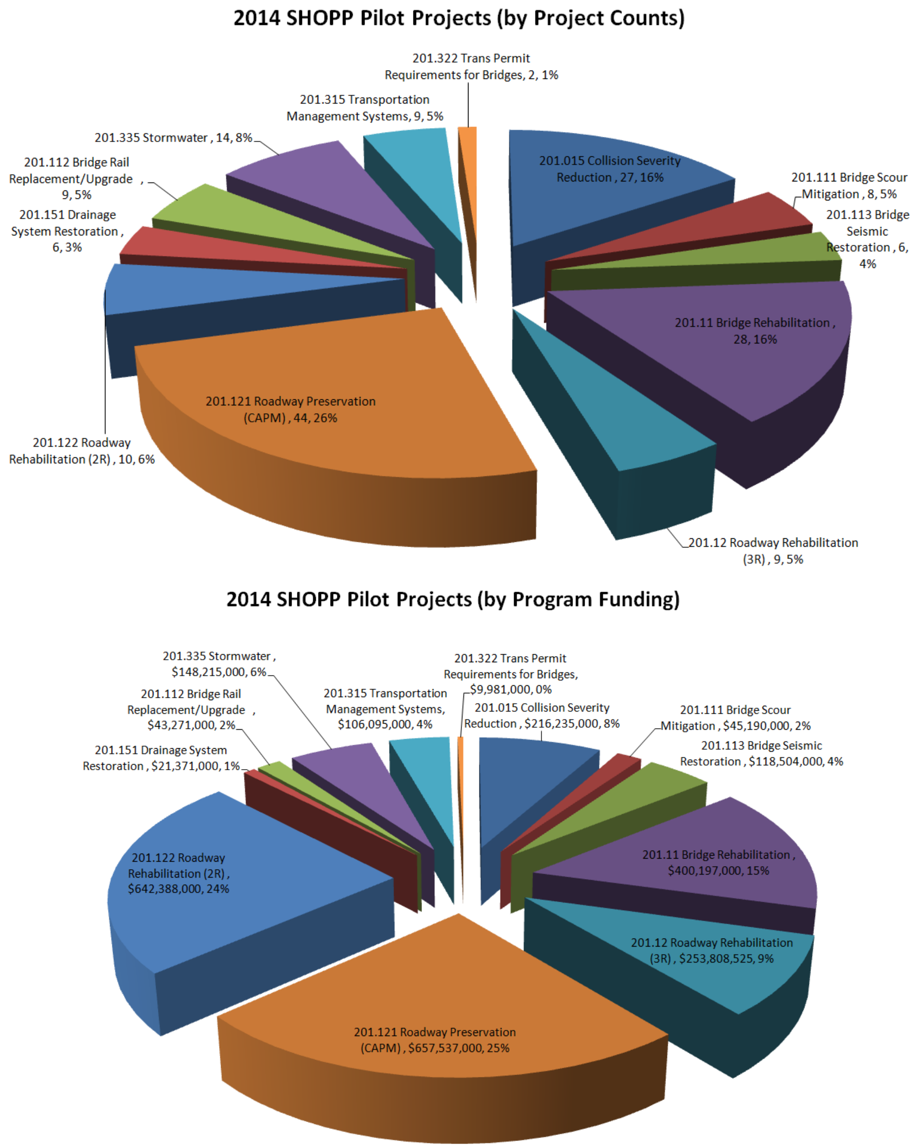


Figure 6-1 – Distribution of Projects by Counts and Funding

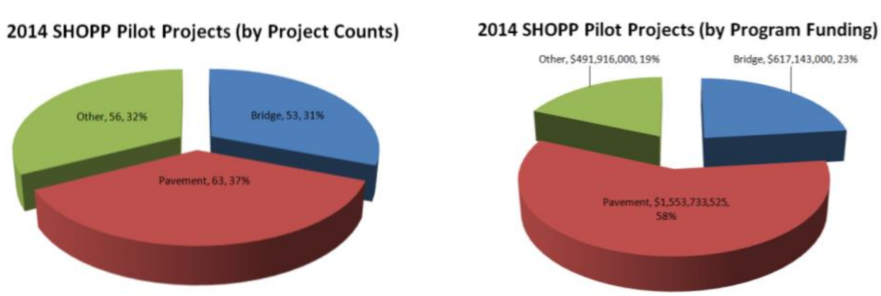


Figure 6-2 - Distribution of Project Types by Counts and Funding

There are a couple of aspects about the portfolio of projects used in the study that are worth noting. They have a significant influence the outcomes and priorities produced by the Pilot Project tool:

- Pavement projects comprised over half (58%) of the project portfolio – $1.6 billion of the $2.7 billion portfolio of 2014 SHOPP projects. The remainder is split between bridge projects (23%) and all other projects (19%).
- 13 programs were not represented in the portfolio, such as facility-related projects.

6.2. Observations on New Prioritization Outcomes

Prioritization outcomes from the new process are highly dependent upon the weights set for the sub-models. In order to make initial observations about the prioritization outcomes, the weights for all sub-models were set to the maximum value of 100. In practice this is not how one would carry out a prioritization task, as more careful assignment of weights by a more rigorous process (e.g., swing weighting) would be carried out by decision makers. Given this initial assumption, observations are presented in the following sub-sections.

6.2.1. The Effects of Weighting on Perceived Strategic Alignment

As implemented in the Microsoft Excel tool, the presentation of the Department's strategic goals and their relationship to fundamental objectives and sub objectives can lead to some confusion. Some goals have more objectives than others. Some of the objectives have sub-objectives while others do not. As a result, when the sub-model weights are summed within a goal, some goals appear to be more heavily "weighted" than others. In the case where all weights are set to 100 (as shown in Figure 6-3), this could lead to an interpretation that the Department values sustainability, livability, and economy over safety and health.

Goal	Goal Weight	Fundamental Objective	Objective Weight	Sub-Objective	Benefit Sub-Model	Swing Weight
Safety and Health	200	Minimize injuries and fatalities of workers	100		Worker Safety Projects	100
		Minimize injuries and fatalities of users	100		User Safety Projects	100
Stewardship and Efficiency	200	Minimize cost to taxpayers	200	Minimize cost of preserving and maintaining existing highway infrastructure	Asset Preservation	100
				Minimize costs to users of the highway system	Vehicle Operating Costs	100
System Performance	300	Minimize inconvenience	200	Minimize travel time for users of the highway system	Travel Time	100
				Maximize travel reliability for users of the highway system	Traveler Information	100
		Maximize quality of travel for all modes	100		Ride Quality	100
Sustainability, Livability, and Economy	400	Minimize disruption of the economy	100		Freight Corridors	100
		Minimize damage to environment	200	Minimize negative health impacts to users, fauna, and flora resulting from air quality degradation	GHG Emissions	100
				Minimize negative impacts to users, fauna, and flora resulting from water quality degradation	Water Quality	100
		Maximize equity and access to multimodal	100		Access to Transit	100

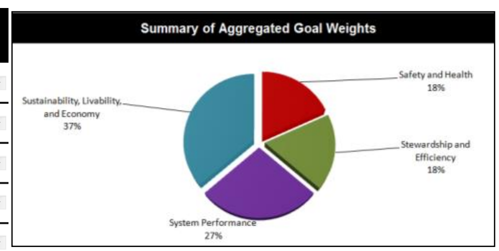


Figure 6-3 – Weighting and Strategic Alignment

The reason for this issue lies in the calculation framework behind the value function. As described in Section 4.2, the model uses a weighted sum calculation based on the sub-model component values. There is no consideration for goal weights in the calculations. The presentation of goal weights serves only as a presentation mechanism, not a calculation constraint. There are likely a number of ways to mitigate the confusion that this causes. A couple of ideas to pursue in future iterations of the tool:

- Dissociate the fundamental objectives from Department goals, and, instead, organize objectives around broader goals. This type of approach was recommended by Merkhofer early in the project.
- Create weights for sub-objectives and objectives that are used in the value function calculation to reflect the goal weights. The sub-models for the sub-objectives would then be handled similar to a constructed metric where multiple calculations are combined to represent the value of a single objective.

6.2.2. Prioritization Bias Tied to Project Cost

As a project's value-to-cost ratio is directly calculated using the project cost as a denominator, it was important that the value be scaled to be proportional relative to the size and scope of the project. The project magnitude scaling factor, described in an earlier section, was an attempt to capture and account for this effect.

The effectiveness of using the project magnitude scaling factor was examined using the project priorities established for the special case where all weights are set to 100. A breakdown of average, maximum and minimum project costs for quartile groupings of projects are presented in Table 6-2.

Table 6-2 - Project Costs by Quartile Grouping

Quartile	Average (mil)	Max (mil)	Min (mil)
First	$6.9	$30.5	$0.4
Second	$14.0	$33.0	$1.9
Third	$21.3	$101.2	$2.4
Fourth	$20.3	$183.9	$2.0

Observations are as follows:

- The most costly project ($183.9mil) was ranked in the lowest 25% of project priorities. The least costly project ($0.4mil) was ranked in the top 25% of project priorities.
- The average and range of project costs in the top 50% of project priorities were significantly lower (by approximately a factor of 3x) than those in the lower 50%.

The statistical analysis clearly suggests that there is a bias in the resulting project prioritization outcomes which favor lower cost projects. However, it is not clear whether this bias is a direct result of an inadequate mechanism to account for project magnitude, or if this is a validation of an assertion that many of the lower cost projects provide more benefit. Additional research on this observed bias is recommended.

6.2.3. Prioritization Bias Tied to Project Type

The type of project or asset (e.g., pavement, bridge, etc.) is expected to have a large influence on its ranking in the overall prioritization. This is in part due to the value function sub-models and the emphasis on data availability. In the development of the sub-models, the team discovered that many of the objectives could be tied to a benefit calculated from a specific data set. This was the case, for example, where different types of benefits were calculated using pavement smoothness (i.e., IRI). This could result in double-counting of benefits, leading to a bias in project priorities.

In order to examine this potential bias further, statistics for quartile groupings were generated. That is, statistics for the top 25% projects in rank order are calculated. Statistics for the 2nd, 3rd, and 4th quartile groups of ranked priorities are also calculated. For each quartile group a breakdown by percentage of primary asset/project types (bridge, pavement, and other projects) is calculated. Figure 6-4shows the percentage of funding for the entire portfolio of projects based on project and asset type. (Note, this is the same information that was presented in Figure 6-1 earlier as a pie chart.)

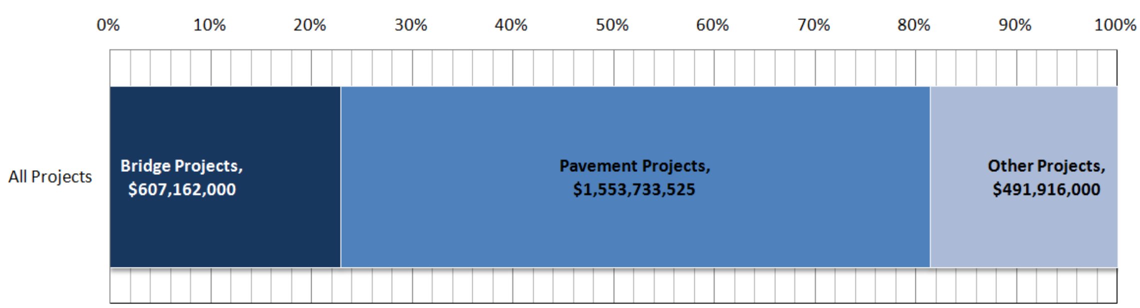


Figure 6-4 - Funding Breakdown for All Projects by Project and Asset Type

The breakdown of funding for each of the four quartiles can be plotted in a similar fashion, as presented in Figure 6-5.

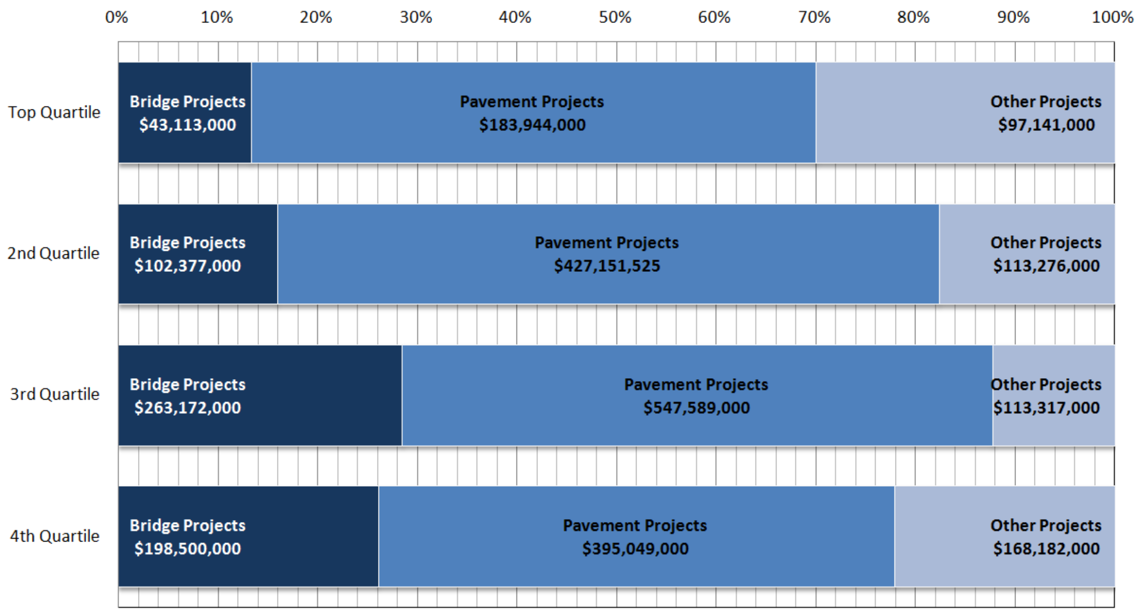


Figure 6-5 - Funding Breakdown for Priority Quartiles by Project and Asset Type

An examination of the distribution of funding by quartiles leads to a number of key observations:

- In the top 25% ranked projects, "other projects" constitute a significant portion of the overall portfolio. In this Pilot Project, these "other projects" include 201.015 Collision Severity Reduction, 201.151 Drainage System Restoration, 201.335 Storm Water, and 201.315 Transportation Management Systems. This could be expected, as many of these "other projects" include the lower cost projects that deliver relatively high benefit.
- The proportion of bridge projects ranked in the lower 50% is nearly double that of the upper 50% ranking. The shift in the proportion of bridge projects is mostly offset by the increase in proportion of other (non-pavement) projects. The rationale behind this shift in proportion of bridge projects across quartiles is not fully understood. Additional analysis of this observation is needed to determine if this is a true bias resulting from the value function calculation.
- Pavement projects fall within a narrow range of 52% to 66% percent across all quartiles. This is consistent with the fact that 59% of the full 2014 SHOPP portfolio are pavement projects. This seems to suggest that pavement projects are uniformly ranked within the overall portfolio. In other words, there doesn't appear to be a bias in the ranking of pavement projects.

6.3. Comparison of New Versus Existing Project Priorities

A comparison of the new versus the existing project priorities was carried out using the rankings derived for the sample set of 2014 SHOPP projects where all objective weights were set to 100. Although this particular analysis represents an atypical weighting scenario, it helps illustrate how the new MODA-based paradigm influences overall project priorities.

Table 6-3 - Comparison of New vs Existing Project Priorities

Program	New Process			Existing Process			
	Projects	Funding	Percent of Funds	Program Priority	Projects	Funding	Percent of Funds
201.015 Collision Severity Reduction	17	$110,480,000	6.9%	2	27	$216,235,000	25.7%
201.111 Bridge Scour Mitigation	5	$26,370,000	1.6%	3	8	$45,190,000	7.6%
201.113 Bridge Seismic Restoration	4	$61,855,000	3.8%	4	6	$118,504,000	5.7%
201.110 Bridge Rehabilitation	16	$253,053,000	15.7%	5	28	$400,197,000	26.7%
201.120 Roadway Rehabilitation (3R)	8	$207,951,525	12.9%	6	5	$136,453,000	4.8%
201.121 Roadway Preservation (CAPM)	43	$622,119,000	38.6%	6	25	$343,979,000	23.8%
201.122 Roadway Rehabilitation (2R)	5	$188,108,000	11.7%	6	6	$383,990,000	5.7%
201.151 Drainage System Restoration	4	$11,431,000	0.7%	7			
201.112 Bridge Rail Replacement Upgrade	2	$4,921,000	0.3%	8			
201.335 Storm Water	9	$59,579,000	3.7%	9			
201.315 Transportation Management Systems	8	$64,670,000	4.0%	10			
Summary by Program/Asset Type							
Bridge Projects	27	$346,199,000	21%		42	$563,891,000	34%
Pavement Projects	56	$1,018,178,525	63%		36	$864,422,000	53%
Other Projects	38	$246,160,000	15%		27	$216,235,000	13%
Totals							
Total Number of Projects		121				105	
Total Project Portfolio Value		18622				16699	
Total Portfolio Funding		$1,610,537,525				$1,644,548,000	

A summary of the results of the comparison is presented in Table 6-3 - Comparison of New vs Existing Project Priorities. The top section of the table presents a breakdown of funding subtotals within each of the existing SHOPP programs. A total of 11 SHOPP programs are listed, as the 2014 SHOPP sample of projects only represented these 11 programs. The center section of the table summarizes these same funding subtotals based on generalized asset types, namely bridges, pavement, and other. The bottom section of the table summarizes key figures for the overall portfolio of projects funded, given a scenario where the budget is constrained to $1.6mil from a pool of projects totaling $2.7mil.

Under the existing SHOPP process, projects are funded based solely on the program priority. Projects are funded in their program rank order until funding limits are reached. As noted in earlier sections, Priority 1 projects were not considered for the pilot project, and are therefore not shown. Projects in program Priority 2 through 6 are funded under this existing process. Projects in lower ranked programs are not funded, as the $1.6mil is fully expended in this scenario. The portfolio of funded projects is comprised of a total of 105 projects, with a cumulative portfolio value of 16,699.

Under the new MODA-based process, projects are prioritized based on the calculated project value with consideration of project cost. The project value-to-cost ratio then determines the rank priority. In this scenario projects across all programs are funded to some level based on the available $1.6mil. The portfolio of funded projects is comprised of a total of 121 projects, with a cumulative portfolio value of 18,622.

Two key observations result from this comparison:

- **More projects across more programs are funded.** The new process results in roughly 20% more projects being funded for the $1.6mil in available funds.
- **More value is realized for the same funding.** The new process yields an approximate 12% increase in portfolio value vs the existing process for the same $1.6mil in available funds.

Although these observations remain relevant, even in alternative scenarios where weighting has been adjusted, caution should be used in the interpretation of these results. As stated in earlier sections, significant limitations exist in approach that require more consideration – e.g., the value function sub-model calculations, biases from project magnitude, data availability, limited sample of projects, etc.

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7. Summary and Recommendations

Throughout this report, observations and issues encountered over the course of the project have been cited. This section presents a summary of the key challenges encountered and puts forth recommendations for application of the prototype method and tool moving forward with future SHOPP cycles.

7.1. Challenges and Limitations

As the Core Team progressed with developing the project prioritization framework, it became apparent that there were significant challenges to developing a useable framework. A number of assumptions needed to be made to continue the development process while working within the short time frame. Some of the more significant challenges and limitations are presented in this section.

7.1.1. Data Availability

Because the SHOPP Pilot Project needed to be executed quickly and tested against hundreds of projects from the 2014 SHOPP, data availability proved to be one of the most significant challenges. The Core Team developed a value function calculation framework that was entirely data-driven, eliminating the need to elicit value judgment scores for individual projects. This was done by design to reduce subjectivity from the scoring process to the extent possible.

As described in Section 5, the data sets that were readily available to team were typically in the form of spreadsheets, databases, and the Department's geospatial data libraries. Although the combination of data sets provided a reasonable basis to carry out many of the calculations, a number of errors, omissions, and misrepresentations were likely introduced into the Pilot project's prioritization outcomes due to the following reasons:

- **Project specific data from Project Initiation Documents (PIDs) were not used.** Although project specific data was available within PIDs, the PIDs themselves and their data were not in a format that could be readily parsed. Furthermore, the sheer number of PIDs that would need to be individually parsed was such that it was not feasible within the scope of the pilot project to carry out this task.
- **Projects with insufficient location information were omitted from consideration in the pilot.** A significant number of ITS and bridge projects included work at disparate locations (and sometimes on different highways). These projects were often reported only by district, county, and route. Since the geospatial analysis required reasonably good project location limits, these projects with "various" locations could not be analyzed.
- **Incorrect inferences are likely as a result of the geospatial analysis and the resulting association of attributes.** In some of the benefit calculations, scoring was based on the proximity of facilities relative to each other. For example, in the calculation of benefit for transit interconnectivity, the proximity of transit stations to the project limits was used. Although this

approach adequately identifies projects with transit stations within the project limits, it does not capture the degree to which the work actually improves transit interconnectivity. In some instances it is possible that the work results in no benefit in this regard.

Most of these data-related issues could be reasonably addressed in the future with more time and a carefully constructed process to parse data from PIDs.

7.1.2. Over-Simplification of Complex Correlations

The project prioritization framework developed for the Pilot Project likely over-simplified many complex correlations. In some instances the simplifications were applied due to the lack of availability of data. For example, program codes were used in many calculations as a proxy to infer benefit provided by a particular type of project. In other instances the simplifications were necessary in order to reduce the complexity of a more rigorous benefit calculation based on multiple factors. For example, IRI was used as the sole metric in the calculation of GHG emissions reduction due to its significant overall impact, even though there are numerous project aspects that can also contribute to GHG emissions reduction (e.g., green fleet, use of LED lights, concrete and asphalt materials, etc.).

The choices made in the calculation framework likely have an impact on the overall determination of project value. However, the influence of these tradeoffs on the resulting project priorities could not be quantified by the team. Additional consideration of this aspect is needed.

7.1.3. Incomplete Set of Sample Projects

The Core Team used a sample list of over 200 projects from the 2014 SHOPP cycle. This project list excluded non-discretionary projects (e.g., safety and mandated projects). The assumption is that these projects are automatically funded and must go to Project Delivery due to legal mandates. Also, some project types (e.g., facilities) are under-represented in the sample project set.

7.2. Recommendations

Based on the findings during the SHOPP Pilot Project, the Core Team has developed the following recommendations for moving forward with an improved project selection process in future SHOPP cycles. The recommendations provided here will require a significant amount of staff time and resources to support fundamental changes in the way we do business, including communication, implementation, training, and policy. Furthermore, a significant level of effort will be required to refine the project prioritization framework and implementation of software tools.

7.2.1. Recommendations for the 2016 SHOPP

Recommendations to be applied to the 2016 SHOPP Development process are as follows:

- Identify the method to capture the data to capture more complete information necessary to carry out an analysis with the Pilot Project *Microsoft Excel* Tool.
- Assess the effectiveness of the enhanced data capture methods and make recommendations as necessary.
- Identify the necessary data to support the next generation decision-making framework and tool.

7.2.2. Recommendations beyond the 2016 SHOPP

Recommendations to be applied to the SHOPP Development process are as follows:

- Evaluate the asset management process and determine how this prioritization framework integrates into the overall SHOPP process.
- Develop an automated data collection tool (that integrates with existing geospatial asset inventories) to capture more complete information necessary to drive the prioritization process.
- Migrate the SHOPP Pilot Project *Microsoft Excel* Tool to a web-based tool that can handle the future data requirements and other feature enhancements. It is recommended that the development of the web-based tool begin relatively soon due to the amount of time for developing a project workplan, developing a Feasibility Study Report, and actual development and implementation of the tool.
- Further research is needed into the MODA framework and its application to SHOPP project prioritization. It is recommended that Caltrans initiates a Research Project through the Division of Research, Innovation, and System Information.

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8. Acknowledgements

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Core Team Management

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Core Team

Donna Berry - Division of Transportation Programming
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Loren Turner - Division of Research, Innovation, and System Information

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9. Appendix

The following documents are included in the Appendix:

"Recommendations about Decision-Making for Caltrans SHOPP Project Prioritization Final Report for Service Agreement Number U5-652785-00"
(September 30, 2014)
By Ralph L. Keeney and Johannes Siebert, U.S. Marketing and Decisions Group, Inc.

Project Prioritization Framing Workshop: Executive Summary and Recommendations
(October 1, 2014)
Prepared by Lee Merkhofer, Ph.D., Lee Merkhofer Consulting, www.prioritysystem.com

Consultation on Caltrans SHOPP Project and Decision Methodologies
(February 18, 2015)
Prepared by Lee Merkhofer, Ph.D., Lee Merkhofer Consulting, www.prioritysystem.com

Recommendations about Decision-Making for Caltrans SHOPP Project Prioritization

Final Report for Service Agreement Number U5-652785-00

by

Ralph L. Keeney and Johannes Siebert

U.S. Marketing and Decisions Group, Inc.

September 2014

The purpose of this report is to make suggestions that would help (a) bring SHOPP decision-making and action more consistent with the new Caltrans vision, mission, and goals, and (b) help the core project team frame their next steps to narrow the scope of what the team should do. Section 1 summarizes the process that we used to develop the product. Section 2 offers suggestions pertaining directly to the tasks in our contract concerning the decision methodology to evaluate prospective SHOPP projects. Section 3 comments on other issues raised by members of Caltrans regarding SHOPP.

1. Review Process

We first reviewed previously provided material that contained information about SHOPP planning and decision-making and a comprehensive list of criteria used in evaluating projects to be carried out with SHOPP funds. Then, on September 22 we had several meetings with groups of Caltrans employees in Sacramento to discuss SHOPP issues. These meetings involved the following individuals:

1. Initial meeting with the core project team: Steve Guenther, Ray Patron, Donna Berry, Loren Turner.
2. Steven Keck (Finance), Karla Sutliff (Project Delivery).
3. Steve Takigawa (Maintenance), Kome Ajise (Planning).
4. Amarjeet Benipal (District 3 Director), Andre Boutros (California Transportation Commission), Ryan Chamberlain (District 12 Director).
5. Follow-up meeting with the core project team.

The topics were to better understand how the SHOPP decision making process works and to gather aspirations about improvements that Caltrans would like in the process. The composition of the discussion participants ensured that we heard a comprehensive overview about Caltrans from an organizational perspective.

2. Comments on the Decision Methodology to Evaluate Perspective SHOPP Projects

Four issues of the SHOPP decision methodology are discussed. They concern selection of the decision criteria for SHOPP projects, specifying metrics for these criteria, prioritizing the criteria, and evaluating prospective projects in terms of the multiple criteria.

Identifying an Appropriate Set of Criteria to Evaluate SHOPP Projects

To evaluate SHOPP projects reasonably and justifiably, it is necessary to identify an appropriate set of criteria to evaluate those projects.

In practice, the process of gathering evaluation criteria can often be characterized by separate phases. In a first phase, criteria that have been previously used in similar decision situations or that are easily available are identified. In a second phase, careful thinking and interviews with experts (individuals with responsibilities for specific processes, program managers, etc.) often lead to a more comprehensive set of criteria. The combined list is frequently large as was the case with the current SHOPP list of criteria. Based on the provided material and our discussions, we believe that the set of criteria identified by the Caltrans SHOPP project covers most of the important criteria. However, such a comprehensive list of criteria is only of limited use to evaluate projects.

In a third phase, the criteria have to be reduced to a reasonable number. In general, a first step is to eliminate redundant criteria. This occurs when the same or a similar criterion is listed in more than one category [*reduce fatalities and injuries* (from Safety, Health, and Equity) and *reduce fatalities, severe injuries, and collisions* (from Stewardship, Efficiency, and Multimodalism)] or the same concern is expressed with two criteria [*effectively manage taxpayers funds* and *maximize the use of available financial resources*, criteria 2 and 3 in Stewardship, Efficiency, and Multimodalism].

A second method to reduce the number of criteria is aggregation. For example, highly specific criteria could be *minimize forest clearing* or *minimize impact on native plants*. These and other criteria could be aggregated to *minimize impacts of flora*. By including animals, an even broader criterion could be *minimize negative impacts on flora and fauna*. Broadening a bit further, we could have a criteria called *minimize environmental impact*.

The most important concept to reduce the number of criteria needed to evaluate projects uses the distinction between means and fundamental criteria. Means criteria are important because they help to achieve the fundamental criteria. For example, *improve pavement* is a means to *minimize accidents* which is a means to *minimize loss of life*. *Minimize loss of life* is a fundamental criterion because it is one of the things that we ultimately value. Evaluation of alternatives using only fundamental criteria includes all of our ultimate concerns. Including additional means criteria in an evaluation leads to double counting.

Most of the criteria Caltrans gathered for the SHOPP project are means criteria. One could go through a thorough analysis of all of the Caltrans SHOPP criteria to identify the fundamental criteria. However, the fundamental criteria for the Caltrans SHOPP project are essentially already specified in the new vision, mission, and goals of Caltrans. Directly from the goals, the fundamental criteria to evaluate potential SHOPP projects should be *maximize safety* from 'Safety and Health', *minimize costs* from 'Stewardship and Efficiency', and *minimize disruption of the economy* and *minimize inconvenience*, both from 'Sustainability, Livability, and Economy'. These four criteria capture most of what Caltrans can influence in terms of the first three goals. The other two goals, 'System Performance' and 'Organizational Excellence', are influenced more by the implications of the totality of Caltrans actions than by the selection of specific projects. It is useful to note that sometimes it is useful to divide a fundamental criterion into components. For example, the objective *maximize safety* could be replaced with *minimize injuries* and *minimize fatalities.*

Selecting Appropriate Metrics for Criteria

The decision frame for any analysis is defined by the set of fundamental criteria and the set of alternatives for achieving those criteria. To describe the consequences of alternatives and prioritize different criteria, it is necessary to identify a metric to measure each criterion. The terms *attribute* and *performance measure* are often used as synonyms for metric.

There are basically three different types of metrics: *natural metrics*, *constructed metrics*, and *proxy metrics* (Keeney 1992). In some cases, an metric may be a hybrid of two of these types, but this trichotomy is useful for discussing features of metrics.

Natural metrics are in general use and have a common interpretation. For a criterion such as *minimize cost,* a natural metric is *cost measured in dollars*. For a criterion such as *minimize fatalities*, a natural metric is *number of fatalities avoided*. Most natural metrics can be counted or physically measured. They also have the important property that they directly measure the degree to which a criterion is met.

Proxy metrics share certain qualities of natural metrics. A proxy metric usually involves a scale that is in general use that can be counted or physically measured. The difference is that it does not directly measure the criterion of concern. For a decision involving highway improvements, an example of a proxy metric for the criterion *minimize fatalities* is the *number of vehicle accidents avoided*. Certainly the number of vehicle accidents is related to the number of fatalities, but it does not directly measure those fatalities. A proxy metric is less informative than a natural metric because it indirectly indicates the achievement of the criterion. Proxy metrics typically are used when it is either difficult to gather information about how well various alternatives measure up in terms of a possible natural metric or when it is politically sensitive to use the natural metric, as may be the case with *number of fatalities avoided*. However, in such a case, the importance of an avoided vehicle accident depends on the avoided fatalities due to that avoided accident. Hence, the relationship between accidents and fatalities is still critical to understand and incorporate in any logically sound analysis.

A constructed metric is sometimes developed to measure directly the achievement of a criterion when no natural metric exists. For example, suppose that you thought that the proxy metric *number of vehicle accidents avoided* was inappropriate because it implicitly assumes that all vehicle accidents are equivalent. You could categorize vehicle accidents in two groups such as head-on collisions, other collisions, and single vehicle accidents. Then you need to relatively prioritize each of these. Suppose you analyze data and decided that a head-on collision is twice as bad as a collision that was not head-on and ten times as bad as a single vehicle accident. Now define x, y, and z respectively as the number of head-on collisions, other collisions, and single vehicle accidents avoided. With the data above, the metric c defined by $c = x + 0.5y + 0.1z$ is the equivalent number of head-on collisions avoided. This is a simple constructed metric that weights different types of accidents. Note that this constructed metric is similar to the common grade-point average used to indicate performance in school.

In evaluating alternatives, it is appropriate to address the issue usually referred to as life-cycle costs. To do this, one can use the full project cost and then also the full consequences of that financial investment. For example, if the project has an effective life of 10 years, estimates of the fatalities avoided and the other consequences should all be specified for the complete tenure. If desired, one can also convert both costs and other consequences to an annualized basis.

Prioritizing Criteria

When one refers to a decision problem as having multiple criteria, it usually means that there are multiple fundamental criteria. A decision with multiple means criteria that influence a single fundamental criterion, such as *maximize profit*, is not a multiple criteria decision. In multiple criteria decisions, the logical prioritization of the fundamental criteria is necessary to evaluate alternative courses of action.

Many people feel that prioritizing criteria is a straightforward intuitive task, namely to simply ask the decision-maker to prioritize the criteria for a problem. However, such a lack of attention in prioritizing criteria results in a number of important logical and practical errors summarized in Keeney (2005). Most of these errors result from an ambiguous meaning for the concept of 'importance of a criteria' and the lack of a logical theoretical basis for the prioritization task.

There is no clear meaning for the concept that 'one criterion is more important than another criterion'. There is a clear meaning for the concept that 'a specific change in the level of achievement on one criterion is more important than a specific change in the level of achievement on another criterion'.

To illustrate this critical point, suppose there are only two criteria for evaluating highway projects, *minimize accidents* and *minimize costs*, measured by metrics *number of accidents avoided* and *project cost in dollars*. You are asked which is more important, accidents or costs, and you answer accidents. Does that mean that one accident is more important than $1 billion? Probably not, as you likely think $1 billion is more important than one accident. Does it mean that one accident is more important than $1000? It does not mean this either, although in this case you may feel that one accident is more important than $1000.

The point is that you absolutely must consider the amounts of different metrics in order to logically prioritize criteria. You may feel that one collision is indifferent to about $2 million, in which case the priority of $2 million should be equivalent to the priority of one accident. You may also than reason that the priority of one accident is twice the priority of $1 million and that the priority of 100 accidents is equal to the priority of $200 million.

If these were the only two criteria for evaluating projects, a project that cost $120 million and avoided 100 accidents would be desirable. The reason is that the positive equivalent value of avoiding 100 accidents is equivalent to the value of $200 million and the cost of the project is less than that, namely $120 million. Indeed, you could conclude that the net value of the project is equivalent to saving $80 million (*i.e.* $200 - $120 million).

Evaluating Prospective Projects in Terms of Multiple Criteria

The logical way to evaluate prospective projects using the prioritized criteria can be illustrated using three fundamental criteria, namely *minimize accidents*, *minimize cost*, and *reduce negative impacts on the California economy*. Suppose we select metrics *a = number of accidents avoided*, *c = cost in millions of dollars*, and *e = number of avoided days of delay delivery for large transportation vehicles (i.e. trucks)*. To prioritize these metrics, we will use units of each of the metrics as indicated in Table 1. The basic information is provided in the first four columns of the table. The task is to specify the relative importance of the changes of going from no impact to a unit impact on each of the metrics. Details on techniques to do this in a logically sound manner are discussed in numerous sources including Keeney and von Winterfeldt (2007). Regardless of how it is done, it relies on value judgments.

Table 1. Framework for Setting Priorities Necessary for an Evaluation Model.

Objectives	Metrics	No Impact	Unit Impact	Judged Priority
Minimize accidents	a = number of accidents avoided	0	1	2
Minimize cost	c = cost in millions of dollars	0	1	1
Reduce negative impacts on the California economy	e = days of delayed delivery avoided	0	1	0.005

Suppose it is decided that one accident is as important as $2 million and one day of delay of a delivery is valued at $5000. Then for consistency, one accident must be equivalent to 400 days of delayed delivery. If this implication seems out of line with the feelings and thoughts about importance of those provided value judgments, adjustments need to be made until the priority seem reasonable. It is important to ensure that these priorities are in line with the intentions of the mission and vision of Caltrans, as the qualitative language there the basis for this quantification. If the stated equivalent values above remain, one can normalize the priorities by setting any one of the metrics priority to 1.0 or by making the three priorities sum to 1.0 or 100. It is often convenient to normalize this by setting one unit of the cost metric to 1.0, as costs are easily understood and fungible. In this case within the priority of $1 million is 1.0, so the priority of one accident 2.0 in the priority of one day of transportation delay is 0.005.

Projects can now be evaluated with an objective function that is either a utility function or a measurable value function (see Keeney and Raiffa, 1976; Dyer and Sarin, 1979). As the concepts are similar, we will use the utility function here to indicate those concepts.

Let u be a utility function for evaluating projects in terms of the three fundamental criteria discussed above, namely *minimize accidents*, *minimize costs*, and *reduce negative impacts on the California economy*. Now, the anticipated impact of a project can be described by the consequence (a,c,e). The utility $u(a,c,e)$ of this specific project is a number, which is an indicator of the desirability of consequence (a,c,e). If (a_1,c_1,e_1) is preferred to (a_2,c_2,e_2), then $u(a_1,c_1,e_1) > u(a_2,c_2,e_2)$ and vice versa. If one begins at a consequence (a_0,c_0,e_0), it is logical to say that an improvement to (a_1,c_1,e_1) is more important than an improvement to (a_2,c_2,e_2) if and only if $u(a_1,c_1,e_1) > u(a_2,c_2,e_2)$.

A utility function also allows one to characterize all the value tradeoffs among fundamental criteria that are necessary to consider in a particular decision. Value tradeoffs specify how much a specific achievement in terms of one criterion is worth in terms of achievement on another criterion. Suppose, $u(a_1,c_1,e_0) = u(a_2,c_2,e_0)$, so the consequences (a_1,c_1,e_0) and (a_2,c_2,e_0) are indifferent to each other. Then, with e_0 fixed, a change from a_1 to a_2 is compensated for by a change from c_1 to c_2, which is referred to as a value tradeoff or and even swap (Hammond et al., 1999).

The set of fundamental criteria is composed of mutually exclusive components of the overall value of potential consequences. This provides the logical basis for the utility function to be represented by additive form (Keeney, 1981), which for our illustrative problem is

$$u(a,c,e) = w_A u_A(a) + w_C u_C(c) + w_E u_E(e), \qquad (1)$$

where u_A, u_C, and u_E are component utility functions and w_A, w_C, and w_E are weighting factors calculated from the priorities of the criteria.

Furthermore, for evaluating alternatives to be included in a portfolio of projects, it is reasonable that the component utility functions are linear. Hence,

$$u_A(a) = a, \quad u_C(c) = c, \quad u_E(e) = e. \qquad (2)$$

It follows from (1) and (2) at an appropriate utility function is the additive function

$$u(a,c,e) = w_A\, a + w_C\, c + w_E\, e. \qquad (3)$$

As the weights are only relative, we can use the normalization in Table 1 and conclude that

$$u(a,c,e) = 2a + 1c + 0.005e. \qquad (4)$$

Equation (4) is appropriate for evaluating proposed projects.

3. Comments on Other Issues of Interest to Caltrans

The following includes some thoughts that relate the prioritization of SHOPP projects to other issues of importance to Caltrans.

How to Explain That an Evaluation Is Logical and Justifiable.

Selection of projects to pursue and communicating the process and its results to stakeholders are different decision problems with different objectives. The analysis for the selection has to be thorough and needs to take all relevant aspects into account in order to be logical or justifiable. If the selection of projects was not done in a logical manner, it would be extremely hard to justify. Such an analysis is often too complex for many stakeholders to readily understand. For this reason, one might also need to create a simplified version of the model to illustrate the information and logic used in the evaluation and decision process to all stakeholders and interested parties.

If the new Caltrans mission is the foundation to guide the selection of SHOPP projects, the task to justify the selection should be easier and better received.

Selection of Portfolios

The inclusion of projects in the SHOPP portfolio includes mandated and discretionary projects. The evaluation model may be thought to be useful only for evaluating discretionary projects. However, the same model could be used to evaluate mandated projects. If the mandates are consistent with the new Caltrans mission and vision, mandated projects should evaluate high enough that they should be funded in the portfolio even if they were not mandated. If some of these mandated projects are evaluated to be less beneficial to California than some discretionary projects that are not funded, this suggests that guidelines for establishing mandated projects should be reviewed.

How to Combine Projects to Get Benefits "More Bang for the Buck"/Creating Better Alternatives

No incentives or disincentives to promote cooperative projects to capture potential positive synergies results in lost opportunities. If the evaluation model incorporating the fundamental criteria is used to evaluate projects, it would not be too difficult to evaluate a bridges project, a separate but related pavement project, and a collaborative project on this pavement and bridge. Comparing the sum of the two independent evaluations to the evaluation of the collaborative project would indicate the potential additional value of the collaborative project. Demonstrating such implications of the current system may lead to, and perhaps hasten, positive changes that would facilitate pursuing collaborative projects.

Funding Projects on Facilities

Projects involving facilities should be included in SHOPP. In such a case, the priority of these projects logically should be evaluated with the same criteria as other SHOPP projects. However evaluating a facilities development project using the fundamental criteria with the evaluation function (4) is not practical, as the consequences (a,c,e) for a facilities project are extremely difficult to specify.

It may be useful for Caltrans to recognize a different decision, namely how to routinely include an appropriate amount of facilities development in its annual plans. It may be possible to clearly identify a minimum percentage of the budget that is required to support a sustainable level of performance on all SHOPP projects. Suppose a sound logical analysis demonstrated that on average at least 3% of the annual budget should be used to develop facilities to avoid a degradation in overall SHOPP performance. Then it is reasonable to have a set-aside budget for facilities of at least 3%. To evaluate appropriate facilities projects to fund, it would be desirable to have a logical and justifiable approach analogous to the approach discussed for evaluating maintenance and improvement projects above.

Managing When Project Cost Comes in Lower or Higher Than Expected

It is not possible to always forecast the exact cost of future projects. Yet, it seems as if there are difficulties that occur when there is a mismatch of the estimates and actual costs of the projects. Given that the circumstance seems to be common, it may be worthwhile to explicitly declare a Caltrans decision as ‘what can we do to lessen any negative impacts of a mismatch of estimated and actual costs’. The first step is to thoroughly identify the negative consequences of mismatches. From these, the objectives of this new decision can be identified, as they are essentially to reduce the magnitude of the negative consequences. Then, each objective can be used to stimulate thoughts about alternatives that may be useful to achieve such objectives. Next, appraise the alternatives intuitively or with some analysis and then implement any new alternatives identified as desirable.

Increase Funding for SHOPP Projects

Using the metrics of the fundamental criteria and the model (4), one can identify the net benefits to Caltrans of any desirable projects that could not be funded with current funds. This information could be used to illustrate the relevance of the consequences for the state of California in negotiations about increasing its SHOPP budget.

In addition, Caltrans may figure out the fundamental consequences of other government spending programs, especially for safety measured with fatalities and severe injuries. Such comparisons could reveal the effectiveness of spending more money on the SHOPP program. For example, if increases in health care costs save one statistical life for each $20 million invested and some additional SHOPP projects could save statistical lives for only $1 million each, that information may be viewed as a sound argument to increase SHOPP funding.

Another possibility is the following. Suppose it can be shown that a currently unfunded SHOPP project could increase total commerce in California by $5 billion over a ten-year period and that the state of California would receive additional tax revenue of $300 million in current dollars because of this increase in commerce. This may support an argument to fund an additional project the costing $120 million if that were the cost to fund this new project.

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Project Prioritization Framing Workshop

Executive Summary and Recommendations

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Tools for Difficult Decisions

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Executive Summary

- We conducted a one-day workshop to begin defining a framework for prioritizing SHOPP projects. The workshop included:
  - Training on the basic principles of project prioritization
  - An analysis of the pros and cons of alternative approaches to prioritizing transportation projects
  - Selecting a preferred approach to prioritizing SHOPP projects
  - Creating a charter to guide the development of improved prioritization capability
  - Specifying an objectives hierarchy, consisting of objectives structured in such a way as to support a defensible, accurate estimation of the value of candidate projects
  - Making preliminary choices regarding the "decision units" for the prioritization system
  - Training on influence diagrams, a tool used for identifying factors and metrics for evaluating the various types of project benefits, together with a sample application of the process to one type of benefit
  - A recommended path forward for continued development of improved prioritization capability

Key principles of project prioritization

- Projects should be ranked by the ratio of project value to project cost. Selecting projects from the top down until the budget is exhausted yields the value-maximizing portfolio of projects, assuming the projects are independent of one another
- The value of a project is the difference between the value that would result if the project is conducted and the value that would result if the project is not conducted
- Project value depends on the degree to which the project contributes to the achievement of different objectives. The objectives define different types of project benefits (e.g., safety benefit, environmental benefit, benefit to the users of the transportation system, etc.).
- The value of a project can be estimated by weighting and combining estimates of the different types of project benefits only if
  - the benefit types and objectives that define them are distinct and do not overlap or double count
  - the weights represent the value created per unit of benefit increase, not judgments about the relative importance of the objectives

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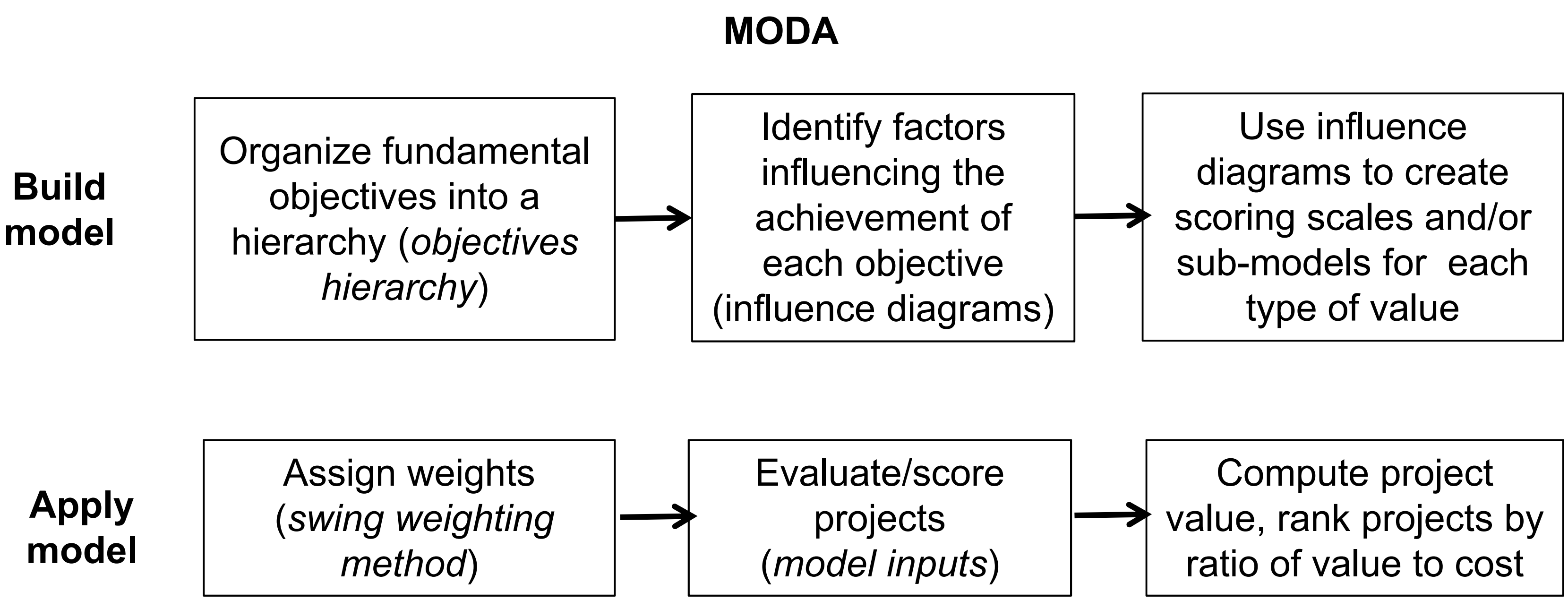
The methods SHOPP has been exploring to this point are not consistent with the key principles

- Too many criteria, many overlap and double count
- Equations for aggregating scores do not measure project value
- No accounting for loss of value that occurs if projects are not conducted
- Weights being assigned do not measure value per unit of score
- Ranking metric does not divide by cost to estimate “bang for the buck”

These methods cannot produce accurate or defensible project priorities

Our efforts to develop a prioritization process require a "fresh start"

- The approach consistent with key principles and viewed best-practice is known as multi-objective decision analysis (MODA)
- MODA is a formal process for building and then applying a project value model



MODA steps

Step	Output	Conducted or demonstrated in workshop?
1. Specify prioritization system design goals	Charter	Yes
2. Identify & structure objectives	Objectives hierarchy	Yes
3. Identify factors influencing each objective	Influence diagram	Yes
4. Identify those factors most impacted by project choices	Influence diagram drivers	
5. Develop scoring scales & equations for computing value	Initial quantification of of value model	
6. Create initial implementation of the model	Excel pilot model	
7. Specify weights & other model parameters	Weight assessment	
8. Test model to ensure inputs can be generated & validate outputs	Pilot test	
9. Make model refinements & provide "production version" software	Validated prioritization tool and process	

The Team created a charter to guide a MODA model development effort

Our goal is to develop and demonstrate a process for prioritizing SHOPP projects. The process should:

- Be based on best-practice and sound decision analysis science and is goal and objectives oriented
- Help us to communicate to stakeholders (e.g., visual)
- Be clear, understandable, transparent, and defendable
- Encourage more projects that meet multiple objectives (break down funding silos and the concept of individual programs) and develop a more well-rounded approach to selecting projects
- Align projects with the new Caltrans strategic goals, objectives, mission, and vision
- Clearly identify project values
- Gain support from internal and external stakeholders
- Recognize mandates and non-discretionary projects (though the value of doing mandated projects should be estimated as with other projects)

The ultimate tool and process should:

- Recognize that initial software may not require expensive, third-party models; vendor software can be selected after gaining pilot experience
- Recognize and value partnership funding
- Quantify project value accounting for the consequences of not doing projects
- Enable us to address Caltrans Improvement Project Workgroup 2 recommendations
- Help us optimize Caltrans limited resources to maximum benefit relative to Caltrans goals and objectives
- Be adjustable to respond to changes in the political and economic climate, while allowing for political override
- Incorporate input from all managers to develop a sense ownership
- Help determine and indicate where additional resources for SHOPP are needed

Schedule:

- We recognize the need to produce concrete process improvements within a couple months

In this one-day workshop we will

- Identify our project prioritization framework
- Identify prioritization approaches to avoid
- Identify next steps and a path forward

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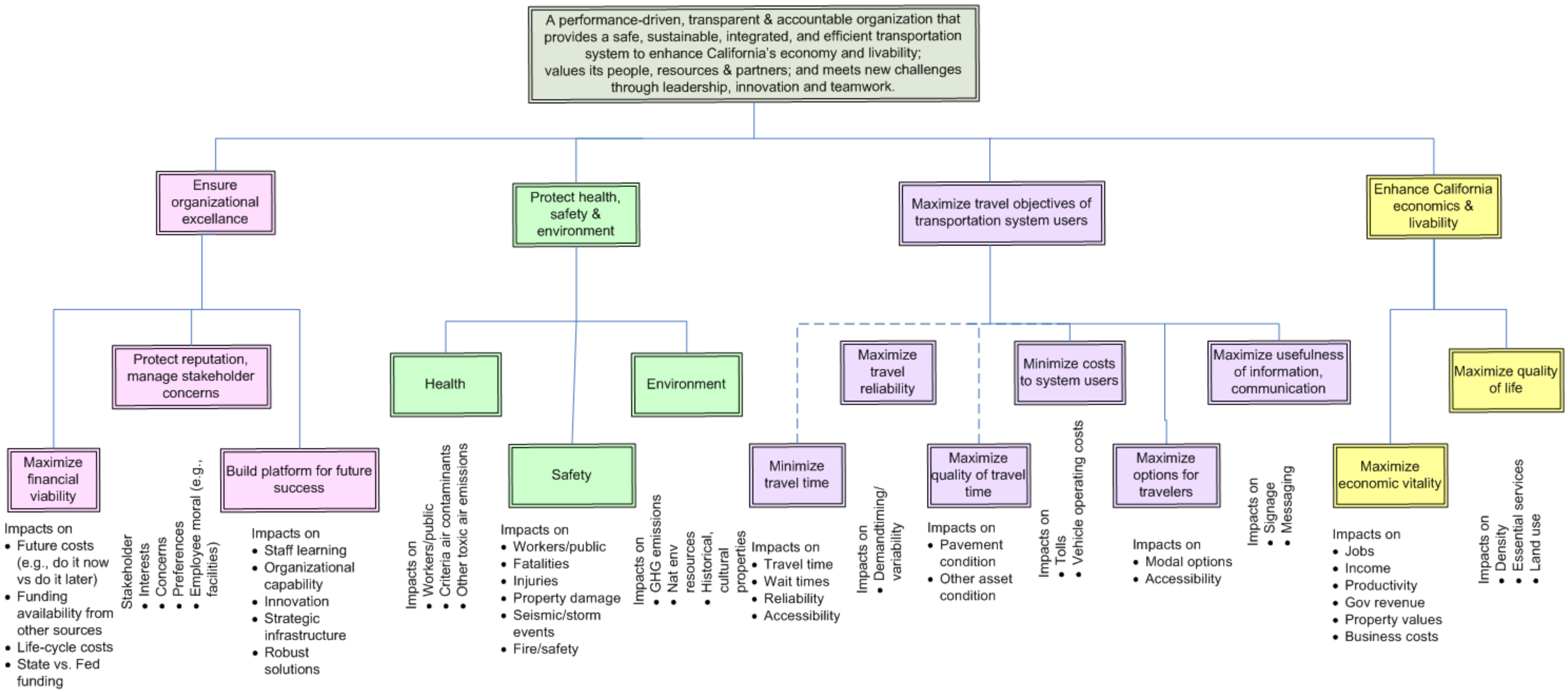
Following the MODA process, we produced a preliminary objectives hierarchy consisting of fundamental, non-overlapping objectives capable of being weighted and combined



Notes:

- Bulleting items indicate examples of influencing factors that projects might impact that could affect the achievement of the related objective. The lists are not meant to be exhaustive. Some influencing factors influence more than one objective (i.e., influencing the factor could simultaneously create multiple types of value).
- Sustainability is covered in part under "platform for future success, plus the understanding that project choices must continue over time to create value in all areas.

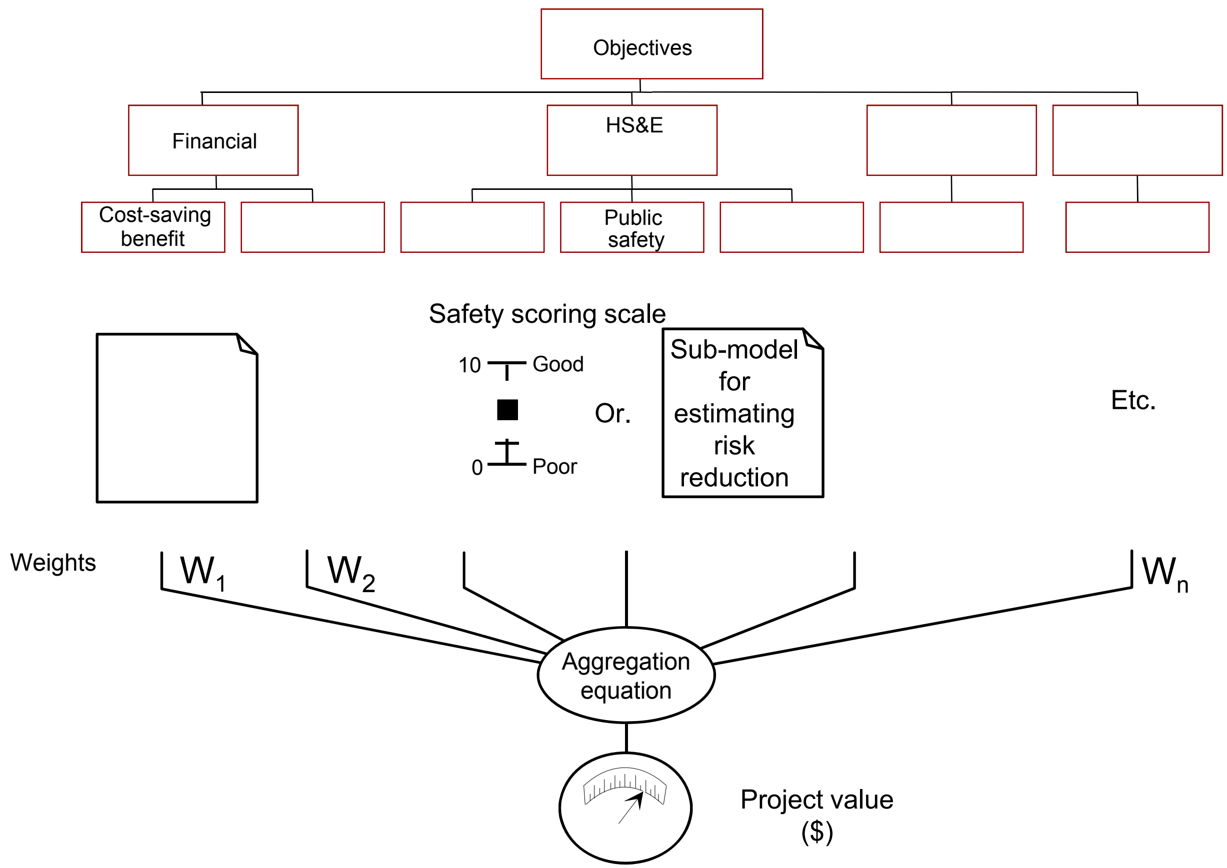
The objectives hierarchy provides the foundation for the quantitative prioritization model

1. ***Objectives identify the types of project benefits***

2. ***Benefits are estimated using scoring scales or sub-models***

3a. ***Benefits expressed in common units & aggregated using tradeoff weights***

3b. ***Non-additive value adjustments applied (e.g., risk, urgency)***



4. ***The ratio of value to cost is the metric used to rank projects***

Project value ÷ Project cost = Priority ranking metric

Confidential information

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Our recommendation is to complete the MODA framing process

- Review, validate, and complete the objectives hierarchy
- For each type of value in the hierarchy, create an influence diagram to identify the factors that must be considered when estimating that type of value
- Identify the drivers in each influence diagram; that is, those factors:
  - That may be impacted by projects and, if so, can significantly affect the achievement of the corresponding objective
  - That may be reasonably estimated based on available data or through informed judgments from knowledgeable staff without undo time or difficulty
- Provide simple, but well-defined scoring scales for documenting estimates
- Implement the resulting model for pilot testing using low-cost software for modeling and analysis (e.g., Excel)
- Test, refine, and apply the model to prioritize SHOPP projects

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Consultation on Caltrans SHOPP Project and Decision Methodologies

Consultant's Report

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Consultant's conclusions & recommendations

1. The Team has correctly identified and selected MODA as the best approach for SHOPP project prioritization
   - MODA, recommended by independent scientific organizations, has the capability to produce accurate funding recommendations that produce the greatest possible value for transportation system users, citizens and other stakeholders
   - Unlike the simplistic "weight-and-rate" approaches being used by some transportation agencies, a MODA model is logically defensible and can be improved over time as data and understanding improves
   - *"It is much better to do the right thing wronger than the wrong thing righter! If you do the right thing wrong and correct it, you get better."* Management Scientist Russell Ackoff

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Conclusions & recommendations (continued)

2. Established wisdom is that successfully creating a MODA model requires advanced training in multi-objective decision analysis
   - Although well-designed MODA models are often simple and intuitive, the process of developing a logically-sound MODA model is complex
   - Government and scientific organizations warn that MODA applications should only be undertaken with direction from specialists
   - Such specialists typically have Ph.D.-level education in decision theory and many years experience conducting real-world applications
   - *"Although well-regarded and effective, [MODA] is relatively complex and best implemented by specialists…."* Multi-Criteria Analysis Manual, Department for Communities and Local Government, Great Britain

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Conclusions & recommendations (continued)

3. Though the Team has not been directed by a MODA specialist, the Team has successfully created a Pilot Model that demonstrates what can be accomplished and indicates a path forward for obtaining the greatest benefit from the application of formal decision methods and tools.
   - Largely through self-study, the Team has achieved a remarkable level of understanding of MODA methodology
   - Though the current model can be improved and brought into better alignment with MODA best practice, the Team's results illustrate the MODA process and the main characteristics of a successful MODA application
   - Furthermore, the Team's efforts clarify the limitations associated with any formal model and the challenges involved for obtaining a comprehensive solution

Conclusions & recommendations (continued)

4. Based on the information provided, I believe the Team has successfully achieved all of the goals established for the effort:
   - Provide early guidance on application of decision methods and tools
   - Engage subject matter experts in the development of criteria, goals, and metrics
   - Produce a draft set of objectives applicable to the SHOPP project prioritization process
   - Provide insight on pros/cons of leading decision making methods
   - Inform executive management on the level of effort and resources required to carry out future project prioritization processes
   - Raise awareness of major issues and limitations associated with alternative decision making methods and software
   - Engage the expertise of decision analysis consultant(s)
   - Enhance decision-making knowledge for a core group of Caltrans staff

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Conclusions & recommendations (continued)

5. Consistent with the limits on expectations established for the effort, the Pilot Project has not and cannot:
   - Replace a comprehensive research effort that carefully considers decision making methods, tools, and applicability to Caltrans-specific use cases.
   - Provide a comprehensive data integration solution for transportation asset management.
   - Provide an in-depth evaluation of alternative decision making methods and applicability to Caltrans practices.
   - Establish a finalized set of criteria for SHOPP project prioritization.
   - Produce a business-ready, fully integrated decision making software tool

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Conclusions & recommendations (continued)

6. Though the current MODA model is sufficient to accomplish all of the goals established for the effort, the model and the process by which it was created deviate from best practice in a number of ways
   – Although most of the individual deviations (see "red flags" below) from best practice are relatively minor, the cumulative impact on model design may be significant
7. The Excel software implementation for the current MODA is very well done and contains almost all of the features found useful in tools for project prioritization portfolio management
   – Though success in this area merits compliment, there is a risk that the polished appearance of the tool may distract from critical appreciation of the limitations of the underlying model

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The following are among the specific "red flags" in model design communicated and discussed during the workshop

- Including within the objectives hierarchy (OH) wording for objectives that doesn't meet MODA technical requirements
  - Organizational objectives and goals that don't directly relate one-to-one to the linked MODA objectives
  - Means rather than ends objectives (E.g., "Maximize the effective use of available funds")
  - Objective statements that include only two out of the three required components--Direction of preference & object of value, but unstated context. (E.g., "minimize cost" –cost to whom, Caltrans? System users? Tax payers?)
  - Lack of sub-objectives that explain and show how the objective might be achieved (E.g., what are the ways that users may be "inconvenienced"?)
  - Negative wording when positive wording is more appropriate (E.g., "Minimize disruption of the economy" should more appropriately be something like "Maximize contribution to the State's economic success"
- Apparently missing objectives—at minimum, should indicate why they are not included
      - » E.g., "Organizational objective = Employ best practices to continuously improve Caltrans facilities, operations and services" seems to suggest that advancing Caltrans capability and learning ought to be an objective
      - » Maximize health benefits—what about minimize adverse impacts to human health (e.g., air pollution)?

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The following are among the specific "red flags" in model design communicated and discussed during the workshop (continued)

- Apparent deviation from recommended process for OH development (E.g., failing to organize objectives according to value to whom/what)
- Wrong terminology (e.g., confusing "value function" for "metric" or "attribute")
- Metrics that fail to measure the delta, or incremental improvement expected from the project
- Including multiple measures for a single objective (Multiple objectives? If, not, what is the aggregation equation to measure performance against the single objective?)
- Non-separable measures that cannot be swing weighted (swing weighting requires assuming all other measures are held unchanged)
- Converting all measures to 0-100 scales not necessary and likely creates problems for swing weighting in that the value of 0-100 swings are not of comparable magnitude
- Metrics that don't adequately distinguish projects
- Excel tool calculations should be organized into to sections such that performance measures are computed for each objective and then (at the end) measures are multiplied by weights to compute components of value

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Next Steps Advice

- Because MODA is a step-by-step process, any deviation from best practice in early steps (i.e., definition of the objectives hierarchy) may lead to sub-optimal results for subsequent steps through a chain reaction the consequences of which are impossible to fully predict
- For this reason, the most efficient and likely only assured way of correcting all current model deficiencies so as to obtain a high-quality, effective MODA model is to repeat the design process with full compliance with all elements of the recommended MODA model-design process
- Before attempting to repeat and improve the SHOPP MODA model, establish an appropriate governance structure for SHOPP project prioritization and portfolio management
- Based on a examination of SHOPP needs, organizational capabilities and culture, and existing data, processes and tools, establish design requirements and plan for making appropriate design tradeoffs between model sophistication and simplicity of use

Next Steps Advice (continued)

- Establish a realistic budget and timeline for model and process development and implementation
- Ensure adequate executive support along with necessary commitments for participation from stakeholders, including technical, subject-matter, and policy experts
- Secure help from recognized MODA expert with relevant application experience
- Determine whether to include external stakeholders in the process of defining the objectives hierarchy (OH) and influence diagrams (IDs) and plan accordingly
- Reconstruct the OH to meet all MODA technical requirements. Also, additional objectives suggested/implied by mission, vision and strategy statements should be included within the OH. Then, if necessary to avoid an overly large or complex model, deliberately remove objectives and document the reason for such removals. This will be useful for explaining the design logic and provide a roadmap for making future model improvements.

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Next Steps Advice (continued)

- Once a MODA compliant OH has been constructed, influence diagrams (IDs) should be constructed to provide more options for metrics and to document the logic for relating candidate metrics to the achievement of objectives. Among other advantages, the IDs will clarify logic for scaling benefits based on the size and scope of projects.
- Include options for improving and expanding the information and data to be submitted as part of project proposals and consider the use of qualified judgments as inputs for the evaluation and prioritization of projects
- Continue to delay the purchase of a project portfolio management (PPM) software tool until gaining further maturity and understanding of the desired MODA model and project prioritization process. An Excel implementation will provide desirable flexibility for making modifications to the model without the constraints and expenses that would be incurred with the use of a vendor's tool.

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