Bart Silicon Valley Phase II - Integrated cost & schedule life-cycle comparative risk analysis of single-bore versus twin-bore tunneling

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ABSTRACT: An independent integrated cost and schedule life-cycle risk analysis has been 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 to extend San Francisco’s Bay Area Rapid Transit (BART) service into downtown San Jose. VTA also conducted a fact-finding mission along with BART to Barcelona’s Metro Line 9 (L9) subway to allow first-hand evaluation of a single-bore system. Construction and system risks were qualitatively assessed and quantified in terms of cost and time to compare the cost and duration of the two options, including the differences in Operations & Maintenance (O&M) costs for the first thirty years of operation.

1 INTRODUCTION

The Santa Clara Valley Transportation Authority (VTA, www.vta.org) 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’s endpoint, 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. Alum Rock, Downtown San Jose and Diridon are underground stations, and Santa Clara is at grade. Phase II has two intermediate ventilation structures and East and West tunnel portals.

VTA re-started the planning efforts for BSV Phase II in 2014 with an update to the project environmental studies. An initial twin bore design effort had been advances to the ~65% complete in 2008 when it was tabled due to funding constraints. In the interim, 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 traditional 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). 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 better inform 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 comparison was part of VTA’s selection process to determine the preferred tunneling alternative. The assessment analyzed, described and compared the qualitative and quantitative risks associated with the two tunneling alternatives. The assessment was carried out within a risk management framework that is intended to proceed throughout design and construction in accordance with the Guidelines for Improved Risk Management on Tunnel and Underground Construction Projects in the United States of America (O’Carroll and Goodfellow, 2015).

Figure 1. Phase II Extension (Source: VTA BSV Phase II Tech Studies, 2017)

2 TUNNEL ALTERNATIVES

The two options are the twin bore (TB) option which constructs two single track 20-foot outer diameter subway tunnels, similar to other tunnels in the BART system, and the single bore (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.
2.1 Twin bore alternative

The TB design consists of two circular tunnels constructed by two TBM
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 has three proposed underground stations in the 65% Preliminary Engineering Phase; Alum Rock, Downtown San Jose station and Diridon/Arena station.

2.2 Single bore alternative

In addition to the feasibility study which found no fatal flaws, several follow-on SB technical studies performed more 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).

Figure 2. Twin Bore (TB) and Single Bore (SB) tunnel alternatives (Source: VTA Board Workshop and General Public Final Review, Sept 22, 2017)
2.3 VTA and BART representatives travel to Spain to inspect Barcelona’s Metro Line 9 single bore system

One of VTA’s commitments to BART was to fully investigate the life-cycle impacts in any evaluation made of the Twin Bore and Single Bore options; not simply to assess the initial constructability impacts. At the forefront of these considerations for BART, as it would be for any subway system operator, was long-term Operation and Maintenance. Getting a first-hand account of how a Single Bore system actually works in practice and how difficult it was to service and maintain was no easy task since there were no SB systems in North America. To do this properly would mean travelling to the first such system built in the world; Barcelona’s Line-9 (L9) in Spain. In addition to be the longest working SB system, Barcelona met the other essential criteria; they also operated a major network of older non-SB lines (like BART) so they had the ability to make valid comparisons between operating both types of systems. The ability to allow both BART and VTA staff to inspect the L9 first-hand, meet their counterparts in Barcelona, ask questions and engage in free-ranging discussion, led VTA officials to make the effort to bring all these people and experiences together. This culminated in a trip to Barcelona by VTA and BART staff for this purpose in July of 2017.

BART’s Observations: BART’s review paid particular attention to Line 9’s technology requirements, how the system was staffed, and security aspects of line. BART observed that L9 required less service labor due to more automation (for example, trains are driverless). BART learned that L9 has roving staff covering multiple stations for station operations and maintenance.

VTA’s Observations: VTA meet with L9 officials and found out that the same challenges of working in a dense urban environment with deep stations (very deep in Barcelona’s case) that were not amenable to cut & cover excavation, were the same issues that first led Barcelona to investigating SB for L9. These same officials confirmed that when these conditions combined, significant cost efficiencies were able to be achieved by utilizing an SB configuration.

VTA was impressed with some new features they had not encountered before, particularly the use of Platform Automatic Screen Doors as well as the use of numerous High-Speed Elevators (great for deep stations). VTA made notes of these features (including their own idea of optimizing the timing of elevators for the arrival/departure of trains) and is currently exploring the benefits of incorporating these improvements into the BSV Phase II design.

VTA learned that Barcelona created an ‘open’ system for L9 O&M Training. They provided everyone a chance to learn O&M for the SB L9 system, but it was completely voluntary. Reviews of this practice were favorable throughout Barcelona’s organization. VTA observed a lot of young people, both staff and engineers, that when interviewed said they loved the challenges of working on something new.

VTA investigated the performance of L9’s Emergency Exits. During one of their site visits to a deep station, they went through one of the Emergency Exits and travelled to the surface. VTA noted that L9 has emergency ramps (not staircases) and that these deposited into a defined rescue area on the surface (as opposed to the street). These features are also under study for inclusion in the final design of the stations.

VTA concluded that the L9 system functions efficiently, even with deeper stations than those planned for San Jose.

The trip was an important milestone in the selection process. It allowed critics to ask “unfiltered” questions directly to the people involved with running a SB system and receive direct answers to those questions. It allowed both BART and VTA to both tangibly vet as well as look “under the hood” of a system that did not exist in North America as well as get a first-hand account of the realities of maintaining such a system. While it would be incorrect to say that views were changed by the trip, it was critical in removing the abstractive veil surrounding the SB option and sharpened the focus of all parties on the task of evaluating the physical/operational issues that differed between the options.

2.4 Risk assessment process

An integrated cost and schedule analysis seeks to identify all risks and uncertainties that might significantly affect the predicted project cost and schedule. Specific methods are used 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 aggregates these impacts to risk-based cost and risk-loaded schedule results that are probabilistic distributions (instead of deterministic single value only estimates).

2.5 Qualitative analysis

The comparative risk assessment process for cost and schedule first reviewed and evaluated comparative base costs for both alternatives and normalized the costs of both options 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 initial cost and schedule risk register and then 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.

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. 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>Risk Control/Mitigation</th>
<th>Residual Risk</th>
<th>Controlling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td><strong>Residual Risk</strong></td>
<td><strong>Comments</strong></td>
</tr>
<tr>
<td>Mitigate</td>
<td>Combination of</td>
<td>1. Minimize use of material subject to tariffs/dues on non-US goods</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitigate</td>
<td>Carry out supplementary site/slab investigations</td>
<td>OP:Yes</td>
</tr>
<tr>
<td>Accept</td>
<td>Educate VTA in Time</td>
<td>OP:Yes</td>
</tr>
<tr>
<td>Mitigate</td>
<td>Combination of</td>
<td>- Reaching out to TBM manufacturer(s) to work out this issue during design of TBM</td>
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<td></td>
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Figure 3. Excerpt from risk register after controls (mitigation) implemented
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 threats/opportunities.

2.6 Quantitative analysis

2.6.1 Probabilistic risk analysis approach

A 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 probability 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 value.

2.6.2 Risk modelling process

Two numerical simulation models were developed using RIAAT software (for more information, please see 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 + Risk Costs. In the models, “Risk” includes both Identified Risk and Unidentified (or Known Unknown) 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 just the subsurface portions.

2.6.3 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.

VTA determined that using the 80th percentile of potential cost distributions would be appropriate for comparative purposes. The P80 level is the result found at the 80th percentile of outcomes, ranked from lowest to highest (i.e., in 100,000 simulations, P80 is the cost result of the 80,000 highest costing project simulation). The relative conservatism of comparing P80 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 Value Engineering (VE) exercise. The comparisons drawn are based on equally less-than-favorable outcomes and that has the benefit of examining overall Risk as a major part of the comparison.
2.6.4 Comparison of results

The simulations analyzed the comparative Base Costs which were subject to variable uncertainty in future prices and quantities based upon the level of each option’s design maturity or 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 reasonable minimal level of oversight and diligence on the Owner’s part (equivalent for both options). This is not the Aldea Team’s usual practice, nor was it anticipated at the onset. However, we 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 were based on assessments of project development factors, most notably design maturity. Additionally, a Real Estate Savings Opportunity and a Business Interruption Risk based on assessments of the differences in local community impacts expected by each option were evaluated and modeled. Finally, there is Schedule Risk which is calculated by RIAAT based upon Owner-caused delays; 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. The figures below present the full range of results for the simulated Base + Uncertainty Construction Cost (Figure 7), the Construction Program Risk Cost (Figure 8), and Heavy Civil Construction Completion Dates (Figure 9) for both options.

Figure 4. P0 through P100 comparison SB - TB (construction base + uncertainty cost)
Figure 5. P0 through P100 comparison SB - TB (construction program risk cost)

Figure 6. P0 through P100 comparison SB - TB completion dates heavy civil construction

A summary of the P80 results is presented in Tables 1 and 2.

<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>P80 Results Compared</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>
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<td>√</td>
<td>-3.6%</td>
</tr>
<tr>
<td>Lower Potential Risk Cost</td>
<td>√</td>
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<td>-39.9%</td>
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<tr>
<td>First to Revenue Service</td>
<td></td>
<td>√</td>
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<tr>
<td>Lower O&amp;M Cost (1st 30 Years - No Escalation)</td>
<td>√</td>
<td></td>
<td>-2.8%</td>
</tr>
<tr>
<td>SCHEDULE</td>
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<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>-247 calendar days</td>
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</tr>
<tr>
<td>First to Heavy Civil Completion (Ready for Trackwork)</td>
<td>√</td>
<td>-293 calendar days</td>
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Table 1. Comparison of twin bore and single bore options
3 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 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 the 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. All identified uncertainties were quantified wherever possible. All cost and schedule cost impacts have been probabilistically aggregated to Comparative Total Cost of Ownership at a Value at Risk 80% (P80) level thereby, providing VTA a risk-based, objective and thorough comparison to support their decision-making process to determine 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.

<table>
<thead>
<tr>
<th>Twin Bore vs. TB</th>
<th>Single Bore vs. TB</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>(TB)</td>
<td>(SB)</td>
<td>SB-TB</td>
</tr>
<tr>
<td>Base Cost Based on Designers’ Estimates</td>
<td>$2,143,407,000</td>
<td>$2,071,656,000</td>
</tr>
<tr>
<td>Based on Designers’ Estimates + Uncertainties</td>
<td>$2,338,793,000</td>
<td>$2,424,327,000</td>
</tr>
<tr>
<td>Total Potential Risk Cost Based on Risk Workshops &amp; Aldea’s Analysis incl. Takaura P80</td>
<td>$779,234,200</td>
<td>$1,296,065,000</td>
</tr>
<tr>
<td>O&amp;M Costs (1st 30 Years) ($2016, i.e., No Escalation) Based on Aldea’s Analysis P80</td>
<td>$1,759,099,000</td>
<td>$1,807,657,000</td>
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</table>

Table 2. P80 comparison summary spreadsheet

4 PROJECT STATUS AND OUTLOOK

- VTA’s Board accepted the single bore solution on April 5, 2018.
- BART Board of Directors approved the single bore tunnel plan on April 26, 2018.
- VTA received additional funding of $730 million from California’s Senate Bill 1, the newly passed gas tax, on April 26, 2018.
- VTA received a Record of Decision by Federal Transit Authority (FTA) on June 4, 2018.
- As per September 1, 2018 (date of submittal of this paper), the selection of a General Engineering Contractor (GEC) is ongoing.
- Our WTC presentation will deliver an updated insight into one of North America’s currently biggest infrastructure projects heading for construction.
5 REFERENCES

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VTA Board Workshop and General Public Final Review, Sept 22, 2017
VTA website (www.vta.org) & BSVII project information (http://www.vta.org/bart/)