Bart Silicon Valley (BSV) Phase II, Tunneling Methodology – Comparative Analysis Independent Risk Assessment

Authors:

* Aldea Services LLC
+ Santa Clara Valley Transportation Authority
× Moergeli Consulting, LLC

ABSTRACT
A risk analysis approach can be used to compare the viability of two competing tunneling options even at different levels of design maturity. This paper describes the process used to provide the Santa Clara Valley Transportation Authority (VTA) with a comprehensive decision-making basis using comparative risk profiles for two tunneling alternatives; a single large diameter tunnel versus two smaller twin tunnels for extending BART service into downtown San Jose. Quantification of construction risk impacts were assessed in terms of cost and time for comparing the subsurface construction cost and duration of the two options. The analysis also compared the differences in O&M costs for the first 30 years of operation.

INTRODUCTION
The Santa Clara Valley Transportation Authority (VTA) is based in San Jose, California. It is an independent special district that provides multi-modal transit services. The Santa Clara Valley Transportation Authority is responsible for the design and implementation of highways and transit projects including the BART Silicon Valley (“BSV”) Program. The BSV Phase II Extension project is a 6-mile extension which starts from the Phase I Berryessa Station as shown in Figure 1. It passes through Downtown San Jose to a new station in Santa Clara. This phase consists of 4.8 miles of running tunnels through San Jose. It includes four stations. The Alum Rock, Downtown San Jose and Diridon are underground stations, and Santa Clara is at grade. It has two intermediate ventilation structures and East and West tunnel portals.

VTA started the planning efforts for BSV Phase II in 2014 with an update to the project environmental studies. The continued ongoing community and public concerns about disruption during construction drew VTA’s attention towards a single bore (SB) large diameter tunnel as an alternative to the twin bore (TB) option. The advances made by the tunneling industry with respect to developments in larger diameter, soft ground mechanized tunneling in urban settings encouraged VTA to initiate a feasibility study of a SB alternative. Project alignment, station configurations, emergency egress and ventilation tasks were studied in the SB feasibility study which was completed in early 2016. The SB feasibility study concluded that a single bore option is technically feasible for the prevailing ground conditions and did not exhibit any fatal flaws (VTA BSV Phase II Tech Studies, 2017). It, and subsequent technical studies, further concluded that single bore might be a viable alternative to the twin bore configuration.

VTA selected Aldea Services, LLC (Aldea) to conduct an independent risk assessment to assist the decision-making process between the SB and TB tunneling options. The alternative configurations under consideration are a TB tunnel system and a deeper SB tunnel system. A risk assessment process was part of VTA’s selection process to determine the preferred tunneling alternative. The assessment analyzed and described and compared the qualitative and quantitative risks associated with the two tunneling alternatives (RFP S16308, 2016). The assessment was carried out within a risk management framework that is intended to proceed throughout design and construction in accordance with the
TUNNEL ALTERNATIVES
The two options are the TB option which constructs two single track 20-foot outer diameter subway tunnels, comparable with other tunnels in the BART (Bay Area Rapid Transit) system, and the SB option which constructs a single 45-foot external diameter subway tunnel that is designed to carry two tracks within the same tunnel, using a dividing wall between the trackways. Both alternatives are shown in Figure 2.

Twin Bore Alternative
The TB design consists of two circular tunnels constructed by two TBM s to interconnect the open-cut stations, mid-tunnel vent structures and portals. The tunnels will be connected to each other by cross passages at regular intervals along the alignment. The project had three proposed underground stations in the 65% Preliminary Engineering Phase; Alum Rock, Downtown San Jose station and Diridon/Arena station.

Single Bore Alternative
In addition to the feasibility study which found no fatal flaws, several follow-on SB technical studies further performed detailed evaluations of the SB tunnel option and indicated that a minimum internal diameter of 41 feet was desirable to meet the minimum clearances and vehicle envelopes stipulated in the BART Facilities Standards (BFS) through all of the necessary guideway configurations and transitions along the project alignment (VTA BSV Phase II Tech Studies, 2017).
During early inter-agency coordination discussions, BART indicated a preference for side-by-side rather than stacked track configuration in the running track alignment. This arrangement required transitions from side by side running tunnel to the over/under configuration at the stations which controlled the diameter because the maximum open space was needed to facilitate the transitions. The SB Feasibility Study concluded a minimum depth of cover of 65 feet for the SB tunnel. Subsequent technical studies with more detailed evaluations indicated that a shallower minimum cover depth of 50 feet was constructible and appropriate for further evaluation of a SB tunnel as the design progressed (VTA BSV Phase II Tech Studies, 2017).

![Two 20 ft. diameter tunnels](image1.png)

![One 45 ft. diameter tunnel](image2.png)

**Source:** VTA Board Presentation 09/22/17

**Figure 2. Twin bore and single bore tunnel alternatives**

### RISK ASSESSMENT PROCESS

The risk assessment process for an integrated project cost and schedule analysis seeks to identify all risks and uncertainties that might significantly affect the predicted project cost and schedule. It uses methods to quantify what each of those impacts might be by using estimates of minimum, most likely and maximum values of cost and schedule. A numerical simulation model is used to aggregate these impacts to obtain risk-based cost and schedule estimates for the project that are probabilistic distributions rather than single value estimates. This process is illustrated in Figure 3.

#### Qualitative Analysis

The comparative assessment process for project cost and schedule first worked to accurately derive comparative base costs for both alternatives and normalize the costs to a common date (December 31, 2016 in this case). Next, a workshop process was used, including stakeholders (such as BART, VTA, the City of San Jose etc.) and nationally recognized subject matter experts to identify risks and uncertainties that might significantly affect the predicted project cost and schedule for both options. Risk assessment workshops were used to:

- Identify significant potential events and conditions (both risks/threats and opportunities) that could affect project cost and schedule.
- Assess risk impacts and likelihoods.
- Develop an integrated cost and schedule risk register as shown in Figure 4.
- Develop an integrated analytical cost & schedule risk model to quantify risks to cost and schedule with a probabilistic approach.
- Produce a distribution of probable cost and schedule outcomes for each option.
- Identify and discuss mitigation measures for significant risk components and estimate the potential risk reduction from each mitigation measure together with the residual risk after mitigation as shown in Figure 5.
- Identify, discuss and quantify potential opportunities and ways to exploit them.

During the workshops, a numerical ranking method was used to quantify the range of each of those impacts using estimates of minimum, most likely and maximum values for each alternative for cost and schedule risks/opportunities as shown in Figure 6. 127 Total Risks, including 64 specific and 63 generic risks, were identified for the TB option, while 121 Total Risks, including 74 specific and 47 generic risks, were identified for the SB option. In the above usage a “generic” risk was a risk that came from Aldea’s generic tunnel “seed” register that was determined to be applicable to the option. The “specific” risks were unique risks identified during risk workshops for the two options.
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Main Category</th>
<th>Identified Hazard/Identified Risk</th>
<th>Cause/Trigger</th>
<th>Effect</th>
<th>Risk Materialization on Phase</th>
<th>Risk Owner</th>
<th>Risk Rating</th>
<th>Risk Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>02</td>
<td>Compliance/Law/Regulation</td>
<td>Tariffs/duties on non-US made goods</td>
<td>Federal requirements</td>
<td>Additional cost</td>
<td>Project execution</td>
<td>V/A</td>
<td>4</td>
<td>High</td>
</tr>
<tr>
<td>07</td>
<td>Construction</td>
<td>Different ground conditions encountered from the ones assumed during Preliminary Engineering</td>
<td>Map unforecast soil conditions</td>
<td>Additional cost &amp; delays</td>
<td>Construction</td>
<td>V/A</td>
<td>3</td>
<td>High</td>
</tr>
<tr>
<td>06</td>
<td>Procurement/Commercial/Scope</td>
<td>Overspecified requirements</td>
<td>VTA might follow a very strict prescriptive approach</td>
<td>Potential combination of • No room for contractor's experience • Conflicts with contractor's planned and estimated performance</td>
<td>Construction</td>
<td>V/A</td>
<td>3</td>
<td>High</td>
</tr>
<tr>
<td>08</td>
<td>Quality/Health &amp; Safety/Environment (QHSE)</td>
<td>Risk cutters handling more time-consuming than originally expected</td>
<td>Cutters handled in TBM cutter head</td>
<td>Accidents</td>
<td>Construction</td>
<td>V/A</td>
<td>3</td>
<td>High</td>
</tr>
</tbody>
</table>

Figure 4. Example risk register before controls (mitigation)

**Risk Control/Mitigation**

<table>
<thead>
<tr>
<th>Strategy/5E = Strategy / System / Substitution</th>
<th>Importance</th>
<th>Impact</th>
<th>Likelihood</th>
<th>Comments</th>
<th>Risk Rating</th>
<th>Risk Level</th>
<th>Action Owner</th>
<th>Milestone Target Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigate Combination of 1. Minimize use of material subject to tariffs/duties on non-US goods 2. Ask for waiver well ahead in time.</td>
<td>OP Yes</td>
<td>5</td>
<td>5</td>
<td>By Design-Build (DBB) per VTA's &amp; ADE's decision</td>
<td>Threat Medium</td>
<td>PM</td>
<td>Part of Preliminary Engineering after system decision</td>
<td>Planning</td>
<td></td>
</tr>
<tr>
<td>Mitigate Carry out supplementary staged site investigations.</td>
<td>OP Yes</td>
<td>3</td>
<td>2</td>
<td>By Design-Build (DBB) per VTA's &amp; ADE's decision</td>
<td>Threat Medium</td>
<td>PM</td>
<td>Part of Preliminary Engineering after system decision</td>
<td>Planning</td>
<td></td>
</tr>
<tr>
<td>Accept Educate VTA in time.</td>
<td>OP Yes</td>
<td>3</td>
<td>2</td>
<td>By Design-Build (DBB) per VTA's &amp; ADE's decision</td>
<td>Threat Medium</td>
<td>PM</td>
<td>Part of Preliminary Engineering after system decision</td>
<td>Planning</td>
<td></td>
</tr>
<tr>
<td>Mitigate Combination of 1. Reaching out to TBM manufacturer(s) to work out this issue during design of TBM 2. Investigate TBM manufacturer(s) on use of real-time monitoring of main bearing</td>
<td>ST OP</td>
<td>2</td>
<td>1</td>
<td>By Design-Build (DBB) per VTA's &amp; ADE's decision</td>
<td>Threat Medium</td>
<td>PM</td>
<td>Part of Preliminary Engineering after system decision</td>
<td>Planning</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Example risk register after controls (mitigation) implemented
The probabilistic approach was used to quantify risks. Conventional construction estimates are presented in terms of a single number. This form of estimating is termed “deterministic” cost estimating. A more reliable way of establishing budget costs is by use of probabilistic forms of estimating that can consider uncertainties and give a range of possible outcomes. These uncertainties can be in the form of pure quantity or material uncertainty or in the form of identified and unidentified risks. When these are combined, a full probabilistic cost and schedule distribution can be developed. The advantage over standard deterministic methods is that it delivers more reliable contextual information because the result is a probabilistic distribution with a range for the risk potential (incl. best case and worst case). The analysis facilitates decision-making in line with the respective project stage. Since actual empirical data for risk analyses is often not available, the exact probability of occurrence can be difficult to estimate.

However, use of probabilistic methods allows risks and costs to be depicted for each project phase with individual density distributions: larger distributions for larger uncertainties, narrower distributions for smaller uncertainties. Using this approach, reality can be modeled more accurately than with a single deterministic figure.

Probabilistic risk assessment allows the use of uncertain values and requires various inputs:

- The probability of occurrence depicted in Figure 7 describes the pure likelihood that a risk actually produces an impact. If the risk does not occur, the impact is always zero. If the risk does occur, a financial impact should be evaluated. For evaluation of the probability of occurrence there are two options available (pick only one per risk):
  - Risks expected to occur only once (in the project lifetime)
Probability of occurrence must be chosen as a percentage value.

- Risks potentially occurring multiple times
  - An average occurrence rate must be chosen. Through this value, a Poisson distribution is modeled which maps the potential frequency of occurrence based upon the probability of no (0) occurrence.

![Figure 7. Probability of occurrence or average rate of occurrence](image)

- The cost impact is modeled by various distributions as shown in Figure 8. For simplification, three values can be used, e.g. in a triangular distribution: minimal impact, expected (most likely) impact and maximum impact. The area above the x-axis stands for the probability of occurrence of the specific hazard. Probability of occurrence of the two boundary values (min. and max.) is practically zero. The expected value is the most likely value.

![Figure 8. Cost impact distribution](image)

However, the summation of risks cannot be calculated by simple mathematical additions. Combining risks defined by probability density functions requires statistical simulations (e.g. Monte Carlo Simulation, Latin Hypercube Sampling) to determine a probability density function for the combined risks and therefore depict the overall risk potential. If the information about a potential cost distribution is accounted for by including uncertainties (probability functions), the likely budget variability and impacts can be estimated.
Figure 9. Example of a distribution function for aggregated project cost

Figure 9 shows an example for an overall cost distribution of a project. The distribution is developed by aggregating the effects of base costs, risks and escalation using the simulation method described above. The figure shows that $5M would cover 70% of the project cost potential. However, even with such coverage, there is a 30% probability that the budget would be exceeded.

**Introduction to Risk Modeling Process**

Two numerical simulation models were developed using the RIAAT software (for more information, please see [http://riaat.riskcon.at/](http://riaat.riskcon.at/)) to aggregate these impacts to obtain risk based cost and schedule estimates for each of the two project options. RIAAT performs numerical simulations to aggregate the contribution of each source of cost and schedule uncertainty to the overall project cost and schedule estimate. Cost impacts of schedule delays including potential changes to the critical path schedule are incorporated in the calculations. The result is an integrated cost and schedule model for the project that includes risk impacts together with the quantified uncertainties in these predictions.

The models aggregated the simulation results of Base + Uncertainty and Risk Costs. In the models, “Risk” includes both Identified Risk and Unidentified (or Unknown Known) Risk. The models also include cost elements to calculate the estimated cost impacts of schedule delays resulting from both Owner-caused and Contractor-caused delay risks. The results are presented in terms of probabilistic distribution ranges rather than single value estimates.

Escalation costs have not been included in the comparative analysis because their calculation is typically a financing calculation reserved for evaluating the time dependent cost of the entire project and the comparative analysis was not based on analyzing the entire project. Therefore, presenting the results of an escalation calculation would be premature and misleading at this time. Further, the schedule (time-related) outcomes of the comparative schedule analysis show critical differences in both the construction period and when subsequent revenue service will start. Any accurate escalation cost would have to be based upon both of these findings. In sum, the escalation calculation was determined to be premature at the comparative analysis phase. It is recommended that escalation calculations be performed for the entire selected project option as part of a budgetary/funding risk analysis and should incorporate the durations identified in the risk dependent schedule.
**Quantitative Assessment Models using RIAAT**

The quantitative alternative comparison between the subsurface portions of the TB and SB options was performed using the RIAAT software to analyze 100,000 project cost simulations and 10,000 project schedule simulations for each option. The $P_{80}$ level is the result found at the 80th percentile of outcomes, ranked from lowest to highest (i.e., in 100,000 simulations, $P_{80}$ is the cost result of the 80,000 highest costing project simulation).

VTA chose the 80th percentile for logical reasons. Washington State DOT e.g. routinely looks at cost using probabilistic methods and their standard practice is to use the 60th percentile of cost for their projects so that they can be assured of maintaining their project budgets over half the time. Due to the one-off nature of this program, coupled with its size and complexity, it was considered appropriate to use a more conservative assessment. Based on that understanding, it was determined that using the 80th percentile of potential cost distributions would be appropriate for comparative purposes. The relative conservatism of comparing $P_{80}$ outcomes had a beneficial effect of weeding out any tendency toward “optimism bias” during the process in that participants were never confused that the purpose of this task was not a VE exercise where proponents of the competing alternatives were there to “sell” their option by optimizing their way to a rosy outcome. The comparisons drawn are based on equally less than favorable outcomes and that has the benefit of examining overall Risk in the comparison phase. The conservatism also helped the process steer clear of being misconstrued as a budgeting exercise.

**SUMMARY OF RESULTS**

The simulations analyzed the comparative Base Costs which were then subject to variable uncertainty in future prices and quantities based upon the level of each option’s design maturity/level of design completion (approximately 65% for TB versus 20% for SB). Risks that differentially affected the cost or duration of either option were rated to derive a probability of occurrence and range of possible consequences (should the risk be triggered) and loaded into the models. Risks used in the model underwent a “Basic Mitigation” assessment to filter out that portion of the original unmitigated risk that would be removed or reduced after acknowledging a basic level of oversight and diligence on the Owner’s part. This was not the Aldea Team’s usual practice, nor was it anticipated at the onset (typically unmitigated risks are used in order not to falsely claim mitigation benefits that have not yet occurred).

However, as we progressed with this investigation it was realized that a basic level of mitigation was needed for comparative scenarios because otherwise all the risk uncertainty affected by design maturity level becomes effectively double-counted. In addition to specifically identified risks assessed during the workshops, the model also includes future Market Risk and Unidentified Risk which was based on assessments of project development factors; most notably design maturity. Finally, a Real Estate Savings Opportunity and a Business Interruption Risk based on assessments of the differences in local community impacts provided by each option were evaluated and modeled. Finally, there is Schedule Risk which is calculated by RIAAT based upon Owner-caused delays to achieving the project schedule; both Pre-Award and Post-Award of the Heavy Civil (Tunnel & Shafts) Contracts.

Another difference in the evaluation between the two options is that TB was evaluated as a traditional Design-Bid-Build Contract due to the level of design progress (65% Design) while SB (20% Design) was evaluated as a Design-Build Contract to investigate the advantages in potential schedule savings that pursuing this type of contract delivery method might provide. While not “identical” this distinction accurately reflected the Owner’s most advantageous approach to each option based on their current level of investment and development. The figures below present the full range of results ($P_0$ to $P_{100}$) for the simulated Base + Uncertainty Construction Cost (Figure 10), the Construction Program Risk Cost (Figure 11), and Heavy Civil Construction Completion Dates (Figure 12) for both options. $P_0$ is the lowest ranked result from the model’s simulations defining the left end of each curve and $P_{100}$ is the highest ranked result defining the right end of each curve.
Figure 10. $P_0$ through $P_{100}$ comparison SB - TB (construction base + uncertainty cost)

Figure 11. $P_0$ through $P_{100}$ comparison SB - TB (construction program risk cost)

Figure 12. $P_0$ through $P_{100}$ comparison SB - TB completion dates heavy civil construction
The P_80 level of comparison was selected by VTA as its organizational risk tolerance level which was to be used in the comparison of results. A summary of the P_80 results is presented in Tables 1 and 2.

### Table 1. Comparison of twin bore and single bore options

<table>
<thead>
<tr>
<th>Twin Bore vs. Single Bore Snapshot Comparison</th>
<th>Twin Bore</th>
<th>Single Bore</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P80 Results Compared</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Base Cost</td>
<td>✓</td>
<td></td>
<td>-3.5%</td>
</tr>
<tr>
<td>Lower Base + Uncertainty Cost</td>
<td>✓</td>
<td></td>
<td>-3.6%</td>
</tr>
<tr>
<td>Lower Potential Risk Cost</td>
<td>✓</td>
<td></td>
<td>-39.9%</td>
</tr>
<tr>
<td>First to Revenue Service</td>
<td>✓</td>
<td></td>
<td>-8.2%</td>
</tr>
<tr>
<td>Lower O&amp;M Cost (1st 30 Years - No Escalation)</td>
<td>✓</td>
<td></td>
<td>-2.8%</td>
</tr>
<tr>
<td><strong>SCHEDULE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First to Start of Construction</td>
<td>✓</td>
<td></td>
<td>-540 calendar days</td>
</tr>
<tr>
<td>Shortest Heavy Civil Construction Duration (Tunnels &amp; Shafts)</td>
<td>✓</td>
<td></td>
<td>-247 calendar days</td>
</tr>
<tr>
<td>First to Heavy Civil Completion (Ready for Trackwork)</td>
<td>✓</td>
<td></td>
<td>-293 calendar days</td>
</tr>
</tbody>
</table>

### Table 2. P80 comparison summary spreadsheet

<table>
<thead>
<tr>
<th>BSV Phase II Tunneling Alternatives - Comparative Analysis - Independent Assessment</th>
<th>Twin Bore vs. TB</th>
<th>Single Bore vs. TB</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results Summary DRAFT Final (Based on RIAF_B5VII_Mitigated_V25_F01_R2, August 10, 2017)</td>
<td>(TB) 100%</td>
<td>(SB) 100%</td>
<td>SB-TB</td>
</tr>
<tr>
<td><strong>Base Cost</strong></td>
<td>$2,143,407,000</td>
<td>$2,071,065,000</td>
<td>6.6%</td>
</tr>
<tr>
<td>Based on Designers' Estimates</td>
<td>Det.</td>
<td>$2,071,065,000</td>
<td>(72,342,000)</td>
</tr>
<tr>
<td>Based on Designers' Estimates + Uncertainties</td>
<td>P_80</td>
<td>$2,336,793,000</td>
<td>103.7%</td>
</tr>
<tr>
<td>Total Potential Risk Cost</td>
<td>$779,234,200</td>
<td>$1,296,035,000</td>
<td>66.3%</td>
</tr>
<tr>
<td>Based on Risk Workshops &amp; Alden’s Analysis incl. Unknown</td>
<td>P_80</td>
<td>$1,296,035,000</td>
<td>516,770,800</td>
</tr>
<tr>
<td>O&amp;M Costs (1st 30 Years) ($2016, i.e., No Escalation) Based on Alden’s Analysis</td>
<td>P_80</td>
<td>$1,758,099,000</td>
<td>102.8%</td>
</tr>
<tr>
<td></td>
<td>$1,807,957,000</td>
<td>49,858,000</td>
<td></td>
</tr>
</tbody>
</table>

| Heavy Civil Construction Completion Date                                         | P_80             | 07-09-2027         | 08-19-2026 | -286 d |
| Heavy Civil Construction Start Date                                             | P_80             | 05-20-2021         | 11-27-2019 | -540 d |
| Heavy Construction Duration (P_80 Heavy Construction End - P_80 Heavy Construction Start) | P_80             | 2241               | 2488       | 247 d |

**Note:** Risk-based aggregated costs do not equal the sum of the sub-components because probabilistic metrics like P80's are not additive.
RECOMMENDATIONS
The following recommendations were based on the results of this risk assessment and the Aldea Team’s current understanding of the project based on information provided by VTA up to the date of this report.

- The integrated cost and schedule risk model should be updated at significant milestones during project development, execution and into commissioning (e.g. at pre-award, 25% completion, 50% completion and substantial completion for examples) to obtain improved project controls including risk-focused claim management and cash flow analysis.
- A strong focus on identifying and implementing risk mitigation measures and their resulting potential impacts on estimated total costs, and especially on schedule, should start and then continue with frequent involvement of VTA management and eventually include the contractor.
- Key Risk Indicators should be developed for significant risks and these should be monitored over time to indicate when risk mitigation measures should be started for optimal mitigation.
- The contractor should be required to submit a qualitative Risk Register with his bid and then with his Base Schedule and update and review that Risk Register with VTA staff quarterly.
- Project Cost Controls that include risk components should be implemented to track cost development and to merge risk management and change order management. This will help VTA identify risks that did not materialize so that any associated contingency funds allocated for these risks can be released for other uses. It will also give VTA the opportunity to track risks that have materialized and what impact they have on the project and to improve its risk management practices for future projects.

CONCLUSION
VTA understood that any decision for selecting a tunneling method from competing options at two different levels of design maturity would need to be uncertainty-based in order to ensure that overall project risk was not overlooked due to lack of design completeness or inadequately evaluated due to lack of independent vetting. This analysis provided that context to the decision makers and can be set alongside non-cost factors such as the desire for geometric consistency within the BART system, or the desire to not disrupt downtown San Jose for extended periods during construction. One area that was impossible to resolve in this analysis was one of operation, where a fundamental disagreement on the means and criteria for safe and efficient operation of the system existed. Our analysis cannot resolve this area because the base criteria for quantifiable model input could not be agreed upon. Additional expert input has been solicited to discuss these operational issues, but further development of design will probably be necessary to bring resolution to these discussions.

In order to provide an analytical basis for a fair comparison between the two system geometries, we undertook the following:

- Both alternatives were carefully reviewed per their respective level of design,
- Base Cost and Base Schedules of both alternatives have been kept substantially unchanged,
- All issues that might affect both alternatives in an equivalent way have been transparently excluded,
- All cost estimates have been updated to the same basis (December 31, 2016),
- Schedules have been carefully reviewed, and respective activities have been loaded with identified risks,
- Intensive meetings with all stakeholders well ahead of the risk assessment assured a joint team and shared risk-based approach,
- A moderated qualitative risk assessment with workshops including all major stakeholders identified project risks across the full spectrum of project development; Planning to O&M,
All identified project risks have been quantified,

An integrated cost and schedule model was built and aggregated probabilistically,

VTA, as well as both design teams, have been working together very professionally for the complete IRA/CA process,

VTA’s Project Management Team were exceptionally responsive to our requests for information and were essential to making this process work.

An Extended Appendix included a full disclosure of all model inputs and results and concluded the IRA/CA.

All identified uncertainties were quantified wherever possible.

- Base Elements (for both cost & time) as well as Risks
- Risk-loaded schedules with the resulting probabilistic impacts on cost,
- Owner’s expectable “soft” cost (for own & external staff, business interruption, property value increase, etc.),
- Expected cost for Operations & Maintenance for the first 30 years,

All cost and schedule cost impacts have been probabilistically aggregated to Comparative Total Cost of Ownership at a Value at Risk 80% (P80) level. Therefore, supporting VTA for a risk-based, objective and unambiguous decision-making on the most advantageous solution. Contracted on March 9, the IRA/CA report was delivered on October 13, 2017 as per VTA’s requirements and directions. This validated approach sets the stage for future risk-based project evaluations.

REFERENCES

- Some recent publications about Risk-Based Cost Estimation and Controlling like e.g. from [http://www.moergeli.com/en/download](http://www.moergeli.com/en/download) => Risk Management (RM) III
- VTA’s BART Silicon Valley - Phase II Single Bore Tunnel Technical Study, February 2, 2017
- VTA Board Workshop and General Public Final Review, Sept 22, 2017 ([Live Recording - YouTube Video](https://www.youtube.com/watch?v=QkzQzQkzQzQz))