RESILIENCE AND SUSTAINABILITY OF UNDERGROUND TRANSPORTATION INFRASTRUCTURE: CLIMATE VULNERABILITY AND SUSTAINABILITY ASSESSMENTS

FINAL PROJECT REPORT

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For

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16. Abstract
The literature related to sustainability and resilience in underground transportation infrastructure (UTI) was reviewed. Two planning frameworks were investigated for their suitability to UTI and to illustrate the application of the framework for UTI. The first framework investigated was the Vulnerability Assessment Scoring Tool (VAST). VAST was found to work well for UTI. However, there is a need for additional guidance for the "tunnel" asset class. The second framework investigated was the Envision rating system for sustainability. Envision was found to capture both the advantages and disadvantages of underground transportation infrastructure. However, areas in which underground transportation infrastructure holds comparative advantages over other types of infrastructure are likely to be the least familiar to practitioners. Specific fruitful areas of research were identified to improve the relative benefit of underground transportation infrastructure.

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LIST OF ABBREVIATIONS

CS: Canal Street
CSFP: Canal Street with Flood Protection
CR: Climate and Risk (Envision category)
DCO: Design, construction, and operation
DHS: Department of Homeland Security
DOT: Department of Transportation
FEMA: Federal Emergency Management Agency
FHWA: Federal Highway Administration
IDOT: Illinois DOT
IPCC: Intergovernmental Panel on Climate Change
LA Metro: Los Angeles County Metropolitan Transportation Authority
LD: Leadership (Envision category)
MHHW: Mean higher high water
MTA: Metropolitan Transit Authority
NASEM: National Academies of Science, Engineering, and Medicine
NOAA: National Oceanic and Atmospheric Administration
NRC: National Research Council
NW: Natural World (Envision category)
NYSDOT: New York State DOT
PDF: Portable Document Format
QL: Quality of Life (Envision category)
RA: Resource Allocation (Envision category)
RMS: Roads and Maritime Services
SF: South Ferry
SFFP: South Ferry with Flood Protection
SLR: Sea-level rise
SS: Storm surge
SS: Spring Street
SSFP: Spring Street with Flood Protection
TL: Transport for London
TRB: Transport Research Board
TWUL: Thames Water Utilities Limited
UI: Underground infrastructure
UTI: Underground transportation infrastructure
VAST: Vulnerability Assessment Scoring Tool
WCED: World Commission on Environment and Development

EXECUTIVE SUMMARY

Resilience and sustainability are important goals for the long-term viability of transportation infrastructure. The topic has been widely studied. However, there is relatively little planning guidance specifically for underground transportation infrastructure (UTI). This study addresses the knowledge gap through the following goals:

1. Summarize existing knowledge related to sustainability and resilience planning in underground transportation infrastructure (Chapter 1).
2. Evaluate two assessment frameworks for infrastructure (Chapters 2 and 3).

Each framework is applied to representative underground transportation infrastructure with two sub-goals. The first is to illustrate how the framework is applied to underground transportation infrastructure. The second is to evaluate the framework's suitability for underground transportation infrastructure.

The Vulnerability Assessment Scoring Tool (VAST) is a component of a larger Federal Highway Administration (FHWA) effort to standardize climate vulnerability and assessment. VAST was evaluated for a subset of subway stations in New York City for storm surge coupled with sea-level rise. Indicators were defined for vulnerability due to exposure, sensitivity, and adaptive capacity. VAST calculates an overall vulnerability score as the weighted sum of the three indicators. This procedure and the results are detailed in Chapter 2. The example illustrates well how VAST encourages planners to consider multiple factors when prioritizing improvements. During this study, it was noted that the built-in guidance for tunnels lacks some details. Adding this information would help standardize the assessment of underground assets.

Sustainable design makes use of rating systems to encourage best practices. Rating systems assign points to various considerations of importance. They then establish tiers based on the total number of points earned. Envision is a widely used framework for all types of civil infrastructure. Envision was evaluated for a hypothetical, representative underground project and compared to an equivalent above-ground project. Envision highlighted many of the unique aspects of UTI. Strengths of UTI are primarily due to preserving beneficial above-ground features such as green space and cultural centers. However, these and similar considerations are the areas that are likely to be least familiar to a UTI practitioner. This negates the benefits unless additional efforts are made to communicate these benefits effectively. Disadvantages of UTI include higher upfront cost, the need for specialized equipment and labor, and energy- and carbon-intensive construction methods. Promising areas of research were identified to improve the relative weaknesses of UTI. These are dismantling and reuse of tunnel components, removal of pollutants from tunnels during operations before the pollutants reach the surface, and reuse of tunnel waste generated during construction. Finally, it was noted that Envision's treatment of resilience places significant emphasis on robustness and little on the speed of recovery after a disaster.

CHAPTER 1 - INTRODUCTION

The chapter is a reprint from a paper presented at the International Conference for Sustainable Infrastructure, 2019, with editorial modifications (Rodriguez-Nikl and Mazari, 2019). A portion of the paper also appears in Chapter 3.

RESILIENCE AND SUSTAINABILITY IN TRANSPORTATION INFRASTRUCTURE

The long-term longevity of transportation systems requires consideration of sustainable practices in construction and operation as well as resilience to a variety of possible hazards (NASEM, 2018a). A wide range of guidance exists on these topics for the transportation sector, but underground transportation infrastructure (UTI) has received less attention. This work has the following aims:

1. Summarize existing knowledge related to sustainability and resilience planning in underground transportation infrastructure.
2. Apply two of the frameworks to representative underground transportation infrastructure. Each assessment has two sub-goals:
    a. Provide an example application of the framework to underground transportation infrastructure, and
    b. Conduct a more in-depth evaluation of the assessment framework to assess its suitability for underground transportation infrastructure.

The terms “resilience” and “sustainability” are widespread beyond transportation infrastructure. Depending on the application, the terms carry different meanings. At times, the terms are not defined clearly. It is not the purpose in this chapter to address these difficulties, but to describe the state of their use in transportation practice. The literature review on resilience and sustainability contains four sections: guidance for transportation infrastructure, guidance for climate vulnerability assessments, rating systems, and underground-specific guidance.

The National Research Council (NRC, 2012) defines resilience as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.” Succinctly, resilience is the ability of a system to return to normal function after suffering a sudden shock. Bocchini et al. (2013) identify two key components of resilience: the ability to limit damage (robustness) and speed of recovery back to normal functioning (rapidity). Resilience has been identified as a national priority (NRC, 2012) and had generated a significant amount of literature (Gilbert, 2010). Efforts are underway to refine and formalize the concept in the transportation sector (Fletcher and Ekem, 2016; NASEM, 2018b). Shortcomings include a lack of quantitative metrics (which would help resilience efforts compete for funding) and disjointed understanding of core concepts. On the latter, NASEM (2018b) states, “climate change, risk assessment, asset deterioration as reflected in asset management plans, operational performance, and safety performance have yet to be fully integrated to demonstrate how each affects the other.” Other priorities in the resilience of transportation systems include integration with other systems (infrastructure and social), weather and climate forecasts, cyber-physical security, and employee qualification (TRB, 2016). The organizational capacity of transit agencies is also important, and related guidance has recently been developed (NASEM, 2017abc).

Since the late 1980s, the term sustainable development has referred to meeting our needs in the present without preventing future generations from meeting their needs. This international concept emphasized improving conditions for the poor and focused on the preservation of economic, social, and environmental resources (WCED 1987). In common practice, the shorter term “sustainability” is often employed. Although this introduces some vagueness, consistent with the state of the practice, we primarily use “sustainability” in this report. The bulk of available guidance for sustainability is reviewed in the next two sections on climate vulnerability and rating systems. Not falling under those categories are two tools developed for transit agencies (NASEM 2018c). One is a “roadmap” for organizational change to facilitate sustainability efforts, and the other is an ROI+S calculator (Return on Investment + Sustainability) limited to fleet operations.

There is a debate about the relationship between the two concepts (Redman, 2014). Indeed, there are differences. For instance, sustainability tends to consider longer durations and chronic stresses, while resilience considers shorter durations and sudden shocks (Bocchini et al., 2013). Yet, resilience to sudden shocks is a necessary condition for long-term sustainability. Both considerations become intertwined with climate change. As the climate changes, so do the characteristics of weather-related shocks. At a theoretical level, the two concepts can be viewed similarly (Rodriguez-Nikl, 2015), but at an operational level, they tend to emphasize different values and involve different professionals.

CLIMATE VULNERABILITY

Climate change is an increasingly relevant consideration for transportation systems. There is a need to (a) mitigate the contribution of transportation to climate change, and (b) adapt transportation systems to more severe weather/climate, e.g., increased storm severity, sea-level rise, and increased heat. TRB (2012) provides a summary of essential information for Climate Change and Transportation. TRB (2011) also provides overview articles covering the case for adaptation, history of Federal Highway Administration (FHWA) efforts related to climate change, international and state DOT experiences, airports, emergency response, and research needs. Impacts can vary regionally, so any assessment of a specific system or asset must consider the effects specific to the region. The FHWA (2017a) outlines the expected impacts across regions in the United States.

Based partly on the experience of pilot studies in various agencies in the United States (FHWA, 2016), FHWA (2017c) released a standardized framework for climate vulnerability assessment and adaptation. The framework details best practices in each step of the following process:

(1) Articulating objectives and defining the study scope,
(2) Obtaining asset data for the vulnerability assessment,
(3) Obtaining climate data for the vulnerability assessment,
(4) Assessing vulnerability,
(5) Identifying, analyzing and prioritizing adaptation options, and
(6) Incorporating assessment results in decision-making.

The framework contains a spreadsheet tool called the Vulnerability Assessment Scoring Tool (VAST) for assessing the vulnerability of assets to climate-related stressors (step 4 above). VAST is available from hyperlinks in the PDF version of the framework. VAST is a detailed spreadsheet that guides the user in performing an indicator-based desk review of vulnerabilities. Once the user chooses the asset and stressor types, the tool suggests indicators for exposure, sensitivity, and adaptive capacity. Chapter 2 details an application of VAST to underground transportation infrastructure (Martinez et al., 2018).

RATING SYSTEMS

Rating systems are common in sustainability-related practice (less so in resilience). They define areas of importance and assign point values to each area, depending on how well it is addressed. Based on the overall point total, rating systems then categorize the overall performance of a project. For example, **Envision** includes 64 credits organized into five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Resilience. These can be satisfied at various levels, each of which earns a different number of points: Improved, Enhanced, Superior, Conserving, and Restorative. Based on the overall point total, a project can be recognized at one of four levels: Verified, Silver, Gold, and Platinum (ISI, 2018). Chapter 3 details the application of Envision to UTI.

The only other rating system to recognize resilience (with only one credit) is **INVEST** (Infrastructure Voluntary Evaluation Sustainability Tool) for highways offered by the FHWA (2019). An advantage of INVEST is that it includes separate criteria depending on the phase of the project: Planning, Design, and Operation/Maintenance. Other readily available sustainability rating systems for infrastructure are **Greenroads** (2017); **GreenLITES**, which stands for "Green Leadership In Transportation Environmental Sustainability" (NYSDOT, 2019); **I-LAST**, which stands for "Illinois - Livable and Sustainable Transportation" (IDOT, 2012); and **BE^{2}ST-in-Highways**, which stands for "Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways" (RMRC, 2019). Also mentioned in the literature, is **Greenpaths** for shared use pathways (Oswald Beiler and Waksmunski, 2015). Rating systems face significant competition for adoption, and this listing will likely be outdated within five years.

Rating systems for sustainable infrastructure differ in what credits are selected, how these are organized, and what importance is attached to each (Oluwalaiye and Ozbek, 2019; Clevenger and Ozbek, 2013; Lineburg and Barella, 2017). Rating systems can also differ in their (a) suitability to various types of projects and project phases (pre-design, design, construction, operations, and maintenance); (b) project recognition requirements; and (c) professional credentials required of the project team (Vargas and Thorton, 2014). FHWA (2017b) argues that although rating systems have limitations (they are simplified and limited in scope, it is difficult to agree on what to include, and they can be used mindlessly), their ease of use offers encourages better practices and facilitates communication of the issues.

Similar frameworks exist for resilience. Notable examples are the framework to measure the resilience of New Zealand's transportation infrastructure (Hughes and Healy, 2014) and the subsequent adaptation to the needs of the Los Angeles County Metropolitan Transportation Authority (LA Metro, 2015). In these frameworks, the major categories of technical resilience measures are robustness, redundancy, and safe-to-fail. The major categories of organizational resilience measures are change readiness, networks, and leadership, and culture.

RESILIENCE AND SUSTAINABILITY IN UNDERGROUND TRANSPORTATION INFRASTRUCTURE

NRC (2013) describes the contribution of underground infrastructure (UI) to sustainable development, with resilience being understood as a requirement for sustainability. Benefits of UI to sustainability include efficient use of space, isolation of nuisances such as noise, preservation of the above-ground space (both cultural and natural), and improvement of mobility corridors (NRC, 2013; Hunt et al., 2016). Gaps that need to be filled to facilitate the contribution of UI to sustainable development include (a) understanding the place of UI among infrastructure systems, (b) making a long term commitment to UI, (c) developing life cycle assessment capabilities for UI, (d) promoting the resources offered by underground space, and (e) improving user acceptance (NRC, 2013). Regarding robustness, underground infrastructure is more vulnerable to flooding (but there are methods for mitigating the risk), more vulnerable to fire and blast (due to confinement), and less vulnerable to earthquakes as long as faults are avoided (Hunt et al. 2016). Given current developments with the COVID-19 pandemic, the relation of underground space to epidemiology is a relevant future consideration.

In a series of related papers, Nelson (2012), Nelson and Sterling (2012), Nelson (2016), and Sterling and Nelson (2013) argue that increasing urban densification will make proper stewardship of underground space increasingly important. Because of the increasing complexification of urban infrastructure, they argue strongly for a holistic, interdisciplinary systems approach. Their analytical resilience framework emphasizes Performance Response Functions, which are related to the work of Bruneau et al. (2003) and subsequent developments, and which describe performance over time as a system suffers a shock and recovers. In a unique proposal, Nelson (2016) suggests using Performance Response Functions to develop a fine-grained approximation of system performance using sales tax receipts. Such a measure would provide a quick idea of the system's performance similar to the way body temperature is used in medicine and would allow identification of regions with possible infrastructure malfunction.

The literature identifies some advanced topics for resilience in underground transportation infrastructure. A report by Beer et al. (2018) focuses on structural health monitoring, reliability and risk methods, and modeling of critical infrastructure networks. Makana et al. (2015) identify a lack of appropriate frameworks for evaluating resilience and sustainability in underground space and propose a data-driven, fuzzy framework to score project alternatives. This evaluative framework, while detailed, thorough, and interesting, seems to be limited to research applications. These types of approaches are beyond the scope of this project.

CONTENT OF THE REPORT

The next two chapters of this report presents the results from two related studies. Each project evaluated a framework for its use with underground transportation infrastructure. Each study illustrates an example of the tool's application and to evaluate the tool itself for use with UTI. Chapter 2 presents the application of VAST to subway stations in New York City. These assets were assessed for storm surge and sea-level rise. Chapter 3 presents the application of the

Envision framework to a hypothetical underground project. Conclusions from both studies are summarized in Chapter 4.

CHAPTER 2 – CLIMATE VULNERABILITY ASSESSMENT OF UTI IN COASTAL REGIONS SUBJECT TO SEA-LEVEL RISE AND STORM SURGE

This chapter is based on a paper presented at the International Conference for Transportation and Development (ICTD), 2018, with editorial modifications and some changes in the calculations (Martinez et al., 2018).

INTRODUCTION

Transportation infrastructure in coastal areas is vulnerable to extreme weather events such as storms, high tides, flooding, and severe precipitation. These events may result in increased construction, maintenance, and rehabilitation costs. Global climate change, especially increased precipitation, increased temperature, and sea-level rise, will further exacerbate the problem. The risk of sea-level rise coupled with storm surge will increase the vulnerability of coastal transportation infrastructure, including bridges, roads, tunnels, ports, and harbors. Sea-level rise combined with storm surge is the focus of this chapter.

According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." Factors such as environmental conditions, exposure to weather stressors, and the network relation of infrastructure components contribute to the vulnerability of the system (IPCC, 2007). Other factors affecting the vulnerability of infrastructure include age, design criteria, exposure level, service conditions, and structural integrity. A disruption in one component of the infrastructure at a local scale may affect the regional network based on the proximity of the connected assets and level of service. Coastal underground transportation infrastructure can be especially vulnerable to these network effects (Larsen et al., 2007; Kirshen et al., 2006). FHWA efforts to assess climate vulnerability are detailed in Chapter 1.

This chapter reports on a vulnerability assessment of a representative set of underground transportation assets to sea-level rise combined with storm surge. The vulnerability was assessed using VAST, which was described in the previous chapter. The two goals were to provide an example of the application of VAST to UTI and to assess VAST for its suitability to UTI. This work can be thought of as a light "stress test" of the VAST tool in a realistic context to observe how it works for underground assets.

VULNERABILITY ASSESSMENT ANALYSIS

This section begins with a definition of the study area and a description of data sources. Next, the stressors, scenarios, and assets are defined. Following this, indicators for exposure, sensitivity, and adaptive capacity are selected and defined for each asset and stressor. These terms are all defined as they are introduced below. The calculations performed by VAST and the resulting vulnerability scores are then presented.

Study Area

The study area encompasses three stations in Manhattan, New York City: South Ferry, Canal Street (red lines), and Spring Street (green lines). The stations were chosen to be representative of different elevations and susceptibility to flood and storm surge. Figure 1 shows the location of these and nearby subway stations in the vicinity. Many of these stations are susceptible to the intrusion of flood and stormwater during extreme weather events.

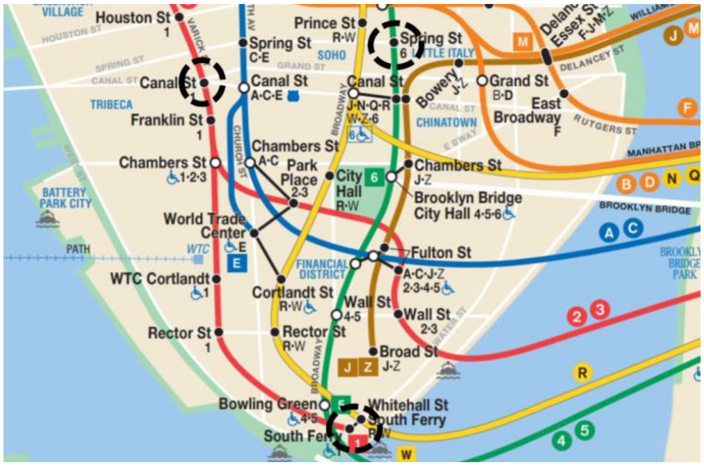

Figure 1 – Study area and assets chosen for the study

Data Sources

This section describes the sources used to obtain data related to exposure indicators for sea-level rise (SLR) and storm surge (SS). Federal Emergency Management Agency (FEMA) flood zones are used as an exposure indicator; these zones are shown in Figure 2. This map identifies two zones: high risk with a 1% annual chance of exceedance and moderate risk with a 0.2% annual chance of exceedance. The National Oceanic and Atmospheric Administration (NOAA) provides a visualization tool that estimates the flood exposure in coastal regions due to shallow coastal flooding, storm surge (SS), and sea-level rise (NOAA 2017a). NOAA also provides a sea-level rise viewer (NOAA 2017b) and a tool to view the National Storm Surge Hazard Maps (NOAA 2107c). Figure 3 illustrates the modeled storm surge inundation depths for Category 1 and Category 4 storms. No storm surge predictions were available for Category 5 storms. Figure 4 shows the prediction of water levels for 2 ft. and 6 ft. of sea-level rise above the current Mean Higher High Water (MHHW). These estimates or inundation depth are approximate and preliminary. A complete study should consider an advanced geospatial analysis, e.g., Vahdettin and Ozgur (2016) and Cohen et al. (2017).

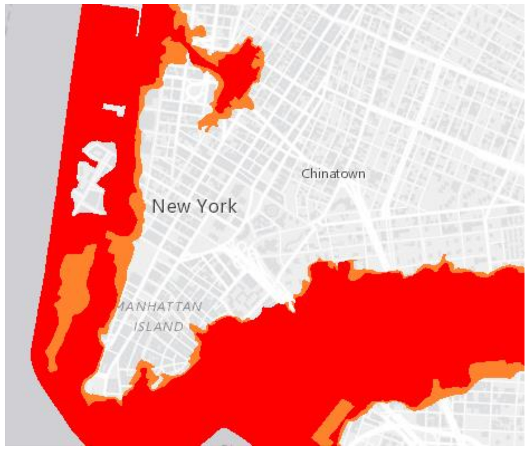

Figure 2– FEMA flood zones (red is high risk, orange is moderate risk)

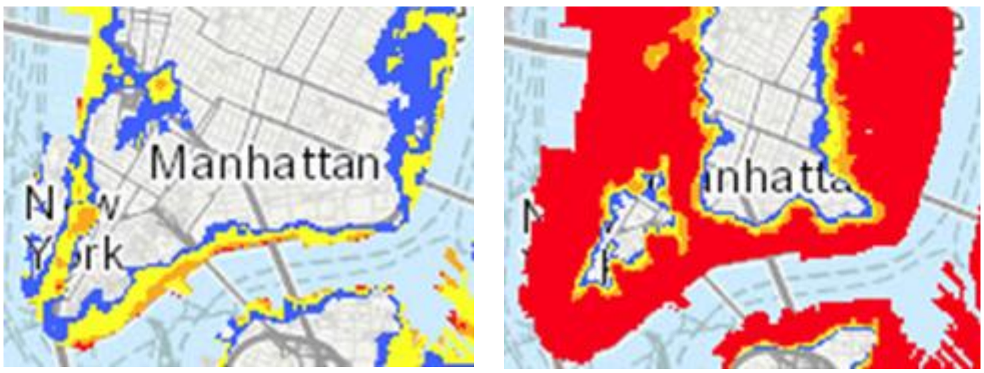

Figure 3 – Storm surge inundation depth, Category 1 (left) and Category 4 (right); less than 3 ft (blue), 3-6 ft (yellow), 6-9 ft (orange), greater than 9 ft (red)

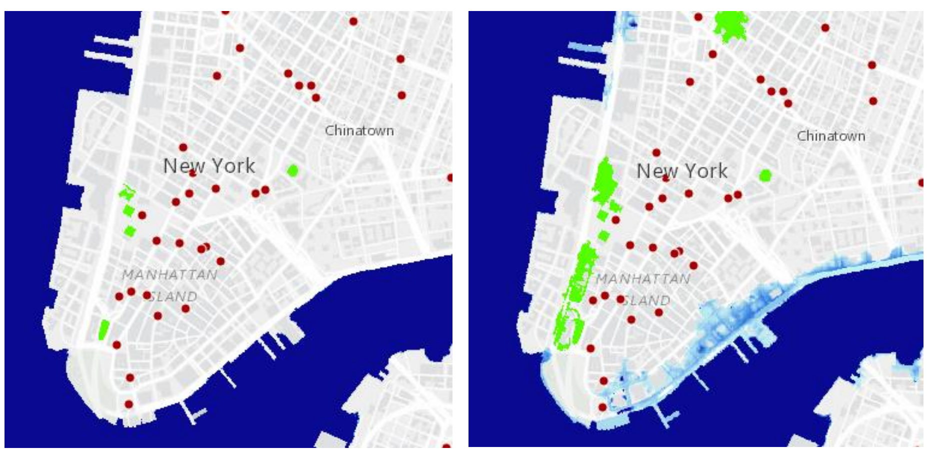

Figure 4 – Inundation areas for 2 ft. (left) and 6 ft. (right) of sea level rise

Stressors, Scenarios, and Assets

A climate stressor, as defined by VAST, is an external change in climate that may cause damage to the transportation system. As the New York subway system is located near coastal regions, it is vulnerable to sea-level rise (SLR) and storm surge (SS) flooding. These are the two stressors considered in this study. Scenarios are combinations of stressors at various levels of severity. This study considered two scenarios, corresponding to a less and a more severe case.

- Scenario 1: Low SLR (2 ft) plus SS from a Category 1 storm
- Scenario 2: High SLR (6 ft) plus SS from a Category 4 storm

The assets are the three selected stations defined previously. VAST guides the user in selecting an asset type. The asset type subsequently guides the choices the user makes in populating the model. The asset type “tunnels” was selected. For storm surge, each asset was modeled twice to simulate stations with and without flood protection. This results in the following six assets (the asset code is in square brackets):

- South Ferry [SF]
- Canal Street [CS]
- Spring Street [SS]
- South Ferry with Flood Protection [SFFP]
- Canal Street with Flood Protection [CSFP]
- Spring Street with Flood Protection [SSFP]

Exposure Indicators

An exposure indicator is a quantity that is related to the severity of exposure of each asset to the selected stressors. VAST provides an exposure indicator library that can be browsed for each climate stressor. This guidance was used in our selections. The following two indicators were used: presence in a FEMA flood zone and inundation depth. Inundation depth considered storm surge imposed on top of sea-level rise. The reported SS inundation depths are rough because of the resolution of the map. The SS inundation depth was added to the expected sea-level rise. This operation carries with it the assumption that the storm surge depth is measured from the MHHW at the time of the scenario. Table 1 details the calculation. VAST converts the indicator values to a score ranging from 1 to 4. Alternatively, an asset can be classified as “not exposed.” The default setting in VAST converts the indicators to scores by creating limits such that the largest indicator values correspond to a score of 4 and the smallest values to a score of 1. This setting was used in this study. Areas that were not subject to inundation were categorized as “not exposed.” Presence in the FEMA flood zone was categorized as follows: 4 points if in the zone, 1 point if near the boundary, 0 points if not in the zone. In this case, the calculated score using the VAST default is the same as the indicator value.

Table 1 –Inundation Depths (ft); NE = Not Exposed

Asset	Inundation Depths			
	SS Cat 1	2ft SLR +SS Cat 1	SS Cat 4	6 ft SLR +SS Cat 4
South Ferry	5	7	15	21
Spring Street	NE	NE	NE	NE
Canal Street	3	5	12	18

Sensitivity and Adaptive Capacity Indicators

Sensitivity refers to how assets fare when exposed to a climate variable. Adaptive capacity refers to the system's ability to cope with climate impacts (FHWA 2017c). Perhaps counterintuitively, the adaptive capacity indicator is larger if the disruption will affect the system to a greater extent. This may seem counterintuitive because higher values of the adaptive capacity indicator correlate to a lower capacity to adapt (but to a higher vulnerability). These indicator values are converted to a score between 1 and 4 in the same way as the exposure indicator. Unfortunately, the indicator library in VAST did not provide suggestions for either sensitivity or adaptive capacity for the "tunnel" category. The libraries for roads, transit assets, and rail lines were used instead.

The indicator library for roads lists flood protection as a sensitivity indicator. Given recent developments in flood protection for tunnels, e.g., the Resilient Tunnel Project from the Department of Homeland Security (DHS 2014), flood protection was used as an indicator of sensitivity to storm surge. Two assumed levels of flood protection were considered for each asset. The indicator value for unprotected stations was 100, indicating 100% water intrusion. The indicator value for protected stations was 20, indicating imperfect protection with 20% water intrusion. Greater water intrusion indicates greater sensitivity.

The indicator library for roads lists average annual daily traffic as an indicator of adaptive capacity. This is because a station with higher traffic will affect a greater number of people if disrupted. Given the public data easily available, we used traffic volume in trains per minute as the indicator. Traffic volume was calculated from the Metropolitan Transportation Authority (MTA) subway schedules. For stations without a schedule, we used the closest station with a schedule. For simplicity, the morning workweek rush hour portion of the timetable was used. The timetable lists time between trains (headway); the reciprocal of this is the traffic volume. For stations with multiple lines passing through it, the traffic volume was calculated for each line and summed. The indicator values thus obtained are:

- 0.13 trains/min for South Ferry
- 0.35 trains/min for Canal Street
- 0.40 trains/min for Spring Street

Other possible indicators were considered but neglected in this study for simplicity. Soil parameters were initially considered as sensitivity indicators. Water intrusion is an important factor in the durability of underground infrastructure components, and soil parameters will affect how an asset responds to rising sea levels. However, it was impractical to include this information in a study of this scope. Subway network considerations were also ignored, given the preliminary nature of the study. An important adaptive capacity indicator is the existence of alternate routes if one station is compromised. Another important consideration is how exposure of one station affects other stations due to being connected. A more comprehensive study would need to consider how the vulnerability of individual stations affects the entire network of linked tunnels and stations.

Results

VAST combines the indicator scores to calculate overall vulnerability scores. The vulnerability score is a weighted sum of the exposure, sensitivity, and adaptive capacity indicators. Following the defaults in VAST, each of the indicators was given equal weight. Different weights can be used if there is less confidence in some of the inputs. Table 2 and Figure 5 summarize the final results. The figure indicates the number of assets at each level of vulnerability and was produced directly in VAST. These results illustrate how VAST assigns a single metric for vulnerability to aid decision-makers in allocating limited resources. A full analysis would include the full array of stations, additional indicators, and use more precise numbers for the inputs. Assets with higher scores would then be prioritized for mitigation measures.

The calculated vulnerability scores are reasonable and highlight features of VAST. The vulnerability score for each asset is higher in the more severe scenario. However, the relative vulnerability ranking is unchanged between the two scenarios. The relative rankings could change in a more refined analysis. Flood protection reduces the vulnerability scores of the two stations by the same amount. The results illustrate that in the vulnerability assessment, some assets can simply be found to be unexposed to the hazard. In our study, the Spring Street station has scores of zero due to being unexposed to flooding in both scenarios. This station is indicative of assets that are considered initially but are not a priority for additional consideration. VAST encourages multi-factor decision making. This is exemplified in this study for the Canal Street and South Ferry stations. Canal Street has a higher vulnerability score than South Ferry even though it is less exposed. It may be tempting to prioritize the South Ferry station due to its proximity to water and greater inundation depth, but a full consideration of the factors indicates otherwise. The Canal Street station has a higher vulnerability score because of its higher traffic. Although it is less exposed than the South Ferry station, its higher traffic results in greater consequences from the disruption.

Table 2 – Vulnerability Scores

ID	Asset	Scenario 1	Scenario 2
CS	Canal Street	3.0	3.5
SF	South Ferry	2.5	3.0
CSFP	Canal Street (with flood protection)	2.0	2.5
SFFP	South Ferry (with flood protection)	1.5	2.0
SS	Spring Street	0.0	0.0
SSFP	Spring Street (with flood protection)	0.0	0.0

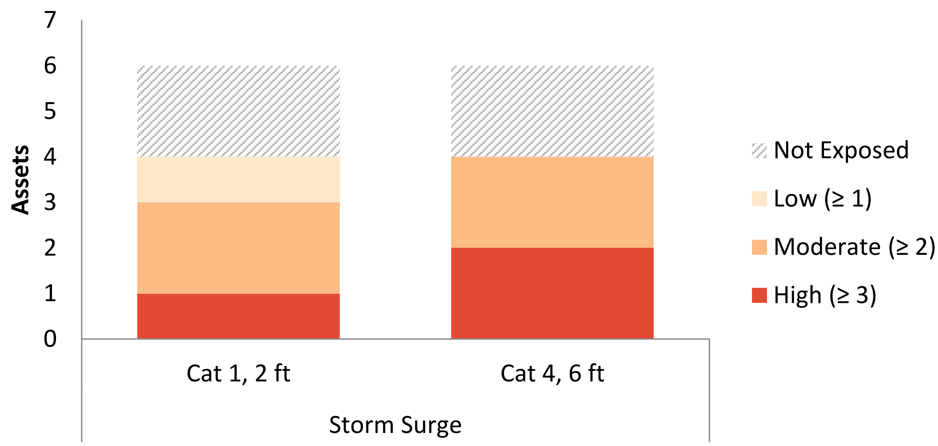

Figure 5 – Number of assets in each vulnerability tier for each scenario

SUMMARY AND CONCLUSION

The Vulnerability Assessment Scoring Tool is a powerful program used to assess assets in a transportation system. In this chapter, the tool was used to evaluate a representative subset of the New York subway system to show how the tool is used and to determine how well it applies to underground assets. The goal was to conduct a light "stress test" of VAST in a realistic context. Three representative stations were evaluated to assess the vulnerability to storm surge and sea-level rise. Two scenarios were defined: 2 ft. of sea-level rise with a Category 1 storm surge, and 6 ft. of sea-level rise with a Category 4 storm surge. Indicators were defined for exposure, sensitivity, and adaptive capacity. The resulting vulnerability score is the weighted sum of the various indicators. The results show how the tool can be used for decision-making. The most important shortcoming that was noted with using VAST for the tunnel asset class was the lack of guidance for choosing indicators for sensitivity and adaptive capacity. Adding this information to the model would help standardize the selection of indicators.

CHAPTER 3 - ENVISION SUSTAINABILITY RATING SYSTEM APPLIED TO UTI

This chapter is a reprint of a paper presented at the International Conference for Sustainable Infrastructure, 2019, with editorial modifications (Rodriguez-Nikl and Mazari, 2019). A portion of the paper also appears in Chapter 1.

INTRODUCTION

This chapter presents results from an assessment of the Envision Sustainable Infrastructure Framework for a representative UTI project. Envision was chosen for this study because it is well recognized, widely used, applicable to a wide range of infrastructure, and includes resilience explicitly. The Envision Framework was introduced in Chapter 1. Envision assigns credits to infrastructure projects in six areas

- Quality of Life, with subcategories of Wellbeing, Mobility, and Community
- Leadership, with subcategories of Collaboration, Planning, and Economy
- Resource Allocation, with subcategories of Materials, Energy, and Water
- Natural World, with subcategories of Siting, Conservation, and Ecology
- Climate and Risk, with subcategories of Emissions and Resilience

Envision has only been discussed in the scope of underground infrastructure by Shivakumar et al. (2014), who provide a case study of a pipeline project.

This study applies Envision to a hypothetical, representative transit tunnel. In this study, each credit was evaluated for its familiarity to the UTI community and the benefit of a UTI project as compared to a different type of infrastructure. Envision was found to capture the unique aspects of UTI. The areas in which UTI is most beneficial are, unfortunately, those that are least familiar to design professionals. This indicates a need to communicate these benefits to the appropriate decision-makers. At the end of the chapter, specific suggestions are made for potentially fruitful avenues of research and to strengthen Envision's treatment of resilience.

ASSESSMENT OF ENVISION FOR UTI

Methodology

Each Envision credit (excluding innovation credits) was assessed individually in three rounds. First, initial thoughts were recorded then reviewed to find the salient themes. Two dimensions were selected: familiarity to the underground community (Familiarity) and comparable benefit of the underground solution compared to an equivalent above-ground project (Benefit). In the next pass, each credit was assessed using preliminary rubrics. In the final pass, the rubrics were refined and the results were checked for consistency. The finalized rubrics for this assessment are provided in Table 3 and Table 4. Summary scores were calculated for each Envision category and subcategory. The score was calculated by a weighted average with the weighting factor taken as the maximum possible points for each credit. The spreadsheet used in this process is available for download (Rodriguez-Nikl, 2019).

Table 3 – Rubric for familiarity scores

Score	Description
4	Requires only minor extra attention to design, construction, and operation (DCO)
3	(a) Requires only minor extra attention to tasks beyond DCO OR (b) requires a significant advancement in DCO
2	Requires a significant advancement in tasks beyond DCO
1	Unfamiliar, outside of regular process

Table 4 – Rubric for Benefit scores

Score	Description
2	High positive
1	Low positive
0	Neutral or variable
-1	Low negative
-2	High negative

Results and Discussion

The results are presented in tabular and graphical form, aggregated for each of the five main categories and then for each of the fourteen subcategories (Table 5 and Figure 6). The downward trend in Figure 6 suggests that the categories in which UTI can outperform other types of infrastructure are also the categories least familiar to the design professional (alternatively, the most familiar categories are those with the least benefit). Effective presentation of these results to the appropriate decision-maker will help make the most of the beneficial aspects of underground infrastructure.

The **Natural World (NW)** category offers the most significant benefit primarily because underground development preserves above ground space. Of the subcategories, NW1 (Siting) offers the greatest benefit but is the most challenging, as it addresses foreign topics such as sites of high ecologic value and prime farmland. Both NW2 (Conservation) and NW3 (Ecology) contain credits that do not offer UTI a comparative benefit, e.g., reclamation of brownfields and reduction of pesticide and fertilizer impact for the former and control of invasive species and maintenance of floodplain functions for the latter.

The **Quality of Life (QL)** category offers nearly the same benefit as NW but addresses tasks that are more familiar. UTI is especially strong in subcategory QL2 (Mobility), because (a) it leaves above ground space undisturbed and (b) provides access and promotes mobility that may not be possible in fully-developed above ground space. In QL3 (Community), UTI faces challenges addressing equity due to the high cost of underground construction. In QL1 (Wellbeing), UTI gains a small benefit from the ability to better minimize noise, vibration, and light pollution.

The **Leadership (LD)** category is as familiar as QL. However, UTI is at a slight disadvantage when compared with other types of infrastructure. The relative disadvantage is due to the performance of LD3 (Economy) in which UTI faces challenges in two areas: (a) economic prosperity due to the higher cost and (b) developing local skills because some labor and equipment are highly specialized and must be imported. The cost considerations are possibly biased by the high initial cost of underground projects. It is possible that a comprehensive life cycle cost assessment would reach different conclusions. Because they deal with issues such as commitment to sustainability goals and stakeholder input, both LD1 (Collaboration) and LD2 (Planning) depend more on the agency than the type of infrastructure. Improvement in LD2 could be achieved by the development of techniques to dismantle and reuse tunnel components at the end of life, e.g., the tunnel dismantling machine proposed by Ng et al. (2017).

The **Climate and Risk (CR)** category is about as familiar as LD and QL, but UTI fares the same as other types of infrastructure because the credits refer either to topics common to all types of infrastructure (e.g., risk assessments) or depend on the agency (e.g., transit pollution). In subcategory CR1 (Emissions) UTI is at a slight disadvantage in terms of embodied carbon because of the energy-intensive construction methods (Chau et al. 2012), but this can be mitigated by attention to the tunnel route, low carbon materials (TWUL, 2013), and operational improvements (TL, 2016). Although it is not yet viable to remove pollution from tunnels during operation (RMS, 2014), improvements in this area would improve the relative benefit of UTI in this subcategory.

The **Resource Allocation (RA)** category is the most familiar and offers no comparable benefit over other types of infrastructure. This category is the closest to business as usual as it deals with activities such as waste production and resource use during construction and operation. There has been a recent interest in the reuse of tunnel waste (muck or spoil). Rahimzadeh et al. (2018) review the literature and identify difficulties in material quality, supply chains, and management. BDCP (2104) suggests such possible uses as strengthening levees, raising subsiding islands, restoring natural habitats, and as structural fill. Bellopede et al. (2011), Gertsch et al. (2001), and Oreste and Castellano (2012) address challenges for recycled material used as concrete aggregate. Ketelaars and Saathof (2000) study issues with the treatment of bentonite slurry, and Ritter et al. (2013) consider the treatment of uncertainty in this process. Additional developments in these areas can benefit UTI in this category.

Envision deserves credit for including resilience more thoroughly than other sustainability rating systems. However, speed of recovery is insufficiently addressed. As stated in Chapter 1, all definitions of resilience must address robustness (the ability to limit damage) and rapidity (speed of recovery after suffering damage). On many occasions, when Envision uses the term “resilience,” it is referring more appropriately to “robustness.” For instance, credit 2.3 (Evaluate Risk and Resilience) requires a multi-hazard risk study but requires no consideration for the rapidity of recovery. Credit 2.4 (Establish Resilience Goals and Strategies) requires alignment with broader community resilience plans, which may result in a more comprehensive resilience effort but does not guarantee it. It is only in credit 2.5 (Maximize resilience) that explicit mention is made of (a) engaging operators in learning and improvement and (b) accelerated recovery time as a metric. Credit 2.5 also requires satisfying one of seven “properties” of resilient systems (reflective, resourceful, inclusive, integrated, robust, redundant, and adaptable, based on Rockefeller Foundation, 2015). However, these properties are vaguely defined, and it is questionable whether satisfying a subset is sufficient.

Table 5 – Maximum points (MPts), Familiarity (Fam), and Benefit (Ben) aggregated by Envision category and subcategory

Category	Description	MPts	Fam	Ben
QL	**Quality of Life**	**200**	**1.4**	**0.8**
QL1	Wellbeing	92	1.6	0.4
QL2	Mobility	44	2.0	1.0
QL3	Community	64	0.7	1.2
LD	**Leadership**	**182**	**1.5**	**-0.3**
LD1	Collaboration	72	1.0	0.0
LD2	Planning	60	1.9	-0.2
LD3	Economy	50	1.6	-0.7
RA	**Resource Allocation**	**196**	**1.9**	**0.0**
RA1	Materials	66	2.4	-0.1
RA2	Energy	76	1.7	0.0
RA3	Water	54	1.8	0.0
NW	**Natural World**	**232**	**0.6**	**1.1**
NW1	Siting	82	0.2	1.8
NW2	Conservation	78	1.1	0.6
NW3	Ecology	72	0.3	0.9
CR	**Climate and Risk**	**190**	**1.6**	**-0.1**
CR1	Emissions	64	1.3	-0.3
CR2	Resilience	126	1.8	0.0

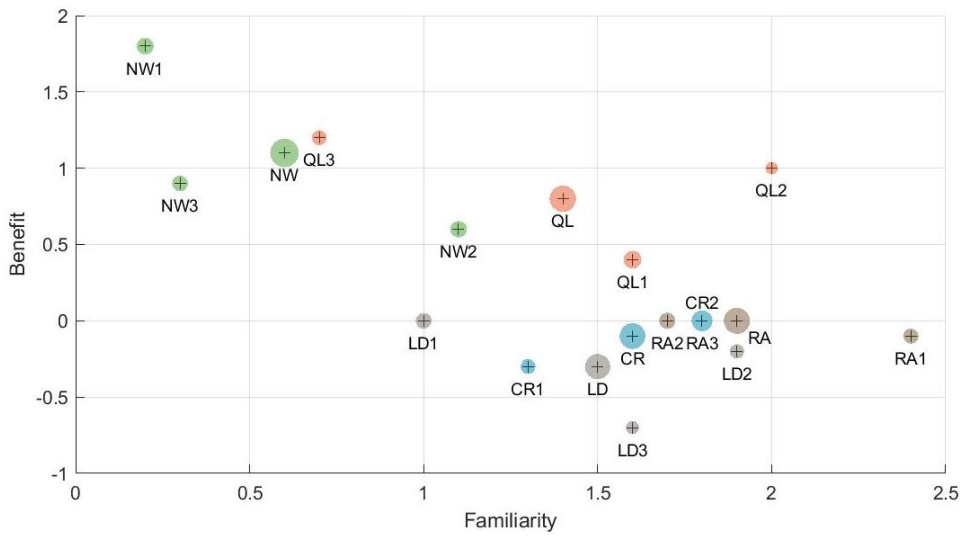

Figure 6 – Benefit vs Familiarity aggregated by Envision category and subcategory. Marker sizes are proportional to maximum points and colors correspond to the color used by Envision.

SUMMARY AND CONCLUSION

In this chapter, Envision was assessed for use with a typical UTI project. The assessment graded the UTI solution on familiarity to the UTI community and relative benefit of the UTI solution over other types of infrastructure. Envision, generally speaking, captured the advantages and disadvantages of UTI well. Unfortunately, the areas in which UTI outperforms above-ground infrastructure are those that are least familiar. Promoting these benefits requires effective communication of these results to the appropriate decision-makers. The most beneficial categories overall were Natural World and Quality of Life. Research in the following areas could improve the relative benefit of UTI: techniques for deconstruction and reuse of materials at the end of life, low-carbon materials and construction processes, pollution removal technology, and effective reuse of material. It was also noted that Envision's treatment of resilience focuses almost exclusively on the reduction of initial damage and ignores almost completely the speed of subsequent recovery.

CHAPTER 4 – SUMMARY AND CONCLUSIONS

OVERVIEW

This work has the following aims:

1. Summarize existing knowledge related to sustainability and resilience planning in underground transportation infrastructure (Chapter 1).
2. Apply two of the frameworks to representative underground transportation infrastructure (Chapters 2 and 3). Each assessment has two sub-goals:
    a. Provide an example application of the framework to underground transportation infrastructure, and
    b. Conduct a deeper evaluation of the assessment framework to assess its suitability for underground transportation infrastructure.

The first framework evaluated was the Vulnerability Assessment Scoring Tool (VAST) for climate vulnerability assessment. The evaluation was conducted for a subset of subway stations in New York City for storm surge coupled with sea-level rise. The second framework evaluated was the Envision scoring framework for sustainable infrastructure. The evaluation was conducted for a hypothetical, representative underground project in comparison to an equivalent above-ground project. This chapter summarizes the conclusions of the study.

LITERATURE REVIEW

Resilience is the ability to recover from a sudden shock. Resisting natural or man-made disasters has long been central to the design process in all kinds of infrastructure, including underground infrastructure. However, resilience goes further in considering broader community response, not just the robustness of any particular facility. Sustainability refers to meeting the needs of today while not preventing future generations from meeting their own needs. It requires consideration of environmental, financial, and social resources. The two concepts are related, but not the same. Sustainability tends to consider a larger time window and addresses slowly developing conditions such as sea-level rise. Resilience considers a smaller time window and addresses faster-developing conditions such as hurricanes and earthquakes. This report focuses on climate change vulnerability and sustainability rating systems for infrastructure. These are summarized next.

Climate change is an increasingly important consideration for transportation systems. Changes are needed in transportation systems to (a) mitigate their contribution to climate change, and (b) adapt them to the more severe impacts that are expected. The VAST framework, evaluated in Chapter 3, addresses the latter. VAST is component of a larger FHWA effort to standardize climate vulnerability and assessment.

Sustainable design makes regular use of rating systems to encourage best practices. Rating systems assign points to various areas of importance. These systems then establish tiers based on the total number of points earned. Envision, a rating system for sustainable infrastructure, was evaluated in-depth in Chapter 3. The FHWA identifies shortcomings of rating systems. They can be simplified and limited in scope, it is difficult to decide what to include, and they can be used mindlessly. Nonetheless, the FHWA argues that their ease of use encourages better practices. Rating systems are most common for sustainability, but some also are in use for resilience.

Underground infrastructure has unique aspects that differentiate it from other types of infrastructure in how it addresses the twin goals of sustainability and resilience. Compared to above-ground infrastructure, underground infrastructure is more vulnerable to flooding, blast and fire, and less vulnerable to earthquakes. The VAST study (Chapter 2) was an example of how to address such vulnerabilities. Increasing urban densification will increase the value of underground space and promote its use. Underground infrastructure can improve mobility while preserving important natural or cultural above-ground spaces. The Envision study (Chapter 3) highlighted these and other advantages.

VULNERABILITY ASSESSMENT FOR UNDERGROUND ASSETS SUBJECTED TO SEA LEVEL RISE AND STORM SURGE

This study considered three subway stations in Manhattan representative of different levels of vulnerability. Each asset was considered with and without flood protection. These assets were subjected to two stressors: storm surge and sea-level rise. Two scenarios were considered: sea-level rise of 2 ft. with storm surge from a Category 1 storm, and sea-level rise of 6 ft. with a storm surge from a Category 4 storm.

The VAST procedure requires defining indicators for vulnerability due to exposure, sensitivity, and adaptive capacity. The exposure indicators were (a) presence in a FEMA flood plain, and (b) inundation depth, which added the predicted storm surge depth to the projected sea-level rise. The values used were preliminary and approximate. An advanced geospatial analysis would ideally be conducted. The presence of flood protection was considered a sensitivity indicator. This indicator took on two values for no protection or good but not perfect protection. The indicator for adaptive capacity was traffic volume. A higher traffic volume was indicative of greater vulnerability because a greater number of people would be affected by a disruption at the station.

VAST calculates an overall vulnerability score as the weighted sum of the three indicators. These scores are reported in Chapter 2. The example illustrates how the scores can help planners prioritize improvements with limited resources. Of particular interest is noting how VAST encourages multi-factor decision-making. In this example, a station with a greater inundation depth was not rated the most vulnerable as might have been expected. Instead, the station with greater traffic volume and slightly lower inundation depths was determined to be the most vulnerable. An area of improvement was identified for the use of VAST with underground infrastructure. The indicator library did not suggest any sensitivity and adaptive capacity indicators for the "tunnel" class. Adding this information would standardize the assessment of underground assets.

ENVISION RATING SYSTEM FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

In this study, Envision was applied to a representative UTI project and contrasted with an equivalent above-ground solution. Envision was selected because it is well recognized, widely used, and applicable to a wide range of infrastructure types. Envision was found to be suitable for UTI. In fact, it highlighted many of the unique aspects of UTI. The main challenge identified is that those areas in which UTI compares most positively are also the areas that are likely to be least familiar to a UTI practitioner. This negates the benefits unless additional efforts are made.

Applying Envision in this way elucidates all of the principal benefits and drawbacks of underground infrastructure. Because underground infrastructure preserves above-ground features it scores well in the Natural World and Quality of Life categories. However, because these aspects are also least familiar to "business as usual" scenarios, reaping these benefits requires a concerted effort to make these benefits better known. Some of the disadvantages of underground infrastructure are highlighted in the Leadership category. One disadvantage is the higher upfront cost. This can be mitigated by demonstrating a competitive life cycle cost. Another is the specialized equipment and labor required, which makes it difficult to include as much local labor in the project. Related to high cost is also high embodied carbon because of energy-intensive construction methods. Improvements in the relative benefit of underground infrastructure can be found with development in the following promising areas of research and development.

- Dismantling and reuse of tunnel components at the end of life.
- Removal of pollutants from tunnels during operations before the pollutants reach the surface.
- Reuse of tunnel waste generated during construction.

Although Envision did consider resilience better than any other sustainability rating system, in the opinion of the authors, it did not lend sufficient attention to the recovery aspect of resilience. It focused primarily on robustness, which is usually done well in ordinary design. It was not until the higher levels of achievement that the issue of recovery speed of the surrounding community was addressed. This is one possible area of improvement for Envision.

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APPENDIX A – TECHNOLOGY TRANSFER ACTIVITIES

1 Accomplishments

1.1 What was done? What was learned?

The literature on sustainability and resilience in underground transportation infrastructure was compiled (ICSI paper). There is extensive literature on sustainability and resilience in general transportation infrastructure. This literature review makes it accessible within the context of underground transportation infrastructure.

Two planning frameworks were investigated for their suitability to underground transportation infrastructure and to illustrate the application of the framework for underground transportation infrastructure. The first framework investigated was the Vulnerability Assessment Scoring Tool (VAST). This study found that VAST works well for underground transportation infrastructure but can be improved with additional details for the “tunnel” asset class. The second framework investigated was the Envision rating system for sustainability. Envision was found to work well, capturing both the advantages and disadvantages of underground transportation infrastructure. The study found that the areas in which underground transportation infrastructure holds comparative advantages over other types of infrastructure are likely to be the least familiar to practitioners. Specific fruitful areas of research were identified to improve upon the relative weakness of underground transportation infrastructure.

1.2 How have the results been disseminated?

The results have been disseminated at the International Conference on Transportation and Development (ICTD), 2018 (poster and paper), and the International Conference for Sustainable Infrastructure (ICSI), 2019 (lectern session and paper).

2 Participants and Collaborating Organizations

Name: Tonatiuh Rodriguez-Nikl
Location: Cal State LA
Contribution: Princial investigator, project oversight,conducted Envision study (calculations, paper, and presenting at ICSI 2019). Guided student researchers in VAST study.

Name: Merhran Mazari
Location: Cal State LA
Contribution: Co-Principal Investigator, conceived VAST study and guided student researchers.

Name: Edwin Martinez
Location: Cal State LA

Contribution: Graduate Student, conducted initial calculations on VAST study and wrote draft of ICTD conference paper

Name: Jose Hernandez
Location: Cal State LA
Contribution: Undergraduate Student, conducted initial calculations on VAST study and wrote draft of ICTD conference paper

3 Outputs

Presentations

- International Conference on Transportation and Development (ICTD), 2018, Poster session and paper
- International Conference for Sustainable Infrastructure (ICSI), 2019, Lectern Session and paper

4 Outcomes

The ICSI paper contains a thorough summary of the literature related to sustainability and resilience in underground transportation infrastructure. Two planning frameworks were investigated for their suitability to underground transportation infrastructure and to illustrate the application of the framework for underground transportation infrastructure. The first framework investigated was the Vulnerability Assessment Scoring Tool (VAST). This study found that VAST works well for underground transportation infrastructure but can be improved with additional details for the "tunnel" asset class. The second framework investigated was the Envision rating system for sustainability. Envision was found to work well, capturing both the advantages and disadvantages of underground transportation infrastructure. The study found that the areas in which underground transportation infrastructure holds comparative advantages over other types of infrastructure are likely to be the least familiar to practitioners. Specific fruitful areas of research were identified to improve upon the relative weakness of underground transportation infrastructure.

4 Impacts

This project identifies important goals for follow-up studies. This project identifies specific ways for enhancing the VAST framework. VAST will benefit from specific guidance for sensitivity and adaptive capacity indicators for the "tunnel" asset class. The envision study identifies a need for communicating the broader potential benefits to sustainability of underground transportation infrastructure.

APPENDIX B - DATA FROM THE PROJECT

Chapter 2

Data for Chapter 2 consists of the completed VAST spreadsheet. The input data and resulting output are copied in full in the tables, lists, and figures below.

Tab 1 (Set Up)

- Number of stressors: 1
- Stressor type: Storm Surge
- Number of assets: 1
- Asset type: Tunnel

Tab 2 (Enter Assets)

Asset ID	Asset Name
SF	South Ferry
SS	Spring Street
CS	Canal Street
SFFP	South Ferry (FP)
SSFP	Spring Street (FP)
CSFP	Canal Street (FP)

Tab 3b (Exposure Indicators)

1	Modeled Surge Inundation Depth
2	Presence in FEMA Coastal Flood Zone

Tab 3d (S&AC Indicators)

Indicators of Tunnels Sensitivity to Storm Surge

Write in indicator names or click the "🕮" button.

1	Flood Protection

Indicators of Tunnels Adaptive Capacity

Write in indicator names or click the "🕮" button.

1	Vehicle Traffic

Tab 4a (Exposure Data)

Enter Climate Scenarios

Enter the scenarios you want to use for the climate stressor(s) below. If you do not want to consider multiple scenarios, check the box below the table.

Climate Stressor	Scenario 1	Scenario 2
Storm Surge	Cat 1, 2 ft	Cat 4, 6 ft

Tab 4b (Asset Data)

		Sensitivity Indicators	Adaptive Capacity Indicators
Asset ID	**Asset Name**	**Flood Protection**	**Vehicle Traffic**
SF	**South Ferry**	100	0.13
SS	**Spring Street**	100	0.35
CS	**Canal Street**	100	0.4
SFFP	**South Ferry (FP)**	20	0.13
SSFP	**Spring Street (FP)**	20	0.35
CSFP	**Canal Street (FP)**	20	0.4

Tab 5a (Exposure)

	Storm Surge									
	Cat 1, 2 ft		Cat 4, 6 ft		Cat 1, 2 ft		Cat 4, 6 ft		Cat 1, 2 ft	Cat 4, 6 ft
	Modeled Surge Inundation Depth				Presence in FEMA Coastal Flood Zone				Exposure Scores	
Asset Name	**Value**	**Score**	**Value**	**Score**	**Value**	**Score**	**Value**	**Score**		
South Ferry	7	1	21	4	4	4	4	4	2.5	4
Spring Street	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Canal Street	5	1	18	4	1	1	1	1	1	2.5
South Ferry (FP)	7	1	21	4	4	4	4	4	2.5	4
Spring Street (FP)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Canal Street (FP)	5	1	18	4	1	1	1	1	1	2.5

Exposure Scoring Approach for Storm Surge

How much should each indicator contribute to the overall exposure score?

Modeled Surge Inundation Depth	50%
Presence in FEMA Coastal Flood Zone	50%
Total Weight:	100%

Tab 5b (Sensitivity)

		Flood Protection		Sensitivity Score
Asset ID	**Asset Name**	**Value**	**Score**	**Score**
SF	South Ferry	100.0	4	4.0
SS	Spring Street	100.0	4	4.0
CS	Canal Street	100.0	4	4.0
SFFP	South Ferry (FP)	20.0	1	1.0
SSFP	Spring Street (FP)	20.0	1	1.0
CSFP	Canal Street (FP)	20.0	1	1.0

Tab 5c (Adaptive Capacity)

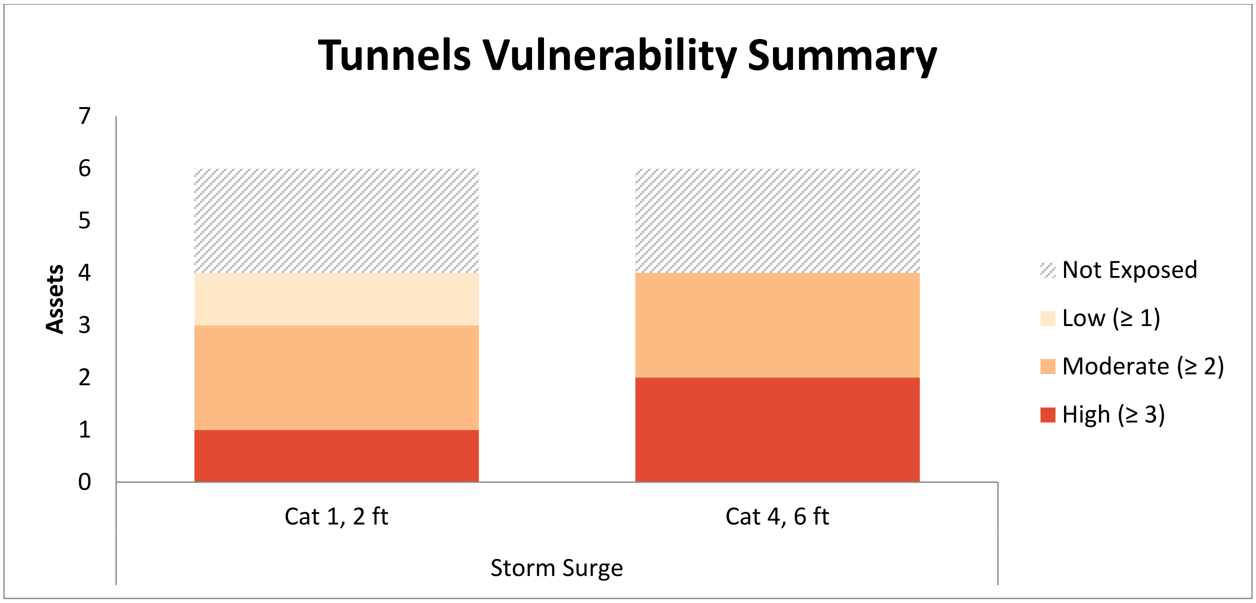
		Vehicle Traffic		Adaptive Capacity Score
Asset ID	**Asset Name**	**Value**	**Score**	**Score**
SF	South Ferry	0.1	1	1
SS	Spring Street	0.4	4	4
CS	Canal Street	0.4	4	4
SFFP	South Ferry (FP)	0.1	1	1
SSFP	Spring Street (FP)	0.4	4	4
CSFP	Canal Street (FP)	0.4	4	4

Tab 6 (Vulnerability)

Asset ID	Asset Name	ID Num	Storm Surge Cat 1, 2 ft Exposure	Storm Surge Cat 4, 6 ft Exposure	Storm Surge Sensitivity	Storm Surge Adaptive Capacity	Storm Surge Cat 1, 2 ft "Damage"
CS	Canal Street		1.0	2.5	4.0	4.0	2.5
SF	South Ferry		2.5	4.0	4.0	1.0	3.3
CSFP	Canal Street (FP)		1.0	2.5	1.0	4.0	1.0
SFFP	South Ferry (FP)		2.5	4.0	1.0	1.0	1.8
SS	Spring Street		NE	NE	4.0	4.0	0.0
SSFP	Spring Street (FP)		NE	NE	1.0	4.0	0.0

Storm Surge Cat 1, 2 ft Vulnerability	Storm Surge Cat 4, 6 ft "Damage"	Storm Surge Cat 4, 6 ft Vulnerability	Data Availability Score
3.0	3.3	3.5	100%
2.5	4.0	3.0	100%
2.0	1.8	2.5	100%
1.5	2.5	2.0	100%
0.0	0.0	0.0	100%
0.0	0.0	0.0	100%

Dashboard



10 Most Vulnerable Assets to Each Stressor (highlighted assets appear in multiple lists)

◉Scenario 1 ○Scenario 2

Storm Surge

ID	Name	Score
CS	Canal Street	3.0
SF	South Ferry	2.5
CSFP	Canal Street (FP)	2.0
SFFP	South Ferry (FP)	1.5
SS	Spring Street	0.0
SSFP	Spring Street (FP)	0.0

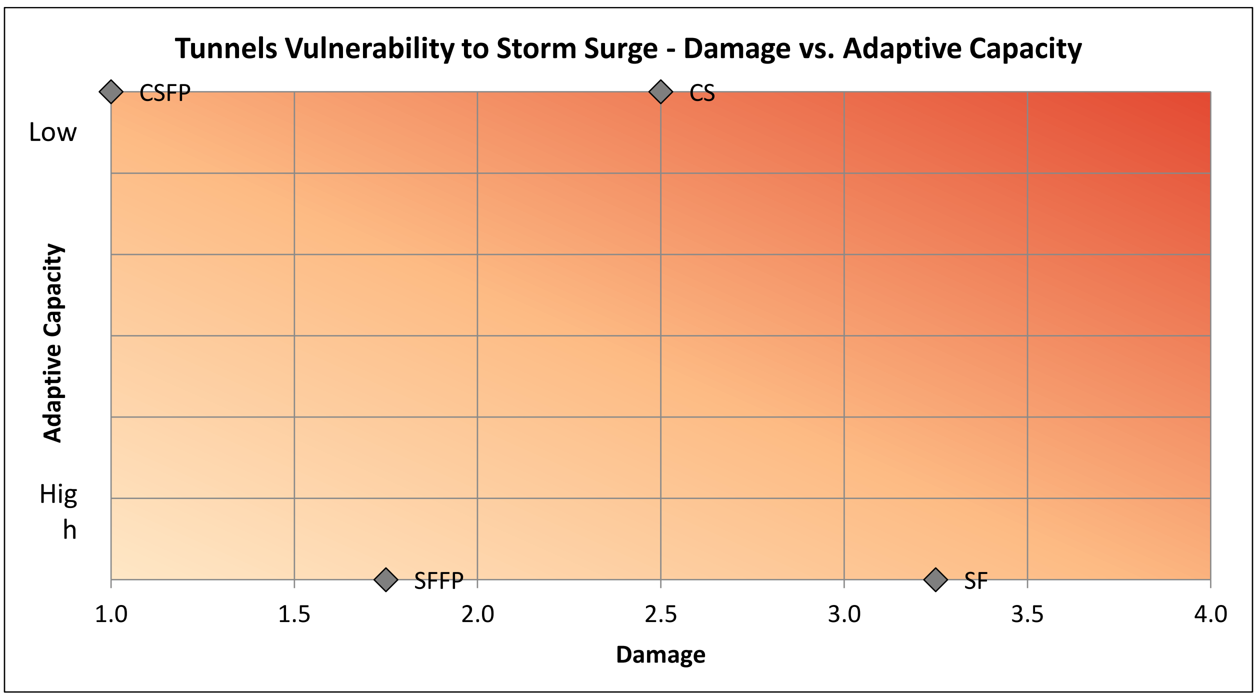
10 Most Vulnerable Assets to Each Stressor
(highlighted assets appear in multiple lists)

○Scenario 1 ◉Scenario 2

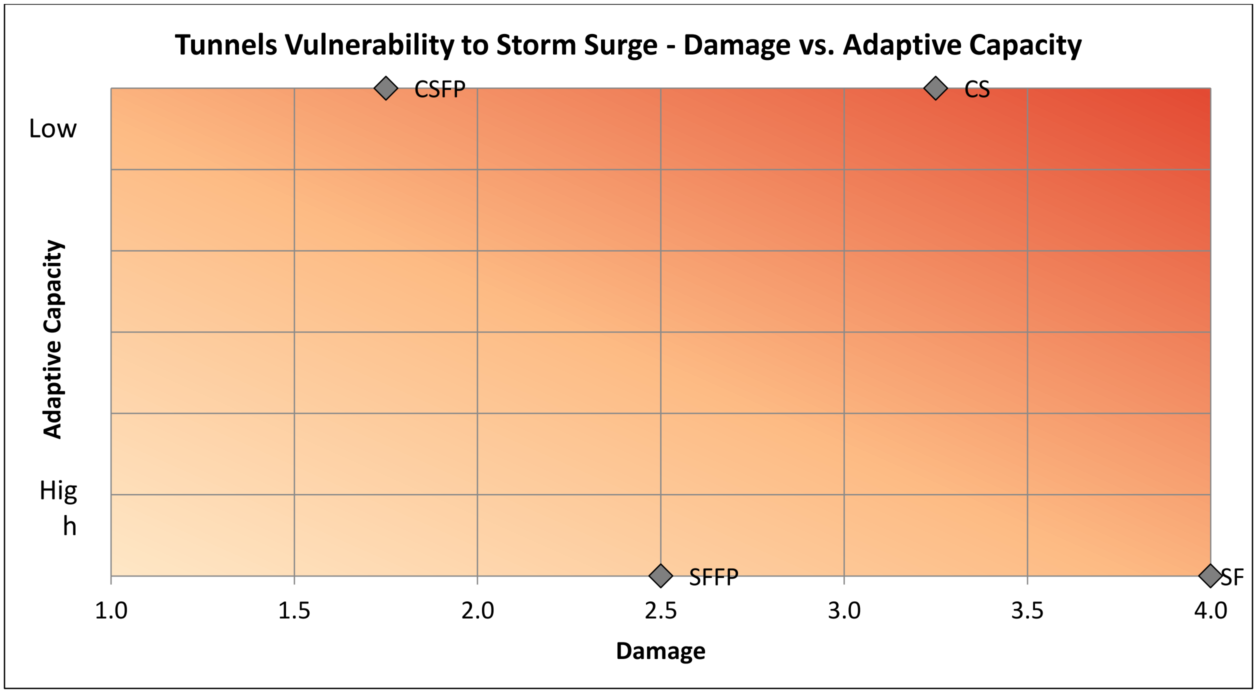
Storm Surge

ID	Name	Score
CS	Canal Street	3.5
SF	South Ferry	3.0
CSFP	Canal Street (FP)	2.5
SFFP	South Ferry (FP)	2.0
SS	Spring Street	0.0
SSFP	Spring Street (FP)	0.0

Cat 1, 2ft



Cat 4, 6 ft



Tunnels Vulnerability to Storm Surge - Damage vs. Adaptive Capacity
CSFP
CS
SFFP
SF
Low
Adaptive Capacity
Hig
h
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Damage

Chapter 3

Data for Chapter 3 consists of the spreadsheet used to perform the analysis. This spreadsheet is available for download (Rodriguez-Nikl 2019) and is reproduced below.

No	Cat	SubCat	Credit	Max Pts	Credit Name [clarification]
1	QL	QL1	QL1.1	26	Improve Community Quality of Life [community engagement process]
2	QL	QL1	QL1.2	20	Enhance Public Health and Safety [during operation]
3	QL	QL1	QL1.3	14	Improve Construction Safety
4	QL	QL1	QL1.4	12	Minimize Noise and Vibration [during operations]
5	QL	QL1	QL1.5	12	Minimize Light Pollution
6	QL	QL1	QL1.6	8	Minimize Construction Impacts [temporary inconvenience]
7	QL	QL2	QL2.1	14	Improve Community Mobility and Access
8	QL	QL2	QL2.2	16	Encourage Sustainable Transportation
9	QL	QL2	QL2.3	14	Improve Access & Wayfinding
10	QL	QL3	QL3.1	18	Advance Equity & Social Justice
11	QL	QL3	QL3.2	18	Preserve Historic & Cultural Resources
12	QL	QL3	QL3.3	14	Enhance Views & Local Character
13	QL	QL3	QL3.4	14	Enhance Public Space & Amenities
14	LD	LD1	LD1.1	18	Provide Effective Leadership and Commitment [specific to sustainability goals]
15	LD	LD1	LD1.2	18	Foster Collaboration and Teamwork [specific to sustainability goals]
16	LD	LD1	LD1.3	18	Provide For Stakeholder Involvement
17	LD	LD1	LD1.4	18	Pursue Byproduct Synergies
18	LD	LD2	LD2.1	18	Establish A Sustainability Management Plan
19	LD	LD2	LD2.2	16	Plan For Sustainable Communities [choosing right project based on sustainability principles]
20	LD	LD2	LD2.3	12	Plan For Long-Term Monitoring and Maintenance [includes durability]
21	LD	LD2	LD2.4	14	Plan For End-of-Life [consider impacts]
22	LD	LD3	LD3.1	20	Stimulate Economic Prosperity and Development
23	LD	LD3	LD3.2	16	Develop Local Skills and Capabilities
24	LD	LD3	LD3.3	14	Conduct a Life-Cycle Economic Evaluation
25	RA	RA1	RA1.1	12	Support Sustainable Procurement Practices
26	RA	RA1	RA1.2	16	Use Recycled Materials
27	RA	RA1	RA1.3	14	Reduce Operational Waste
28	RA	RA1	RA1.4	16	Reduce Construction Waste
29	RA	RA1	RA1.5	8	Balance Earthwork On Site
30	RA	RA2	RA2.1	26	Reduce Operational Energy Consumption
31	RA	RA2	RA2.2	12	Reduce Construction Energy Consumption
32	RA	RA2	RA2.3	24	Use Renewable Energy
33	RA	RA2	RA2.4	14	Commission and Monitor Energy Systems

No	Cat	SubCat	Credit	Max Pts	Credit Name [clarification]
34	RA	RA3	RA3.1	12	Preserve Water Resources [use and discharge of water]
35	RA	RA3	RA3.2	22	Reduce Operational Water Consumption
36	RA	RA3	RA3.3	8	Reduce Construction Water Consumption
37	RA	RA3	RA3.4	12	Monitor Water Systems
38	NW	NW1	NW1.1	22	Preserve Sites of High Ecological Value
39	NW	NW1	NW1.2	20	Provide Wetlands and Surface Water Buffers
40	NW	NW1	NW1.3	16	Preserve Prime Farmland
41	NW	NW1	NW1.4	24	Preserve Undeveloped Land
42	NW	NW2	NW2.1	22	Reclaim Brownfields
43	NW	NW2	NW2.2	24	Manage Stormwater
44	NW	NW2	NW2.3	12	Reduce Pesticide and Fertilizer Impacts
45	NW	NW2	NW2.4	20	Protect Surface and Groundwater Quality [due to pollutants]
46	NW	NW3	NW3.1	18	Enhance Functional Habitats
47	NW	NW3	NW3.2	20	Enhance Wetland and Surface Water Functions
48	NW	NW3	NW3.3	14	Maintain Floodplain Functions
49	NW	NW3	NW3.4	12	Control Invasive Species
50	NW	NW3	NW3.5	8	Protect Soil Health
51	CR	CR1	CR1.1	20	Reduce Net Embodied Carbon
52	CR	CR1	CR1.2	26	Reduce Greenhouse Gas Emissions [during operations]
53	CR	CR1	CR1.3	18	Reduce Air Pollutant Emissions [during operations]
54	CR	CR2	CR2.1	16	Avoid Unsuitable Development [avoid hazards through proper siting]
55	CR	CR2	CR2.2	20	Assess Climate Change Vulnerability
56	CR	CR2	CR2.3	26	Evaluate Risk and Resilience [multihazard evaluation]
57	CR	CR2	CR2.4	20	Establish Resilience Goals and Strategies
58	CR	CR2	CR2.5	26	Maximize Resilience [implement risk reduction plan]
59	CR	CR2	CR2.6	18	Improve Infrastructure Integration [includes risk of cascading failure]

No	Familiarity	Familiarity note	Benefit	Benefit note
1	0		0	Scenario dependent
2	1		0	Possible benefits to placing operations underground, but counterbalanced by safety concerns in tunnels
3	3	Could be rated 1 at the higher levels	0	
4	3		1	Underground placement of operations will reduce above-ground noise and vibration
5	2		2	No light emissions from below ground
6	3		0	
7	2	Depends on broad strategic plan	1	May be only option for more mobility in dense public space
8	2	Depends on broad strategic plan	1	Potential to improve above ground bikeabiltiy and walkability
9	2		1	Potential to improve above ground access
10	0		-1	Tunnels are expensive, so they could easily become inequitable choices.
11	1		2	Potential to leave existing above ground resources intact
12	1		2	Potential to leave existing above ground character intact
13	1		2	Potential to develop public above ground space
14	1		0	
15	1		0	
16	2		0	
17	0	All except tunnel operations depend on agency	0	Tunnel operations are relatively negligible in terms of byproducts
18	2		0	
19	1		0	
20	3		0	Similar potential for advanced methods in tunnels as well as other types of infrastructure.

No	Familiarity	Familiarity note	Benefit	Benefit note
21	2		-1	One use of a "tunnel dismantling machine" but little other information found. Easier for other facilities. Research needed.
22	1		-1	The cost of tunnels must be overcome
23	1		-1	Tunneling uses specialized imported labor
24	3	Standard for any major capital project	0	
25	2		0	
26	2		0	Similar potential as other construction
27	2	Waste of vehicles using tunnel may be foreign to tunnel group	0	Consider both tunnel support systems and transportation operations
28	3		0	R&D is in early stages
29	3		-1	Net balance seems to be extraction (cut)
30	2		0	Potential in both tunnel support systems and transportation operations
31	2		0	
32	1		0	Dependent on agency / municipality
33	2		0	
34	2		0	Mostly unrelated to tunnel - consider for transit operations
35	2		0	See RA3.1
36	2		0	
37	1		0	See RA3.1
38	0		2	Above ground space is undisturbed
39	1		1	See NW1.1, development near wetlands is troublesome for tunnels due to flood concern
40	0		2	See NW1.1
41	0		2	See NW1.1
42	0		0	
43	2		2	See NW1.1

No	Familiarity	Familiarity note	Benefit	Benefit note
44	0		0	
45	2		0	
46	0		2	See NW1.1, small tunnels could also be used to provide connectivity for wildlife
47	1		1	See NW1.1, but tunnel could still interfere with deeper hydrologic processes
48	0		0	Avoid floodplains
49	0		0	
50	0		1	See NW1.1
51	1		-1	Some evidence tunnel construction is more energy-intensive
52	1		0	Depends on transit operations
53	2		0	Transit, support systems. Removing pollution not viable.
54	3		0	Depends. Could be restorative if, e.g. a tunnel replaces an aging viaduct in a seismic zone.
55	1		0	Depends
56	2	Levels of achievement increase project assessment boundary from project/site to associated infrastructure, to broader community. At narrower scopes, the procedure should be familiar to the tunnel community.	0	
57	2	At lower levels this is a risk reduction plan. At the conserving level, the project must seek alignment with broader community resilience plans.	0	
58	2		0	
59	1		0	