Evaluating User Benefits and Cost-Effectiveness for Public Transit State of Good Repair Investments

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ABSTRACT

Aging public transit systems will require significant investment into state of good repair (SGR) over the coming decades, while at the same time many metropolitan areas in the United States seek to expand existing services and infrastructure. The prioritization of limited funding is a challenging process, particularly when choosing between new transit infrastructure and SGR for existing assets. Furthermore, this process rarely takes user benefits into consideration in a rigorous quantitative way.

While asset management professionals have made significant progress in age-based and condition-based methodologies to prioritize transit asset replacement, it is more difficult to assess the impact of these SGR investments on users. This paper develops a new methodology to estimate user benefits across a metropolitan region resulting from transit SGR funding. The method builds on existing age-based models of asset failure and the San Francisco Bay Area’s regional activity-based travel model. The method is applied to the transit asset inventory of the entire Bay Area to compare two regional funding scenarios to a baseline scenario reflecting current funding levels. The results indicate that the benefits from regional funding for transit SGR in the Bay Area far exceed expenditures. Further research using this method could assist planners in determining the optimal level of funding for transit SGR and assist in prioritizing specific SGR projects in a consistent manner to expansion investments.
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BACKGROUND

Over the past decade, regional transportation plans (RTPs) in the San Francisco Bay Area have allocated a progressively higher level of regional transportation funding to maintaining a state of good repair (SGR) for existing assets instead of new infrastructure projects. The share of regional funding going towards SGR increased from approximately 75% in 2001 to 88% in the 2013 RTP, Plan Bay Area (1). Even with this significant increase in RTP funding, the amount of backlogged repair and replacement in the Bay Area’s transit inventory is $4.8 billion with the average transit asset replaced at approximately 120% of its useful life (2, 3). Moving forward, there is some debate about how to best respond to this asset management challenge. Some argue that that funding would be better spent on constructing new transit infrastructure to serve growing suburban communities than on maintaining the current transit system. Others argue that preserving all existing assets should take precedence over any expansion project regardless of its ridership potential. As transportation planners inform funding allocation decisions related to maintenance and repair of the transit network, it is crucial to be able to assess the cost effectiveness of such funding for the region as a whole.

In its latest RTP, the nine-county San Francisco Bay Area metropolitan planning organization – known as the Metropolitan Transportation Commission (MTC) – completed a rigorous performance assessment for expansion and operational improvement projects (3). Projects proposed for inclusion in this RTP, known as Plan Bay Area, were evaluated for their cost-effectiveness using a model-based methodology to calculate a benefit-cost (B/C) ratio. This ratio assisted planners in allocating funding, with low performing projects (below B/C ratio of 1) only eligible for inclusion in the Plan if they could develop a compelling case indicating significant regional benefits not fully captured in the analysis.

In order to consistently estimate the benefits associated with every major regional transportation investment – for freeways, arterials, and public transit – MTC leveraged its activity-based Travel Model One. This model allows for the simulation of daily travel in the year 2040 and the comparison of build and no-build scenarios. The benefits of a given transportation projects were assessed by calculating the differences for various nominal and monetized benefits between these scenarios. Benefits evaluated included traditional measures such as travel times and travel costs in addition to air quality, public health, safety, and noise. Table 1 provides a complete list of benefits and the monetary values from the Plan Bay Area analysis (3). Benefit-cost ratios were then developed by comparing the year 2040 benefits to the annualized project costs.
<table>
<thead>
<tr>
<th>Benefit</th>
<th>Plan Bay Area Valuation ($2013)</th>
<th>What does this valuation include?</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Vehicle Travel Time (Auto and Transit) per Person Hour of Travel</td>
<td>$16.03</td>
<td>This valuation is set equal to one-half of the mean regional wage rate ($32.06). The valuation represents the discomfort to travelers of enduring transportation-related delay and the loss in regional productivity for on-the-clock travelers &amp; commuters. Sources: Caltrans Cal-B-C Model; Bureau of Labor Statistics National Compensation Survey, 2011</td>
</tr>
<tr>
<td>Out-of-Vehicle Travel Time (Transit) per Person Hour of Travel</td>
<td>$35.27</td>
<td>This valuation is set equal to 2.2 times the valuation of in-vehicle transit time. The valuation represents the additional discomfort to travelers of experiencing uncertainty of transit arrival time, exposure to inclement weather conditions, and exposure to safety risks. Source: FHWA Surface Transportation Economic Analysis Model (STEAM)</td>
</tr>
<tr>
<td>In-vehicle Travel Time (Freight/Trucks) per Vehicle Hour of Travel</td>
<td>$26.24</td>
<td>The valuation is set equal to the average wage rate for a Bay Area employee in the Transportation – Truck Driver (average of heavy and light) occupation sector ($23.83/hour), plus the average hourly carrying value of cargo ($2.41/hour). Sources: FHWA Highway Economic Requirements System; Bureau of Labor Statistics National Compensation Survey, 2011</td>
</tr>
<tr>
<td>Travel Time Reliability per Person Hour (Auto) or per Vehicle Hour (Truck) of Non-recurring Delay</td>
<td>$16.03 [Auto] $26.24 [Truck]</td>
<td>The valuation represents the additional traveler frustration and loss of regional productivity of experiencing non-expected incident related travel delays. The value is set equal to the value of in-vehicle travel time for autos and trucks. Source: SHRP2 L05 Project – “Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes”</td>
</tr>
<tr>
<td>Fatality Collisions (valuation per fatality)</td>
<td>$4,590,000</td>
<td>The valuation includes the internal costs to a fatality collision victim (and their family) resulting from the loss of life, as well as the external societal costs. The valuation represents: • Loss of life for the victims • Medical costs incurred in attempts to revive victims • Loss of enjoyment of family member to other members of the family • Loss of productivity to the family unit (e.g. loss of earnings) • Loss of productivity to society • Loss of societal investment in the victim (e.g. educational costs) Sources: Caltrans Cal-BC Model, 2010; National Safety Council, 2010</td>
</tr>
<tr>
<td>Injury Collisions (valuation per injury)</td>
<td>$64,000</td>
<td>The valuation includes the internal costs to an individual (and their family) resulting from the injury, as well as the external societal costs. The valuation represents: • Pain and inconvenience for the individuals • Pain and inconvenience for the other family members • Medical costs for injury treatment • Loss of productivity to the family unit (e.g. loss of earnings) • Loss of productivity to society Sources: Caltrans Cal-BC Model, 2010; National Safety Council, 2010</td>
</tr>
</tbody>
</table>
### TABLE 1  Benefit Valuations and Sources (continued)

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Plan Bay Area Valuation ($2013)</th>
<th>What does this valuation include?</th>
</tr>
</thead>
</table>
| Property Damage Only (PDO) Collisions        | $2,455                          | The valuation includes the internal costs to a property damage collision victim (and their family) resulting from the time required to deal with the collision, as well as the external societal costs from this loss of time. The valuation represents:  
  • Inconvenience to the individual and to other members of the family  
  • Loss of productivity to the family unit  
  • Loss of productivity to society  
  
  *Source: Caltrans Cal-BC Model, 2010*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| CO\textsubscript{2} per Metric Ton            | $55.35                          | This valuation represents the full global social cost of an incremental unit (metric ton) of CO\textsubscript{2} emissions from the time of production to the damage it imposes over the whole of its time in the atmosphere.  
  
  *Source: BAAQMD Clean Air Plan, 2010 (uprated to year 2035 using a 2% annual adjustment)*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Particulate Matter per Ton                    | $490,300 [diesel PM\textsubscript{2.5}]  
$487,200 [direct PM\textsubscript{2.5}]  | These valuations represent the negative health effects of increased emissions including:  
  • Loss of productive time (work & school)  
  • Direct medical costs from avoiding or responding to adverse health effects (illness or death).  
  • Pain, inconvenience, and anxiety that results from adverse effects (illness or death), or efforts to avoid or treat these effects  
  • Loss of enjoyment and leisure time  
  • Adverse effects on others resulting from their own adverse health effects  
  
  *Source: BAAQMD Clean Air Plan, 2010*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| NOx per Ton                                   | $7,800                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| ROG per Ton                                   | $5,700 [acetaldehyde]  
$12,800 [benzene]  
$32,200 [1,3-butadiene]  
$6,400 [formaldehyde]  
$5,100 [all other ROG]  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| SO\textsubscript{2} per Ton                   | $40,500                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| Vehicle Operating Costs per Vehicle Mile Traveled (VMT)  | $0.2688 [Auto]  
$0.3950 [Truck]  | This valuation represents the variable costs (per mile) of operating a vehicle. This valuation includes fuel, maintenance, depreciation (mileage), and tires.  
  
  *Source: Caltrans Cal-BC Model, 2010*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Noise per Vehicle Mile Traveled               | $0.0012 [Auto]  
$0.0150 [Truck]  | This valuation represents the value of property value decreases and societal cost of noise abatement.  
  
  *Source: FHWA Federal Cost Allocation Report*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Costs of Physical Inactivity                  | $1,220                          | This valuation represents the savings achieved by influencing an insufficiently active adult to engage in moderate physical activity five or more days per week for at least 30 minutes. It reflects annual Bay Area health care cost savings of $326 (2006 dollars), as well as productivity savings of $717 (2006 dollars).  
  
  *Source: California Center for Public Health Advocacy/ Chenoweth & Associates 2006, “The Economic Costs of Overweight, Obesity, and Physical Inactivity Among California Adults”*                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Auto Ownership Costs per Vehicle (change in the number of autos)  | $6,290                          | This valuation represents the annual ownership costs of vehicles, beyond the per mile operating costs. This valuation includes purchase/lease cost, maintenance, and finance charges.  
  
  *Source: MTC Bay Area auto ownership analysis, 2011*  
  


Despite this rigorous model-based assessment for expansion projects, a lack of available data and methodologies to translate SGR funding levels into operational inputs for the travel model made it impossible for planners to calculate consistent benefit-cost ratios for SGR investments using the valuations above. Certainly, this limitation is not unique to MTC – few regional agencies simulate the user impacts associated with maintenance projects, instead focusing their analytical energies on key expansion investments.

To allow for consistent model-based evaluation of SGR and expansion investment evaluations for future long-range plans, the proposed methodology discussed in this paper was developed as part of internal research effort to link asset management and travel demand models for the first time. The preliminary methodology could be used in future Bay Area RTPs to calculate consistent B/C ratios for all infrastructure investments, facilitating both cross-modal and cross-investment type tradeoff discussions. For example, replacing aging BART heavy rail cars could be easily compared against a BART rail extension project – helping to better prioritize SGR projects and understand their cost-effectiveness compared to expansion investments.

MTC has developed a similar methodology for roadway maintenance to incorporate those SGR investments into the benefit-cost evaluation process as well; this is described in a counterpart report (4).

LITERATURE REVIEW

Transit asset management is an emerging field, and efforts to quantify benefits of transit state of good repair have generally stopped short of linking asset condition with user impacts or ridership. It has been demonstrated that poorly maintained transit systems can experience large ridership reductions based on the experience of rail systems in New York, Chicago, and Philadelphia in the 1970s and 1980s (5). However, the link between transit asset management and user impacts has yet to be modeled using a regional travel demand model to understand systemwide and multimodal impacts.

A study by the United States Government Accountability Office finds that while transit agencies sometimes track SGR backlog and on-time service, generally, these agencies do not maintain an inventory of observed asset conditions, with some exceptions. None of the agencies studied linked SGR to future ridership. The report suggests that understanding the implications of SGR on ridership could help transit agencies optimize their asset management strategies (6).

Another recent report by the Transit Cooperative Research Program, TCRP Report 157, includes a comprehensive literature review of transit asset management practices. The report finds that programs across the country generally rely upon asset ages to determine predicted condition and needed replacement. The only system currently tying asset condition to user impacts is the London Underground. Unfortunately, this methodology has not yet been published (7). TCRP Report 157 begins to fill the gap between asset age and user impacts by estimating models of non-vehicle transit asset failure probability, vehicle failures per mile, and the share of delays occurring from vehicle failures (7). These prove extremely useful for the purpose of this research effort.

Perhaps the most powerful and widely used transit asset management software is the FTA’s Transit Economic Requirements Model (TERM), and its counterpart for local- and regional-level analysis, TERM-Lite. MTC uses a version that operates on a regionwide inventory of transit assets to track age, rehabilitation, and SGR expenditure. However, as highlighted by a broad review of TERM by Harry Cohen, the software tracks asset age without linking it to system performance or public benefits. Cohen proposes that a useful addition to TERM’s capabilities would develop and utilize a model to quantitatively link failures to total passenger delay, building upon the TCRP 157 framework (8).

One exception to the dearth of systematic linkages between transit SGR and user impacts is a 2012 regional impacts study examining SGR investments into the San Francisco Bay Area’s heavy rail system known as BART (5). The authors draw upon deterioration rates based on national data, an inventory of
BART asset ages, conversations with BART staff, and focus groups of current and potential riders to investigate the impacts of three funding scenarios. They conclude that cutting funding for BART SGR would result in shorter trains, reduced hours of operation, slow zones, mode shifts to auto travel, and increased congestion and air pollution.

While the impacts found in the BART SGR study are all reasonable, the quantification and resulting magnitude of the impacts is questionable. The study assumes that a SGR funding shortfall affects all asset categories equally, whereas in reality, funding sources and operators actually prioritize assets for funding based on their impact on system operations. Secondly, the authors predict ridership reductions corresponding with projected decreases in train capacity (assuming older trains have declining availability), and reduce predicted ridership further due to delays and discomfort. However, because BART trains are generally not currently full to capacity, capacity reductions will likely not translate directly into ridership reductions. These two weaknesses very likely lead to an overestimation of the impacts of a funding shortfall. The study does not specify formulas for translating asset age into reported delays and asset failures.

One of the most interesting and useful findings of the BART report comes from focus group interviews, which found that travel times and costs are the predominate factors in transit mode choice. Non-riders were especially concerned with crime, cleanliness, and noise, potentially already attracted to driving by an automobile environment perceived as being more controlled and comfortable.

Our study builds upon BART’s work by better quantifying the linkages between asset ages, failure rates, delay, ridership, and broader regional impacts for 25 of the Bay Area’s transit systems. We focus on delay as the primary operational impact of transit asset failure based on the results of the BART focus group interviews and assume that transit operators will hold ticket prices constant in various SGR scenarios. While passengers’ experience of comfort, cleanliness, and safety may have an impact on travel behavior, Cohen notes that there is a lack of analytical procedures for relating asset age to passenger comfort (8). We link asset age to delay in part by drawing in part on models from TCRP Report 157 and those within TERM-Lite. We then translate delay into ridership outcomes by utilizing MTC’s activity-based regional travel model. In this way, we are able to answer Cohen’s call to link transit asset management best practices with user impacts. We believe this gives the best and most detailed estimation yet of the regional impacts of funding for transit state of good repair.

**METHODOLOGY**

In order to predict regional benefits for transit SGR funding scenarios, we calculate travel delays associated with aging transit assets and use those as inputs into Travel Model One in the form of in-vehicle and out-of-vehicle travel times. We focus on travel time instead of cost or safety for the following reasons: (a) the cost of transit to users is determined by operators and not directly dependent upon SGR maintenance funding, and (b) safety risks are generally dealt with by instituting slow zones or removing assets from operation, actions that count as a “failure” in our model and thus contribute to delays (8).

Travel Model One simulates travel behavior for a typical workday. In this context, we cannot simulate location-specific failures which occur less than once daily. Additionally the Bay Area’s Regional Transit Capital Inventory (RTCI), which tracks all transit assets, does not yet contain locational information. For these reasons, we calculate average delay occurring when the average asset (by type) in the average location fails for each operator and mode. We then add this expected delay to all of the operator’s routes of that mode. This effectively serves a proxy for system reliability due to the level of system maintenance. **Figure 1** summarizes the approach taken to link funding scenarios, travel times, and regional benefits.
Step 1: Link Funding Scenarios with Asset Conditions using TERM-Lite Model

MTC’s RTCI is used in conjunction with TERM-Lite to help prioritize the allocation of funding to be used for maintenance, rehab, and replacement of transit assets. Under a given funding scenario or a backlog target for a future year, the TERM-Lite model can output the age of each transit asset in the RTCI for a future year. We use TERM-Lite to approximate the replacements made by system operators in each year in order to predict asset ages in year 2040.

In assessment of new infrastructure projects, benefits and costs are evaluated against a “no-build” scenario. In examining regional funding scenarios for SGR, there are an infinite number of “build” scenarios. Each should be compared to a baseline of current conditions. This will mean that in some cases, both benefits and costs will be negative (in cases of spending less than is necessary to achieve baseline conditions and getting fewer benefits). Benefit-cost ratios for such degradation scenarios can be seen as representing the cost effectiveness of moving from a funding level below baseline to the baseline funding level.

Step 2 (Vehicles): Link Vehicle Ages with Failure Rates and Energy Costs Using TCRP’s Vehicle Model

TCRP’s Vehicle Model (7) provides this equation for linking vehicle age with energy consumption:

\[ CME(LM) = k_{e2}e^{k_{e1}LM} \]  

where

- \( CME \) = energy costs per vehicle mile as a function of lifetime mileage
- \( LM \) = lifetime mileage
- \( k_{e1} \) = a constant reflecting the sensitivity of energy cost to lifetime mileage
- \( k_{e2} \) = a constant set to match base year energy cost

The first constant \((k_{e1})\) was derived using national data and found to be 6.27 x 10^{-7} for buses and 4.0 x 10^{-7} for rail. We estimate lifetime mileage based on age using a constant for average annual mileage by operator and asset type calculated using National Transit Database (NTD) data. Base year energy costs per mile for 2040 \((k_{e2})\) were calculated using standard MTC projections for year 2040. Equation 1 is applied to each transit vehicle in the RTCI. Average energy costs per mile for each operator and vehicle type can then be used to calculate total projected energy costs for each operator in 2040, drawing upon outputs from Travel Model One which show how many miles are traveled by each transit operator in...
2040. The difference between total scenario energy costs and baseline energy costs for each operator is subtracted from the benefits side of the benefit-cost ratio. This reflects additional energy costs due to aging vehicles in a given scenario.

TCRP’s Vehicle Model also provides an equation for linking bus and train ages with road calls or vehicle failures per mile. The following equation from TCRP Report 157 predicts failures which occur while the vehicle is in service.

\[ RM(LM) = k_{r2}e^{k_{r1}LM} \]  
\[ \text{where} \]
\[ LM = \text{lifetime mileage} \]
\[ RM = \text{road calls or failures per vehicle mile} \]
\[ k_{r1} = \text{a constant reflecting the sensitivity of road calls or failures to lifetime mileage} \]
\[ k_{r2} = \text{a constant set to match base year road calls or failures} \]

The value for \( k_{r1} \) was estimated as 1.98E-06 for busses using national data from *The Useful Life of Transit Buses and Vans* (9). The value for \( k_{r1} \) was estimated for rail using NTD data, and found to be 7E-07 for heavy rail and 1E-06 for light rail. We use data on base year failures by operator and mode previously collected by MTC.

**Step 2 (Non-Vehicle Assets): Link Non-Vehicle Asset Ages with Failure Rates Using TCRP’s Age-Based Model**

TCRP’s Age-Based Model can be used to calculate the probability of failure based on the age of nonvehicle transit assets. The following equation is derived from a Weibull distribution identified in TCRP Report 157.

\[ PF = 1 - \frac{e^{-(\frac{t+1}{\lambda})^k}}{e^{-(\frac{t}{\lambda})^k}} \]  
\[ \text{where:} \]
\[ PF = \text{probability of asset failure in 2040, given that the asset has lasted until 2039} \]
\[ t = \text{asset age} \]
\[ k = \text{shape parameter} \]
\[ \lambda = \text{scale parameter} \]

National data from TERM-Lite was used to estimate Weibull distributions for non-vehicle transit assets. A table of shape and scale parameters resulting from this estimation can be found in TCRP Report 157 for a range of asset types. While there are 127 specific asset types listed in the TCRP report, we only model a subset which we believe will cause delay when failure occurs. These include guideway assets (31 categories including tracks, viaducts, crossovers, tunnels, fill, and ballast), systems assets (15 categories including train control, catenary, and signal systems), and electrification assets (8 categories including third rail, power cables, and substations).
Step 3 (Vehicles): Link Per Mile Failure Rates with Travel Delays Using a Modified Version of TCRP’s Vehicle Model

TCRP Report 157 recommends using the following equation to calculate passenger delay per road call or vehicle failure:

\[ PDR = H \left( \frac{PM}{VM} + \frac{RT \cdot PT}{VH} \right) \]  \hspace{1cm} (3)

where

- \( PDR \) = passenger delay per road call
- \( H \) = headway
- \( PM \) = passenger miles
- \( VM \) = revenue vehicle miles
- \( RT \) = recovery time
- \( PT \) = passenger trips
- \( VH \) = revenue vehicle hours

Data on passenger miles, vehicle miles, headways, and boardings for each operator are taken from Travel Model One’s baseline 2040 projections. Equation 3 assumes that passengers on the failing vehicle and those waiting for the failing vehicle will be picked up by the next scheduled vehicle, and that therefore their delay is equal to headway. The average number of passengers on the bus or train is \( \frac{PM}{VM} \). The number of people waiting for the broken vehicle along the route until a replacement bus or train takes over is \( \frac{RT \cdot PT}{VH} \). This second calculation is problematic for MTC’s data since the number of busses and trains running is likely not distributed evenly throughout a day’s worth of revenue vehicle hours. In order to account for this, we substitute equation 4 to calculate the number of people waiting for the failed vehicle. For this analysis, we assume revenue mile recovery miles are equivalent to one-half the operator’s average route length, but further research could improve this assumption.

\[ PWV = \left( \frac{PT}{VM} \right) \cdot MR \] \hspace{1cm} (4)

where

- \( PWV \) = passengers waiting for the failed vehicle
- \( PT \) = passenger trips
- \( VM \) = revenue vehicle miles
- \( MR \) = recovery miles (miles before another bus takes over the route)

An added component of delay can occur in the case of rail failures when a failed train is blocking the passage of other trains. There is no TCRP equation to quantify this, so we use our own. If the average time to remove a blocking train is less than headways, there will be zero delay due to waiting behind a stalled train, because the train will be cleared before the next train gets there. If this is not the case, equations 5-7 can be used.

\[ DWBT = AWT \cdot \left( \frac{PM}{VM} \right) \] \hspace{1cm} (5)

\[ AWT = \sum_{i=NT}^{\frac{TC}{H}} (\frac{TC}{H})^{-i} \cdot H \] \hspace{1cm} (6)

\[ NT = \text{RoundDown} (\frac{TC}{H}) \] \hspace{1cm} (7)
where
\[ DWBT = \text{delay from waiting behind stalled trains} \]
\[ AWT = \text{average wait time in headways for trains stuck behind stalled train} \]
\[ PM = \text{passenger miles} \]
\[ VM = \text{revenue vehicle miles} \]

**i = each additional train**

\[ TC = \text{average time it takes to clear tracks} \]
\[ H = \text{headway} \]
\[ NT = \text{the number of trains that are delayed due to a stalled train ahead} \]

In equation 7, we round down the number of headways that pass during the time it takes to clear the tracks, because an additional train only reaches the delay point every full headway. The average time it takes to clear tracks is information gathered from individual rail operators. Another adaptation we make to TCRP's model of vehicle delay is to differentiate between two types of expected delay which we call Type 1 Expected Delay and Type 2 Expected Delay. Expected delay is the chance of experiencing a failure multiplied by the delay that arises when a failure occurs. Expected delay is what we will use as an input into Travel Model One.

Type 1 Expected Delay adds to in-vehicle travel time. Delay experienced by passengers who are on a bus or train that fails is Type 1 Delay, as is delay experienced by passengers waiting behind a stalled train. The chances of experiencing these types of delay rise with the number of miles traveled; therefore, they should be calculated per mile. Type 2 Expected Delay adds to out-of-vehicle travel time. Delay experienced by passengers who are waiting to board a bus or train that has failed is type 2 delay. The chance of experiencing this type of delay rises with the number of trips taken; therefore, it should be calculated per boarding.

In order to calculate the two types of expected delay, we can combine parts of equations 2-7.

\[ T1ED(V) = RM \left( DWBT + \left( H \times \left( \frac{PM}{VM} \right) \right) \right) \quad (8) \]
\[ T2ED(V) = \frac{(H \times PWV) + (RM \times VM \times 300)}{PT \times 300} \quad (9) \]

where
\[ T1ED(V) = \text{Type 1 Expected Delay from vehicle failures} \]
\[ RM = \text{road calls per mile from equation 3} \]
\[ T2ED(V) = \text{Type 2 Expected Delay from vehicle failures} \]
\[ H = \text{headway} \]
\[ PM = \text{passenger miles} \]
\[ VM = \text{revenue vehicle miles} \]
\[ PBDV = \text{per boarding delay from vehicle failures (type 2 delay)} \]
\[ PWV = \text{passengers waiting for the failed vehicle} \]
\[ PT = \text{passenger trips} \]

In equation 9, the numerator is composed of total passenger delay per boarding \((H \times PWV)\) and the expected number of annual failures \((RM \times PM \times 300)\). This total annual delay is per annual boarding \((PT \times 300)\). Miles and boardings are annualized using 300 instead of 365 to represent the fact...
that travel on weekends is expected to be less than travel on the typical weekday modeled by Travel Model One. This is consistent with other assessments used by MTC based on travel model outputs.

We adjust equations 8 and 9 to cap the time people wait (on vehicles, behind stalled vehicles, and waiting for a failed vehicle) at 30 minutes, since some average headways longer than that. We assume that after 30 minutes, a delayed passenger will either choose another mode in order to get to his/her destination or decide not to take the trip. Thus, we replace $H$ with $\min(H, 30)$ in both equations.

**Step 3 (Non-Vehicle Assets): Link Probability of Failure with Travel Delays Using a New Operator-Informed Model**

For non-vehicle assets such as fixed guideways, train control systems, and electrification elements, there is no established model for translating non-vehicle transit asset failures into travel time delays; the next step relied upon consultation with regional rail operators to better understand how non-vehicle failure relates to delay. Based on discussions with BART and Caltrain staff, we developed a set of equations to quantify Type 1 and Type 2 Expected Delay associated with the age of non-vehicle assets.

When a non-vehicle asset fails, three groups of riders are potentially affected: (1) those on vehicles affected by slow zones, (2) those on vehicles that have been stopped and cannot proceed until a non-vehicle failure has been addressed, and (3) those waiting to board a vehicle that has been stopped. Due to the potential for long repair times, we cap the wait time for groups (2) and (3) at 30 minutes – assuming that they will either switch modes or operators or cancel their trip. This assumption is fundamentally conservative but reflects the realities of the Bay Area’s robust transit infrastructure, which includes multiple modes serving core corridors and the frequent use of “bus bridges” to accommodate rail passengers in the event of a system failure.

Delay experienced by both riders affected by slow zones and riders riding in a vehicle that has been stopped contributes to Type 1 Expected Delay. Delay experienced by people waiting for a stopped vehicle contributes to Type 2 Expected Delay. Expected delay for those on trains affected by slow zones can be calculated using the following equations:

$$SZD = PF \left( \frac{NT \cdot MD}{VM \cdot 300} \right)$$  \hspace{1cm} (11)  

$$NT = \text{RoundDown} \left( \frac{(TR) - \left( \frac{H}{2} \right)}{H} \right) \cdot LA$$  \hspace{1cm} (12)

where:

- $SZD$ = expected delay arising from slow zones
- $PF$ = probability of failure in 2040 (from equation 10)
- $NT$ = number of trains affected by failure
- $MD$ = minutes of delay to the train caused by slow zone
- $VM$ = revenue vehicle miles
- $TR$ = time until repair or replacement of the failed asset in minutes
- $H$ = headways
- $LA$ = average number of lines affected by failure

Equation 12 assumes the average train is one-half of a headway away from the location of the non-vehicle asset at the time it fails. Average minutes of delay resulting from a slow zone (MD), average time until repair or replacement (TR), and the average number of lines affected by asset failure (LA) is information specific to each non-vehicle asset type and operator. Rough estimates were developed in consultation with operators based on each Bay Area rail system’s unique characteristics; future efforts
should use statistical data on the real-world operational impacts of failures to supplement our baseline assumptions.

Expected delay for passengers on trains that must stop until a non-vehicle asset is repaired or replaced can be calculated using equation 13. This is similar to the calculation for expected delay due to a slow zone (equation 11).

$$STD = PF \times \left( \frac{NT \times \left( TR - \frac{1}{2} H \right)}{VM \times 300} \right)$$

(13)

where

- $STD = \text{expected delay from being on a stopped train due to a non-vehicle asset failure ahead}$
- $PF = \text{probability of failure in 2040}$
- $NT = \text{number of trains affected by failure (equation 12)}$
- $TR = \text{time until repair or replacement of the failed asset in minutes}$
- $VM = \text{revenue vehicle miles}$

Equation 13 assumes that the average train has to wait $\frac{1}{2}$ the total time it takes to repair or replace the asset. We cap $TR/2$ at 30 minutes, assuming that if a vehicle is stopped beyond that time, people will off-board and choose a different route.

As stated above, Type 1 Expected Delay for non-vehicle assets (arising per mile, experienced in-vehicle) is the sum of expected delay arising from slow zones (equation 11) and expected delay arising from having to wait in a vehicle while a non-vehicle asset is repaired or replaced (equation 13).

$$T1ED(NV) = SZD + STD$$

(14)

where

- $T1ED(NV) = \text{Type 1 Expected Delay from non-vehicle asset failures}$
- $SZD = \text{expected delay arising from slow zones (equation 11)}$
- $STD = \text{expected delay from being on a stopped train due to a non-vehicle asset failure ahead (equation 13)}$

Type 2 Expected Delay (arising per boarding, experienced out-of-vehicle) is associated with waiting for vehicles which have been stopped until a failed asset is repaired or replaced. We do not calculate Type 2 Expected Delay for circumstances involving a slow zone because we assume that operators are able to adjust train scheduling or communication to compensate for later arrival times. Type 2 Expected Delay can be calculated using equation 15.

$$T2ED(NV) = PF \frac{WT + WN}{WB \times 300}$$

(15)

$$WT = TR - \left( \frac{1}{2} H \right)$$

(16)

$$WN = BM \times \left( \frac{1}{2} ARL \right) \times \min(NT, DT)$$

(17)

$$DT = LA \left( \frac{MOD}{H} \right)$$

(18)

where

- $WT = \text{additional out-of-vehicle wait time when a vehicle is stopped by a non-vehicle asset failure}$
- $WN = \text{number of passengers waiting to board a vehicle stopped by a non-vehicle asset failure}$
- $TR = \text{minutes until asset repair or replacement}$
- $WB = \text{average weekday boardings}$
BM = average boardings per mile
ARL = average route length
DT = number of trains passing through affected area in one day
NT = number of trains affected by failure (equation 13)
MOD = minutes of operation daily (for example, this is 1080 minutes if trains run from 6 a.m. to 12 a.m.)
H = headways
LA = average number of lines affected by failure

We cap WT at 30 minutes. We estimate the number of lines affected by failure for each asset type (LA) based on the number of lines using the average section of track for each operator and whether a failure of the specific asset type would affect travel in one or both directions.

Two further factors related to asset recovery time affect our analysis. The first is that it is likely that lower funding scenarios would in reality spur longer asset recovery times since repair facilities may also be degrading, and operators can only fix a limited number of failures at a time. In order to take this into account, we use repair delay functions that predict recovery time; note that recovery time is identified as MR in equation 4 and as TR in equations 12, 13, and 16.

Our repair delay functions are linear for simplicity and specific to each operator. We assume that an additional 25% of a vehicle’s route would pass before recovery of vehicles for every additional 10% of the operator’s vehicle stock breaking down in a given day. For non-vehicle assets, we assume that each operator would take an additional 30 minutes to respond to non-vehicle failures for every 2 non-vehicle failures daily. These numbers could be improved through further conversations with operators. In the scenarios we model, failure rates never get high enough to trigger use of the repair delay function for non-vehicles. However, vehicle failures in a zero funding scenario increase recovery times by an average of 81% across operators using the delay function described above.

The second factor related to recovery time of failed assets is that in assigning such a time, we assume that the operator spends the needed funding to quickly get the asset back into service. Because the cost of such emergency repairs is not already factored into the cost side of the B/C equation (which is based on the scenario’s funding level), we must add it in once we know which assets are likely to fail. In order to do this, we assume that the cost of emergency repair or replacement is roughly equal to the value of the asset. We can then multiply the probability of failure by the value of each asset and add that to the cost side of the B/C equation.

After calculating the two types of expected delay for both vehicle and non-vehicle assets, we add them together to get for each operator a total amount of in-vehicle delay per mile (Type 1 Expected Delay) and a total amount of out-of-vehicle delay per boarding (Type 2 Expected Delay). These totals are used as inputs in Travel Model One.

Step 4: Link Travel and Wait Time Delays to Benefits Using Travel Model One

To input delays into Travel Model One, we manually adjusted in-vehicle and out-of-vehicle travel time skims. Type 1 Expected Delay is added to the in-vehicle travel time skims based on the distance traveled on each operator and mode. Type 2 Expected Delay is added to the out-of-vehicle time skims based on the number of boardings on each operator between zones. Once transit travel time skims are adjusted, these new times influence all travel choices made within the model, including auto ownership, activity choice, destination choice, mode choice, and route choice. Results of Travel Model One runs, when compared to the baseline model run, can be used to calculate the full set of benefits included in the standard B-C assessment based on valuations listed in Table 1.
RESULTS

Scenarios and Costs

We assessed two regional funding scenarios in comparison to a baseline scenario: a zero funding (0F) scenario and a zero regional funding (0RF) scenario. The baseline scenario is defined as the funding required to maintain the current transit capital backlog until the year 2040. The 0F scenario examined conditions in 2040 if assets were allowed to degrade without any SGR investment. The 0RF scenario – approximately 40% of the baseline scenario funding – examined the consequences of cutting all regional funding to transit SGR so that the only funds available were from the Federal Transit Administration, bridge tolls, sales taxes, and bonds.

We intended to examine an additional scenario where transit backlog is completely paid down by 2040; however, the difference in delays between the baseline and improvement scenarios was negligible. This is due to the fact that MTC’s version of TERM-Lite prioritizes timely replacement of assets most linked with delay in part by using a Transit Capital Priorities (TCP) score. This score is also used in regional funding decisions and places highest priority on replacement of revenue vehicles, which have the greatest capacity to create delay. While the baseline scenario includes enough funding for timely replacement of revenue vehicles, in a zero backlog scenario, the region is able to pay for timely replacement of all assets including those which are not directly linked to delay (stations and facilities). While these assets likely have an impact on passenger comfort and ridership, previous research has suggested that this impact is secondary to that of delay (5).

The costs of the baseline scenario are $27 billion over the next 28 years in 2013 dollars. The 0RF scenario spends $11 billion in the same period. Expected emergency replacement costs for assets that fail in the 0RF scenario is $1.1 billion in comparison with baseline. Emergency replacements beyond baseline total $1.2 billion in the 0F scenario. Total costs for each scenario include the cost savings from decreasing SGR funding and cost expenditures on emergency replacements. Final costs for each scenario in comparison to baseline are -$617 million annually for the 0RF scenario and -$1,011 million annually for the 0F scenario.

Benefits

Using the methodology used for assessment of new infrastructure projects, we can compare the outputs of Travel Model One under baseline, 0RF and 0F scenarios. We use travel model outputs to calculate the following benefits experienced by the region’s population in 2040: travel time savings for all modes; travel cost savings related to driving, auto ownership, and parking; air pollution reduction including PM2.5, CO2, and other pollutants; reductions in fatalities, injuries, and property damage due to collisions; active transport health benefits; and noise reduction. These benefits are monetized according to the values in Table 1.

Lower spending on transit SGR is linked with greater in-vehicle and out-of-vehicle delays, as seen in Figures 1(a) and (b). These delays cause a shift away from transit to driving, causing increased VMT as seen in Figure 1(c). Both transit delays and the negative externalities from increased VMT (including congestion, pollutions, and collisions) are reflected in the total regional benefits in Figure 1(d). Figure 2 shows the breakdown of regional benefits, with the greatest benefits from SGR spending coming from travel time savings.
When we compare the total benefits and costs in Figure 2, we find a B/C ratio of 2.8 for moving between a zero funding and baseline scenario. We find a B/C ratio of 2.6 for moving between a scenario with zero regional funding and a baseline scenario. These ratios demonstrate diminishing returns to SGR investment. This is to be expected when operators prioritize replacement of assets linked to the greatest user benefits.
CONCLUSIONS AND FUTURE WORK

This research efforts enables MTC to compare transit SGR and expansion efforts using a consistent benefit-cost framework. We find that current SGR funding levels as compared to scenarios where funding is reduced generates a benefit/cost ratio of between 2.6 and 2.8 over the 28-year planning period. The Plan Bay Area Performance Assessment (3), which uses a parallel methodology to assess new transit infrastructure projects finds that transit efficiency projects, such as frequency and speed enhancements to existing transit services, generate an average benefit/cost ratio of 1.4 when weighted by size. Transit expansion projects, such as rail extensions and bus rapid transit corridors, generate an average benefit/cost ratio of 2.8 when weighted by size. From these numbers, we can conclude that SGR funding should indeed be a high-ranking regional priority.

We recognize that the benefit-cost ratio here is relatively conservative and that it does not directly illustrate how core systems like San Francisco’s Muni and regional rail providers (BART and Caltrain) may have higher-than-average cost-effectiveness for maintenance given their high ridership levels. Further refinements to the methodology, combined with operator-specific model runs, may address these issues. However, this analysis is a clear proof-of-concept, demonstrating that a consistent model-based analysis is possible for projects of all types.

While it is clear that current funding levels for transit SGR have societal benefits that far exceed their costs, the shape of the benefit/cost curve in Figure 1(d) indicates diminishing returns. This implies that at some point, increasing funding for transit SGR is not economically efficient. Testing more scenarios would help to indicate where this point lies. Our inability to show travel time benefits when moving from
current funding levels to a state of zero backlog suggests that it is possible that we have either reached or exceeded this point. Additionally, the lack of delay resulting from current funding and prioritization algorithms also indicates that transit operators are already maximizing benefits to society through their judicious use of limited funding.

LIMITATIONS

Most importantly, benefits calculated here are likely underestimated because we do not model the impact of degradation for a large set of assets not directly linked with delay, such as stations and facilities. These non-operational impacts, such as user comfort or perceived security, certainly affect modal choice decisions; future efforts may incorporate these issues through adjusted modal constants. Additionally, the lack of geographic specificity in terms of asset location makes it impossible to estimate the impacts of specific asset failures, which may be significant in the case of assets impacting numerous transit lines. This can only be addressed by a longer-term effort to geocode all regional transit assets. Finally, additional operational data is necessary to confirm estimates of failure recovery times, rail lines affected by non-vehicle asset failures, slow zone speed restrictions, and additional delay to excessive failures and staff constraints in very degraded scenarios.

It is important to emphasize that we have used TERM to prioritize funding allocation based on asset condition and TCP score. While no asset management system will exactly match real-world operator decisions, our implementation of TERM allowed it to prioritize funding without regard for operator-specific funding silos. In the future, TERM model runs could be completed for each operator to better reflect available funding. Furthermore, we depend upon TERM’s asset ages to link funding to failure probability, even though age is not necessarily the best representation of condition. Ridership, terrain, and rehabilitations have an impact on asset condition not reflected here; future research activities can help to mitigate the impact of these limitations.

REFERENCES


