Programmatic Cost Risk Analysis for Highway Megaprojects

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Abstract: Highway megaprojects (construction projects over $100 million) are fraught with uncertainty. These projects have historically experienced increases in project costs from the time that a project is first proposed or programmed until the time that they are completed. Persistent cost underestimation reflects poorly on the industry in general but more specifically on engineers. Traditional methods take a deterministic, conservative approach to project cost estimating and then add a contingency factor that varies depending on the stage of project definition, experience, and other factors. This approach falls short, and no industry standard stochastic estimating practice is currently available. This paper presents a methodology developed by the Washington State Department of Transportation (WSDOT) for its Cost Estimating Validation Process. Nine case studies, with a mean cumulative value of over $22 billion, are presented and analyzed. Programmatic risks are summarized as economic, environmental, third party, right-of-way, program management, geotechnical, design process, construction, and other minor risks. WSDOT is successfully using the range cost output from this procedure to convey project costs to management and the public.

DOI: 10.1061/(ASCE)0733-9364(2005)131:3(343)

CE Database subject headings: Highway construction; Cost estimates; Risk analysis; Uncertainty analysis; Risk management; Transportation planning; Scheduling.

Introduction and Motivation

Large transportation projects have historically experienced significant cost overruns from conceptual planning estimates. A recent study of 258 infrastructure projects spanning a time period of more than 70 years found that project costs are underestimated in approximately 90% of the projects, and the actual costs averaged 28% higher than estimated on this sample (Flyvbjerg et al. 2002). Although highway projects fared better than rail and fixed-linked projects, the sample still displays an increase in project costs of more than 20%. Recent high profile highway projects, such as Boston's Central Artery/Tunnel (the "Big Dig") and Virginia's Springfield Interchange have made engineers, contractors, and public taxpayers acutely aware of the problem. For example, the Big Dig was estimated at a cost of $2.6 billion (1982 dollars) and is expected to be completed at a cost of $14.6 billion (2002 dollars) with completion anticipated in 2005 (Completing 2003). Additionally, it can be argued that construction cost estimating on major infrastructure projects has not increased in accuracy over the past 70 years. The underestimation of cost today is in the same order of magnitude that it was then. New ideas and techniques need to be developed to improve this area where no leaning seems to have taken place (Flyvbjerg et al. 2002). Cost estimation practices need to improve for many reasons. Projects are often cut in scope or canceled altogether due to other projects exceeding their budgets. This persistent cost underestimation reflects poorly on the industry in general, but more specifically on engineers.

The root cause of inaccurate cost estimating on megaprojects (projects over $100 million) can stem from a multitude of reasons. Managing the capital construction of megaprojects requires the coordination of a multitude of human, organizational, technical, and natural resources. Engineering and construction complexities can include a lack of information on the extent of utility impacts, required environmental mitigation, maintenance of traffic requirements, and work-hour restrictions, etc. (Arditi et al. 1985; Completing 2003; Hecker and Etta 2002; Merrow et al. 1988). Quite often however, the engineering and construction complexities of such projects are overshadowed by economic, societal, and political challenges. In addition to these challenges, a number of observers have suggested that project estimates have purposely been misrepresented in an effort to secure project approval (Bruzelius et al. 1998; Flyvbjerg 1996; Flyvbjerg et al. 2002; Pickrell 1992).

Cost estimates should transparently convey the true nature of uncertainty involved with the project at each stage of the process. Estimating procedures must model both the technical and nontechnical nature of the challenges in quantifying capital costs early in the project's life cycle. Engineers should convey the true nature of these risks to all stakeholders in the process. They should offer them for public debate to the extent that it raises the level of understanding of relevant issues or actions among the affected and interested parties, and those involved are satisfied that they are adequately informed within the limits of available knowledge (National 1989). A fundamental premise of this paper is that estimates derived from stochastic methods (range cost estimates) better convey the uncertain nature of project costs at the conceptual phase of project development. This paper presents a methodology for a programmatic approach to cost-risk analysis

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Note. Discussion open until August 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 16, 2003; approved on March 16, 2004. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 131, No. 3, March 1, 2005. ©ASCE, ISSN 0733-9364/2005/3-343–353/$25.00.

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Table 1. AACEI Generic Cost Estimate Classification Matrix (AACE 1997)

	Primary characteristic	Secondary characteristic			
Estimate class	Level of project definition (expressed as percentage of complete definition)	End usage (typical purpose of estimate)	Methodology (typical estimating method)	Expected accuracy range (typical +/− range relative to best index of 1)[a]	Preparation effort (typical degree of effort relative to least cost index of 1)[b]
5	0 to 2	Screening or feasibility	Stochastic or judgment	4 to 20	1
4	1 to 15	Concept study or feasibility	Primarily stochastic	3 to 12	2 to 4
3	10 to 40	Budget, authorization, or control	Mixed, but primarily stochastic	2 to 6	3 to 10
2	30 to 70	Control or bid/tender	Primarily deterministic	1 to 3	5 to 20
1	50 to 100	Check estimate or bid/tender	Deterministic	1	10 to 100

[a]If the range index value of "1" represents +10/−5%, then an index value of 10 represents +100/−50%.

[b]If the cost index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%.

for cost estimation of highway megaprojects. Nine case studies, with a mean cumulative value of over $22 billion, are presented and analyzed as a validation of this procedure.

Background and Context

Cost-estimating technique and tools must relate and adapt to the various phases of project development. When estimating costs on megaprojects, this becomes even more profound (Merrow et al. 1988). The Association for the Advancement of Cost Engineering International (AACEI) defines a cost estimate classification system with five classifications for estimates. This system provides an expected range of accuracy for each phase, as shown in Table 1. A Class 5 estimate is based on the lowest level of project definition, and a Class 1 estimate is closest to full project definition and maturity. Table 1 also describes the methodological approach to the estimate as either stochastic or deterministic, depending on the level of design and information available. While stochastic estimating techniques are well defined in literature (Ayyub 2003; Kumamoto 1996; Clemen 1996) and often applied by highway engineers in design decision making, the Federal Highway Agency and state highway agencies rely almost exclusively on deterministic unit price estimates for conceptual cost estimates. At present, there is no industry standard stochastic estimating practice available for cost estimates of highway megaprojects.

More generally, at any stage in the development of a highway, cost estimates will be composed of three types of information, which can be termed as the "Known/Knowns" (known and quantifiable costs), the "Known/Unknowns" (known but not quantified costs), and the "Unknown/Unknowns" (as yet unrecognized costs). These three types of information must be combined in a comprehensive and complete cost estimate or cost management approach. All too often, if the cost of an item is not known, it does not get included in early project cost estimates. At other times, items such as right-of-way or construction engineering costs get left out of early estimates entirely. The three types of information also require different approaches to define and quantify their possible contribution to a cost estimate at any particular time. Traditional methods take a deterministic, conservative approach to project cost estimating and then add a contingency factor that varies depending on the stage of project definition, experience, and other factors. This approach falls short of the needs for contemporary assessment and management of uncertainty. The approach presented in this paper uses a broader definition of cost estimating and is illustrated in Fig. 1.

Fig. 2 explains how identifying, quantifying, and managing cost and schedule uncertainty relates to management of the cost of major projects. Two primary points are illustrated in Fig. 2, which applies to situations where the scope is unchanged and where an estimate at some early stage (i.e., 5% design) has included uncertainty. The first point is that there should be a reduction in the range of cost or schedule uncertainty as a project proceeds from concept to completion. The reduction in estimated cost is a result of better defining cost variables and eliminating uncertainty as cost factors are finally incorporated into the project plan. The second point is that if the problems or uncertainties included in the early stages of a cost estimate do materialize, then a higher range of the cost estimate will be expected. In contrast, when risk management and other cost control processes are used effectively, a lower range of expected costs will likely result. These key ideas have been incorporated into the Washington State

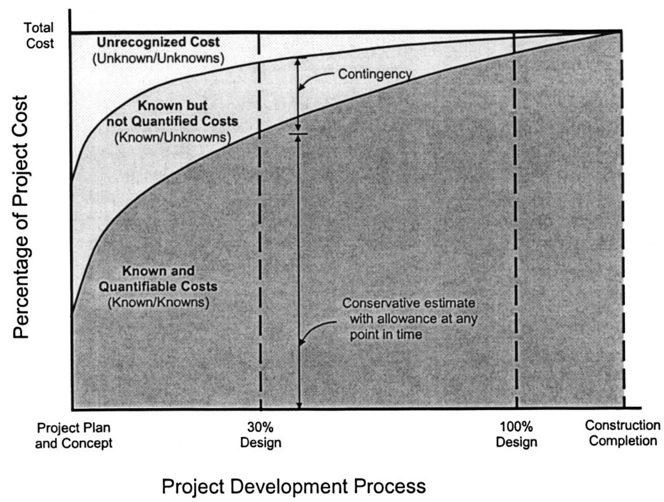

Fig. 1. Conceptual components of a cost estimate

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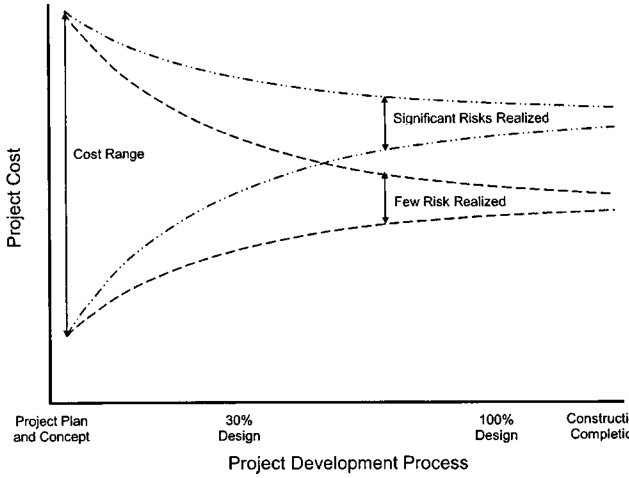

Fig. 2. Conceptual refinement of a cost estimate

Department of Transportation's (WSDOT) Cost Estimating Validation Process (CEVP). The CEVP methodology of programmatic cost risk analysis is the basis of the remainder of this paper.

Cost Estimating Validation Process

In 2002, WSDOT recognized that the success of their cost estimating on large projects had been mixed. While WSDOT's overall program estimating and delivery track record was generally regarded as very good by public perception, significant individual project cost variations did exist. There have been many success stories, such as the on-time, on-budget completion of the (I)-90 project, but the State Road (SR)-167 completion project saw very significant preliminary cost estimate increases, raising questions regarding the credibility of WSDOT cost estimates.

CEVP is an intense workshop process, somewhat resembling value engineering. A rigorous peer review and uncertainty analysis process is the foundation CEVP. Each project is examined by a multidisciplinary team of professionals from both the public and private sectors in the disciplines of engineering, construction, planning, and risk management. CEVP uses systematic project review and risk assessment methods, including statistics and probability theory, to evaluate the quality of the information at hand and to identify and describe cost and schedule uncertainties. CEVP recognizes that every project cost estimate will be a mix of the very likely, the probable, and the possible. Meeting the estimate of the number of yards and the cost of concrete to be poured for a roadway is very likely. It's probable that if the project is built 5 years from now, inflation will add 10–15% to "today's" project costs, and it is possible that contaminated soil may be encountered during construction requiring expensive cleanup costs. Importantly, from the very beginning, the process examines how risks can be communicated and lowered and cost vulnerabilities managed or reduced (National 1989). In other words, a dividend of CEVP is to promote the activities that will improve end-of-project cost and schedule results.

CEVP involves two primary tasks: (1) a due diligence review of the project "base" cost estimate; and (2) a modeling of uncertainty to more accurately define contingencies and allowances as distributions of cost and schedule. The project development team accomplishes these two tasks with the assistance of a CEVP core team of specialists. After the project team compiles the project data, the CEVP team assists the project team in reviewing the current project estimates. Next, the CEVP core team removes the contingencies from the base cost estimate and explicitly identifies, assesses, and models the risks, opportunities, and uncertainties in cost and schedule and provides a project cost and schedule distribution for the project team to verify and utilize for planning and engineering throughout the development of the project. The fundamental milestones in CEVP are listed below.

- Phase I—Project Identification and Preparation
- Phase II—Workshop Initiation
- Phase III—Cost Validation and Risk Identification
- Phase IV—Integration and Model Construction
- Phase V—Presentation of Results
- Phase VI—Validation of Results and Generation of Alternatives
- Phase VII—Implementation and Auditing

Depending on the level of project development and unique project characteristics, as well as CEVP time and budget constraints, milestones for Phases II–IV may be completed in an intensive 3-day to 1-week workshop with additional time for preparation, reporting, and review. The final determination of the CEVP workshop is made in conjunction with WSDOT management, project sponsors, and the CEVP team. The details of each individual CEVP workshop vary slightly given different project characteristics, varying levels of design, and workshop budget constraints. However, there are critical processes and milestones that must be maintained in order to provide consistent and valid results. All of the process milestones need to be maintained if the CEVP results are to be consistent and valid. Table 2 provides a brief description for each of the CEVP phases.

Risk Analysis Process

Although all seven phases of the process are important, this paper focuses on the key aspects of the risk analysis and the results from this analysis—Phases III to V of the CEVP process. The CEVP core team performs the risk analysis. The risk team is comprised of a risk analyst, who must be an expert in risk elicitation and modeling, and project team members who are familiar with the technical and political issues on the project. The risk team also relies on the input of key subject matter experts in estimating and engineering disciplines from outside the workshop risk team. The risk team's goal is to model the uncertainty in the project cost and schedule. The primary objectives for the risk team are listed next. Refer also to Appendix I for a list of key definitions.

1. Identify and screen a comprehensive set of risk and opportunity events.
2. Assess the cost and schedule impacts for each event if it occurs.
3. Assess the probability of each event (and its associated impacts) occurring.
4. Combine base costs and risk costs into a final range estimate of project costs.
5. Conduct a sensitivity analysis to identify the most critical risks.
6. Present the final result to the project and management teams to begin risk mitigation strategies.

Defining a risk vocabulary for all of the risk team to use is essential. Some of the risk team members are not likely to make probabilistic estimates or think in probabilistic terms in their daily course of business. Therefore, a refresher on risk terms and con-

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Table 2. CEVP Process Summary

CEVP process phase	Summary description
Phase I—Project identification and preparation	Project data compilation.
	CEVP training and education.
Phase II—Workshop initiation	Establishment of workshop goals, workshop scope, and project alternatives being explored.
	Project team presentation of scope and assumptions for each decision alternative, cost and schedule estimate, and major issues and concerns.
	Development of project flow chart or schedule (the basis for the cost and schedule risk and uncertainty mode).
Phase III—Cost validation and risk identification	Cost validation team breakout activities.
	Risk team breakout activities.
	Environmental costing team breakout activities.
	Modeling team breakout activities.
Phase IV—Integration and model construction	Breakout team reports.
	Reconciliation of breakout assumptions.
	Construction of cost and schedule risk and uncertainty model.
Phase V—Presentation of results	Oral presentation of workshop results.
	Written presentation of workshop results.
Phase VI—Validation of results and generation of alternatives	Project and CEVP teams validate workshop results.
	Alternative project scenarios are explored and evaluated.
Phase VII—Implementation and auditing	Development of risk mitigation planning and integration into project management.
	Reviewing and updating of workshop results and predictions as compared to actual project results.

cepts will be helpful. Key definitions include uncertainty, variability, likelihood, probability, magnitude, expected value, risk event, opportunity event, independence, first-order analysis, Monte Carlo simulation, confidence level or percentile, conditional consequence, event tree, risk, and correlation. Also, the experience of the risk analyst in elicitation of uncertainties and their consequences is critical.

CEVP defines project cost and schedule uncertainty primarily in two categories: risk events and opportunity events. Risk events are defined as potentially adverse events that negatively affect the defined project resulting in negative impacts to cost and schedule, but do not include the minor uncertainty inherent in base costs. Examples include political, policy and /or management changes, changes in regulations and laws, earthquakes, fires, floods, and unknown archeological sites, etc. Opportunity events are potentially beneficial events that positively affect the project, resulting in improvements to cost and schedule. Examples include strategies to reduce cost or accelerate the schedule, beneficial funding decisions, and improved revenue projections, etc. Uncertainties are often difficult to identify and even harder to quantify. This step requires a multidisciplinary team for accurate results. The identification and quantification of uncertainties requires a balance of project knowledge, program knowledge, risk analysis expertise, cost estimating expertise, and objectivity. Project knowledge is essential to identify the uncertainties. Risk analysis expertise is required to elicit probabilities and model uncertainties. The multidisciplinary team identifies these risks and opportunities through a series of structured brainstorming and risk elicitation sessions.

Two key issues must be kept in mind during the risk identification step. First, *all risks and opportunities should be considered*. This is truly a brainstorming session and no issues should be disregarded. Issues will be filtered at the risk quantification stage but not at this point. Second, if a true first-order model is used *all risks and opportunities must be approximately independent*. A first-order model will likely be the outcome from this process. This type of model does not allow for modeling of significant correlation among risks. The risk analyst should have the experience to determine if a risk or opportunity is independent. If it is not, it will need to be decomposed into independent parts or combined with its correlative events to form one event that can be modeled independently. However, in enhanced first-order models, important correlations among event occurrences are included.

Once identified, the consequences or "impact" of the uncertainties must be quantified. Quantification involves an assessment of the likelihood and magnitude of occurrence. Quantification is often difficult, and the risk analyst expert must be experienced in eliciting probabilities and costs. The risk analyst may also rely on the assistance of a cost engineer to assess the impact of the events. Predicting probabilities of occurrence can be a difficult task. For example, the risk analyst might ask the team, "what is the probability that a storm-water permit will delay this project 1 month?" The team will rely on their experience and any available technical data to estimate this probability. If not checked, judgments can contain biases. The risk analyst must be adept in making heuristic judgments and act as a quality-control mechanism for all estimates. This example also describes why risk assessment training and the creation of a risk vocabulary are so important. Table 3 describes one simple format used for this quantification.

As seen in Table 3, risks and opportunities are quantified by their likelihood of occurrence and their impact if realized. Before a detailed quantification is made, an initial quantification should be done to filter out minor or inconsequential risks using an order-of-magnitude assessment of conditional expected consequences and likelihood for all events on the list. Filtering is accomplished by creating baseline criteria for the assessment and inclusion of risks and opportunities. Example criteria are to include risk with a probability of occurrence of more than 1% or an impact of occurrence of more than $1 million, but these will change depending

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Table 3. Example of Uncertainty Assessment

		If event occurs	
Potential event (considering current mitigation)	Likelihood of event occurrence[a]	Activities affected and change in activity costs ($)	Activities affected and change in activity duration (months)
Change in storm-water collection and treatment requirements of the upcoming *Office of Ecology Design Manual*.	Likely	31 million	3 months

[a]Probability can be expressed directly (0–100%) as a range of probability or at first categorically in ranges similar to the following: very likely (50–100%); likely (10–50%); unlikely (1–10%); and very unlikely (<1%).

Risk Issue

Commercial Property Value

Issue: Project ROW costs were developed by applying a percentage increase to the assessed valuations for each parcel. During the CEVP review the estimated cost of commercial properties carried in the ROW estimate for the project have been updated, and the multiplier increased to 75% of the assessed value, to better reflect current market conditions. There is a low level of confidence in the updated values and it is estimated that actual market conditions may be as high as 100% of the assessed valuations.

Impacts: The actual market conditions will increase the cost of acquiring commercial properties by an average of $25M. There are no significant schedule impacts.

Probability: 85%.

Mitigation: Monitor the commercial real estate market and track the actual cost of recent transactions. Keep the project ROW estimate up to date and reflective of the current commercial property real estate market. Buy early if appropriate.

Fig. 3. Risk event identification example

on project size. A sensitivity analysis, described later in this paper, will assist in setting proper criteria. However, the inconsequential risks should not be neglected, but rather grouped into a category of "other events" and treated as one risk event with impacts specified as a percentage (i.e., 10%) of the sum of the other major risks.

After the initial filtering is accomplished, the remaining risks are revisited and quantified in detail. The probability is generally estimated by the person on the team with the greatest knowledge of the subject and the remainder of the team verifies that estimate. If a particularly difficult probabilistic estimate is required, the risk analyst may employ a group estimating method (Delphi), they may employ a more theoretical elicitation tool (indifference curve or swing weighting), or they may decompose the issue into its parts, which are easier to assess (through use of a fault tree or event tree) (Ayyub, 2001; Clemen 1996; Cooke 1991; Vick 2002).

Estimating the magnitude of occurrence is generally more straightforward and involves fundamental conceptual estimating techniques. Cost engineers are often consulted to estimate the magnitudes of occurrence, or the cost may be expressed relative to the base cost (i.e., as a percentage). These magnitudes are estimated in terms of total cost or duration changes without contingencies. If required, they may need to be modeled with some uncertainty. During the quantification, it is important to keep good records. The team will likely need to revisit the calculations later in the process for coordination or mitigation purposes.

While identifying the risks and opportunities, it is an excellent idea to also identify mitigation alternatives. The team has a unique perspective and a wealth of experience with which to identify these alternatives. However, the identification of mitigation alternatives and strategies are not required to develop a risk-based cost estimate, and the team must be cautious not to get sidetracked. If workshop time and budget allows, an attempt at capturing possible risk mitigation plans should be made. Before the actual cost modeling occurs, the team must revisit the final issues, impacts, likelihoods, and mitigations. There are often minor changes debated and implemented at this point because the team can view all the issues at once. Fig. 3 shows the completed risk write-up for the SR-395 CEVP commercial property value risk issue.

Risk modeling may vary on the basis of objectives, resources available, project complexity, modeling tools, and modeler preferences. Although the details of the modeling will vary, the goals and objectives are the same on each project. The goal of the modeling effort is to generate probability distributions for total cost and schedule to completion that includes the base cost/duration estimate and the probable cost/duration of risk and opportunity events. The objectives are to allocate the base costs accurately into the risk-based model, and to model the risk and opportunity events in a probabilistic fashion. The modeling for the 2002 WSDOT CEVP Workshop was done using Monte Carlo simulation software packages. There are a number of commercially available software packages that perform Monte Carlo simulation. Whatever the modeler's preference for software, this step will be essentially the same.

Monte Carlo simulation is a risk analysis technique that incorporates multiple simulations of outcomes with the variability of individual elements to produce a distribution of potential results (Clemen 1996). In essence, the risk analyst incorporates both base costs and durations and risk events that correlate to the project schedule or flowchart. For each simulation, the Monte Carlo simulation engine randomly chooses one value for each risk event from within its range of possible values, but in accordance with the likelihood of each value. These randomly chosen values are then combined with the fixed costs and durations from the base estimate to generate a single total for one simulation. This process is repeated a number of times (typically 1,000 iterations), and a range of equally likely potential outcomes is produced.

The risk analysis combines the base cost and risk costs for each activity to determine that activity's total cost (in current dollars). Similarly, the model combines the base duration and risk delays for each activity to determine that activity's total duration. Based on the precedence requirements shown in the project schedule and in conjunction with the total duration for each activity, the project schedule (i.e., when each activity occurs) is determined. The total cost (in current dollars) for each activity is then escalated (using the prescribed inflation rate) to the midpoint of that activity to determine its escalated cost (in future or year-of-expenditure dollars). The total project cost (in year-of-expenditure dollars) is simply the sum of the total escalated costs for all the activities.

The results can be presented in a number of fashions. Fig. 4 and Table 4 provide examples of model output from the I-90 2002 CEVP. Fig. 4 is a probability mass function (or histogram) of the results from the same project. It shows the probability distribution

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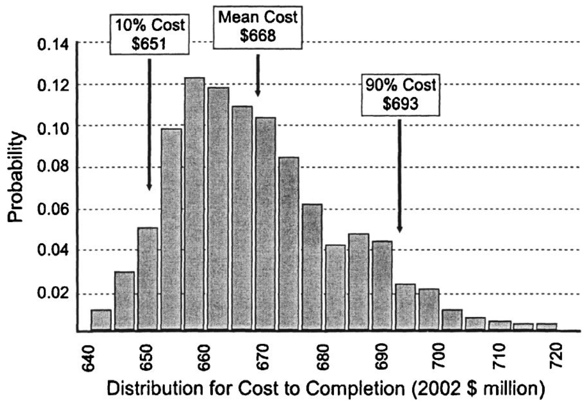

Fig. 4. Probability mass function example (I-90)

for the cost of the project. The 10, 50, and 90% confidence intervals are provided on the figure. Table 4 is a tabular presentation of the simulation results. In addition to providing cost distribution in 2002 and time of complete dollars, the table provides the confidence level for the final completion time. The time of completion dollars is a function of cost escalation due to inflation and the final completion date due to the occurrence of risk events. As the compounding effects of multiple risk events are realized, the duration and cost of the project escalates. The impact from some of the risk events is significant, but their related probability of occurrence is low; therefore, the final cost probability mass function contains a long tail toward the upper costs.

Aggregate Cost Results

WSDOT conducted a series of CEVP workshops for nine megaprojects in 2002. These results are presented as an illustration of the application of this process for programmatic cost-risk analysis. The projects encompass a wide variety of scopes in a number of different environments. Table 5 illustrates the design level, base estimate, and scope of each of the nine projects. The I-405 Tukwila to Lynnwood additional lanes project and the I-5/SR-16 Tacoma Pierce County HOV project both call for additional general lanes to be added to the existing highway as well as High Occupancy Vehicle (HOV) lanes. The SR-509 South Access Road and I-90 Snoqualmie Pass East projects both call for additional general purpose lanes to be built. The SR-509 scope also requires the road to be extended to a new interchange with I-5. Beyond the additional lanes, the I-90 scope calls for the realignment of I-90 through a portion of the project; this will entail the construction of a double bore tunnel through slide curve and dual bridges along the shore of Lake Keechelus. The purpose of the SR-99 Alaskan Way Viaduct and seawall replacement is to retrofit or replace the Alaskan Way Viaduct and associated waterfront seawall which have been deteriorating and have become a risk to public safety. Both the SR-520 Trans-Lake Washington project and the SR-104 Hood Canal bride retrofit and east half replacement projects call for the replacement and/or retrofit of a floating bridge. All new roadways will be built under the SR-167 Tacoma to Edgewood new freeway construction and the US-395 North Spokane Corridor projects.

Table 4. Example Tabular Presentation of Results from the I-90 CEVP

Estimate confidence level[a] (%)	Total project cost in 2002 dollars	Total project cost in "year-of-expenditure" dollars	Overall project duration in months
10	651	770	128
50	668	791	136
90	693	837	148

[a]The percentages below indicate the probability that the project will cost less than the estimate amount shown and the probability that it can be completed in less time than the overall project duration shown—for each percentage. For example, "…there is a 90% probability that the cost, in 2002 dollars, will be less than $693 million." This distribution is graphically shown in Fig. 4.

Table 5. Project Description Summary

Project	Level of design (%)	Base cost estimate (in millions of 2002 dollars)	Abbreviated scope
I-405	<1	4,752	Additional lanes
SR-99	1	5,589	Corridor replacement
SR-520	1	3,320	Replace bridge
SR-509	10	772	Lengthen and additional lanes
SR-167	10	1,231	New corridor construction
I-5/SR-16	10	1,170	Additional lanes
I-90	15	645	Replace and additional lanes
US-395	30	1,104	New corridor construction
SR-104	30+	227	Replace bridge

An individual CEVP workshop of 3 to 5 days was performed for each of the nine projects. The workshop output was documented in a formal report to the project team and was followed by a feedback workshop. The project costs are described as a snapshot in the project development process. The risk analysis completed by each team evolved into a cost range estimate that is presented in a probability mass function. Several projects, such as the I-5/SR-16 Tacoma Pierce County HOV, resulted in a common bell-shaped curve. Other projects had findings that were much different. Fig. 5 depicts the probability mass functions for the I-15/SR-5, I-90, and SR-509 projects. The I-90 project resulted in a cost distribution curve that has a long tail. This is due to the limited escalation in construction cost over time because the tunnel construction on this project is an early activity. The probability mass function for SR-509 shown in Fig. 5 has a cost distribution with a long tail and second "hump" due to the potential right-of-way delay and subsequent escalation in construction cost. The project team can quickly see the effects of the potential right-of-way delay and work to mitigate this risk. The other projects resulted in cost distribution curves that generally fall into one of these three curve types.

Table 6 is a tabular summary of the cost results. The base estimate of each project represents the project estimate without any risk events (or contingency). In other words, the base estimate includes the known and quantifiable costs (as a function of quantities multiplied by unit costs), as well as the known but as yet unquantifiable costs (as a function of design and construction allowances). The mean and 90% probability estimates represent the cost of each project after the CEVP with the identified risks. The base estimate is shown as a percentage of the mean estimate to represent the portion of the known quantities and allowances in the estimate. The remainder represents the unknown risks associated with the project (refer to Fig. 1).

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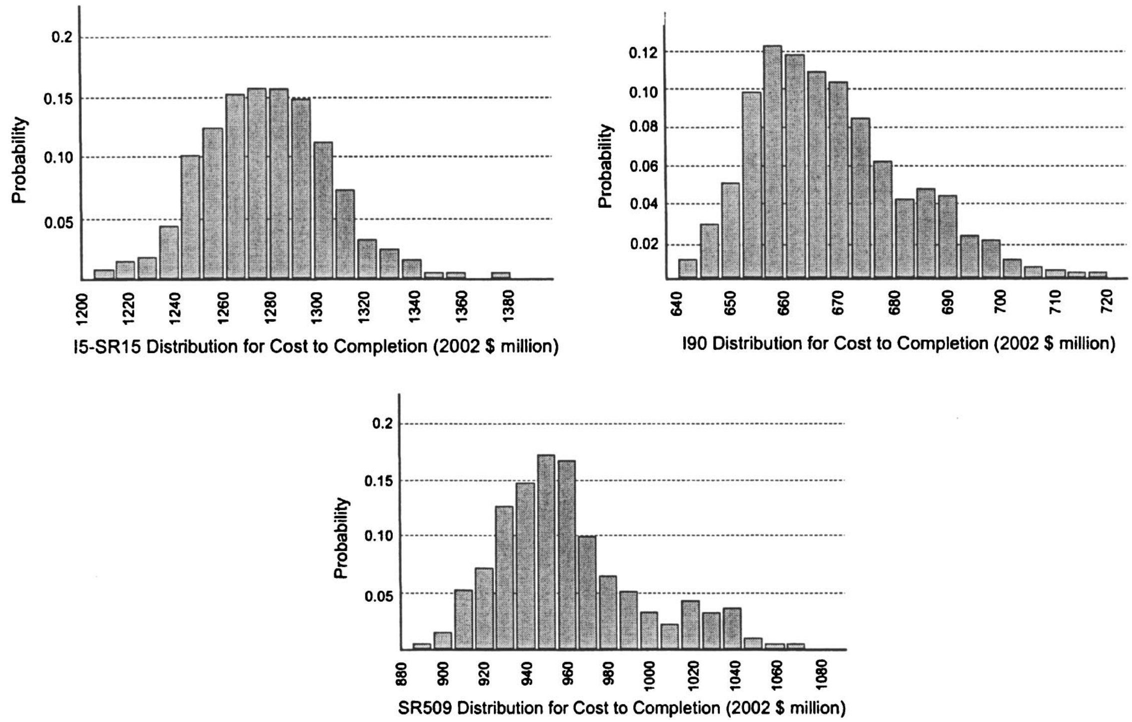

Fig. 5. Probability mass functions (I-5-SR16, I-90, and SR-509)

Fig. 6 depicts a scatter plot of the estimate uncertainty versus percent of design for the nine projects. A logarithmic trend line has been added to the scatter plot, and the SR-104 project has been treated as an outlier. As expected and described in Fig. 1 and 2 and Table 1 at the beginning of this paper, the level of uncertainty decreases with project development, much as predicted by the AACEI generic cost estimate classification matrix shown in Table 1. As design progresses, uncertainty is resolved through sound engineering design. There is one exception, which has been treated as an outlier on these projects. The SR-104 project is a floating bridge, and it has one very large monetary risk associated with the "market conditions" of marine contractors available at the expected bid time due to a number of bridges bidding on the West Coast. Lastly, Table 6 depicts the number of risks identified for each project. This also tends to decrease throughout the project development lifecycle.

Significant Risks Identified

In an effort to capture the uncertainty in project costs, the project teams identified numerous generic and project specific risks. Risk identification was conducted though structured brainstorming sessions that focused on the project team's issues and concerns. As previously described, a generic set of risk was quickly developed into a risk checklist. This checklist was carefully employed so as not to inhibit the project team's risk identification procedures.

The risks have been categorized for ease of reference into Economic, Environmental, Third Party, Right of Way, WSDOT Management, Geotechnical, Design Process, Construction, and Other Risks (Minor Risks) in Appendix II. The Economic category includes subcategories pertaining to risks with market conditions and labor disruptions. Environmental risks include stormwater treatment and/or quantities, permitting changes, wetlands,

Table 6. Project Cost Summary

Project	Design level (%)	Base estimate (2002 $millions)	Mean estimate (2002 $millions)	90% probability cost (2002 $millions)	Base/mean (%)	Number of risks
I-405	<1	4,752	6,266	6,922	76	44
SR-99	1	5,589	6,886	7,273	81	26
SR-520	1	3,320	4,091	4,522	81	31
SR-509	10	772	816	859	95	31
SR-167	10	1,231	1,341	1,386	92	16
I-5/SR-16	10	1,170	1,274	1,305	92	26
I-90	15	651	668	693	97	16
US-395	30	1,104	1,154	1,199	96	24
SR-104	30+	227	285	303	80	19

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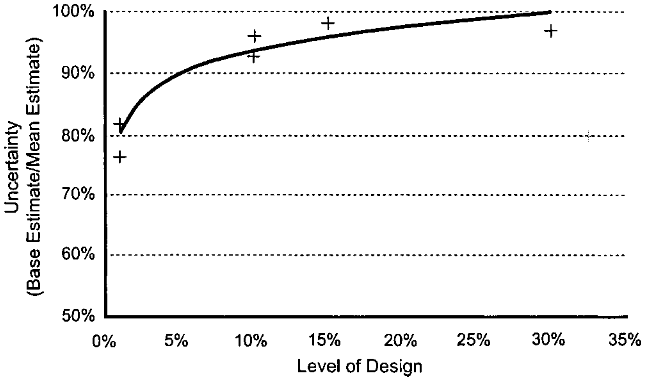

Fig. 6. Uncertainty cost as a function of design progress

and resource agency approvals. Third Party risks incorporate utility and rail lines issues. The Right of Way issues category contains risks pertaining to acquisition problems and values and impact. WSDOT Management contains risks relating to WSDOT program management decisions. The Geotechnical category contains only one risk, geotechnical conditions. The Design Process category address risks with the design process such as design of foundations and bridges, and also the various design approvals from agencies such as the Federal Highway Administration, Federal Aviation Administration, and municipalities. Environmental approvals could have been included with the Design Process category but were determined to be significant enough to include separately under the Environmental category rather than with the other design approvals. The construction category deals with all the risks that may be encountered during the construction phase of the project such as contaminated soil, natural hazards, work window, balances and cost of earthwork, auxiliary lanes, and staging areas. The Other Risk category contains all of the minor risks that have likelihoods and/or impacts that were individually negligible in comparison to identified risks, but included as a group to represent unknown risks, which may be significant.

Appendix II can be used as a programmatic checklist of risks, but it does not provide for a sensitivity measure of the risks. Table 7 presents a ranking of the most significant risks for the program of nine projects. A majority of the project teams completed a sensitivity analysis for the identified risks. The models ranked the most significant risks for each project in terms of their direct affect on the project cost uncertainty. An average of these rankings, as shown in Eq. (1), is provided in Table 7

$$S = \frac{\sum R}{P} \tag{1}$$

where S=sensitivity; R=normalized ranking from project model sensitivity ranking; and P=number of projects with this risk identified that provided a sensitivity analysis.

As the sensitivity value approaches 1 (one), the risk has a greater cost or schedule impact on the projects. The frequency provided in Table 7 represents the number of projects where that particular risk was identified. Risks presented in Table 7 had some effect on either the direct costs or time uncertainty and were identified in at least one-third of the projects.

There were 73 risks identified as significant by the nine project teams. Of these, 37 were identified as having a large impact through a sensitivity analysis. Table 7 represents the 23 most significant risks identified when viewed in aggregate. The risks that have the greatest impact on project costs include Market Conditions, ROW Acquisition Problems, Other Risks (Minor Risks), and Change in Seismic Criteria. The risks that were identified as having the largest influence on the project schedules include National Environmental Projection Act (NEPA)/404 Merger Process, Changes in Permitting, Inadequate Design/Design Uncertainty for Interchanges, Environmental Impact Statement, and ROW Value and Impact. These risks provide a strategic direction for WSDOT management and the individual project teams. By focusing their engineering efforts on the mitigation of the most sensitive risks, WSDOT will have a higher probability of completing the projects successfully.

Table 7. Program Risk Sensitivity Ranking

Risk	Cost sensitivity	Time sensitivity	Frequency (%)
Market conditions	0.90	0.32	89
ROW acquisition problems	0.54	0.18	89
Other risks (minor risks)	0.51	0.30	100
Change in seismic criteria	0.50	0.13	67
Inadequate design/design uncertainty for interchanges	0.34	0.48	56
Geotechnical conditions	0.27	0.00	44
Local arterial improvements and access	0.27	0.00	33
Rail lines (regular and light)	0.23	0.33	56
Off- and on-site wetlands	0.20	0.30	44
ROW value and impact	0.20	0.40	44
Bridge foundations	0.15	0.00	44
Storm water treatment and/or quantities	0.11	0.12	89
Changes in permitting	0.10	0.60	56
Natural hazards	0.08	0.14	56
Traffic demand	0.07	0.30	33
Staging areas	0.05	0.00	33
NEPA/404 merger process	0.00	0.80	33
Environmental impact statement	0.00	0.45	44
Utility issues	0.00	0.30	56
Work window	0.00	0.20	56
Auxiliary lanes	0.00	0.20	33
WSDOT program management	0.00	0.10	67
Labor disruptions	0.00	0.10	44

Conclusions and Application

The process for programmatic cost-risk analysis of highway megaprojects presented in this paper provides for a transparency of project cost and uncertainty to both program management, the public, and other stakeholders. It provides for better understanding and communication of the risks involved with large transportation projects. WSDOT is successfully using the range cost output from this procedure to convey project costs to the management and the public (WSDOT 2003). Rather than providing a point estimate, which is unrealistic and quite easily manipulated at the conceptual stage of project planning, the range estimating output better represents the uncertain nature of project costs prior to design engineering. As sound engineering removes or mitigates cost uncertainties, a realistic project budget can be obtained. The sensitivity analysis from the process conveys the extent of technical and nontechnical risks in the project budget to

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all stakeholders. This transparency in project estimates helps to limit the opportunity for purposeful underestimation of project budgets.

An extremely useful byproduct of the process is an expert peer review early in the project development process. WSDOT utilized a national team of experts to review the project and conduct a "due diligence" of the project budget and scope. The teams included senior professionals with background in planning, design, construction contracting, cost estimating, economics, and associated quantitative analysis, environmental programs, and project delivery strategy expertise. This multidisciplinary team was critical to the overall success of the CEVP initiative. Team members with different backgrounds and expertise brought perspectives and insights that complemented other team members. Without question, the interactive group workshop process created a situation where the total group exceeded the sum of the individual parts. These teams of experts worked along side each project engineering team to understand the projects, assess the estimates and associated project risks, and develop mitigation approaches that can be used to help manage projects more effectively. Although the team focused on the cost estimate validation and uncertainty analysis, numerous value engineering and constructability suggestions arose from each workshop. The engineering team members were able to voice their issues and concerns to upper project management and a team of national experts in a forum that is not typically provided for in the production engineering process. The project teams received feedback on their concerns in an open and nonthreatening forum, which is a key in successful communication of project attributes including risks (National 1989). The teams worked together to explore resolution or mitigation of the issues and concerns.

At the programmatic level, the cost of uncertainty can be better defined. As displayed in Fig. 6, the process has helped WSDOT to better understand uncertainty and quantify more appropriate contingencies throughout the project development process. The process can be used to help determine where the cost risks and opportunities lie across the program, and management can focus its resources to effectively manage and mitigate these uncertainties.

Unfortunately, the process was not inexpensive. WSDOT spent upwards of $3 million to complete the CEVP workshops and feedback sessions. While it is too early to measure the cost-benefit ratio of the process, early risk avoidance and mitigation planning points to a large benefit from the process. WSDOT is incorporating CEVP into their standard project development process and believes that the investment is prudent. More accurate and transparent conceptual cost estimates have obvious technical benefits, not to mention to the public confidence that can be gained through better management of public funds.

The process does create the need for risk-analysis experts, which few departments of transportation currently employ. The tools to build the models described in this paper are commercially available, but the skills of probabilistic modeling are only developed with years of academic and practical experience. Identification and quantification of uncertainty is difficult, and the risk-analysis expert must be experienced in eliciting probabilities and costs. The risk analyst must be adept in making heuristic judgments and act as a quality-control mechanism for all estimates. Consultants can be used for this purpose, but highway agencies should consider in-house risk-analysis experts if they want to build a sustainable cost risk analysis program. Additionally, risk identification and quantification education and training are important for the project teams because people do not make probabilistic estimates or think in probabilistic terms in their daily course of business. For example, project members might be required to estimate the likelihood of a road closure due to a landslide or the magnitude of the closure in terms of time or cost. A small amount of education and training in probabilistic estimating is very beneficial for this exercise.

One serious consideration regarding the process is the nature of the risk-analysis model. There is a fundamental trade-off between providing a sophisticated risk model and providing quick and effective feedback to the project team. In the process described in this paper, the team must identify risks, assess uncertainties, and produce a model and results within 3 to 6 days. This compressed schedule precludes development of advanced risk models. Consideration should be given to allow for more time for model development. The models described in this paper are first-order models wherein the uncertainty is represented using the mean of each uncertain variable, and risk events are modeled as independent occurrences (not correlated events as they actually may be). One possible enhancement to the risk modeling process would be to construct second-order models wherein the uncertainty is modeled by both the mean and the standard deviation of the uncertain variables, including delay variables. Such models will produce more accurate results at the outermost ranges of the cost and time distributions. However, second-order models require proportionately more time and effort to assess both the mean and standard deviation values for the risk items.

The process for programmatic cost-risk analysis of highway megaprojects presented in this paper provides a major step forward in the understanding of project costs. It provides a methodology for stochastic estimating of highway project costs, which provides for a more transparent assessment of uncertainty. A significant and immediately tangible benefit of the process is the ability to identify high-risk items and potential mitigation measures that can be taken to reduce the uncertainty. Unfortunately, the process is not inexpensive. A cost-benefit analysis should be done on a case-by-case basis, but the potential savings will likely outweigh the costs. The process also creates the need for highway agencies to employ trained risk analysts or develop relationships with consultants who have the appropriate competencies. Future advancements of the process could include the development of a risk knowledge base, improvements to modeling formats, and longitudinal students to document performance and catalogue repetitive elements.

Acknowledgments

Numerous CEVP participants provided information for this report. The following individuals helped to establish the CEVP methodology and contributed substantially to this paper: Adam Brown, WSDOT; Jennifer Brown, WSDOT; Jeff Carpenter, WSDOT; James Diekmann, University of Colorado; David Dye, WSDOT; Bill Elliott, WSDOT; Art Jones, KJM Associates; Cliff Mansfield, Parsons Corporation; Mike McBride, McBride Consulting; Travis McGrath, Golder Associates; Richard Rast, Azimuth Group, Ltd; John Reilly, John Reilly Associates International; William Roberds, Golder Associates; Keith Sabol, Parsons Corporation; Dwight Sangrey, Golder Associates; Jennifer Shane, University of Colorado; Shari Schaftlein, WSDOT; Greg Selstead, WSDOT; and George Xu, WSDOT.

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Appendix I. Definitions

Allowance—Additional resources included in an estimate to cover the cost of known but undefined requirements for an activity or work item.

Base Cost—The most probable cost for a unit or element of the project. The Base Cost represents the cost that can most reasonably be expected if no significant problems occur, with typically small uncertainty or variance.

Contingency—A markup applied to account for substantial uncertainties in quantities, unit costs, and the possibility of currently unforeseen risk events related to quantities, work elements, or other project requirements.

First Order Analysis—A risk assessment technique that incorporates Contingency and Risk but does not model uncertainty and correlation in Base Costs or schedule. Does consider uncertainty in the occurrence of risk events. Sensitivity analyses are based on expected-value trends.

Future Costs—Costs that are escalated by estimated inflation rates to a specific point in time, consistent with a particular project schedule.

Opportunity Events—Potential beneficial events that positively affect the project resulting in improvements to cost, schedule, safety, performance, or other characteristic but are greater than the minor variance inherent in Normal Costs. Examples include strategies to reduce cost or accelerate schedules, beneficial funding decisions, and improved revenue projections, etc.

Risk—The combination of the probability of an adverse event and its consequences.

Risk Events—Potential adverse events that negatively affect the defined project resulting in impacts to cost, schedule, safety, performance, or other characteristic but do not include the minor variance inherent in Base Costs. Examples include political, policy and/or management changes, changes in regulations and laws, earthquakes, fires, floods, and unknown archeological sites.

Appendix II. Risk Descriptions

Economic

Market Conditions

Implementing several megaprojects at the same time may create a shortage in management, contractors, financing/funding, labor, and material.

Labor Disruptions

Labor shutdowns are likely.

Environmental

Storm Water Treatment and/or Quantities

Stricter requirements in the future would require additional cost to provide additional detentions ponds and the collecting and treatment of all runoff, which may have a base amount in the estimate but there may be higher amounts of treatment required or higher then expected volumes.

Changes in Permitting

Permit requirements may change over the long duration of some projects.

Off- and On-Site Wetlands

There is a chance that conditions actually encountered in the field may be different than assumed when the base estimate was compiled, and the measures used my also change requiring additional mitigation.

Environmental Impact Statement

Disagreement between WSDOT and resource agencies and/or among agencies and the public on project impacts and associated disagreement on mitigation approaches may prompt impacts.

NEPA/404 Merger Process

Failure to reach concurrence on the range of alternatives and a preferred alternative could delay the environmental process.

Third Party

Utility Issues

Routine investigations and coordination with utility companies can identify and relocate conflicting utilities throughout the project. However, unforeseen discovery of previously unknown utilities and the need to relocate these utilities after the job is awarded and construction has started can be a significant cost and schedule liability to the project. Utilities, adjacent landowners, and other affected parties may demand "betterment" or excessive mitigation.

Rail Lines (Regular and Light)

Regional and national offices may need to approve new railroad alignments and rights-of-way (ROW) or the encroachment of new highway alignments on existing rail ROW.

Right of Way

Acquisition Problems

Changing property values and revolving funds, etc. may cause problems along with property owners who may hold out and cause economic problems and/or delays.

Value and Impact

Several risks may be encountered such as property owner relocation, sudden growth, and area development that may cause monetary and time impacts.

WSDOT Management

WSDOT Program Management

The organizational make-up of WSDOT is being revised to accommodate megaprojects. This management structure will need constant care and feeding to ensure that decisions and information are growing in a responsible way.

Geotechnical

Geotechnical Conditions

Inadequate geotechnical investigations during the conceptual and alignment selection phases can cause unforeseen conditions during excavation and construction of tunnels, bridges, and walls, etc. This could be compounded by inadequate characterization of groundwater conditions.

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Design Process

Change in Seismic Criteria

The American Association of State Highway Transportation Officials (AASHTO) is developing new seismic design criteria for bridges. The timing of the release of this criteria and WSDOT's adoption of the criteria is uncertain.

Bridge Foundations

The foundation type for bridges in the project may need to be adapted to new information that becomes available as the project progresses.

Local Arterial Improvements and Access

Local agencies may demand additional improvements to local arterials as a condition for support of the project.

Inadequate Design/Design Uncertainty for Interchanges

Interchanges may be planned but there may be some uncertainty from the design (i.e. unit cost, inadequate design, deviation approval, and municipality involvement, etc.).

Traffic Demand

Traffic demands may not be accurate in some areas (i.e., inconsistent growth patterns and age of traffic projections).

Construction

Contaminated Soil

It is possible that even after thorough due diligence and the identification of contaminated sources during design of the project, new contaminated soils or groundwater may result in discovery of new or unknown conditions that need to be taken care of during construction.

Natural Hazards

Storms, floods, and earthquakes, etc. can cause damage to work under construction and may result in a shutdown during construction. Such conditions may damage temporary water pollution controls, temporary structures, and earthwork that must then be repaired.

Work Window

There may be restrictions in conducting some activities (i.e., earthwork) during some parts of the year (i.e., winter).

Auxiliary Lanes

There may be uncertainty regarding if auxiliary lanes are going to be used/constructed temporarily during construction and/or permanently.

Staging Areas

Due to limitations in ROW and traffic flow, staging areas may be inadequate for construction.

Other Risks (Minor Risks)

Risks that have likelihoods and/or impacts that were minor in comparison to identified risks.

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