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Relationship of Asset Condition Rating to Transit System Performance

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Problem Statement

FTA's Transit Economic Requirements Model (TERM) focuses on the physical condition of transit assets, leaving unanswered the question of how physical condition relates to transit system performance. The objective of federal transit aid is to provide certain benefits to the public, including safe and convenient service to riders and secondary community benefits, in a cost-effective manner. TERM is applied to project the costs of meeting targets for condition of transit assets, but FTA's reporting of TERM's results does not make clear the relationship between this condition target and transit benefits or compare the benefits of alternative condition targets. Therefore, TERM is not now providing direct guidance to Congress on how to meet the federal transit program's objectives.

To assist in addressing this problem, this paper:

- Outlines a practical research and data collection effort that FTA could undertake to better quantify the condition/performance relationship.

- Suggests how FTA's Conditions and Performance reports might characterize the performance impact of attaining the national state-of-good-repair standard incorporated in TERM.

This paper draws heavily on a review of recent literature on rehabilitation and replacement of existing capital assets presented in TCRP Report 157 (published in 2012). The review provides a comprehensive summary of approaches that have been used for prioritizing transit capital assets or have been developed for managing other assets, but could be adapted for application to transit capital assets. It addressed materials related to transit state of good repair, asset and infrastructure management, management systems, best management practices, and performance metrics. This paper highlights results from the TCRP 157 literature review and from the project itself that may be useful in better quantifying the condition/performance relationship.

Most of the reviewed reports, papers, and presentations dealing with current and future transit asset conditions characterized assets using asset age or a conditions scale like that used in TERM. The literature review found only a small number of reports, papers, and presentations that provide analytical procedures for relating asset ages or conditions to more direct measures of impacts on transit users and others.

The review of asset management practices in the freight railroad industry found that rehabilitation and replacement of rail and other assets is guided by frequently-collected and detailed data on defect or failure rates, and involve determination of threshold values at which rehabilitation or replacement is shown to be most cost-effective. However, the review did not yield examples of analytical models being used to support prioritization of rehabilitation and replacement investments for railroads across asset types. For freight rail, sufficient resources are available so that defects in tracks and rolling stock can be addressed when they are identified, rather than allowing a backlog of rehabilitation and replacement projects to develop.

<u>Overview of Relationships between Performance and Asset Condition</u>

Exhibit 1 presents summary assessments of key relationships between performance areas and asset condition and highlights priority areas for research and data collection activities to improve TERM's ability to quantify these relationships. The assessments are based on the following considerations:

- The relative importance of performance areas in making decisions about asset rehabilitation and replacement for each type of asset

- The availability of analytical models and tools on performance area/asset condition relationships

- Whether TERM already has the transit system and asset data necessary to support models and, if not, the cost of adding that data to TERM.

- The availability of other data to support building and testing models.

- Whether models will produce outputs that are easily communicated to policy makers and others.

These assessments are discussed by performance area in the following sections. Also, proposed research and data collection activities are outlined for those areas identified in Exhibit 1 as high priority.

<u>Travel Time and Reliability</u>

Travel time and reliability is identified as a high priority area for TERM research and data collection because:

- Passenger hours lost due to delays, expressed either in the aggregate or on a per trip basis, is a measure readily understood by policy makers and others.

- The availability of data on mechanical and other failures in the National Transit Databases (by transit system and mode for each year) provides a useful connection between asset condition and performance for model building.

- Measures based on average speeds, delays, and in-service failures are prominently featured in transit agency performance reporting.

- As discussed below in the section on safety, problems in other performance areas are often converted to adverse impacts on travel time (e.g., slow zones for deteriorated tracks that might otherwise pose a safety risk).

The literature review found several studies that might be especially useful in estimating the effects of asset age and condition on transit passenger travel time and the reliability of transit service:

- London Underground has developed analytical procedures for predicting impacts on journey time and lost customer hours for various types of service interruptions. These procedures, which have not yet been documented in the literature, could be used (together with relationships between asset age or condition and vehicle failure rates discussed below) to quantify impacts of asset condition on travel time and reliability.

- Kuiper describes the decline of the New York City transit system in the 1970's and details its impact on rail fleet reliability. He shows a decline in mean distance between failures from about 23,000 miles in 1971 to 7,000 miles in 1980. He attributes the decline to staff turnover, an increase in the inspection interval, and deferral of needed maintenance, repair, and rehabilitation actions.

- Kuiper also details the effects of deferral of rail replacement during the 1970's in New York City. The immediate impact of the deferral was a substantial increase in delays. He presents exhibits comparing rail replacement tonnage and delays over time.

- Boylan describes the impacts of the turnaround of the New York City transit system beginning in the 1980's. From the early 1980's to 2008, MTA spent an estimated $74 billion on state-of-good-repair work, including the rehabilitation or replacement of about 6,000 rail cars, 700 miles of track, and 200 stations. Between 1982 and 2008, subway reliability increased by 155%, delays decreased by 59%, and the mean distance between failures increased from 7,000 miles to over 156,000 miles.

- Arkin discusses the relationship between system reliability and preventative maintenance and the negative impacts of allowing transit components to fail.

- The 2010 *Conditions and Performance* report provides estimates of the percent reduction in heavy rail and bus revenue service disruptions relative to 2008 for the State of Good Repair (SGR) Benchmark scenario.

- *Useful Life of Transit Buses and Vans* (prepared for FTA by Booz Allen Hamilton) provides a relationship between road calls per mile and the age of buses, which was developed using data from five transit agencies.

- TCRP Report 157 developed a procedure for predicting passenger delay cost per road call based on load factors, headways, and average speeds. This procedure was used, together with the relationship between road calls per mile and the age of buses (from the Booz Allen Hamilton report), to estimate passenger delay costs per year as a function of bus lifetime-to-date mileage.

- TCRP Report 157 also presents the results of regression analyses using National Transit Database (NTD) data for light and heavy rail systems to estimate the effects of lifetime-to-date mileage on the number of failures per vehicle mile.

- TCRP Report 157 also provides information on costs and failure rates for escalators, assuming characteristics of escalators similar to those described in "Asset Replacement for an Urban Railway Using a Modified Two-Cycle Replacement Model" by Scarf, McCusker, and Chan.

Augmenting TERM to model passenger delays due to road calls, mechanical failures, slow zones, and other incidents could be of great value in communicating to policy makers and others the performance implications of changes in asset condition under different funding scenarios. A research effort directed to that end might include the following tasks:

- Identify assets whose failure (or severe deterioration) might result in delays to passengers. For a start, these would include vehicles, tracks, elevators, escalators, and systems critical to rail operations.

- For each type of asset failure, develop a model that can be used to calculate total passenger delay, depending on parameters such as the number of passengers using the asset, headways, the amount of time the asset is out of service, etc.

- Compile information on how these parameters vary across transit agencies. To facilitate use within TERM, it would be useful if the parameters were linked to transit agency variables that are reported in the National Transit Database (NTD).

- Compile information on failure rates for assets, depending upon asset age or condition. These would include studies conducted for groups of transit agencies (such as that reported by Booz Allen Hamilton in *Useful Life of Transit Buses and Vans*) and studies conducted using the NTD (as reported in TCRP 157).

- Where gaps exist, contact individual agencies to obtain data (or at least informed judgments) regarding the effect of asset age or condition on failure rates.

- Augment TERM to calculate passenger delay due to asset failures by transit agency and mode for each year of the forecast period. This calculation will be performed using (1) models of passenger delay, (2) model parameters appropriate for the agency and mode, and (3) asset failure rates depending on the age and condition of the agency's assets.

The procedure for estimating bus passenger delays in TCRP Report 157 provides a practical example of how to model travel time and reliability effects of asset deterioration.

First, a simple model was developed to estimate passenger delay due to a bus road call. Passengers delayed by a road call include those who were already on the bus at the time it went out of service and those who are waiting for the bus. The delay experienced by those on the bus when the road call occurs is equal to the schedule headway time, assuming they are picked up by the next bus after the road call. Up to the time when a replacement bus takes over the slot occupied by the road call bus, those passengers who were going to board the road call bus are also assumed to board the next bus, so their delay is also equal to the schedule headway. The average number of passengers on the bus when the road call occurred can be estimated as passenger miles divided by revenue bus miles. The number of passengers delayed waiting to board the road call bus can be estimated as the product of average boardings per revenue bus hour and the recovery time (defined as the time until a replacement bus takes over the place that should have been occupied by the road call bus). Putting all this together:

$$PDR = H * (PM / VM + RT * PT / VH)$$

where

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

For a given transit agency and mode, passenger miles, revenue vehicle miles, passenger trips, and revenue vehicle hours are all available from the NTD. Other data sources would be required to estimate headways and recovery times.

Road calls per vehicle mile were then estimated as a function of bus lifetime-to-date mileage using the following equation:

$$RM = k_{r2} * e^{k_{r1} * LM}$$

where

- RM is road calls per vehicle mile
- LM is lifetime-to-date mileage
- k_{r1} is a constant reflecting the sensitivity of road calls to lifetime-to-date mileage

- k_{r2} is a constant set to match base year road calls observed for a transit agency, given the lifetime-to-date mileage of its fleet.

In TCRP 157, a value of 0.000002 was selected for k_1 based on road calls vs. vehicle age data provided in *Useful Life of Buses and Vans*.

With minor exceptions (appropriate assumptions regarding headways and recovery times), all of the information necessary to apply this procedure is available from the NTD and could be drawn on to implement it as part of TERM.

<u>Safety</u>

Several of the reports and presentations reviewed in TCRP 157 highlighted instances where transit passenger fatalities and injuries were due, at least in part, to the deteriorated condition of transit assets. However, the literature review did not find any analytical procedures for predicting the effects of asset condition on the number of fatalities or injuries suffered by transit passengers.

The National Transit Database (NTD) contains information on the number of fatalities, injuries, and incidents by year, agency, and mode. However, using these data to estimate direct impacts of asset condition on safety would be challenging because injuries and fatalities are rare events at individual transit agencies and only a portion of the injuries and fatalities are due to asset condition. Also, assets that pose a safety risk because of their deteriorated condition are often taken out of service or operated more slowly. Thus, potentially adverse impacts on safety are often converted to adverse impacts on travel time and reliability.

One possibility for relating asset condition to safety performance is through a link with procedures developed to estimate the effects of asset condition on travel time and reliability. Many incidents that cause delays also cause hazards. For each agency and mode, the NTD provides annual data on mechanical and other failures, as well as annual data on fatalities and injuries. FTA should undertake statistical analyses of NTD data to investigate possible correlations between safety and failure data that might be used to predict safety performance (after models of the effect of asset condition on failures have been constructed).

<u>Comfort</u>

Passenger comfort can be an important consideration for the rehabilitation and replacement of vehicles, guideways, stations, and bus shelters. However, producing understandable measures of the nationwide or per rider effect on comfort as part of TERM would be a challenge.

Unlike travel time and reliability (where impacts can be measured in hours of delay), safety (where impacts can be measured in the number of fatalities and injuries), and transit agency operating expenses, there is no simple metric for comfort.

Many transit agencies use customer satisfaction surveys or surveys filled out by trained checkers to assess their on-going performance regarding passenger comfort. Factors evaluated in these surveys include cleanliness and appearance, customer information, customer service, and condition of equipment. The customer and checker ratings are sometimes yes or no questions, but more commonly subjective scales (e.g., poor to excellent). The literature review did not find any analytical procedures for relating asset age or condition to these mostly subjective measures of comfort.

Availability

Measures of transit service availability typically reflect the locations of routes and stations, as well as hours of operation. As such, they are affected more by service expansions (or contractions) and less by asset condition.

Environmental and Other Non-User Costs

As discussed above, investments in asset rehabilitation and replacement can provide direct benefit to transit users in the form of lower travel time, improved reliability, and improved safety. Also, these investments can reduce transit agency operating and maintenance costs, which may be passed through to transit users in the form of fare reductions.

Transit service improvements and fare reductions encourage travelers to shift from automobiles to transit. These shifts lead to reductions in highway congestion, air pollution, noise, and highway crashes.

TERM already has the capability to estimate non-user benefits associated with investments that provide new or expended services. For these investments, TERM produces estimates of time and cost savings to transit users, applies elasticities to estimate shifts from autos to transit, and applies estimates of the social cost of auto use (expressed on a per vehicle mile basis from the Federal Highway Cost Allocation Study).

Currently, TERM does not have the capability to estimate benefits to transit users of asset rehabilitation and replacement projects; however, the research and data collection activities recommended in other sections of this paper will, if successful, provide TERM with that capability. At that point, the procedures used in TERM to estimate social cost savings due to new or expanded services might be augmented to provide estimates of social cost savings for asset rehabilitation and replacement projects.

Agency Operating Expenses

Developing estimates of the effect of asset age and condition on transit agency operating expenses is identified as a high priority area for research and data collection efforts to improve TERM because:

- Effects on transit agency operating expenses are an important (often central) consideration in asset rehabilitation and replacement decisions.

- Cost savings, either in the aggregate or per passenger, are an impact readily understood by policy makers and others.

- The National Transit Database (NTD) provides annual data on operating expenses by agency and mode. This data can be used to support model building and testing.

- With performance impacts expressed in dollar terms, traditional economic analysis tools such as life-cycle and benefit-cost analysis can be applied to assess and prioritize asset rehabilitation and replacement projects in TERM.

The Vehicle Model presented in TCRP Report 157 provides procedures that can be incorporated directly into TERM to model the effects of vehicle age or lifetime-to-date mileage on transit agency operating expenses. The Vehicle Model incorporates functional relationships between vehicle mileage and transit agency expenditures for energy and maintenance of vehicles. It uses NTD data on base year fleet composition and transit agency expenditures for energy and maintenance.

Specifically, the following equation is used to estimate energy costs per vehicle mile as a function of lifetime mileage:

$$CME = k_{e2} * e^{k_{e1} * LM}$$

where

- 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

Similarly, the following equation is used to estimate maintenance costs per vehicle mile as a function of lifetime mileage:

$$CMM = k_{m2} * e^{k_{m1} * LM}$$

where

- k_{m1} = a constant reflecting the sensitivity of maintenance cost to lifetime mileage

- k_{m2} = a constant set to match base year maintenance cost

For buses the values for the constants k_{e1} and k_{m1} were derived based on regression analyses of energy cost per mile, maintenance cost per mile, lifetime mileage, and average speed using data from the 2009 NTD normalized to 2010 dollars. A value of 6.27E-07 was derived for k_{e1} and 1.26E-06 was derived for k_{m1}.

NTD data were used to derive constants for these values for rail, as well. The research team identified instances where rail fleets did not change from one year to the next (except, naturally, that they were one year older and had more lifetime mileage). For these fleets, energy consumption (measured in kilowatt hours) and vehicle maintenance costs were analyzed to determine how they increased from one year to the next.

Regarding energy consumption, the analysis indicated that consumption increased by 2.1% per year for heavy rail and 1.6% per year for light rail. Using annual mileages per vehicle of 58,000 for heavy rail and 42,000 for light rail (per the NTD) the estimated value for k_{e1} is 4E-07 for both light and heavy rail.

Regarding maintenance costs, the analysis indicated that maintenance costs increased by 2.2% per year for heavy rail and 2.1% per year for light rail. Using the NTD mileages this equates to values for k_{m1} of 4E-07 for heavy rail and 5E-07 for light rail.

As for non-vehicle assets, the literature review did not provide simple analytical procedures like those presented above for vehicle assets. However, the TERM database does contain information that can be used as a starting point in modeling the impacts of asset deterioration on transit agency operating expenses. Specifically, for each type of asset, the TERM database provides typical replacement and rehabilitation costs, a functional relationship between asset condition and age, and the age or condition at which the asset should be replaced (assuming funds are available). Appendix A describes an analytical procedure for using this information to develop relationships between asset age and deterioration costs. Specifically, the procedure produces year-by-year estimates of transit agency operating expenses caused by asset deterioration.

The following research and data collection activities are recommended for transit agency operating expenses:

- Augment TERM to estimate the impacts of vehicle age, lifetime mileage, or condition on transit agency operating expenses, using procedures like those developed in TCRP 157 (and described above)
- Investigate the possibility of using the procedure presented in Appendix A to estimate the impacts of age or condition on non-vehicle assets as follows:
    - Apply the procedure to non-vehicle assets of individual transit agencies
    - Compare the results obtained at the agency level with actual non-vehicle maintenance and related transit agency expenditures.
    - To the extent that problems are uncovered, investigate whether the problems are due to assumptions regarding replacement and rehabilitation costs, optimum age or condition for replacing the asset, the shape of the deterioration cost curve, or some other difficulty.
    - Make revisions as necessary to resolve these problems.

- If the revised procedures produce reasonable results, implement them as part of TERM

Benefit-Cost Test for Selecting Assets to be Replaced

The research and data collection efforts outlined in the preceding sections of this paper will, if successful, provide TERM with the capability for estimating the impacts of asset condition on travel time and reliability, safety, transit agency operating expenses, and other non-user costs. This capability can serve as the basis for improving the benefit-cost test used in TERM to select assets to be replaced.

In the benefit-cost test currently used in TERM, the benefits of an asset replacement project for a given transit agency and mode are estimated as the cost savings experienced by passengers using the agency and mode calculated relative to the next best mode of travel (e.g., the savings experienced by bus users in comparison with their making the same trip by automobile or taxi). This test might be appropriate if the only option to replacing an asset now is shutting down service and forcing current passengers to shift to a different mode. However, this is seldom the only option and using it as the base against which a proposed project is compared can inflate the benefits of the project.

In analyzing asset replacement decisions, the issue is usually when to replace the asset (with "never" as an option but usually not a good one). As assets deteriorate over time, the risk of failure grows along with the associated impacts on users, non-users, and the agency.

The process is illustrated in the life-cycle cost analyses presented in Appendix A. Total annualized life-cycle costs consist of two components: the initial cost of replacing the asset and the deterioration-related costs of keeping the asset in place. As the asset-replacement age is increased, annualized asset replacement costs decrease since the cost of replacing an asset is spread over a longer period of years. On the other hand, deterioration-relation costs increase with increases in asset-replacement age. The relationship between total annualized life-cycle costs and asset-replacement age is typically a "U-shaped" curve. Initially, replacement costs dominate so annualized life-cycle costs decrease with age; then, deterioration costs dominate so that these costs increase with age.

If an asset has exceeded the age at which it should be replaced (in order to minimize life cycle cost), the benefits of replacing the asset during the next year (vs. the base alternative of replacing it in the following year) can be estimated as the difference between its asset deterioration cost in the next year (C) and its annualized life cycle cost (AC). As discussed in Appendix E of TCRP Report 157, C – AC represents the difference between the future cost streams generated by two competing alternatives: one in which the asset is replaced now and one in which the asset is replaced a year from now. For the "Replace Now" alternative, the future stream of costs is equivalent to a cost of AC in each future year (if we assume that the replacement asset is again replaced at the end of its useful life and so on off into the indefinite future). This is because AC is, by definition, the total annualized life-cycle cost of the replacement asset. For the "Replace

Next Year" alternative, the future stream of costs is C for this year and then AC for each subsequent year. Hence, the only difference between the two alternatives is their first year cost: C for the "Replace Next Year" alternative and AC for the "Replace Now" alternative.

The quantity (C – AC)/R, where R is asset replacement cost, is referred to as the prioritization index in TCRP 157. This quantity can be used to prioritize asset replacement projects to be implemented from a fixed budget, in the same way that a benefit-cost ratio can be used to select capital improvement projects. The quantity (C – AC) is the increase in net present value achieved by replacing the asset now. The replacement cost R is the impact on this year's budget. By selecting projects in order of the quantity (C – AC)/R until the budget is used up, the increase in net present value that can achieved from the budget is maximized

Summary

This paper outlines practical research and data collection activities that FTA could undertake to better quantify condition/performance relationships in four performance areas:

- Travel time and reliability
- Safety
- Transit agency operating expenses
- Environmental and other non-user costs

Augmenting TERM to produce information in these performance areas would be of great value to policy makers and others in understanding the consequences of different budget scenarios. For example, FTA's Condition and Performance reports might then provide the following measures for scenarios:

- Lost passenger hours, both total and per trip
- Fatalities and injuries
- Transit agency operating expenses, both total and per trip
- Highway congestion, crash, air pollution, and noise costs

Developing the capability to better quantify condition/performance relationships also could serve as the basis for augmenting TERM to include an improved benefit-cost test for prioritizing asset rehabilitation and replacement projects. Currently, TERM does not have the capability to estimate the benefits of a specific project. The recommended research and data collection activities would provide this capability.

References

Spy Pond Partners, KKO & Associates, Harry Cohen, and Joseph Barr. *TCRP Report 157. State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit*. Transportation Research Board. Washington, D.C. 2012

Booz Allen Hamilton Inc. *Useful Life of Transit Buses and Vans*. Technical Report FTA VA-26-7229-07.1 prepared for FTA. FTA, 2007.

Kuiper, W. *Three Case Studies: The Impact of Deferred Maintenance in Rail Transit.* Technical Report UMTA-IT-06-0242-85-1 prepared for UMTA. UMTA, 1985.

Boylan, C. "The View from the Subway: The Challenges of Maintaining a 100 Year Old System." Presented at the 88th Annual Meeting of the Transportation Research Board, 2009.

Arkin, Y. "Contribution of RAMS Specifications to State of Good Repair (SGR)." Presented at the APTA 2010 Rail Conference. APTA, 2010.

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Appendix A

Effects of Asset Condition on Transit Agency Operating Expenses

This appendix presents an analytical procedure that could be used in TERM to estimate the effects of asset age and condition on transit agency operating expenses for non-vehicle assets.

<u>Overview of the Procedure</u>

The inputs to the procedure for each asset are the following items from the TERM database:

- Asset condition vs. age curves, where asset condition is measured on TERM's 1 to 5 scale
- Asset replacement and rehabilitation costs
- The age or condition, typically 2.5, at which the asset would be replaced if sufficient funds are available.

The analytical procedure produces year-by-year estimates of transit agency operating expenses caused by the fact that assets have aged and their condition has deteriorated over time. By convention, these asset deterioration costs are assumed to be zero when the asset is in new condition.

The procedure is based on two key assumptions: (1) as assets age, deterioration costs increase in direct proportion to the drop in condition rating[1] and (2) the age or condition at which the asset would be replaced is selected so as to minimize life cycle costs for the asset.

The procedure operates to "reverse engineer" an asset deterioration cost curve that is consistent with the two assumptions. Specifically, the first assumption is used to determine the shape of the deterioration cost curve and then the second assumption is used to scale the curve so that total annualized life-cycle costs are minimized at the age or condition when the asset should be replaced

The first assumption is consistent with TERM's use of system-wide average condition rating as a benchmark in defining scenarios to be analyzed. Nonetheless, for some assets, the assumption is questionable since it implies that as the asset approaches a rating of 1.0, asset deterioration costs flatten out rather than continue to drop as the asset ages further. For example, consider an asset with an asset deterioration cost of $100,000 per year at a condition rating of 2.5—assumed to be the condition rating at which the asset should be

[1] For example, asset deterioration cost for an asset with a 1.5 condition rating is 40% higher than asset deterioration cost for the same asset with a 2.5 condition rating since (5.0-1.5)/(5.0-2.5) = 1.40.

replaced. Under assumption that deterioration costs increase in direct proportion to the decrease in condition rating, the deterioration cost per year could never increase beyond $160,000 per year[2] no matter how long the asset remains in place. Later in this appendix, an alternative to this assumption, which may be more realistic for some assets, is suggested.

Regarding the second assumption, it is true that in most cases, judgments about the age or condition at which assets should be replaced are not based on formal life cycle cost analyses. However, these judgments generally are based on observations about how assets deteriorate over time and the associated consequences and so they take into account, at least in a qualitative way, the important inputs to a formal life cycle cost analysis. Also, to the extent that the analytical procedure produces asset deterioration costs that seem unreasonably high or low, it may highlight instances where the asset replacement policies assumed by TERM should be reviewed and, if necessary, revised.

Example

Exhibit A-1 illustrates the operation of the analytical procedure for an asset that is to be replaced when its condition drops to 2.5.

The first two columns in Exhibit A-1 are asset age and condition. Asset condition declines with age from 5.0 to 1.0, following an “S-shaped” curve. The third column is asset replacement and rehabilitation costs by year. In this example, it is assumed that the replacement asset costs $100,000 and that the asset is rehabilitated in year 7 at a cost of $50,000. Following the approach used in TERM, it is assumed that the asset condition is not affected by the rehabilitation. The fourth column is asset deterioration cost per year. It’s the cost that would be eliminated if the asset were in “new” condition. In the exhibit, these costs are calculated as b * (5 – C) where C is asset condition and b is a constant set so that the total annualized life cycle cost of the asset (calculated in the seventh column) is a minimum when asset condition is 2.5.

The fifth, sixth, and seventh columns show annualized life cycle costs as a function of the age at which the asset is assumed to be replaced. These costs are calculated by discounting the costs in the third and fourth column (using a discount rate of 7% in this example), summing the discounted costs over the asset’s life, and then annualizing the result. Except for age 7, when the asset is rehabilitated, the annualized costs for asset replacement and rehabilitation decrease with replacement age, since these costs are spread over a longer asset life. The annualized life cycle costs for asset deterioration naturally increase with asset age. Total annualized life cycle costs decrease and then increase with replacement age. By design, total annualized life cycle costs are at a minimum when the asset condition is at 2.5, which was assumed to be the point at which the asset should be replaced. This result was achieved by adjusting the asset deterioration cost factor (b) applied in the fourth column.

[2] Calculated as $100,000 * (5.0-1.0)/(5.0-2.5).

Alternative Assumptions on Growth of Deterioration Costs over Time

The assumption that deterioration costs increase in direct proportion to the decrease in condition rating is consistent with TERM's use of system-wide average condition rating as a benchmark in defining scenarios to be analyzed. Nonetheless, for some assets, the assumption is questionable since it implies that as the asset approaches a rating of 1.0, asset deterioration costs flatten out rather than continue to drop as the asset ages further.

The Weibull distribution, which is widely used in modeling failure rates and survival analysis, provides the basis for an alternative assumption about how asset deterioration costs increase over time. The Weibull distribution is defined by two parameters: a shape parameter (k) and a scale parameter (λ). The probability (P) that an asset will fail between time t and time t+Δt (given that it has not yet failed by time t and that Δt is small) is given by

$$P = (t/\lambda)^{k-1}\,\Delta t$$

TCRP 157 used the Weibull distribution in developing an age-based model for predicting asset deterioration costs and prioritizing asset replacement projects. As part of this effort, Weibull shape and scale parameters were developed for over 100 common transit agency assets other than vehicles using deterioration data from TERM-Lite. Specifically, it was assumed that 50% of assets would fail at a condition rating of 2.5 and that 75% of assets would fail at a condition rating of 1.5. The shape parameters all fell within the range of 1.8 to 4.4. For 95% of the asset, the shape parameters fell within the range of 2.2 to 3.8. The middle of this range is a shape parameter of 3, implying that asset deterioration costs increase over time roughly in proportion to asset age squared.

Exhibit A-2 illustrates the analytical procedure with the assumption that asset deterioration cost varies in proportion to $(\text{Asset Age})^2$. As with the Exhibit A-1 example, it was assumed that life-cycle costs would be minimized at when asset condition is equal to 2.5, corresponding to an asset age of 15 years in this case. Exhibit A-3 plots the asset deterioration costs by age for the two cases. At age 15, when the asset condition rating is 2.5 and the replacement of the asset is assumed to minimize life cycle costs, estimated annual deterioration costs are very close (about $16,000 for the first case and $16,900 for the second). As asset age increases, however, asset deterioration costs for the two cases diverge. This is because in the first case, asset deterioration costs flatten out as asset age increases, while in the second case asset deterioration costs continue to increase in proportion to asset age squared.

Application to User and Non-User Costs

The analytical procedure in this appendix is proposed as a means for estimating the effects of asset deterioration on transit agency operating expenses for non-vehicle assets. It might also be considered for those assets where significant impacts of deterioration include not only transit agency operating expenses but also passenger delays and other impacts on users and non-users. In this broader context, the definition of asset deterioration costs would be expanded to include these user and non-users costs.

One problem with applying the procedure to deal with user and non-user costs is that the key assumption of the procedure—that the age or condition at which assets should be replaced has been selected to minimize asset life cycle costs—is more questionable in this broader context. Also, when the procedure is applied just to transit agency operating expenses, the results can be checked for reasonableness since each year individual transit agencies report operating expenses by mode to the National Transit Database. When the procedure is applied in a broader context, for example to include transit passenger delay costs, checking the results is much more difficult.

Notwithstanding these problems, the procedures presented in this appendix can still be used to estimate effects on operating expenses for assets whose deterioration also have significant impacts on users and non-users, provided other means exist to estimate the user and non-user costs.

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Exhibit 1 Priorities for Research and Data Collection Efforts to Improve TERM's Modeling Capability

Performance Areas	Illustrative Metrics	Assets					
		Vehicles	Guideways	Maintenance Facilities	Other Facilities	Stations	Systems
Travel Time and Reliability	Lost customer hours Delay per trip Revenue vehicle mph	■	■	□		■	■
Safety and Security	Fatalities per pass. mile Injuries per pass. mile Incidents per trip	□	□	□		□	□
Comfort	Pass. satisfaction ratings Percent with specified feature(e.g. climate control)	□	□			□	
Environmental and Other Non-User	Delays to highway users Air pollution costs Noise costs	□	□			□	□
Availability	Population within specified distance of stops or stations Hours of service						
Agency Operating Expenses	Added expenses due to asset deterioration Expense per passenger	■	■	■	■	■	■

■ High priority for research and data collection effort to improve TERM

□ Performance area is often an important consideration in asset rehabilitation and replacement decisions.

Exhibit A-1 Illustration of Procedure for Estimating Asset Deterioration Cost (based on decrease in condition)

Age (years)	Asset Condition	Rehabilitation and Replacement Cost	Asset Deterioration Cost*	Annualized Life Cycle Cost (given age at which asset is replaced)**			
				Rehabilitation and Replaceme	Asset Deterioration	Total	
1	4.99	100,000	38	100,000	38	100,038	
2	4.99	-	63	51,691	51	51,741	
3	4.98	-	105	35,612	67	35,680	
4	4.97	-	172	27,591	91	27,682	
5	4.96	-	283	22,794	124	22,918	
6	4.93	-	463	19,607	172	19,779	
7	4.88	50,000	756	23,119	239	23,358	
8	4.81	-	1,223	20,866	335	21,201	
9	4.69	-	1,958	19,124	471	19,594	
10	4.52	-	3,079	17,740	659	18,399	
11	4.26	-	4,712	16,616	916	17,532	
12	3.91	-	6,945	15,687	1,253	16,940	
13	3.48	-	9,743	14,908	1,675	16,583	
14	2.99	-	12,890	14,247	2,172	16,419	
15	2.50	-	16,025	13,680	2,723	16,403	Minimum
16	2.06	-	18,795	13,189	3,300	16,489	
17	1.72	-	20,994	12,762	3,873	16,635	
18	1.47	-	22,596	12,386	4,424	16,810	
19	1.30	-	23,692	12,055	4,940	16,995	
20	1.19	-	24,409	11,761	5,414	17,175	
21	1.11	-	24,865	11,499	5,848	17,347	
22	1.07	-	25,149	11,264	6,242	17,506	

* Asset Deterioration Cost is assumed to vary in proportion to the decrease in asset condition and is scaled so that total annualized life cycle cost is a minimum when asset condtion is 2.5.

** Annualized life cycle cost is calculated using a discount rate of 7%.

Exhibit A-2 Illustration of Procedure for Estimating Asset Deterioration Cost (based on Age^2)

Age (years)	Asset Condition	Rehabilitation and Replacement Cost	Asset Deterioration Cost*	Annualized Life Cycle Cost (given age at which asset is replaced)**			
				Rehabilitation and Replaceme	Asset Deterioration	Total	
1	4.99	100,000	75	100,000	75	100,075	
2	4.99		300	51,691	184	51,875	
3	4.98	-	675	35,612	337	35,949	
4	4.97	-	1,200	27,591	531	28,122	
5	4.96	-	1,875	22,794	765	23,558	
6	4.93	-	2,700	19,607	1,035	20,642	
7	4.88	50,000	3,675	23,119	1,340	24,459	
8	4.81	-	4,800	20,866	1,677	22,543	
9	4.69	-	6,075	19,124	2,045	21,168	
10	4.52	-	7,500	17,740	2,439	20,179	
11	4.26	-	9,075	16,616	2,860	19,476	
12	3.91	-	10,800	15,687	3,304	18,991	
13	3.48	-	12,675	14,908	3,769	18,677	
14	2.99	-	14,700	14,247	4,254	18,501	
15	2.50	-	16,875	13,680	4,756	18,436	Minimum
16	2.06	-	19,200	13,189	5,274	18,463	
17	1.72	-	21,675	12,762	5,806	18,567	
18	1.47	-	24,300	12,386	6,350	18,736	
19	1.30	-	27,075	12,055	6,904	18,959	
20	1.19	-	30,000	11,761	7,468	19,228	
21	1.11	-	33,075	11,499	8,038	19,537	
22	1.07	-	36,300	11,264	8,615	19,879	

* Asset Deterioration Cost is assumed to vary in proportion to asset age squared and is scaled so that total annualized life cycle cost is a minimum when asset condtion is 2.5.

Exhibit A-3 Asset Deterioration Cost Per Year