# Connecting the Northeast: A Cost Estimate for the North-South Rail Link

## Faculty Research Working Paper Series

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# Abstract

This paper presents rough order-of-magnitude estimates for the capital cost of the North South Rail Link (the "Link"), a proposed infrastructure project to connect the commuter rail and Amtrak lines that currently terminate at Boston's North and South Stations via underground tunnels. The Link's design and construction cost was estimated using a financial model built from actual line item-costs in the Federal Transportation Administration's database of transportation projects.[1] A regression analysis of comparable completed tunneling projects was performed to validate this estimate. The Link is estimated to cost approximately $5.9 billion in 2025 dollars for the maximum build alternative (two tunnels, four tracks, and three stations). The minimum build alternative (one tunnel, two tracks, and two stations) is estimated to cost approximately $3.8 billion. Both estimates represent a mean of several estimation techniques and are the center of a distribution of possible cost outcomes. The study also identified the areas in which cost overruns have occurred in previous tunnel and rail projects and proposes steps to mitigate against such overruns. The study did not examine the potential benefits of constructing the Link and we recommend further study of both the costs and benefits of this important project.

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[1] The source of the past project costs was the Capital Cost Database maintained by the Federal Transit Administration (FTA), U.S. Department of Transportation. The Capital Cost Database includes actual project costs in all Standard Cost Categories for 54 federally funded transit projects.

# Acknowledgments

The research for this paper was conducted independently by public administration graduate students at the Harvard Kennedy School (HKS) under the supervision of HKS Professor Linda Bilmes and as a part of the Rappaport Greater Boston Applied Field Lab.[2] This program is supported with funding from the Rappaport Institute for Greater Boston and the Taubman Center for State and Local Government.

We wish to thank Professor José A. Gómez-Ibáñez [3] for his initial advice on transportation research and his feedback on this study's methodology. Executive Dean John Haigh[4] gave us insight into construction project management and risk mitigation. We also thank Kristen Koob at the Kennedy School library for her research assistance and Ellen Gallagher MPA '16 for her help throughout the project. We also acknowledge the assistance of Matthew Tyler MPP '17 and Chetan Jhaveri MPA, MBA (Sloan) '17, who each gave thorough feedback on the regression analysis.

We also thank Dr. Ali Touran,[5] who provided guidance and information regarding past infrastructure project costs. Brian Iammartino[6] gave us insight into construction cost trends and provided feedback on our financial spreadsheet model. Maya Sarna at the Federal Transit Administration clarified technical details of the FTA's infrastructure cost data. Roberta Brzezinski[7] provided helpful background on infrastructure finance. Peter M. Zuk[8] confirmed key aspects of the cost estimation approach.

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[2] Since its inception in 2005, the Rappaport Greater Boston Applied Field Lab program has undertaken dozens of complex projects in the fields of budget and finance, public-private partnerships, economic development, public works, transportation, and city management in communities throughout Greater Boston. This study was undertaken at the request of U.S. Representative Seth Moulton, who represents Massachusetts' 6th congressional district. We gratefully acknowledge the assistance of Congressman Moulton and his staff members Ian Hatch and Charlene Lee, who provided us with background information on this project.

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# Executive Summary

Boston has 16 commuter rail and Amtrak lines that terminate at either North Station[9] or South Station.[10] Today, rail commuters cannot travel continuously through the city because these two stations are not directly connected by track. The short stretch between North Station and South Station is the lone missing link in the MBTA[11] commuter rail system and in Amtrak service lines from Virginia to Maine.

The North South Rail Link (the "Link") would connect North Station and South Station through one or two underground tunnels. If built, the Link would permit Amtrak and commuter rail passengers to traverse Boston without interruption. It would also allow residents of Boston suburbs to access any commuter rail station throughout the city without switching to another mode of transportation.

This paper presents order-of-magnitude[12] estimates for the design and construction cost of the Link. A financial spreadsheet model using historical project data from the Federal Transit Administration (FTA) was used to estimate an order-of-magnitude cost. A regression analysis using publicly available information from comparable projects was used to validate the spreadsheet model. Interviews with experts informed the methodology of these estimates. The paper also examines risk factors that could lead to cost overruns beyond the estimates presented. These factors most likely include professional service costs, unforeseen challenges regarding site structures or tunnel construction, schedule delays, or project management structure.

Based on our methods, the Link is estimated to cost approximately $5.9 billion for the maximum build, which includes four tracks, two tunnels, and three stations. The minimum build (two tracks, one tunnel, and two stations) is estimated to cost approximately $3.8 billion. The tunnel length used was 2.958 miles for the maximum build and 2.788 for the minimum build, based on figures

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[9] North Station is one of Boston's major transit hubs. North Station is the terminus of four commuter rail lines (Fitchburg, Haverhill, Lowell, and Newburyport/Rockport) serving Central Massachusetts and the North Shore. North Station is also the terminus of Amtrak's Downeaster line, which runs up through New Hampshire to New Brunswick, Maine. North Station is a stop on the Orange and Green MBTA (or "T") subway lines and on the #4 bus line.

[10] South Station is another major Boston transit hub. South Station is the terminus of eight commuter rail lines (Framingham/Worcester, Needham, Franklin, Providence/Stoughton, Fairmount, Greenbush, Plymouth/Kingston, and Middleborough/Lakeville) serving Central Massachusetts and the South Shore. South Station is also the terminus of Amtrak's Acela Express, Lake Shore Limited, and Northeast Regional trains. South Station is a stop on the T's Red and Silver Lines (the latter serving Boston's Logan Airport) and multiple bus lines.

[11] The Massachusetts Bay Transportation Authority (MBTA, colloquially known as the "T") is the state agency that administers most public transportation in Greater Boston and surrounding communities.

[12] An order-of-magnitude cost estimate is a rough and preliminary assessment of a proposed infrastructure project's cost before the development of detailed design and engineering plans. The estimates presented in this paper are not meant to replace a thorough and detailed assessment of the Link's likely cost based on the final design parameters, construction conditions on the ground, and verified unit costs for construction materials, machinery, labor, professional services, and other project inputs.

used in a study conducted in 2003 of this potential project.[13] All cost figures are inflated to 2025 dollars (the assumed midpoint of construction). Our estimates examined the same build components as the 2003 study.

The estimate is highly conservative. We increased the unit costs for each item in the spreadsheet model by 16.4% to account for higher-than-average construction costs in Boston.[14] We also added a 50% contingency supplement to our model in line with guidance from the FTA. Additionally we performed a Monte Carlo simulation to model the actual cost of historical projects, including cost overruns if they incurred, rather than using average costs.

Our updated estimates suggest that the economic case for the project may be significantly more attractive than earlier understood. We recommend further study of the Link proposal to develop detailed cost estimates, assess the potential benefits, and determine its benefit-cost ratio.

# Background on the North South Rail Link

The first study of a direct connection between North and South Stations' rail tracks was conducted in 1909 (Wallis 2010). An underground rail tunnel to connect North Station and South Station was included in the original plan for the Central Artery/Tunnel (CA/T),[15] or the "Big Dig" (Luberoff 2002). This rail connection was later taken out of the CA/T plan in order to secure federal funding for the highway component of the larger project (Luberoff 2002).

The Link garnered renewed attention in 1993 when Governor William Weld commissioned the Central Artery Rail Link Task Force to assess its feasibility (Federal Transit Administration 1995). A Major Investment Study/Draft Environmental Impact Report (MIS/DEIR),[16] released in 2003, remains the most detailed review of the project's scope and potential (Massachusetts Bay Transportation Authority 2003). Based on the cost estimates presented in that study, Governor Mitt Romney shelved the project (Chesto 2016).

The Link has received more attention over the past few years due to the advocacy of two former Massachusetts governors, U.S. Congressman Seth Moulton, and a consortium of civic leaders in the Greater Boston region. In August 2015, former Governors Michael Dukakis and William Weld

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[13] We evaluated the tunnel components specifications that were publicly available for the 2003 Major Investment Study/Draft Environmental Impact Report (MIS/DEIR). The detailed methodology for that study was not publicly available.

[14] Based on the city cost index in the FTA database.

[15] The Central Artery/Tunnel (CA/T), also known as the "Big Dig," was a major infrastructure project in Boston. The CA/T involved multiple components over the span of 25 years, including the construction of the Tip O'Neill Tunnel for the I-93 highway, the Zakim Bridge over the Charles River, and the Ted Williams Tunnel connecting I-90 to Logan Airport.

[16] The 2003 MIS/DEIR report contains the most detailed examination to date of the North South Rail Link's estimated ridership, benefits, cost, design, environmental impact, and financing options, among other aspects of the project.

penned a joint op-ed in the Boston Globe calling for the Link's funding and construction (Dukakis and Weld 2015). In September of the same year, Governor Dukakis convened the North South Rail Link Working Group, a coalition of legislators, mayors, transportation experts, and business leaders, to advocate for the project (Dungca 2015). More recently, Congressman Moulton has become a strong supporter of the Link and is now the leading voice for the project in Washington (Chesto 2016). In early 2016, Governor Charlie Baker's administration allocated up to $2 million for a new study to revisit the Link proposal (Leung 2016).[17]

# Potential Benefits

Proponents of the North South Rail Link highlight several potential benefits of linking North Station and South Station through an underground tunnel system.[18]

1. *Seamless commuter transit across Greater Boston*. Currently, Boston has two unconnected commuter rail systems to the north and south of the city. To transfer between the two systems, commuters must either travel by bus, two T lines, or walk more than a mile.

2. *Streamlined rail transportation along the Northeast Corridor*. The span between North Station and South Station is the only gap in Amtrak service from Virginia to Maine. Building the Link would allow Amtrak train passengers to travel continuously through Boston.

3. *Spur economic development in Greater Boston*. Many companies in Boston cluster near T stops and commuter rail stations. With the Link, more workers who live in Boston suburbs would be able to access job opportunities throughout the urban core.

4. *Ease negative traffic effects of Boston's growth.* Proponents argue that the Link would reduce highway congestion and encourage sustainable development as more car drivers switch to rail commutes (Citizens for the North South Rail Link 2017).[19]

5. *More efficient commuter rail system.* Managing stub-end stations (end-of-line terminals such as North Station and South Station) is highly complex.[20] The Link would convert North Station

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[17] A contract for $1.5 million was granted in July 2017 to Arup USA to study a proposal for the North South Rail Link (Seiffert 2017).

[18] The focus of this paper is on presenting an order-of-magnitude capital cost estimate for the North South Rail Link. Potential benefits cited by the Link's proponents are briefly described here but are not examined in detail. Furthermore, this paper does not present ridership estimates for the Link, compare the Link proposal to other rail infrastructure projects under consideration (such as the South Station Expansion plan), or consider the costs of electrifying Amtrak's Downeaster line. These topics lie outside the scope of our study.

[19] The 2003 MIS/DEIR projected that the project would increase daily trips by 19,000 under a minimal build scenario (an increase of 1.5%) or by 54,350 in a maximum build scenario (an increase of 4.1%) (Massachusetts Bay Transportation Authority 2003).

[20] A stub-end station is a station where train lines terminate at the station. To resume service at the end of a line, a train must turn around or remain stationary while the train is reset. The operation of a stub-end station therefore

and South Station into run-through stations, allowing trains to continue serving passengers on the other side of the city.

## Cost Estimate Methodology Overview

This paper develops order-of-magnitude estimates for the construction and design of the North South Rail Link by creating a *financial spreadsheet model* based on federal government line-item construction cost data for past rail projects in the FTA database. This cost database includes the Standard Cost Categories (SCC) (see Technical Appendix for list of SCCs). These comprise construction costs, as well as purchase of land, professional services, and vehicles.

A Microsoft Excel financial spreadsheet model was developed to calculate the total capital cost of the Link from the individual line item costs of the project. This model was based on the Federal Transit Administration's (FTA) spreadsheet for new infrastructure projects[21] and uses unit cost data retrieved from the FTA's Capital Cost Database. The FTA is an agency within the U.S. Department of Transportation that provides financial and technical assistance to local transit systems. The Capital Cost Database includes as-built costs for 54 federally funded transit projects (Federal Transit Administration 2017).[22] To be conservative, the Excel model adds a 16.4% surcharge to federal data to account for local construction costs and applies a 50% contingency factor to the construction costs. Additionally, we performed Monte Carlo simulations to generate a range of possible outcomes based on variation in the FTA unit cost database.

The parameters used for the North South Rail Link in our study were based on the publicly available information in the 2003 MIS/DEIR.[23] That study considered several build alternatives, including the CA/T alignment route evaluated for our study. The CA/T alignment runs from North Station to South Station along the Central Artery/Tunnel corridor, and includes building a new Central Station at the Aquarium Station for our maximum build alternative.

To check and validate the magnitude of this estimate, we conducted a linear regression based on the total cost of comparable tunnel projects. The regression equation was derived from publicly available data on construction parameters and total costs for tunneling projects that resemble the Link. This regression equation was then populated with the Link's construction parameters to obtain point estimates and confidence intervals for the cost of building the Link. The regression

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requires non-revenue train movements and a less efficient use of the station for the loading and unloading of passengers. Furthermore, a delay in such a non-revenue movement for a single train can have a cascading effect, resulting in further train delays elsewhere in the system (Massachusetts Bay Transportation Authority 2017).

[21] The New Starts SCC Workbook is available at https://www.transit.dot.gov/funding/grant-programs/capital-investments/new-starts-scc-workbook

[22] The Capital Cost Database is available at https://www.transit.dot.gov/capital-cost-database

[23] We were asked to conduct a new analysis based on the current data. We were not able to conduct a direct comparison to the 2003 study as the detailed methodology for that study is not available on the website.

equation and the spreadsheet models were developed independently[24] in order to ensure objectivity.

Both approaches were supplemented by interviews and correspondence with experts in transportation, infrastructure, financial modeling, and regression analysis.[25] These expert consultations served to corroborate the methodology of this paper and validate its findings.

Each method was applied to two potential North South Rail Link designs.[26] The four-track (or maximum) build follows the maximum specifications outlined in the 2003 MIS/DEIR. It includes two underground tunnels, each with two tracks, as well as the construction of a third station between North Station and South Station. The alignment is illustrated in Figure 1. The two-track (or minimum) build consists of a single tunnel with two tracks and two stations. The alignment of the minimum build does not include the portals in South Bay, but would include an alternate method for connecting to commuter rail served by these portals. It does not include a new third station. Both designs follow the CA/T alignment option.[27] Tunnels for both builds would be bored using tunnel-boring machines (TBM).[28]

Additional parameters of each build[29] are based on the MIS/DEIR as well as a technical report conducted by the MBTA in 1995 that looked at the same parameters. (Massachusetts Bay Transportation Authority 1995). The project timeline and construction specifications were updated based on reports from more recent comparable projects in the United States (Federal Transit Administration 2016). All cost estimates are reported in 2025 dollars, the assumed midpoint year of construction.[30] All methods in this paper assume a future yearly inflation rate of 3.5%.[31]

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[24] While the team members primarily responsible for the regression analysis and the financial spreadsheet model regularly collaborated on expert interviews and team discussions, they did not provide input on the details of each other's cost estimation approach until the verification stage of the study.

[25] A listing of experts consulted for this study can be found in the Technical Appendix of this paper.

[26] The 2003 MIS/DEIR considered six build alternatives for the Link. These designs varied in terms of their tunnel alignment (along either Dorchester Avenue or the CA/T path), the number of tracks (two or four), and number of stations (two or three). We chose to develop cost estimates for the minimum and maximum builds from these alternatives to provide the full plausible range of likely project costs.

[27] The 2003 MIS/DEIR examined three potential alignments and concluded that the CA/T path provided the fewest obstacles to the project's completion. The Logan Airport Corridor was ruled out for requiring more miles of track. The second alternative, the Congress Street Corridor, would only allow for a two-tunnel build. As a result, the study centered on the CA/T alignment for its analysis. The alignment in our study led to South Bay, rather than the Back Bay option included in the MIS/DEIR.

[28] A tunnel-boring machine (TBM) is a large industrial machine that excavates underground tunnels with a pressurized cutting face at the front of the machine. The excavated material is removed through the middle of the machine and out of the tunnel, allowing for mostly continuous operation. TBMs that drill through soft soil install prefabricated concrete segments as they progress, leaving behind a reinforced tunnel. One of the major advantages of TBMs over other tunnel construction methods is that they generally do not create disturbances above ground, allowing for tunnel building below dense urban areas.

[29] Additional parameters include items such as tunnel lengths, power systems, and estimated number of locomotives and coaches needed. All build parameters were derived from these prior studies.

[30] The FTA requires inflating cost estimates to the projected midpoint year of construction to provide a more realistic picture of the final project costs (due to expected inflation during the course of the project).

[31] A 3.5% future yearly inflation rate assumption was chosen to maintain comparability with the 2003 MIS/DEIR.

Figure 1: *Map of a proposed alignment for the North South Rail Link maximum build* (Citizens for the North South Rail Link 2017)

# Financial Spreadsheet Model

The primary estimation approach consists of an Excel model that incorporates the various build parameters of the Link to deliver a cost estimate within a range of plausible outcomes.

Cost data for each line item was primarily derived from the FTA's Capital Cost Database[32] (Federal Transit Administration 2017). The database includes actual cost data from 54 completed transportation infrastructure projects in the United States, recorded in accordance with the FTA's

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[32] The Capital Cost Database "is a Microsoft Access database of as-built costs for 54 federally funded projects in the following modes: bus rapid transit, commuter rail, light rail, heavy rail, and trolley." (Federal Transit Administration 2017).

Standard Cost Categories (SCCs)[33]. The FTA's Standard Cost Categories are defined budget line item categories for costs associated with the construction of transportation infrastructure projects. This database was intended for performing historical cost analysis and developing order-of-magnitude cost estimates for transit projects (Federal Transit Administration 2017).

We generated an Excel report of all project data in the Capital Cost Database. We used 2017 as the base year for adjusting the as-built project line item costs to current-year, nationally representative costs (i.e., accounting for construction cost inflation and regional construction cost differences).[34] We then filtered this dataset to include only those projects built in the last 20 years that included a significant tunneling component.[35] This filtering was done to ensure the relevance of unit cost data to the Link project. We then created a pivot table to determine the average, minimum, maximum, and standard deviation values for each Standard Cost Category from the projects in the filtered dataset.

The average and range figures for each Standard Cost Category were linked to the project budget spreadsheet. This sheet calculates the baseline project cost for the Link by multiplying the unit costs from the pivot table by the unit quantities (or project design parameters) in the Link as specified in the 2003 MIS/DEIR.[36] The national unit costs were then increased by 16.4% to reflect Boston's higher construction costs.[37]

We adjusted total line item costs for inflation to 2025,[38] the assumed midpoint of Link construction, according to the expected year of expenditure for each line item.[39] These line item

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[33] In 2005, the FTA implemented these categories "to establish a consistent format for the reporting, estimating, and managing of capital costs for New Starts projects" (Federal Transit Administration 2017).

[34] The actual, or "as-built," project costs in the Capital Cost Database are recorded at the midpoint of construction for each project element. In order to use these historical costs to generate cost estimates for proposed projects, these costs must be adjusted to account for inflation and for regional cost differences. The Access database uses the user-provided base year to apply the relevant inflation and regional factors for each line item. The resulting Excel report contains the historical midpoint costs, quantities, and unit costs for each project, as well as the inflation and region adjusted unit cost. We used the adjusted unit cost as the basis for subsequent analysis.

[35] We excluded projects older than 20 years (before 1996) to account for potential unobserved changes in long-term construction practices and cost trends that could not be accounted for through other means. We excluded projects that did not include a significant tunneling component to ensure that the data sample was comparable to the Link project. Sensitivity analysis determined that these exclusion criteria generated higher line item cost averages when compared to the averages for all projects. The exclusion criteria therefore lead to a more conservative (i.e. higher) cost estimate. This is appropriate, given that underground rail projects are typically more complex and expensive than comparable at-grade or aerial projects.

[36] We adjusted the unit quantities to generate separate cost estimates for the minimum and maximum Link builds.

[37] Construction costs in Boston are among the highest in the U.S. (JLL Research 2016). A shortage of labor and growing housing demand may be driving these increasing costs (Gonzalez 2017). The 16.4% regional adjustment factor to reflect higher Boston construction costs was obtained from the FTA's Capital Cost Database cost models (Federal Transit Administration 2017). An interview with Brian Iammartino, CFA, confirmed that this regional factor is a reasonable adjustment to account for Boston's higher construction costs (Iammartino 2017).

[38] Total line item costs were adjusted to 2025 dollars in order to remain consistent with the regression estimates and to provide a realistic picture of future project costs. As previously mentioned, the future yearly inflation rate assumption was 3.5%.

[39] Year of expenditure adjustments were calculated based on a projected construction schedule of eight years, beginning in the year 2021 and ending in 2029 (with 2025 as the midpoint of construction).

components include not just construction costs, but also a variety of other estimated project costs, such as real estate acquisition, construction mitigation, and new rolling stock purchases (specifically, coaches and dual-mode locomotives) that are associated with the Link project. Finally, the sheet sums the total line item costs for all project components to arrive at a baseline capital cost estimate for the project.[40]

Following the FTA's guidance for presenting order-of-magnitude estimates, this baseline capital cost total for the project is adjusted to reflect the uncertainty surrounding the design, engineering, construction, and financing of a project at a conceptual stage (Federal Transit Administration 2016). In order to account for potential cost overruns stemming from this uncertainty,[41] the FTA recommends incorporating unallocated contingency allowances and conducting early project risk assessment to arrive at a more realistic preliminary cost estimate for large transportation infrastructure projects (Federal Transit Administration 2016).

The financial spreadsheet model incorporates two distinct methods to take into account the potential for cost overruns: a contingency approach and a simulation approach.[42]

First, we added a 50% contingency allowance factor on construction costs to the project budget. This contingency was added to account for minor design changes and unexpected circumstances that could lead to cost overruns.[43] This contingency approach is the most straightforward and most common method used to account for early project risk. (Federal Transit Administration 2016). The contingency approach generates a single cost figure for the Link project.

The second cost overrun estimation approach consists of a Monte Carlo[44] simulation of potential cost outcomes. For each trial in the simulation, a normally distributed unit cost outcome[45] was generated for each line item in the project budget sheet. These unit cost outcomes were then applied to the Link parameters to generate a total cost outcome for the project. This procedure was repeated for 10,000 trials. The output of the simulation is a distribution of the 10,000 project

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[40] This cost estimate does not take into account financing costs. However, the project budget spreadsheet applied a 3% finance charge factor to all project costs immediately before generating the baseline project cost estimate, in line with FTA guidelines (Federal Transit Administration 2016). A detailed examination of potential financing options and costs for the Link are outside the scope of this study.

[41] Cost overruns are commonplace in large infrastructure projects. Bent Flyvbjerg, professor at Oxford University's Saïd School of Business and the leading researcher in this field, found that almost nine out of every ten infrastructure projects run over budget, and that the average cost overrun for rail projects is 45% of budgeted costs (Flyvbjerg, Skamris Holm and Buhl 2003).

[42] At the recommendation of Professor Gómez-Ibáñez, these two cost overrun estimation methods are presented separately; integrating the two methods might lead to double counting the cost risk (Gómez-Ibáñez , Review of financial spreadsheet model 2017).

[43] This 50% contingency rate is highly conservative; the Federal Transit Administration recommends a baseline 30% contingency for an order-of-magnitude cost estimate (Federal Transit Administration 2016). The higher 50% contingency allowance was used in this paper to maintain consistency with the 2003 MIS/DEIR.

[44] A Monte Carlo simulation "uses random sampling and statistical modeling to estimate mathematical functions and mimic the operations of complex systems" (Harrison 2010).

[45] The line item normal distributions were established using the mean and standard deviation values in the project sample item (as calculated in the aforementioned pivot table). The line item cost outcomes within each trial were then calculated using a random number function constrained by the line item's normal distribution.

cost outcomes.[46] The mean value of the trials was used as the point estimate for the Link project cost.[47]

Using the 50% contingency approach, the financial spreadsheet model estimated the cost of the maximum (four-track) Link build at $6.55 billion (all costs reported in projected 2025 dollars). The 50% contingency approach yielded an estimate of $3.90 billion for the minimum (two-track) build.

Using the Monte Carlo simulation approach, the financial spreadsheet model estimated the cost of the maximum Link build at $6.46 billion, with a standard deviation of $2.08 billion. The simulation approach yielded an estimate of $3.83 billion for the minimum build, with a standard deviation of $1.02 billion. The range of two-standard deviations below and above the mean was from $2.29 billion to $10.62 billion for the maximum build, and from $1.79 to $5.87 billion for the minimum build. This range represents 95% of the outcomes in the distribution that resulted from the simulation.

# Regression Analysis Confirmation

We undertook a regression analysis -- using a different method and different data sources -- to validate the spreadsheet model estimate. The regression analysis derives an estimated preliminary capital cost for the North South Rail Link based on the construction characteristics and total cost of similar tunneling projects that have been constructed recently.

A preliminary dataset was assembled from publicly available information on transportation projects (mainly rail and highway projects) that included a significant tunneling component. Key data points, such as construction start and end dates, tunnel length, project location, and total capital cost, were collected for each project. Where primary sources (such as official project websites, press releases, or project reports) were not available for particular project costs or parameters, we used secondary sources (including industry journals and news reports). Where conflicting total cost figures for the same project were encountered, we used the higher figure. These total project costs were then adjusted for inflation and currency exchange differences (in the case of foreign projects).[48]

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[46] According to Flyvbjerg et al. 2003, the percentage of cost overruns for the infrastructure projects in the study was normally distributed with a slight right skew (Flyvbjerg, Skamris Holm and Buhl 2003). The simulation in this study generated a moderately right-skewed cost outcome distribution, indicating the existence of considerable tail risk.

[47] One limitation of the simulation in this model is that line items varied independently in each trial, whereas in reality some degree of covariance would be expected among related costs.

[48] Following established practice (Flyvbjerg, Skamris Holm and Buhl 2003), we first adjusted for inflation (to 2016) in the original project currency and then converted to US dollars using the January 1st, 2016 exchange rate for the relevant currency (XE 2017). For projects in Western Europe, we used the European Union's Construction Cost Index (Eurostat 2017) to account for inflation. For projects in the U.S., we used the FTA's inflation index table from the Capital Cost Database cost models (Federal Transit Administration 2017).

From the preliminary dataset of 48 tunneling projects, 19 projects were selected for inclusion in the final regression dataset. Each project in the final dataset met six criteria that made it similar to the Link. These were:

1. Designed for rail or road
2. Included a significant tunneling portion
3. Used a tunnel-boring machine
4. Less than 10 miles long
5. Completed in the last 15 years
6. Located in the U.S. or Western Europe

See technical appendix for further explanation of criteria.

In assembling the dataset, there was a tradeoff between the number of projects and the similarity of the projects to the Link. The final dataset, which incorporated the stringent selection criteria outlined above, favored similarity to the Link over sample size. This selectivity reduced the risk that the resulting estimates are biased by projects that are substantially different from the Link, at the expense of potentially larger confidence intervals for the cost estimates.[49] Despite the small sample size, we adopted this approach because it was a method to corroborate the accuracy of the cost model estimate. We used the regression to test the results of the spreadsheet model to check that the cost was in the range predicted by the regression.

Several regression specifications were tested on the dataset to determine statistically significant cost drivers. Out of these tests, three independent variables emerged as highly significant cost drivers of comparable tunneling projects: project located in Western Europe or the U.S., tunnel length, and construction duration.

The regression model's three independent variables are significantly and positively associated with the total project cost. The resulting ordinary least squares (OLS) regression formula[50] is as follows:

$$Total\ project\ cost\ =\ \beta_0\ +\ \beta_1 usa\ +\ \beta_2 tunnel\ miles\ +\ \beta_3 construction\ months\ +\ \varepsilon$$

The Link's project parameters were multiplied by the regression model output coefficients to obtain point estimates and confidence intervals for the capital cost of the two project builds.

For the maximum, four-track build, the regression method yielded an estimated cost of $4.82 billion (2025 dollars); the 95% confidence interval ranged between $3.39 and $6.24 billion. The minimum, two-track build was estimated to cost $3.72 billion, with a 95% confidence interval of $2.54 to $4.89 billion.

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[49] Most of the 19 projects included in the final dataset were urban rail projects similar to the Link. The one major difference with the Link was that Western European projects were more prevalent in the sample; just five comparable projects have been constructed in the United States.

[50] Please see the Technical Appendix for additional information on the regression sample, design, and results.

# Order-of-magnitude Cost Estimates

Averaging the regression and financial spreadsheet model results provides an order-of-magnitude cost estimate for the North South Rail Link.[51]

The four-track (or maximum) Link build "mean of means"[52] is $5.94 billion (all estimates in projected 2025 dollars). The two-track (or minimum) Link build mean of means is $3.82 billion. The tables below summarize the point estimates, two-standard deviation ranges, and mean of means for both builds and the different cost estimation approaches. The tables below include the values that are two-standard deviations above and below the mean to illustrate the spread of the normal distribution of possible outcomes in our models. These outlier values represent unlikely scenarios. Tail risk analysis is explored in the next section.

*Figure 2: Maximum (four-track) build order-of-magnitude capital cost estimates (2025 dollars)*

| | **- 2 standard deviations[53]** | **Mean (point estimate)** | **+2 standard deviations** |
|---|---|---|---|
| **Financial spreadsheet model (50% contingency)** | | $6,550,000,000 | |
| **Financial spreadsheet model (simulation)** | $2,290,000,000 | $6,460,000,000 | $10,620,000,000 |
| **Regression analysis** | $3,390,000,000 | $4,820,000,000 | $6,240,000,000 |
| **Mean of means** | | **$5,940,000,000** | |

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[51] One important caveat to the preliminary cost estimates presented in this study is that they rely on the Link design specifications from the 2003 MIS/DEIR. Substantial changes to the Link's design beyond the parameters examined here (and outlined in the Technical Appendix) would require a revised cost estimate. Using an average of both the financial spreadsheet and regression method allows us to utilize actual costs from comparable projects in both the U.S. and Europe. However, as stated elsewhere, these order-of-magnitude cost estimates are not meant to replace a detailed cost estimate.

[52] The "mean of means" is an average of the financial spreadsheet model's 50% contingency point estimate, the financial spreadsheet model's Monte Carlo simulation mean, and the regression's point estimate. The mean of means is purposefully weighted toward the financial spreadsheet model; compared to the regression analysis, the financial spreadsheet model has a more robust sample of U.S. projects and better incorporates Boston's relatively high construction costs.

[53] In the case of the regression analysis, the lower and upper bounds reported are the lower and upper bounds of the 95% confidence interval, which is 1.96 standard deviations below and above the mean.

*Figure 3: Minimum (two-track) build order-of-magnitude capital cost estimates (2025 dollars)*

| | **- 2 standard deviations** | **Mean (point estimate)** | **+2 standard deviations** |
|---|---|---|---|
| **Financial spreadsheet model (50% contingency)** | | $3,900,000,000 | |
| **Financial spreadsheet model (simulation)** | $1,790,000,000 | $3,830,000,000 | $5,870,000,000 |
| **Regression analysis** | $2,540,000,000 | $3,720,000,000 | $4,890,000,000 |
| **Mean of means** | | **$3,820,000,000** | |

# Cost Risk Assessment and Mitigation

Both the financial spreadsheet model and the regression analysis used conservative assumptions. As stated above, the financial spreadsheet model incorporated two different risk adjustment mechanisms, accounted for Boston's high construction costs by applying a 16.4% increase construction factor, and adjusted historical project data from the FTA account for actual costs. The regression incorporated strict inclusion criteria to limit the dataset to projects that resembled the North South Rail Link—mainly, urban tunneling projects in high-cost regions.

Furthermore, the inherent uncertainty in predicting the Link's cost at such an early stage of development resulted in a wide range of possible cost outcomes within the two-standard deviation range for the financial spreadsheet model and the regression analysis model. This is expected for a preliminary, order-of-magnitude cost estimate such as the one presented here.[54] As such, the mean estimates reported should not be considered detailed specific estimates. They are rough order-of-magnitude estimates, which generally have a margin of error of -25% to +75%.

Given this uncertainty, there remains a possibility for costs to exceed these estimates, or for cost savings to be realized. One study found that about 90% of major infrastructure projects had

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[54] The FTA recognizes that the earlier the stage of project development, the higher the risk for potential cost overruns in the future. To account for this risk, the FTA recommends a baseline 30% contingency rate on construction costs prior to the development of detailed engineering plans (Federal Transit Administration 2016). This guideline helps projects managers plan for a contingency fund that can be used in extenuating circumstances without exhausting the primary budgeted funds. As the project proceeds through planning and execution milestones, revised cost estimates that incorporate more detailed cost information and actual project outcomes will generate narrower confidence intervals and more accurate point estimates, reflecting the reduced cost overrun risk and (potentially) the use of contingency funds.

exceeded their initial budget—often by large margins (Flyvbjerg, Skamris Holm and Buhl 2003). Recent U.S. projects using TBMs suggest that costs for tunneling may be substantially lower than those used in our model. However, given the historic frequency and consequences of cost overruns, we focused our analysis on this risk rather than on cost savings.

As the two-standard deviation range illustrated, the outcomes near the 95th percentile of our model distribution far exceeded our mean estimate. This result indicates the existence of tail risk[55] that could cause costs to run over budget. Considering which factors can lead to extremely negative outcomes can aid in the development and implementation of cost risk mitigation policies. These policies can in turn reduce the likelihood and magnitude of cost overruns.

Three approaches provided insight into cost overrun drivers that could substantially increase cost risk. First, we calculated the variance for each Standard Cost Category within the FTA Capital Cost Database to approximate each line item's uncertainty. Second, the schedule impact of a delay in key line items on subsequent project milestones was examined.[56] Third, the causes of cost overruns during the construction of the Central Artery/Tunnel project were examined.

This cost risk assessment highlighted five areas of concern. The first three areas are specific Standard Cost Categories that displayed a high degree of variance in the FTA Capital Cost Database. The other two areas were informed by the examination of the Central Artery/Tunnel Project.

1. *Professional services costs.*[57] These are highly variable and sensitive to changes in the project timeline.

2. *Site structures.* While site structures represent a small part of the anticipated cost of the project, they may be higher than expected because of the significant number of downtown landmarks that are in the Link's construction area. These include the Post Office and Federal Reserve buildings located near South Station. Site structure work can greatly influence the construction timeline and costs across the project.

3. *Tunnel construction.* This is the largest construction cost category and can present unforeseen challenges. For instance, differences in soil composition or hard objects encountered during the tunnel-boring phase can cause significant delays in the project.[58]

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[55] "Tail risk" is the potential for extreme outcomes (i.e. outcomes that are far away from the mean, in the tail ends of a probability distribution).

[56] Schedule impact was determined through a rudimentary estimate of the project's critical path based on engineering reports from the 2003 MIS/DEIR and on schedule projections from similar projects.

[57] Professional services include design, engineering, project management, administration, legal, and other similar soft costs associated with executing an infrastructure project. Per FTA recommendations, these are generally calculated as a fixed percentage of total construction costs in an order-of-magnitude estimate (Federal Transit Administration 2016). Our financial spreadsheet model calculates professional services as 30% of the Link's estimated construction costs; this rate is typical for rail projects.

[58] The Alaskan Way Viaduct replacement tunnel project in Seattle provides a recent example of tunnel construction delays leading to cost overruns. The TBM used in that project ran into a steel pipe during tunneling, which severely damaged the cutting head. This resulted in a two-year delay and an estimated $223 million in cost overruns

4. *Schedule delays.* The regression analysis shows that each additional month of construction is associated with a $17 million increase in the project's total cost (controlling for project location and tunnel length). Project delays can impact services and contracts across the construction timeline. A delay in tunneling, for instance, can increase costs in professional services, station construction, and site structures because tunneling schedule impacts final cost in each of these areas.

5. *Project management.* The transportation and infrastructure experts interviewed for this study agreed that project management is a significant contributor to the substantial cost difference between Western European and U.S. projects found in the regression analysis. Contract management needs to be well integrated in order to avoid delays or cost overruns due to conflicts between contractors.[59] If project management leads to cost overruns in one area of the project, it can be correlated with cost overruns in other areas of the project.

Further research should be conducted on these potential drivers of cost overruns to increase the certainty of cost estimates and mitigate tail risk. Furthermore, these estimates are based only on the project parameters and track builds described in the 2003 MIS/DEIR. Decisions to change the parameters of the project would have an impact on the accuracy of this estimate.

While the focus of this section has been on the potential for cost overruns, it should be noted that potential cost savings do exist for the Link project. Most importantly, recent TBM projects in San Francisco and New York City point to substantial reductions in the per-foot cost of tunnel construction compared with older projects.[60] Variance analysis using the financial spreadsheet model indicated that if the per-foot costs of tunneling for the Link resembled these two projects,[61] the Link's total cost could be over a billion dollars lower for the maximum build compared to the preliminary estimates presented above.[62]

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stemming from repair costs and the need to keep staff and consultants on the project for longer than expected (Lindblom 2016).

[59] For instance, San Francisco's Central Subway project has experienced significant challenges in integrating the station and tunneling contract work, leading to delays in station construction (David Evans and Associates, Inc. 2017).

[60] Tunneling costs for the NYC Second Avenue Subway project were reported as $19,000 per foot (Michaels 2016). Data and schematics from the San Francisco Central Subway project suggest a per-foot tunneling cost of around $26,000 (David Evans and Associates, Inc. 2017).

[61] To conduct this variance analysis, we substituted a $22,500 per foot unit cost for tunneling into the financial spreadsheet model and calculated the 50% contingency point estimate. The mean per-foot tunneling cost in the projects selected from the FTA database was approximately $38,000.

[62] However, these variances cut both ways. The San Francisco Central Subway project has also seen far higher station construction costs than the mean value in the FTA database (David Evans and Associates, Inc. 2017). If this were also the case for the Link, the project could exceed the cost estimate figures presented above.

# Impact of Improved Technology Since 2003 on Cost Estimates

Our cost estimates are substantially lower than those presented in the 2003 MIS/DEIR, which estimated the design and construction cost of the Link at between $5.2 and $8.5 billion in 2010 dollars (Massachusetts Bay Transportation Authority 2003).[63] This is equivalent to $9.4 billion for the minimum build and $15.8 billion for the maximum build in projected 2025 dollars.[64] Our study estimates the cost at approximately $3.82 billion (for the minimum, two-track build) to $5.94 billion (for the maximum, four-track build) in 2025 dollars.[65]

We did not conduct a direct comparison with the earlier study. However, there is evidence that the lower project cost is due in part to major technological advances that have occurred since the 2003 study. In particular, the cost of tunnel boring has declined significantly since 2003, when there was less experience using this technology. The 2003 MIS/DEIR states that constructing the Link tunnels would require a 41-foot diameter TBM, and notes that the industry had not yet developed such a large TBM.

This has changed significantly over the past decade. Today TBMs of up to 57.5 feet in diameter have been deployed in U.S. projects. Improvements in TBM technology and tunneling project experience seem to have substantially lowered the per-mile costs of tunnel construction (Michaels 2016). The lower estimates from our regression analysis (which include more recent TBM project cost outcomes) confirm this observation. In addition, there have been major technological advances in a range of construction technology items. Recent studies of other construction projects describe cost savings from automated TBM guidance systems and increased use of software such as building information modeling that can improve project management efficiency (Issa 2014), (Kemlani 2014) .

# Recommendations

This research finds that the design and construction cost of the Link total is approximately $3.82 or $5.94 billion (2025 dollars) for the evaluated designs (the minimum two-track or maximum four-track builds). While the total project cost could exceed the stated ranges around these

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[63] The estimates for the 2003 MIS/DEIR varied according to how many tracks and stations were included in the build alternative.

[64] The 2003 MIS/DEIR cost estimates were adjusted to 2025 dollars using the same methodology as in the financial spreadsheet model. First, the FTA's construction cost inflation index was applied to inflate the figures to 2017 dollars (2010 to 2017 inflation factor = 1.407). Subsequently, the 3.5% yearly future inflation estimate was used to adjust the cost estimates to projected 2025 dollars (2017 to 2025 inflation factor = 1.317).

[65] As noted previously, the purpose of this study was to develop a new cost estimate for the Link, based on current data. We could not compare the methodology our study to the 2003 study as the detailed methodology for that study is not available on its website.

estimates if the Link were built, many of the potential drivers of cost overrun are known and can be mitigated given proper project management and oversight.

The findings presented here suggest that with current technology and good management, the Link could be built at a lower cost than originally anticipated in the 2003 MIS/DEIR. The benefit-cost ratio for the project might therefore be more favorable than previously thought.

Given the considerable potential benefits of the Link and the estimated lower costs found in this paper, we believe it is prudent to examine the proposal in greater detail. Further study should determine if it is in the public interest to pursue the Link project, including a more detailed cost estimate based on engineering and design plans, ridership estimates, economic benefits, and environmental impact. We also recommend further research into effective contract models, management structures, and comparable tunneling projects that have experienced favorable cost outcomes. The experience of the Western European tunneling projects examined in the regression analysis suggest that there may be areas for cost savings that are not anticipated by this study. Incorporating best practices from these projects may further improve the cost and risk profile of the Link proposal.

With Boston's population continuing to rise, streamlined regional transportation will be paramount to the city's future. The North South Rail Link presents an opportunity to improve transit in Greater Boston. The Link could potentially boost economic development in both the Boston urban core as well as suburban communities, alleviate highway congestion, decrease vehicle carbon emissions, and facilitate rail transportation across the region. A more detailed study of the costs and benefits of this project is necessary to understand the role this project could play in meeting the growing transportation demands for the Boston region into the 21st century.

# Technical Appendix

## Financial Spreadsheet Model

### List of Capital Cost Database Projects Included in the Financial Spreadsheet Model

1. Atlanta MARTA - Line Dunwoody Extension
2. Boston MBTA - South Boston Piers – Busway
3. Denver - Southwest Corridor
4. Los Angeles - East Side Extension
5. Los Angeles - Red Line Segment 3
6. Minneapolis - Hiawatha Corridor
7. Pittsburgh - Airport Busway
8. Pittsburgh - Light Rail Stage II
9. Pittsburgh - North Shore LRT Connector
10. Portland - South Corridor/Portland Mall
11. Portland - Wilsonville to Beaverton
12. San Diego - Mission Valley East
13. San Francisco BART - SFO Extension
14. San Juan, PR - Tren Urbano
15. Santa Clara VTA - Tasman West
16. Washington, DC - Anacostia Outer (F)

### List of Standard Cost Categories[66]

- **10: Guideway & Track Elements**
    - 10.010 Guideway: At-grade exclusive right-of-way
    - 10.020 Guideway: At-grade semi-exclusive (allows cross-traffic)
    - 10.030 Guideway: At-grade in mixed traffic
    - 10.050 Guideway: Built-up fill
    - 10.060 Guideway: Underground cut & cover
    - 10.070 Guideway: Underground tunnel
    - 10.080 Guideway: Retained cut or fill
    - 10.090 Track: Direct fixation
    - 10.100 Track: Embedded
    - 10.110 Track: Ballasted
    - 10.120 Track: Special (switches, turnouts)
    - 10.130 Track: Vibration & Noise Dampening

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[66] The Standard Cost Categories in this list are the parent (i.e. major) categories included in the FTA's New Starts workbook for transit projects (Federal Transit Administration 2017). Many of these parent categories have subcategories that record more detailed costs. For instance, under SCC 10.070: Underground Tunnel, there are several subcategories for different types of TBMs that may be used in a project.

- **20: Stations, Stops, Terminals, Intermodals**
    - 20.010 At-Grade Station, Stop, Shelter, Mall, Terminal, Platform
    - 20.020 Aerial station, stop, shelter, mall, terminal, platform
    - 20.030 Underground station, stop, shelter, mall, terminal, platform
    - 20.040 Major stations, landings, terminals: Intermodal, ferry, trolley, etc.
    - 20.070 Elevators, escalators
    - 20.100 Signage and Graphics
- **30: Support Facilities: Yards, Shops, Admin. Bldgs.**
    - 30.011 Administrative Building
    - 30.020 Light Maintenance Facility
    - 30.030 Heavy Maintenance Facility
    - 30.040 Storage or Maintenance of Way Building
    - 30.050 Yard and Yard Track
- **40: Site Work & Special Conditions**
    - 40.010 Demolition, Clearing, Earthwork
    - 40.030 Haz. mat'l, contam'd soil removal/mitigation
    - 40.050 Site structures including retaining walls, sound walls
    - 40.060 Pedestrian / bike access and accommodation, landscaping
    - 40.080 Temporary Facilities and other indirect costs during construction
- **50: Systems**
    - 50.010 Train control and signals
    - 50.020 Traffic signals and crossing protection
    - 50.030 Traction power supply: substations
    - 50.040 Traction power distribution: catenary and third rail
    - 50.050 Communications
    - 50.060 Fare collection system and equipment
    - 50.070 Central Control System
- **60: Row, Land, Existing Improvements**
    - 60.010 Purchase or lease of real estate
    - 60.030 Services
- **70: Vehicles**
    - 70.010 Light Rail
    - 70.020 Heavy Rail
- **80: Professional Services**
    - 80.010 Preliminary Engineering
    - 80.020 Final Design
    - 80.030 Project Management for Design and Construction
    - 80.040 Construction Administration & Management
    - 80.050 Professional Liability and other Non-Construction Insurance
    - 80.060 Legal; Permits; Review Fees by other agencies, cities, etc.
    - 80.070 Surveys, Testing, Investigation, Inspection
    - 80.080 Start up
- **90: Unallocated Contingency**

- **100: Finance Charges**

**List of Key Project Parameter Assumptions for North South Rail Link Builds**[67]

Maximum (four-track) Build

Corridor length (in miles): 2.958
Number of tracks: 4
Number of tunnels: 2
Number of underground stations: 3
Tunnel construction method: Bored Earth Mixed Shield (Standard Cost Category 10.073)
Power distribution: Catenary
Dual-mode locomotives: 85
Coaches: 148
Planning start date: 1/1/2021
Tunnel construction: 4 years
Station construction: 3.8 years
Construction end date: 12/30/2028

Minimum (two-track) Build

Corridor length (in miles): 2.788
Number of tracks: 2
Number of tunnels: 1
Number of underground stations: 2
Tunnel construction method: Bored Earth Mixed Shield (Standard Cost Category 10.073)
Power distribution: Catenary
Dual-mode locomotives: 85
Coaches: 111
Planning start date: 1/1/2021
Tunnel construction: 4 years
Station construction: 3.8 years
Construction end date: 12/30/2028

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[67] The parameter assumptions for these builds are mostly based on the least and most extensive build alternatives presented in the 2003 MIS/DEIR. Appendix F of that study was particularly informative in establishing the parameter assumptions in this paper. The construction schedule parameters were updated based on our critical path analysis of the schedule elements. The estimated total time for construction (about 8 years) is still in line with the 2003 MIS/DEIR schedule estimate.

### Construction Cost Inflation Index[68]

| Year | Index |
|---|---|
| 1970 | 28.7 |
| 1971 | 32.1 |
| 1972 | 34.8 |
| 1973 | 37.7 |
| 1974 | 41.4 |
| 1979 | 57.8 |
| 1980 | 62.9 |
| 1981 | 70.0 |
| 1982 | 76.1 |
| 1983 | 80.2 |
| 1984 | 82.0 |
| 1985 | 82.6 |
| 1986 | 84.2 |
| 1987 | 87.7 |
| 1988 | 89.9 |
| 1989 | 92.1 |
| 1990 | 94.3 |
| 1991 | 96.8 |
| 1992 | 99.4 |
| 1993 | 101.7 |
| 1994 | 104.4 |
| 1995 | 107.6 |
| 1996 | 110.2 |
| 1997 | 112.8 |
| 1998 | 115.1 |
| 1999 | 117.6 |
| 2001 | 125.1 |
| 2002 | 128.7 |
| 2003 | 132.0 |
| 2004 | 143.7 |
| 2005 | 151.6 |
| 2006 | 162.0 |
| 2007 | 169.4 |
| 2008 | 176.5 |
| 2009 | 184.2 |
| 2010 | 192.7 |
| 2011 | 201.9 |

---

[68] The construction cost inflation index was obtained from the cost models in the FTA's Capital Cost Database (Federal Transit Administration 2017). This inflation index was also used to adjust the cost of the projects in the regression analysis.

| | |
|---|---|
| 2012 | 211.8 |
| 2013 | 222.7 |
| 2014 | 234.7 |
| 2015 | 246.5 |
| 2016 | 258.8 |
| **2017** | **271.2** |
| 2018 | 284.2 |
| 2023 | 361.9 |
| 2024 | 379.9 |
| **2025** | **398.7** |
| 2026 | 418.3 |
| 2027 | 438.9 |
| 2028 | 460.5 |
| 2030 | 507.2 |
| 2031 | 532.3 |
| 2032 | 558.7 |
| 2033 | 586.3 |
| 2034 | 615.3 |
| 2035 | 645.7 |
| 2036 | 677.6 |
| 2046 | 1097.8 |

### Regional construction costs index table[69]

| **Location** | **Factor** |
|---|---|
| Akron, OH | 97.0 |
| Albany, NY | 95.5 |
| Albuquerque, NM | 89.5 |
| Allentown, PA | 102.2 |
| Anaheim, CA | 107.4 |
| Atlanta, GA | 89.6 |
| Atlantic City, NJ | 106.2 |
| Austin, TX | 80.1 |
| Bakersfield, CA | 105.6 |
| Baltimore, MD | 92.2 |
| Bangor, ME | 87.4 |
| Baton Rouge, LA | 84.1 |
| Berkeley, CA | 116.3 |
| Billings, MT | 89.7 |
| Birmingham, AL | 88.2 |
| Bismarck, ND | 84.4 |
| Boise, ID | 89.9 |

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[69] The regional construction costs index was obtained from the cost models in the FTA's Capital Cost Database (Federal Transit Administration 2017).

| | |
|---|---|
| **Boston, MA** | **116.4** |
| Boulder, CO | 91.9 |
| Bronx, NY | 124.8 |
| Brooklyn, NY | 127.2 |
| Buffalo, NY | 101.3 |
| Burlington, VT | 86.4 |
| Cedar Rapids, IA | 92.3 |
| Champaign, IL | 99.6 |
| Charleston, SC | 83.3 |
| Charlotte, NC | 79.5 |
| Chattanooga, TN | 80.1 |
| Cheyenne, WY | 85.5 |
| Chicago, IL | 114.7 |
| Cincinnati, OH | 92.9 |
| Cleveland, OH | 100.0 |
| College Park, MD | 92.2 |
| Colorado Springs, CO | 92.9 |
| Columbia, SC | 78.9 |
| Columbus, GA | 84.3 |
| Columbus, OH | 93.9 |
| Dallas, TX | 94.6 |
| Davenport, IA | 95.8 |
| Dayton, OH | 92.5 |
| Dearborn, MI | 103.5 |
| Denver, CO | 94.1 |
| Des Moines, IA | 89.5 |
| Detroit, MI | 103.9 |
| Eugene, OR | 101.4 |
| Everett, WA | 102.2 |
| Fairbanks, AK | 123.5 |
| Fairfax, VA | 92.4 |
| Flint, MI | 96.7 |
| Fort Collins, CO | 91.7 |
| Fort Myers, FL | 86.6 |
| Fort Wayne, IN | 88.6 |
| Fort Worth, TX | 81.3 |
| Fresno, CA | 107.5 |
| Galveston, TX | 86.2 |
| Gary, IN | 99.2 |
| Grand Forks, ND | 81.8 |
| Jackson, MS | 83.9 |
| Knoxville, TN | 78.2 |
| Lakeland, FL | 90.5 |
| Little Rock, AR | 85.4 |
| Logan, UT | 86.0 |
| Long Beach, CA | 104.5 |
| Long Island City, NY | 127.1 |

| | |
|---|---|
| Madison, WI | 89.7 |
| Montgomery, AL | 81.1 |
| Morgantown, WV | 95.3 |
| New Orleans, LA | 87.2 |
| New York, NY | 131.3 |
| Newark, NJ | 110.6 |
| Newport News, VA | 103.7 |
| Newport, RI | 87.4 |
| Norfolk, VA | 87.4 |
| Oklahoma City, OK | 82 |
| Oxnard, CA | 107.3 |
| Peoria, IL | 99.5 |
| Philadelphia, PA | 115.2 |
| Phoenix, AZ | 89.1 |
| Provo, UT | 86.5 |
| Richmond, VA | 88.1 |
| Sacramento, CA | 109.2 |
| Saint Paul, MN | 108.5 |
| Salt Lake City, UT | 87.8 |
| San Jose, CA | 117 |
| St. Petersburg, FL | 83.4 |
| Tallahassee, FL | 79.2 |
| Tampa, FL | 91.3 |
| Tempe/Mesa, AZ | 86.3 |
| Toledo, OH | 99.1 |
| Washington, DC | 99.1 |
| West Palm Beach, FL | 85.1 |
| Wheeling, WV | 96 |
| White Plains, NY | 114.5 |
| Wilmington, DE | 104 |
| Winston-Salem, NC | 78.4 |
| Worcester, MA | 108.1 |
| Yakima, WA | 98.3 |
| Yonkers, NY | 117.4 |
| Youngstown, OH | 94.8 |
| Springfield, OR | 101.4 |
| Secaucus, NJ | 110.6 |

## Regression Analysis

### Project inclusion criteria explanation

1. *Transportation:* Every project in the dataset was either a rail or a road project. This criterion excluded other tunnel infrastructure projects (such as water intakes) that are typically less expensive than transportation projects.[70]

2. *Tunnel:* The projects included a significant underground tunneling component (as opposed to being aerial or at-grade projects).

3. *Tunnel-boring machine:* The projects in the dataset primarily used a tunnel boring machine to excavate the tunnel. This tunneling method would be used for the Link. TBMs have different cost and schedule structures compared to other tunneling methods.

4. *Similar length*: The included projects do not exceed 10 miles of total tunnel length. Longer projects might achieve economies of scale that would not be expected for the Link.

5. *Location:* Included projects were located either in the U.S. or Western Europe. This ensured that projects with lower labor costs (typically located in developing countries) were not included so as not to bias the cost estimates.

6. *Recent:* Every project in the dataset was completed within the last 15 years or is nearing completion. This criterion promoted consistency in TBM technology and experience level across projects in the dataset. It might also have reduced bias from unobserved construction cost changes compared to a longer time span.

### Projects included in the regression analysis

1. Malmo City Tunnel
2. Dedesdorf Wesertunnel
3. Stockholm Citybanan
4. Zurich Durchmesserlinie (Weinberg Tunnel)
5. Nodo di Bologna
6. 4th Elbe Tunnel
7. Port of Miami Tunnel
8. San Francisco Central Subway
9. Leipzig City Tunnel
10. New York City Second Avenue Subway (Phase 1)
11. Seattle Alaskan Way Viaduct replacement tunnel

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[70] Transportation tunnels generally have to incorporate additional safety features (such as emergency access shafts) that are not required for other kinds of projects.

12. Groene Hart Tunnel
13. Madrid Atocha-Chamartin Tunnel 2 (West)
14. New York City 7 Line Extension
15. Antwerp North-South Junction
16. Berlin Nord-Sud Fernbahn
17. Berlin U55 Metro Line
18. Western Scheldt Tunnel
19. Amsterdam North-South Line

### Regression formula

$$Total\ project\ cost\ =\ \beta_0\ +\ \beta_1 usa\ +\ \beta_2 tunnel\ miles\ +\ \beta_3 construction\ months\ +\ \varepsilon$$

### Regression variable descriptions

- *Total project cost* is a continuous variable for the capital cost of the infrastructure project, reported in adjusted 2017 U.S. Dollars.

- *USA* is a dummy variable for the location of a project (1 = United States; 0 = Western Europe).

- *Tunnel miles* is a continuous variable for the sum of all tunnel segments in the project, reported in miles.

- *Construction months* is a continuous variable for the duration of the project (from groundbreaking to revenue service), reported in months.

### Significant correlations found in regression

- Constructing a project in the United States (as opposed to Western Europe) is associated with a total project cost increase of $1.6 billion (controlling for construction months and tunnel miles).[71]

- Each additional month of construction[72] is associated with a total project cost increase of $16 million (controlling for project location and tunnel miles).

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[71] This vast cost differential between U.S. and Western European projects was not surprising to several of the experts consulted for this study. Rail infrastructure research also confirms that U.S. projects are more expensive than Western European projects on a per route-kilometer basis (Flyvbjerg, Bruzelius and van Wee 2008). Commentators point to poor contractor management, a proclivity for expensive stations (Smith 2012), and federal labor and environmental regulations (Beyer 2014) as factors that could explain the cost gap.

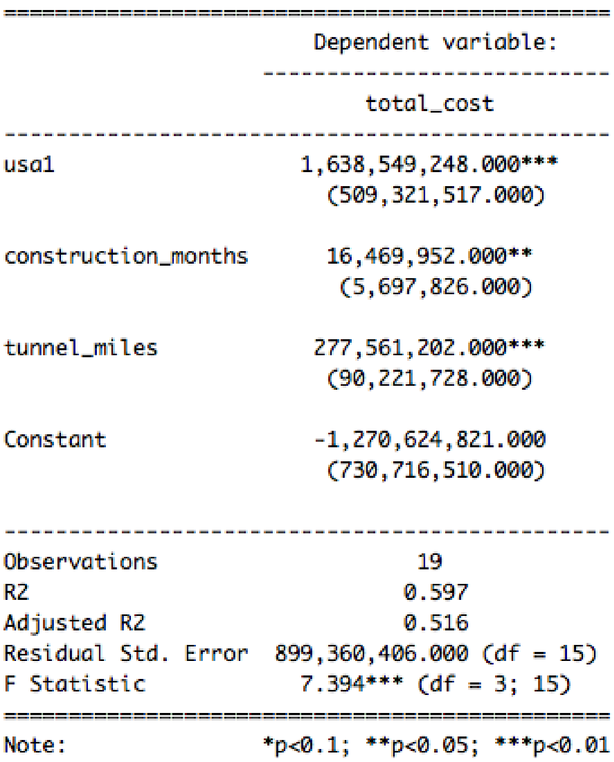
[72] It is important to note that the *construction months* independent variable in the regression model is itself dependent on future project outcomes (e.g., schedule delays). As such, it cannot be predicted with certainty. To generate the cost estimates, we used eight years (96 months) as the *construction months* value. This was the

- Each additional mile of tunnel is associated with a total project cost increase of $278 million (controlling for project location and construction months).

### Regression values for Link estimates

*USA* = 1
*tunnel miles* = 2.788 (minimum build) or 5.97 (maximum build for two tunnels)
*Construction months* = 96

### Regression results[73]



```
================================================
                        Dependent variable:
                    ----------------------------
                             total_cost
------------------------------------------------
usa1                   1,638,549,248.000***
                        (509,321,517.000)

construction_months     16,469,952.000**
                         (5,697,826.000)

tunnel_miles            277,561,202.000***
                         (90,221,728.000)

Constant                -1,270,624,821.000
                        (730,716,510.000)

------------------------------------------------
Observations                    19
R2                             0.597
Adjusted R2                    0.516
Residual Std. Error  899,360,406.000 (df = 15)
F Statistic            7.394*** (df = 3; 15)
================================================
Note:                *p<0.1; **p<0.05; ***p<0.01
```

---

estimated schedule duration of the Link project in the 2003 study. Eight years was also the average construction length of the projects in the regression dataset.

[73] Point estimates and confidence intervals were first obtained in 2016 U.S. Dollars and then adjusted to 2025 U.S. Dollars (assuming 3.5% yearly inflation) to reflect the expected midpoint of the project. Regression table prepared with R package *stargazer* (Hlavac 2015).

## European Construction Cost Inflation Index

| GEO/YEAR | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| European Union (28 countries) | 70.6 | 73.4 | 75.8 | 78.4 | 80.5 | 83.7 | 86.6 | 90.3 | 94 | 98.1 | 98.6 | 100 | 103 | 104.7 | 105.3 | 106.2 | 106.9 | 107.9 |
| Euro area (19 countries) | 74.3 | 77 | 78.7 | 80.5 | 82.1 | 85.1 | 87.6 | 91.1 | 94.6 | 98.2 | 98.2 | 100 | 103.3 | 104.8 | 105.1 | 105.4 | 105.6 | 106 |
| Belgium | : | 83.1 | 83.6 | 85.1 | 85.4 | 87.5 | 90 | 94.4 | 98.7 | 101.1 | 100 | 100 | 103.9 | 105.9 | 106.1 | 107.4 | 109.1 | 110.8 |
| Bulgaria | : | : | : | : | 65 | 67 | 72.6 | 76.8 | 82.2 | 93.1 | 100.8 | 100 | 100.8 | 100.3 | 102 | 103 | 104.4 | 106 |
| Czech Republic | : | 73.7 | 76.2 | 78.1 | 79.7 | 86.3 | 89.6 | 91.4 | 95.8 | 99.2 | 98.9 | 100 | 101.8 | 102.3 | 101.9 | 103.1 | 103.1 | 103.4 |
| Denmark | 75.1 | 77 | 79.4 | 81.1 | 83 | 84.6 | 86.7 | 90.7 | 96.5 | 99.3 | 98.9 | 100 | 103.6 | 106.3 | 107.8 | 109.6 | 111.6 | 113.5 |
| Germany (until 1990 former territory of the FRG) | : | 83.6 | 84.1 | 84.9 | 85.9 | 88.1 | 89.5 | 91.5 | 94.4 | 97.6 | 97.9 | 100 | 103.6 | 105.8 | 106.6 | 107.7 | 109.2 | 110.5 |
| Estonia | 67 | 68.5 | 72.4 | 75.2 | 77.8 | 81.9 | 87 | 96.2 | 108.4 | 112.1 | 102.7 | 100 | 103.5 | 108 | 113.3 | 113.6 | 114.6 | 114.1 |
| Ireland | : | 65.4 | 76.3 | 79.5 | 87.5 | 98.6 | 107.2 | 117.5 | 119.5 | 110.4 | 99.5 | 100 | 97.8 | 98.8 | 99.6 | 100.3 | 100.7 | 100.7 |
| Greece | : | 74.4 | 76.5 | 78.4 | 80.6 | 83.2 | 86 | 89.6 | 93.8 | 98.6 | 98.3 | 100 | 101.1 | 101 | 99.6 | 96.5 | 94.3 | 92.7 |
| Spain | 67.4 | 70.3 | 72.2 | 73.4 | 75 | 78.5 | 82.2 | 87.8 | 92.2 | 96.5 | 97.5 | 100 | 103.8 | 103.5 | 103.8 | 104 | 102.6 | 101.2 |
| France | 76.4 | 79 | 81.1 | 82.8 | 84.4 | 87.9 | 89.9 | 93.1 | 96 | 99 | 97.7 | 100 | 103.7 | 105.2 | 104.5 | 104.3 | 103.6 | 103.9 |
| Croatia | : | 70.8 | 69.4 | 70.7 | 71.9 | 87.6 | 91.7 | 93.3 | 104.2 | 115 | 105.6 | 100 | 101.4 | 98.8 | 93.1 | 93.4 | 96.4 | 95.3 |
| Italy | 72.3 | 74.4 | 76.1 | 79.1 | 81.5 | 84.9 | 88.2 | 90.7 | 94 | 97.6 | 98.5 | 100 | 103 | 105.4 | 106.1 | 105.9 | 106.4 | 106.7 |
| Cyprus | 60.2 | 63.4 | 65.8 | 68.3 | 72 | 77.2 | 80.7 | 84.8 | 89 | 96.1 | 96.9 | 100 | 103.4 | 104.4 | 100.1 | 98.3 | 97.7 | 97.1 |
| Latvia | : | 50.4 | 49.3 | 49.8 | 52.9 | 57.6 | 64.4 | 88 | 107.8 | 117.2 | 108.1 | 100 | 102.6 | 105.7 | 110 | 110.8 | 114.5 | 121.1 |
| Lithuania | 74.4 | 74.9 | 74.1 | 74.3 | 75.3 | 80.6 | 87.3 | 96.6 | 112.1 | 122.8 | 105 | 100 | 103.8 | 106.9 | 111.8 | 115.4 | 117.8 | 120.4 |
| Luxembourg | : | 77.5 | 80.7 | 82.9 | 84.6 | 86.9 | 89.6 | 92.1 | 94.8 | 97.8 | 99.2 | 100 | 102.6 | 105.6 | 107.6 | 109.6 | 110.8 | 111.9 |
| Hungary | : | 59.5 | 66 | 70 | 72.8 | 77.1 | 79.6 | 84.5 | 90.6 | 97.4 | 100.3 | 100 | 100.9 | 105.5 | 110.4 | 113.2 | 117.2 | 119.1 |
| Malta | : | 75.8 | 79.4 | 84.5 | 86.5 | 87 | 88.1 | 89.3 | 98.6 | 100.9 | 102.5 | 100 | 101.5 | 103.8 | 105.5 | 108.1 | 109.2 | 111.7 |
| Netherlands | : | 79.6 | 83 | 85.5 | 86.7 | 87.3 | 88.5 | 91.3 | 95 | 99.4 | 99.7 | 100 | 101.9 | 103.7 | 103.9 | 104.9 | 106.8 | 109 |
| Austria | 71.7 | 73.3 | 74.9 | 76 | 78 | 82 | 83.8 | 87.6 | 91.5 | 96.3 | 96.9 | 100 | 102.3 | 104.6 | 106.4 | 107.6 | 109.3 | 110 |
| Poland | : | 79.6 | 82 | 81.8 | 81 | 83.2 | 85.8 | 87.3 | 93.4 | 99.9 | 100.1 | 100 | 101.1 | 101.5 | 99.9 | 98.9 | 98.2 | 98 |
| Portugal | : | 80.3 | 80.8 | 83.2 | 84.6 | 86.4 | 88.1 | 90.8 | 93.9 | 98.8 | 98.2 | 100 | 101.6 | 103.6 | 105.7 | 106.2 | 106.1 | 108.1 |
| Romania | : | 22.6 | 31.6 | 38.6 | 47.5 | 59.4 | 68 | 75.4 | 83.1 | 96.5 | 98.1 | 100 | 109 | 116 | 111 | 110.4 | 109.6 | 110.6 |
| Slovenia | 54.5 | 59.1 | 65.5 | 67.7 | 71.8 | 77.2 | 80.8 | 85.7 | 91.7 | 97.7 | 94.6 | 100 | 104.6 | 103.4 | 102.2 | 101.7 | 102.4 | 101.2 |
| Slovakia | 59.9 | 65.4 | 69.5 | 72.9 | 76.1 | 81.3 | 85.3 | 88.7 | 92.4 | 98 | 100 | 100 | 100.7 | 100.8 | 101.2 | 102.4 | 103.9 | 105.1 |
| Finland | 76.3 | 78.6 | 80.5 | 81.2 | 82.7 | 84.7 | 87.6 | 90.9 | 96.3 | 100 | 98.9 | 100 | 103.3 | 105.8 | 106.9 | 107.9 | 108.5 | 109 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sweden | 65.3 | 67.8 | 70.9 | 73.3 | 75.8 | 78.8 | 81.9 | 86 | 91.2 | 95.7 | 97.6 | 100 | 103 | 105.7 | 107.4 | 108.3 | 110.8 | 113.2 |
| United Kingdom | 58.5 | 62.3 | 66.7 | 73.3 | 77.5 | 80.8 | 85.2 | 90 | 92.9 | 97.7 | 100.4 | 100 | 101.4 | 103.8 | 106.3 | 110.6 | 113.3 | 116.8 |
| Norway | : | 67.7 | 71 | 73.3 | 75.5 | 77.8 | 80.5 | 83.5 | 89.6 | 94.7 | 96.9 | 100 | 103.7 | 106.9 | 110 | 113.6 | 116.5 | 119.8 |
| Switzerland | 83.6 | 86.9 | 89.6 | 89.3 | 87.8 | 88.3 | 90.3 | 92.7 | 96.3 | 100 | 100.1 | 100 | 102 | 102.3 | 102.4 | 102.8 | 102.3 | : |
| Montenegro | : | 52.8 | 56 | 56.2 | 59.9 | 52.3 | 63.2 | 86.1 | 107.6 | 122.7 | 104.5 | 100 | 106.5 | 90.9 | 93.6 | 90.3 | 84.2 | 77.3 |
| Former Yugoslav Republic of Macedonia, the | : | : | : | : | : | : | 82.6 | 90 | 92.3 | 96.5 | 102.3 | 100 | 105.1 | 106.9 | 108.9 | 108.6 | 106.8 | 103.5 |
| Turkey | : | 21.4 | 33.6 | 45.7 | 55.5 | 63.5 | 69 | 80 | 86.7 | 98.7 | 94.7 | 100 | 112.3 | 118.5 | 124.6 | 137.8 | 146 | 157.3 |

## List of Experts Consulted

- Professor José A. Gómez-Ibáñez (Harvard Kennedy School)
- Executive Dean John Haigh (Harvard Kennedy School)
- Matthew Tyler (Harvard Kennedy School)
- Chetan Jhaveri (Harvard Kennedy School; MIT Sloan School School of Management)
- Professor Ali Touran (Northeastern University)
- Ian Hatch (Office of Congressman Seth Moulton)
- Brian Iammartino, CFA (btcRE LLC; Harvard Kennedy School)
- Maya Sarna (Federal Transit Administration)
- Roberta Brzezinski (CDPQ Washington)
- Peter M. Zuk (Zuk International LLC; Central Artery/Tunnel Project)

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