Key Variables Affecting Decisions of Bus Replacement Age and Total Costs

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Recent budget and fiscal constraints make optimal fleet management more imperative than ever for transit agencies. Fleet data have consistently shown that bus operations and maintenance (O&M) costs per mile increase as buses age. From a purely economic perspective, there is a cost trade-off between the lower O&M costs of newer fleets and their higher initial capital costs. This trade-off has a significant impact on the optimal timing of purchase and replacement decisions. Realistic cost data and an optimization modeling framework were used to analyze the impact of purchase timing decisions on fleet costs per mile. The results indicate that (*a*) increases in diesel prices do not affect total bus fleet costs as much as increases in maintenance costs, (*b*) increases in maintenance costs and utilization per year reduce the optimal replacement age, (*c*) increases in utilization and fuel economy have a similar impact in terms of total fleet costs, and (*d*) bus purchase-price changes have a significant impact on the optimal replacement age. Given uncertain and hard-to-forecast market variables, a thorough sensitivity analysis is presented to ascertain the key variables that affect bus transit replacement timing.

Large transit agencies typically own hundreds of buses. Large fleets' capital and operational costs are a significant expense for resource-strapped transit agencies. In particular, high capital or purchase costs have forced some agencies to postpone bus replacement decisions. The focus of this paper is to present a model and analysis of the key factors affecting bus replacement age and total fleet costs.

Bus fleet costs can be broken down into a handful of key cost factors: capital purchases, vehicle operation, fuel, general administration, and vehicle and facility maintenance. These cost contributions vary widely in operating 40- or 60-ft bus types, depending on the operational policies of the transit agency. This study focuses on 60-ft articulated buses from King County Transit in Seattle, Washington, with particular attention to factors that affect bus replacement age and total costs, such as maintenance costs, which vary with a bus's age (*1*).

LITERATURE REVIEW

The management science and operations research literature has pioneered the use of vehicle replacement models to optimize decisions regarding vehicle purchases, utilization, maintenance, and scrapping. A formal optimization model dealing with machine replacement problems was first introduced in the 1950s (*2*). Since then, many researchers have analyzed replacement problems in a wide range of fleet types, including transit and police fleets (*3, 4*). Some researchers have added budget constraints and even integrated vehicle-manufacturing waste factors in an automobile life-cycle analysis (*5, 6*). Despite the great uncertainty associated with financial variables and forecasts, all the models mentioned have been deterministic. Little or no attention has been given to sensitivity analysis.

Researchers have looked at cost trends in transit agencies by tracking fleet costs over time. Long-term cost data of bus fleets have consistently shown that operations and maintenance (O&M) costs rise with age (*7–9*). Other research has shown the value of modeling preventative and unexpected repair costs over time and their impact on the optimal bus replacement age (*10, 11*). The cost of replacing, refabricating, and rehabilitating buses has been a focus of research by Khasnabis and colleagues, as well as the optimal allocation of FTA funds among transit agencies (*12–14*). Unlike the present work, previous studies have evaluated fleet costs and their impact on replacement age, but they have not modeled all the relevant factors that vary as a function of bus age (e.g., utilization and fuel consumption). A comprehensive literature review on the factors affecting bus replacement modeling can be found in Boudart (*15*).

MODEL FORMULATION

The optimization model used to determine replacement costs is presented in this section. The objective of the model is to minimize bus costs over the planning horizon, including purchasing, utilization, maintenance, salvage, emissions, and road call costs. The decision variable is when to replace buses over the planning horizon.

Indexes

Age of bus in years: $i \in \mathbf{A} = \{0, 1, 2, \ldots, A\}$ and

Time periods (a decision is made at the end of each year): $j \in \mathbf{T} = \{0, 2, 2, \ldots, T\}$.

Binary Decision Variables

X_{ij} = i-year-old bus in use from the end of year j to the end of year $j + 1$ and

PY_j = whether a bus is procured or salvaged at the end of year j.

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Parameters

Constraints

A = maximum or forced salvage age (bus must be salvaged if this age is reached),
u_i = utilization (miles traveled by i-year-old bus), and
mpg_i = fuel economy of i-year-old bus.

Costs

v = cost of purchasing new bus,
om_i = maintenance costs per mile for i-year-old bus,
rc_i = cost of road calls of i-year-old bus,
s = salvage revenue (negative cost) from selling old bus when it is replaced by new bus,
sf_{iT} = final salvage revenue (negative cost) from selling i-year-old bus at time T,
ec = emissions cost per ton of carbon dioxide (CO_2) emissions,
d = price of diesel fuel per gallon, and
dr = discount rate.

Emissions

eps = production and salvage emissions in CO_2-tons and
em_i = utilization emissions in CO_2-tons per mile for i-year-old bus.

Objective Function

Minimize

$$\sum_{i=0}^{A-1}\sum_{j=0}^{T-1}\text{PY}_j\left(v+\text{ec}\ \ \text{eps}-s-\text{sf}_{iT}\right)\left(1+\text{dr}\right)^{-j}$$
$$+\sum_{i=0}^{A-1}\sum_{j=0}^{T-1}X_{ij}\left(u_i\text{om}_i+u_i\text{mpg}_i d+u_i\text{em}_i\text{ec}+\text{rc}_i\right)\left(1+\text{dr}\right)^{-j} \qquad (1)$$

subject to

$$\text{PY}_0=1 \qquad \text{where } s=0 \qquad (2)$$

$$\text{PY}_T=1 \qquad \text{where } v=0 \qquad (3)$$

$$X_{(i-1)(j-1)}=X_{ij}+\text{PY}_j \qquad \forall i\in\{1,2,\ldots,A\},\ \forall j\in\{1,2,\ldots,T\} \qquad (4)$$

$$\text{PY}_j=X_{0j} \qquad \forall j\in\{1,2,\ldots,T-1\} \qquad (5)$$

$$X_{Aj}=0 \qquad \forall j\in\{0,1,2,\ldots,T\} \qquad (6)$$

$$X_{iT}=0 \qquad \forall j\in\{0,1,2,\ldots,T\} \qquad (7)$$

$$\text{PY}_j,X_{ij}\in\mathbf{I}=\{0,1\} \qquad (8)$$

The objective function of Expression 1 minimizes the sum of purchasing, maintenance, salvage, emissions, and road call costs over the period of analysis from time zero (present) to the end of the planning horizon (year T). At the first time period, the model starts with the purchase of a new bus (Expression 2). At the end of the last time period (or horizon time T), the existing bus is sold (Expression 3) at a value equal to the salvage value for whatever age the bus has at time T, that is, sf_{iT}. The age of any vehicle in use increases by 1 year after each time period (Expression 4). A constraint makes sure that a bus procured equals a new bus in use (Expression 5). When a bus reaches the maximum service age it is forced to be salvaged (Expression 6). At the last time period, T, the bus is not used and operational costs are not added (Expression 7). Finally, the decision variables associated with purchasing and salvaging decisions must be binary (Expression 8).

SUPPORTING DATA AND ASSUMPTIONS

The modeling assumptions are supported by historic bus cost and utilization data from a King County trolley and bus evaluation and other King County fleet data (*1*). A bus is modeled that has an average operating cost of $2.05/mi over a 20-year period. It is assumed that the model begins with a new bus, and each subsequent bus purchased is also new.

Maintenance Costs per Mile

Total maintenance costs account for labor, parts, and tire costs as well as the overhead costs required to maintain the building and employee services. Historically, all maintenance costs have been found to rise with age by approximately 1.5% per year, and a new bus has total O&M costs of $1.70/mi per unit (*1*).

Fuel Efficiency (mpg_i)

The average fuel economy of King County diesel buses has been found to be between 2.50 and 3.70 miles per gallon depending on the route characteristics (e.g., topography, number of stops, travel speed). A fuel efficiency of 3.32 miles per gallon is assumed; this value will be held constant for the entire time horizon of the model (*1*).

Passengers' Road Call Costs (rc_i)

A road call occurs when a bus has a mechanical problem, and a mechanic must be sent out to fix it. Road calls are detrimental to the transit agency because of the additional staff and resources required to repair a bus with mechanical problems. The transit cost of road calls is already integrated into the maintenance cost data. However, previous models have not included passengers' time or inconvenience costs when a bus breaks down. On average, a bus is driven with 8.8 passengers, and the waiting time associated with road calls is approximately 30 min in the Seattle metropolitan area (*16, 17*). Using a passenger's value of waiting time equal to $23.67/h, a value based on U.S. Department of Transportation figures and adjusted for inflation, the average user cost per road call is $103.97 (8.8 passengers) (*18, 19*). If the bus is loaded with 50 passengers, the cost increases proportionally to $591.75 per road call.

Utilization (u_i)

The national average for utilization of 60-ft articulated buses is 31,900 mi/year per unit (*20*). This value is held constant for the time horizon of the model.

Salvage Value (*s and* sf_{iT})

Decommissioning a bus is costly because equipment as well as external markings must be removed (Ralph McQuillan, Gary Prince, Kurtis McCoy, and Eric Hesse, personal communication, 2011). Moreover, if revenue from selling a bus exceeds \$5,000, the difference must be reimbursed to FTA if FTA's capital assistance funds were employed (*21*). A salvage value of $s = \$1{,}000$ is assumed. However, in year T when the bus is forced to be sold, a salvage value of \$1,000 may not be realistic, especially if a relatively new bus is sold. For the final time period, a linear depreciation function is used to determine the final salvage value based on the initial purchase cost, salvage value, and maximum life of a bus. The final salvage value is determined by the following equation:

$$\text{sf}_{iT} = \frac{v - A_j * (v - s)}{30}$$

Emissions Output and Cost (eps, em_i, ec)

Life-cycle analysis studies have estimated a passenger vehicle's production and salvage emissions as ranging from eight to nine CO_2-tons for sedans to 13 CO_2-tons for SUVs (*6, 22–24*). To the best of the authors' knowledge, there is no equivalent bus production and salvage emissions study; a bus CO_2-tons estimation is produced based on a ratio of vehicle weight and the CO_2 released to manufacture and scrap a vehicle (*6, 22–24*). An articulated 60-ft bus weighs 44,000 lbs, and a standard sedan and SUV weigh 3,500 and 5,400 lbs, respectively (*25*). The emissions associated with the production and salvage of a bus are estimated at 105 tons of CO_2. In addition, there are CO_2 emissions associated with bus usage; this value equals the CO_2 released when a gallon of diesel is burned, which is well known and equals 0.011 CO_2-tons (*26*).

Additional Data Inputs and Assumptions

On average, transit buses are replaced at Year 15.1, and bus ages rarely exceed 30 years (*26*). Hence, the bus maximum age is set to 30 years. To ensure at least two cycles, time horizon T is set to 60 years. The discount rate varies across the 60-year time horizon and is dependent on King County's bus study (*1*). For reference, after Year 11 of the model, the nominal discount rate is fixed at 9.55%. A New Flyer 60-ft articulated bus is assumed to cost $v = \$756{,}000$ based on what King County pays for its buses, including aftermarket equipment, manuals, and contingency (*1*).

The FTA provides transit agencies grants for up to 80% of bus capital purchases (*21*). When agencies are granted funds, the agencies must adhere to certain FTA guidelines; for example, they must keep heavy-duty buses a minimum of 12 years or 500,000 miles, whichever occurs first (*20*). According to a survey of American transit agencies, the average bus retirement age is 15.1 years (*20*). This model assumes that every bus purchase is granted the 80% subsidy.

Wide variations exist in cost per ton of CO_2 emissions and climate change effects. Valuations range from zero (no link between CO_2 and climate change) to \$200/CO_2-ton or more; a recent metastudy found that the average social cost of CO_2 is \$100/CO_2-ton (*27–30*).

SCENARIO ANALYSIS

Given that some market parameters are highly uncertain or volatile, a set of values is provided for each. Values of parameters varied in the scenario analysis are shown below.

For parameters varied in the baseline scenario, the values are as follows:

- Gasoline prices (d)—baseline or low projected diesel price = \$2.64/gal, 2011 (*1*),
- Emissions prices (ec)—baseline actual emissions price = \$0/CO_2-ton,
- O&M costs (om_i)—baseline actual O&M costs (*1*),
- Utilization (u)—baseline flat utilization $u = 31{,}900$ mi (*20*),
- FTA's capital assistance—capital assistance = 80%, and
- User cost per road call—baseline = zero.

For parameters varied in the extreme scenario, the values are as follows:

- Gasoline prices (d)—high projected diesel price = \$4.46/gal, 2011 (*1*),
- Emissions prices (ec)—high emissions price = \$100/CO_2-ton (*30*), and
- O&M costs (om_i)—high O&M costs = 25% increase over values obtained in King County's study.

For other parameters analyzed individually, the values are

- User cost per road call—an average of \$103.97 (8.8 passengers) or high of \$591.75 (full bus) and
- Purchase costs—decrease total purchase costs by 10%.

RESULTS AND ANALYSIS

When the model is run under a baseline or average scenario, results show that costs of O&M, purchase, and fuel contribute to 63%, 15%, and 22% percent of the bus costs, respectively. In the baseline scenario the optimal replacement age is, on average, 21.5 years. To observe changes in total costs due to budget constraints, the bus purchase or salvage replacement decisions are forced to be 2, 4, and 6 years before and after the optimal replacement age. The lines in Figure 1 illustrate the percentage cost increases over the optimal replacement age.

Cost changes are relatively small (or flat) around the optimal replacement age, partly because of the relatively low increase in O&M costs. A steeper increase in O&M costs would lead to optimal replacement ages close to 16 years. A small change in bus purchase price results in a significant change in optimal replacement age (see section on sensitivity analysis).

The cost impacts of delaying or hurrying the replacement decisions are not symmetrical. For example, if a replacement decision is delayed to 30 years, the total costs of fleet operation are forecast to increase by 0.1%, but if the replacement is advanced to Year 16, the total cost increases approximately 0.3%. Budget constraints may force a delayed replacement, and this is costly, but not as costly as an early retirement due to maintenance problems or lack of reliability.

In an extreme scenario (high diesel price forecasts, high CO_2 emissions costs of \$100/CO_2-ton, and a 25% increase in the initial O&M costs), the optimal replacement age increases from 21.5 to 22 years. Deviating from the optimal bus replacement age is less costly: if a bus is replaced 6 years before its optimal age, the cost is forecast to increase by 0.32% and 0.4%, respectively, in baseline and extreme scenarios. Early and delayed replacement affects total fleet emissions in a different manner. By replacing the bus 6 years earlier than optimal, a total of 1.54% emissions are increased because the manufacturing emissions cost is incurred more frequently. If a bus is replaced 6 years later than optimal, the CO_2 decreases by 1.59%.

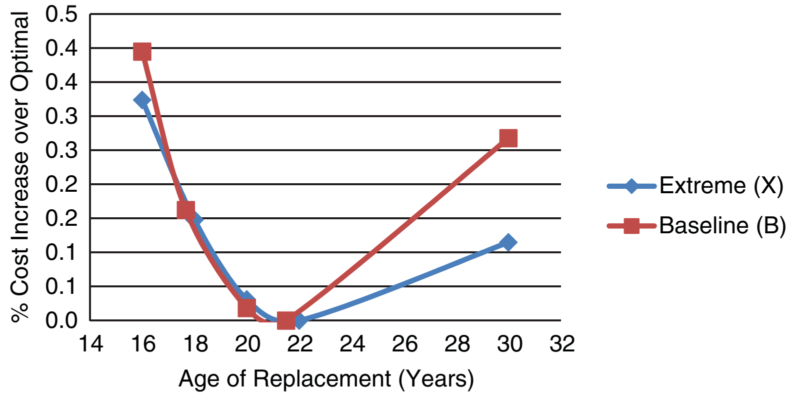

FIGURE 1 Impact of early and delayed replacement age (percentage change over 60-year planning horizon discounted costs).

The difference between low and high diesel price scenarios increases fuel costs by 70.1% and total costs by 34.1% (Table 1). A 25% increase in O&M costs per mile increases total O&M costs 19.2%, total costs by 13.5%, and purchase costs by 4.5%. With higher O&M costs per mile, it is optimal to replace buses earlier. Imposing an emissions cost from zero to \$100/CO_2-ton increases the total costs by 10.5%, which is less than the high diesel price forecast issued by Linwood Capital (*31*). Last, decreasing the bus's purchase price decreases total costs by 10%, total purchase costs by 8%, and O&M costs by 0.7%.

When low and high passenger costs of road calls are integrated into the model, total costs minimally increase by 0.59% and 3.21%, respectively, and the O&M cost category rises by 0.6% and 4%, respectively. A separate scenario included the transit agency cost of having additional staff on call from increased road calls. However, the extra cost was found to be insignificant and was ignored.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed to understand which factor has the highest impact on the replacement age. The elasticity of costs to each factor is computed with the following arc elasticity formula, where η^c_x is the elasticity of per mile cost c to parameter x:

$$\eta_x^c = \frac{(x_1+x_2)/2}{(c_1+c_2)/2}\,\frac{\Delta_c}{\Delta_x} = \frac{(x_1+x_2)}{(c_1+c_2)}\,\frac{(c_2-c_1)}{(x_2-x_1)}$$

The elasticity of replacement to each parameter is calculated by assuming a range shown in Table 2 for both types of elasticity (cost per mile and replacement age). For example, if diesel prices increase by 1%, the cost elasticity is 0.17, meaning that costs per mile increase 0.17%. The replacement age elasticity is 0.00, meaning that the optimal replacement age is not affected by a gas price increase or increases in fuel economy.

Decreasing the purchase price has the most significant impact to decrease the optimal replacement age, which says much about the importance of the 80% capital cost subsidy. Age elasticity is extremely sensitive to changes in vehicle purchase cost; a 2% reduction in purchase price can lead to a 9% (almost 2 years') reduction in optimal replacement age.

Higher utilization also decreases replacement age, as well as higher O&M costs. As expected, maintenance costs have significant impacts on both costs per mile and replacement age. However, the impact of maintenance costs on replacement age has the opposite sign as expected. Among the remaining variables, fuel efficiency turned out to have lower cost elasticity than utilization. This indicates that

TABLE 1 Impact of Cost Increases Relative to Baseline Conditions

Cost Category	High Diesel Cost (%)	Emissions Cost of \$100/CO_2-ton (%)	O&M 25% Cost Increase (%)	Purchase Cost 10% Decrease (%)
Total cost	34.1	10.5	13.5	−1.6
Purchase cost	0.0	−1.2	4.5	−8.0
Salvage revenue	0.0	−9.5	25.8	17.7
Fuel cost	70.1	0.0	0.0	0.0
O&M cost	0.0	0.3	19.2	−0.7

TABLE 2 Cost and Age Elasticity

Variable	Diesel Price Low to High Scenario	O&M 0% to 25% Increase	Utilization (mi/year) 0% to 10% Increase	Miles per Gallon 0% to 10% Increase	Purchase Cost 0% to 10% Increase
Cost elasticity	0.17	0.62	−0.14	−0.20	+0.15
Age elasticity	0	−0.75	−0.82	0	+4.52

improvements in fuel efficiency go a long way to reducing costs per mile and justifying investments in more fuel-efficient buses.

CONCLUSIONS

Budget-constrained transit agencies are challenged to minimize total fleet costs. Changing vehicle prices, utilization levels, and O&M costs have been shown not only to change total per mile costs of fleet operation, but also to change the optimal age of bus replacement decisions. Decreases in purchase costs had the greatest impact on the optimal replacement age, which speaks to the necessity of transit agencies receiving FTA's bus purchase subsidy.

Diesel prices and internalizing CO_2 emissions costs have significant impacts on total costs but not replacement ages. Road calls were shown to have an insignificant impact on total costs. It was also found that early bus replacement, relative to the optimal replacement decision, is more expensive in economic terms than tardy replacement. However, as agencies delay bus replacement, they decrease CO_2 emissions because they decrease the emissions costs associated with manufacturing. In addition, elasticities are useful to understand how changes in market and fleet conditions affect replacement age and costs. For example, an increase in bus maintenance costs has a greater impact on total per mile costs relative to higher gas prices.

Despite the complexities of bus fleet costs and characteristics, federal bus policies, and market factors, bus replacement modeling is shown to be an effective tool to ascertain market and fleet changes on costs and bus replacement timing.

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Any omissions or mistakes are the sole responsibility of the authors.

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