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Transit Bus Fleet Age and Replacement Type Optimization

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FINAL REPORT

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TRANSIT BUS FLEET AGE AND REPLACEMENT TYPE OPTIMIZATION

Final Report

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by

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for

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16. Abstract

Due to recent budget and fiscal constraints, it is ever more imperative for transit agencies to manage their fleets in an optimal way. Fleet data have consistently shown that bus operational and maintenance (O&M) per-mile costs increase as buses age. From a purely economic perspective, there is a cost tradeoff between the lower O&M costs of newer fleets and their higher initial capital costs. This tradeoff has a significant impact on the optimal timing of purchase and replacement decisions. Utilizing realistic cost data and an optimization modeling framework, we analyze (a) the impact of purchase timing decisions on fleet per-mile costs and (b) the key factors and variables affecting the optimization of transit diesel and hybrid bus fleets. Given uncertain and hard-to-forecast market variables, multiple scenarios are examined and sensitivity analyses are performed to study the impacts of key variables on optimal replacement policies and costs.

In terms of the impact of purchase timing decisions on fleet per-mile costs (a), results indicate that: 1) increases in diesel prices do not affect total bus fleet costs as much as increases in maintenance costs; 2) increases in maintenance costs and utilization per year reduce the optimal replacement age; 3) increases in utilization and fuel economy have a similar impact in terms of total fleet costs; and 4) bus purchase-price changes have a significant impact on the optimal replacement age.

In terms of the key factors and variables affecting the optimization of transit diesel and hybrid bus fleets (b), results indicate that: 1) the Federal Transit Administration (FTA) purchase cost subsidy has the highest impact on the optimal replacement policies; 2) without the FTA subsidy, the optimal policy is to choose the diesel bus unless the purchase cost difference is larger than 10%; 3) with an 80% FTA purchase cost subsidy, the hybrid bus is always the best choice unless fuel economy difference between the hybrid and diesel buses is substantial; 4) maintenance costs affect the optimal replacement age but are unlikely to change the optimal bus type when comparing diesel and hybrid technologies; and 5) greenhouse gas emissions costs are not significant and affect neither bus type nor replacement age.

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1.0 INTRODUCTION

Transit agencies typically own hundreds or thousands of buses; large transit agencies may have multiple fleets of buses with different types of buses serving different routes. For example, King County transit (KCT) agency in the state of Washington operates about 1,300 vehicles with multiple bus technologies (electric trolley buses, diesel buses, hybrid buses, etc.); designs (60-foot articulate, 30-foot or 40-foot standard); and models (New Flyer, Gillig, etc.). Fleet capital, operational and maintenance costs are a significant expense for transit agencies. Due to budget and fiscal constraints, it is ever more imperative for transit agencies to manage their fleets in an optimal way without reducing service quality.

To minimize total fleets costs over a certain time horizon, fleet managers have to consider two important tradeoffs when making replacement decisions. The first tradeoff is related to age; as buses age, the per-mile operating and maintenance (O&M) costs tend to increase. Replacing old vehicles with new ones reduces these costs but significantly increases capital costs. Therefore, there is an optimal replacement age (lifecycle) that minimizes the total net cost over a planning time horizon. The second tradeoff is related to bus type. Vehicle purchase price and per-mile operating, maintenance and fuel costs vary across bus types (conventional diesel, hybrid, electric trolley, etc.); bus designs; and operating environments (congested or not congested routes, hilly or flat routes). There is an optimal bus type among all the candidates for each transit agency in certain operating environments.

The objective of this research is to utilize real-world data to study (a) the impact of purchase timing decisions on fleet per-mile costs and (b) the key factors and variables affecting the optimization of transit diesel and hybrid bus fleets. This research studies the impacts of government purchase subsidy levels on replacement decisions, and the impact of the remaining input variables and utilization factors.

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1.1 BACKGROUND

In 2009, King County Transit underwent a follow-up review of a 2007 County Vehicle Replacement performance audit. Recommendations from this follow-up called for the Transit Division to develop its own fleet replacement criteria based on a full-year review of operations and maintenance data for vehicles in the non-revenue fleet[1]. Additionally, in 2009 King County Transit underwent a Performance Audit of Transit to review and evaluate several areas, including trolley bus replacement[2]. This audit revealed that (as of the audit), none of the vehicle fleet replacement criteria was based on economic analysis. Criteria for vehicle replacement ranged from mirroring the FTA's funding guidelines to using professional judgment.

[1] See Recommendation 2 in Management Letter from King County Auditor to Metropolitan King County Council members; Subject: Follow-up on Implementation of Recommendations from 2007 Performance Audit of County Vehicle Replacement; dated: November 9, 2009.
[2] See Performance Audit of Transit Summary Report No. 2009-01, dated September 15, 2009.

More recently, a study commissioned by King County evaluated the economic and environmental tradeoffs between electric trolleys and hybrid diesel buses.3 Among the relevant findings contained in this report entitled King County Trolley Bus Evaluation report (herein denoted KCTB report or study) are the following: (a) diesel price forecast has the greatest influence on life-cycle cost results, (b) a change in the vehicle life span for one or both technologies can significantly affect life-cycle costs, and (c) lower discount rates can change replacement costs but not the type of preferred technology.

1.2 REPORT ORGANIZATION

This research paper is organized as follows: Section 2 briefly introduces the background of bus fleet replacement practices and replacement optimization models. Section 3 describes the methodology employed, data sources and model structure. Section 4 presents the model and results regarding the impact of purchase timing decisions on fleet per-mile costs. Section 5 presents the model and results regarding the key factors and variables affecting the optimization of transit diesel and hybrid bus fleets. Section 6 ends the report with conclusions.

[3] King County Metro. King County Trolley Bus Evaluation. May 2011, http://metro.kingcounty.gov/up/projects/trolleyevaluation.html, http://metro.kingcounty.gov/up/projects/pdf/Metro_TB_20110527_Final_LowRes.pdf

2.0 LITERATURE REVIEW

The Management Science and Operations Research literature have pioneered the usage 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 (Bellman, 1955). Since then, many researchers have analyzed replacement problems in a wide range of fleet types, including transit and police fleets (Rees et al., 1982; Khasnabis et al., 2003). Some researchers have added budget constraints (Karabakal et al., 1994) and even integrated vehicle-manufacturing waste factors in an automobile life-cycle analysis (Kim et al., 2003). Despite the great uncertainty associated with financial variables and forecasts, all the mentioned models have been deterministic. Furthermore, there has been little or no attention given to sensitivity analysis (Keles et al., 2004).

Previous studies in the public transport field have shown how fuel efficiency and operating and maintenance costs change when vehicles age. Significant differences have been found across bus models, transit agencies and service environments (Lammert 2008; Chandler and Walkowicz 2006; Schiavone 1997). Bus life-cycle costs have been previously compared across bus engine types and design models (Clark et al. 2007; Laver et al. 2007; Clark et al. 2009; Kim et al. 2009). The papers referenced in this paragraph focus on vehicle characteristics and life-cycle costs assuming a constant replacement age. Optimal replacement schedules and bus-type choice that minimize bus fleet total net cost have not been studied.

There is a large body of literature dealing with vehicle replacement optimization models in the operations research field. These models can be broken into two categories depending on whether buses in a fleet are homogeneous or heterogeneous. In homogeneous models, the objective is to find the best bus replacement age for a set of identical vehicles. In other words, buses with the same type and age have to be replaced together (also known as the "no cluster splitting rule"). These models are usually solved using a dynamic programming (DP) approach (Bellman 1955; Oakford, Lohmann, and Salazar 1984; Bean, Lohmann, and Smith 1984; Bean, Lohmann, and Smith 1994; Hartman 2001; Hartman and Murphy 2006). DP has the advantage of allowing the consideration of probabilistic distributions for some state variables, such as utilization or operational costs.

Heterogeneous models are more appropriate when multiple bus fleets have to be optimized simultaneously or when budget constraints are needed. For example, the "no cluster splitting rule" cannot be applied when vehicles of the same type and age may be replaced in different years due to budget limitations. These models are able to solve more practical problems, but input variables are usually deterministic. Stochastic heterogeneous models are difficult to solve. Most heterogeneous models employ integer programming (IP) formulations (Simms et al. 1984; Karabakal, Lohmann, and Bean 1994; Hartman 1999; Hartman 2000; Hartman 2004). With additional assumptions, a DP approach can be applied to heterogeneous problems (Jones, Zydiak, and Hopp 1991). None of the theoretical models mentioned in this paragraph deals with real-world fleet data.

Several papers have described the use of optimization models to solve real-world problems. Keles and Hartman (2004) adopted an IP model in a transit fleet replacement problem with multiple types of buses. However, many cost functions were highly simplified or not based on real data; a sensitivity analysis based on key vehicle characteristics, utilization levels or market fluctuations were not studied. Fan et al. (2012) developed a fleet optimization framework using a DP approach; however, the simultaneous optimization of heterogeneous vehicles and sensitivity analysis of input variables were not addressed. Figliozzi, Boudart and Feng (2011) and Feng and Figliozzi (2013) adopted IP models to study a fleet of heterogeneous passenger cars and delivery trucks with real-world operational data. Impacts of policy, market, utilization, emissions, and technological factors were analyzed using scenario analysis and elasticity analysis. Boudart and Figliozzi (2012) studied how economic and technological factors affect a single bus optimal replacement age.

3.0 METHODOLOGY

Given that initial capital cost, O&M and environmental costs vary across vehicle types and over time, it is necessary to find the optimal ownership time that minimizes their sum over a given planning horizon.

The models developed by Portland State University (PSU) will facilitate decision making related to fleet management problems. More specifically, it includes two replacement models to evaluate fleet management decisions regarding vehicle replacement timing for a single vehicle type and vehicle type purchases (e.g., one diesel vs. one hybrid) as well as timing of purchases and scrapping decisions. The corresponding tools[4] (software) are developed to support analysts' work. Regarding the models, it should be noted that:

- The objective of the models is to minimize the Net Present Value (NPV) associated with vehicle purchases, fuel consumption, operations and maintenance costs, and other costs such as road call costs. CO_2 emission costs can also be incorporated into the model. The model selects the bus type and replacement year (or simply replacement year for single vehicle type) that minimize NPV over the chosen planning horizon.
- In the multiple vehicle types model, costs that are the same across vehicles and over time (e.g., driver cost for a hybrid or diesel bus) should not be included in the model since the net NPV savings will not be altered. For example, capital (purchase), fuel and maintenance costs are relevant because hybrid vehicles have an initial cost premium that can be offset over time through incremental annual savings from lower maintenance and/or fuel costs.
- Constraints: The only constraint included in the model is the potential life of a bus. Based on the literature review, two scenarios were tested - 20 years and 30 years. Additionally, if FTA support is used to purchase a vehicle, there is a minimum vehicle life of 12 years.
- The model can use any initial vehicle fleet.

The replacement model is built by using an integer programming model, KCT data, and data from other reports. Two models are developed to find the optimal vehicle replacement age for a single vehicle type, and to find the optimal vehicle type between two candidates and the optimal replacement age. A summary of the methodology and key assumptions follows.

3.1 ASSUMPTIONS

The following assumptions are made throughout the report and study:

- To facilitate comparisons with the KCTB study results, it was assumed that a new bus fleet (either diesel or diesel hybrid) buses would enter into service in 2014. All initial capital costs would be incurred starting in 2014 with annual O&M costs being charged from 2014 onward and discounted to 2010 dollars.

[4] PSU will provide software that runs in any standalone machine (PC or laptop). The software was successfully installed to a KCT laptop during the February 2012 meeting. PSU work does not include installation troubleshooting or issues related to King County computer network or administrative restrictions.

- Because of the uncertainty in predicting some values and costs, such as future fuel prices, maintenance costs and utilization, several scenarios and plausible values were used to test the model and to observe the sensitivity of the model output-to-input variations.
- The annual capital, operating and maintenance expenditures for each vehicle type are summarized in the scenario NPV.
- KCTB study inflation assumptions (future CPI 2.55%) and a 7% annual rate (APR) were employed to calculate NPVs. The 9.55% annual discount rate was specified by King County Executive Policy and includes the cost of money considering time, interest, alternative uses, and risks. The discount rate and fuel prices over time are shown in Figure 1 and 2. The initial fuel prices are the following:

Low fuel price: $/gal	Mid fuel price: $/gal	High fuel price: $/gal
2.64	3.48	4.46

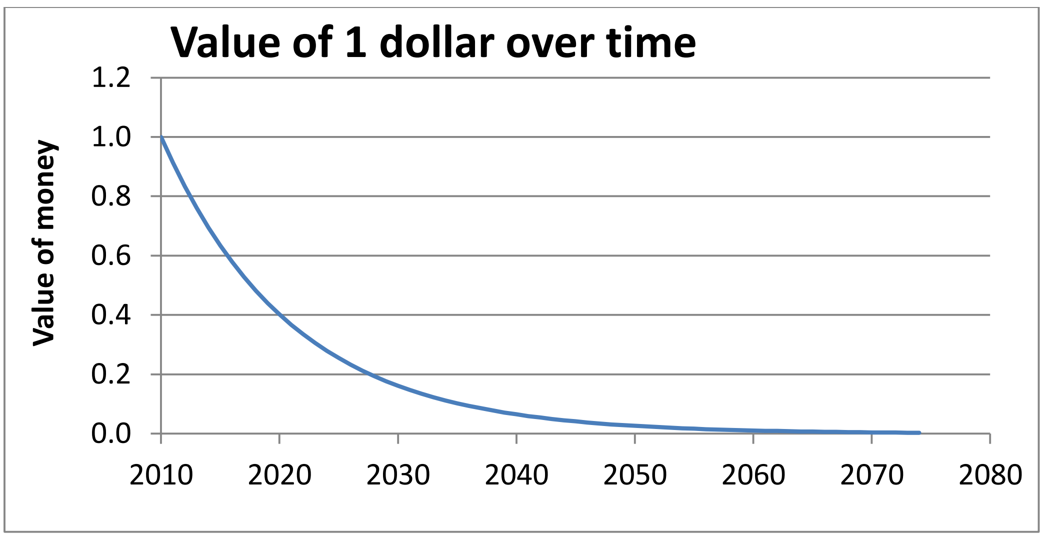


Figure 1. Value of money in future years, 2010 U.S. dollars

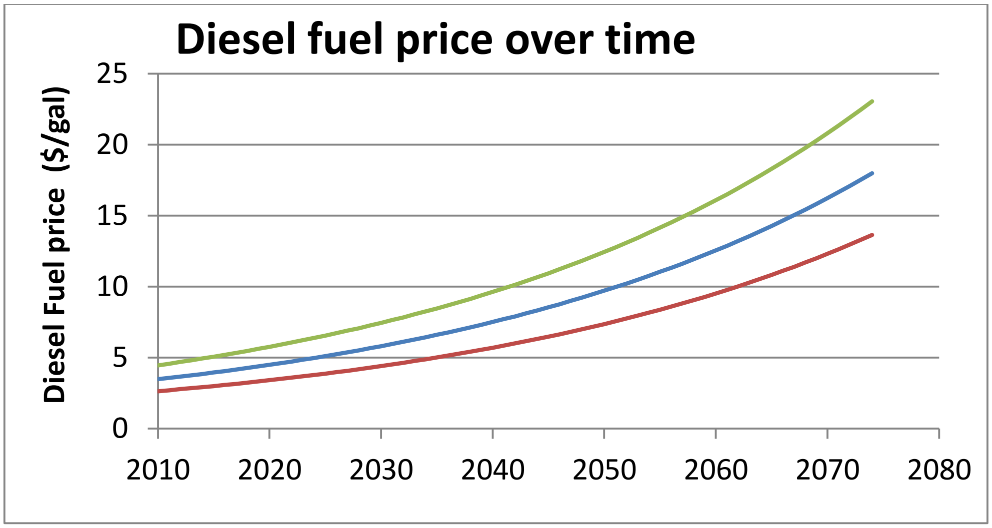


Figure 2. Diesel fuel price scenarios

- The final salvage value per vehicle is assumed to be $1,000 (data provided by KCT). Hence, long planning horizons (60 years for single vehicle type model and 100 years for multiple vehicle types model) are chosen to reduce the impact of depreciation and salvage values on the first replacement cycle.

The following additional assumptions are made for the multiple vehicle types model:

- Costs common to both vehicle types, such as driver costs, can be ignored. The focus of the NPV comparisons is to determine the relative cost difference between different vehicle types or replacement ages; the modeled costs are relative rather than absolute.
- The model will correctly indicate the most economical replacement age and bus type; however, the final cost will be greater than estimated within the model because some common costs are excluded.
- It is assumed that buses are being compared in the same route and operating schedule; the only significant differences are fuel efficiency, operations, maintenance, and purchase costs.
- It is assumed that buses of similar passenger capacity and performance are compared.

3.2 DATA SOURCES

The data provided by KCT includes disaggregated maintenance cost data (labor, parts and material) by fleet and bus number as well as aggregated annual operational and administrative costs by fleet. Data contained in the KCTB study are used to complete some of the data that are necessary to run the replacement model. The KCTB data do have several advantages: (a) it is recent data that have been provided by KCT and validated by the consultants, and (b) most of the data are directly applicable to KCT buses.

Although there are published reports that have studied transit vehicle replacement practices and costs, the published costs tend to be general averages that may not be representative of KCT costs (examples are provided in the report). King County Transit owns more than 1,400 buses, vans and trolleys. Approximately 23% of the fleet is made up of New Flyer and New Flyer hybrid 60-foot buses. These 60-foot buses were selected for the initial analysis because of the higher number of observations and longer data time series. Data for 60-foot buses includes:

- Fleet 23: Detailed maintenance data for 272 New Flyer diesel buses, purchased since 2000 (11 years of available data).
- Fleet 26: Detailed maintenance for 212 New Flyer hybrid diesel buses, purchased since 2004 (seven years of available data).
- Fleet 28: Cost data from a significantly smaller fleet of diesel buses (30 buses) is used to provide an alternative set of diesel maintenance data and fuel economy values.

These are the fleets with the most relevant data and longest time series. The study settings and scenarios sections will state how the data were obtained, especially if the disaggregated maintenance data were employed. KCT has provided aggregated fleet cost data and disaggregated data only for maintenance costs. The aggregated fleet cost data were contained in a series of spreadsheets called "VMCST data;" the data ranges from 1994 to 2009. KCT aggregated data includes annual operations and maintenance costs per bus fleet. The data categories per bus fleet are:

- Age of bus
- Total number of units
- Fuel cost
- Diesel gallons consumed
- Annual miles traveled
- Maintenance costs (mechanics' labor plus parts)
- Tire costs
- Administration costs (management, administrative, etc.)
- General costs (such as facility costs)
- Total costs

From these data categories, useful ratios and performance measures can be created at an aggregated level:

- Total costs per mile
- Miles per gallon (fuel economy)
- Miles per unit
- Maintenance costs per mile
- Total costs per unit

Disaggregated data includes maintenance data, such as date, fleet, unit, repair or task description, labor hours, parts costs, and material costs.

3.3 DATA PREREQUISITES

Potentially, any cost data by mile driven or by age can be incorporated into the models provided by PSU. However, the analyst must feed relevant, high-quality cost and emissions data for each type of vehicle to be analyzed. Data limitations (e.g., disaggregation, format and time-series length) can be easily found if too many categories are included. Furthermore, previously published reports and studies may use simplifying assumptions (linear costs) that may not always be correct. Hence, there is a delicate tradeoff between data quality, number of cost types, and model results quality.

Since the right timing of decisions is a desired outcome, King County Transit should provide quality disaggregated data regarding the impact of vehicle age and history on relevant costs, vehicle performance, and emissions. KCT has only provided aggregated fleet cost data and disaggregated data for maintenance costs.

The replacement model structure is provided in the next page.

3.4 REPLACEMENT MODEL STRUCTURE

Purpose	Minimizes fleet total costs over a planned time horizon by finding the optimal replacement age and vehicle type. Provides flexible and convenient input functions (linear or non-linear) so as to be applicable to as many scenarios as possible for sensitivity and scenario analysis.
Decision variables	When and which existing buses should be replaced with which type of new buses over the planning horizon.
Inputs	Economic factors: planning time horizon, discount rate, utilizations, and energy price forecasts. Vehicular characteristics: annual utilization, maximal life, purchase price, salvage value, energy efficiency, and O&M costs as functions of age. Fleet initial composition: number, types and ages of initial (existing) fleet vehicles.
Outputs	Performance measurements: • Total net cost and cost breakdowns • Per mile net cost • Optimal new bus candidate • First/average replacement age • Fuel consumed • CO_2 emissions tons and costs
Implementation	Uses Excel's format augmented by an optimization package.

4.0 FLEET REPLACEMENT OPTIMIZATION WITH SINGLE VEHICLE TYPE

4.1 MODEL FORMULATION

The objective of this model is to minimize bus net 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.

For the sake of readability and easy interpretation of the model, decision variables or the cardinality of a set are denoted as capital letters; sets are denoted by bold capital letters; and parameters are denoted using small letters, broken down in three categories: constraints, cost or revenue, and emissions.

Indexes

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

Time periods, a decision is made at the end of each year: $j \in \boldsymbol{T} = \{0, 1, 2, \ldots, T\}$

Binary Decision Variables

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

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

Parameters

(a) Constraints

A = maximum or forced salvage age (the bus must be salvaged if this age is reached)

u_i = utilization (miles traveled by an i-year old bus)

mpg_i = fuel economy of i-year old bus

(b) Costs or revenue

v = cost of purchasing a new bus

om_i = maintenance costs per mile for an i-year old bus

rc_i = cost of road calls of an i-year old bus

s = salvage revenue (negative cost) from selling an old bus when replaced by a new bus

sf_{iT} = final salvage revenue (negative cost) from selling an i-year old bus at time T

ec = emissions cost per ton of CO_2 emissions

d = price of diesel fuel per gallon

dr = discount rate

(c) Emissions

eps = production and salvage emissions, in CO_2-tons

em_i = utilization emissions in CO_2-tons per mile for an i-year bus

Objective Function, minimize:

$$\sum_{i=0}^{A-1}\sum_{j=0}^{T-1} PY_j(v + ec \cdot eps - s - sf_{iT})(1 + dr)^{-j} + \sum_{i=0}^{A-1}\sum_{j=0}^{T-1} X_{ij}(u_i om_i + u_i mpg_i d + u_i em_i ec + rc_i)(1 + dr)^{-j} \quad (1)$$

Subject to:

$$PY_0 = 1, \text{where } s = 0 \quad (2)$$

$$PY_T = 1, \text{where} v = 0 \quad (3)$$

$$X_{(i-1)(j-1)} = X_{ij} + PY_j \quad \forall i \in \{1, 2, \dots, A\}, \forall j \in \{1, 2, \dots, T\} \quad (4)$$

$$PY_j = X_{0j} \quad \forall j \in \{1, 2, \dots, T - 1\} \quad (5)$$

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

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

$$PY_j, X_{ij} \in I = \{0, 1\} \quad (8)$$

The objective function 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 purchases of a new bus (2). At the end of the last time period (or horizon time *T*), the existing bus is sold (3) at a value equal to the salvage value for whatever age the bus has at the time *T*, sf_{iT}. The age of any vehicle in use increases by one year after each time period (4). A constraint makes sure that a bus procured equals a new bus in use (5). When a bus reaches the maximum service age it is forced to be salvaged (6). At the last time period, *T*, the bus is not utilized and operational costs are not added (7). Finally, the decision variables associated to purchasing and salvaging decisions must be binary (8).

4.2 SUPPORTING DATA AND ASSUMPTIONS

This section tries to study the impact of various factors that affect the optimal vehicle replacement timing decisions. Therefore, only one vehicle type is considered, which means future purchased new vehicles have to be the same as the type as the existing ones. The input data are supported by the KCTB study. We are modeling a bus that has an average operating cost per mile of $2.05 over a 20-year period.

Maintenance costs

The 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, while a new bus has the total operating and maintenance costs of $1.70 per mile per unit.

Fuel efficiency (mpg_i)

The average fuel economy of King County diesel buses has been found to be between 2.50 and 3.65 miles per gallon, depending on the route characteristics (topography, number of stops, travel speed, etc.). It is assumed herein that the fuel efficiency is 3.32 miles per gallon according to the KCTB study; this value will be held constant for the life of a vehicle.

Passengers' road call (RC) costs (rc_i)

A bus has a "road call" when it 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 in 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 (Davis et al., 2009) and the waiting time associated with road calls is approximately 30minutes in the Seattle metropolitan area (KCMT, 2008). Utilizing a passenger's value of waiting time equal to $23.67 per hour, based on the U.S. Department of Transportation (USDOT, 1997) figures and adjusted for inflation (DOL, 2011), the average user cost per road call is $103.97 (8.8 passengers). If the bus is loaded with 50 passengers, the cost increases proportionally to $591.75 per road call.

Utilization (u_i)

The average utilization of national 60-foot articulated buses is 31,900 miles per year (Laver et al., 2007), per unit and is held constant for the time horizon of the model.

Salvage Value (s & sf_{iT})

Decommissioning a bus is costly because equipment as well as external markings must be removed (KCT, 2011). Additionally, the literature highlights that if revenue from selling a bus exceeds $5,000 the difference must be reimbursed to the FTA if FTA's capital assistance funds were employed (FTA, 1992). A salvage value s = $1,000 is assumed. However, on 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.

$$sf_{iT} = v - A_j * (v - s)/30 \tag{9}$$

Emissions output and cost (eps, em_i, ec)

Life-cycle analysis studies have estimated a passenger vehicle's production and salvage emissions ranging between eight to nine CO2-tons and 13 CO2-tons for sedans and sport utility vehicles (SUV), respectively (Kim et al., 2003; DeCicco and Thomas, 1999; Maclean and Lave, 2003; Samaras and Meisterling, 2008*)*. To the best of the authors' knowledge there is no equivalent bus production and salvage emissions study; a bus CO2-tons estimation is produced based on a ratio of vehicle weight and the CO2 released to manufacture and scrap a vehicle. An articulated 60-foot bus weighs 44,000 pounds, whereas a standard sedan and SUV weigh 3,500 and 5,400 pounds, respectively (USA Today, 2011). The emissions associated to the production and salvage of a bus are estimated at 105 tons of CO2. In addition, there are CO2 emissions associated with bus usage; this value equals the CO2 released when a gallon of diesel is burned, which is well known and equals 0.011 CO2-tons (EPA, 2011).

Additional Data Inputs and Assumptions

On average, transit buses are replaced at year 15.1 and bus ages rarely exceed 30 years (Laver et al., 2007). Hence, the bus maximum age is set to 30 years. A New Flyer 60-foot articulated bus is assumed to cost v = $756,000 based on what King County pays for its buses, including aftermarket equipment, manuals and contingency.

The FTA provides transit agencies grants for up to 80% of bus capital purchases (any capital investment) as indicated in US Code Title 49, Subtitle III, Chapter 53, section 5309 (Public Transportation), page 198[5]: "Based on engineering studies, studies of economic feasibility, and information on the expected use of equipment or facilities, the Secretary shall estimate the net project cost. A grant for the project shall be for 80 percent of the net capital project cost, unless the grant recipient requests a lower grant percentage". When agencies are granted funds, they must adhere to certain FTA guidelines; agencies must keep heavy-duty buses a minimum of 12 years or 500,000 miles, whichever occurs first (Laver et al., 2007). According to a survey of American transit agencies, the average bus retirement age is 15.1 years (Laver et al., 2007). This model will assume that every bus purchase is granted the 80% subsidy.

Regarding CO2 emissions and climate change effects, there is wide variation in terms of cost per ton. Valuations range from zero (no link between CO2 and climate change) to $200/CO2-ton or more (Tol, 2005; Stern, 2006). A recent meta-study found that the average social cost of CO2 is $100/CO2-ton (Peet et al., 2010; Wayne et al., 2009).

Given that some market parameters are highly uncertain or volatile, we provide a set of values for each. Parameters varied in the scenario analysis are presented in Table 1.

Table 1. Scenario analysis parameters and values

	BASELINE
Gasoline Prices (d)	BASELINE or low projected diesel price = $2.64/gallon, 2011 (*33*)
Emissions Prices (ec)	BASELINE actual emissions price = $0/CO2-ton
O&M Costs (om_i)	BASELINE actual O&M costs (*1*)
Utilization (u_i)	BASELINE flat utilization u = 31,900 miles (*21*)
FTA's Capital Assistance	BASELINE capital assistance = 80%
User Cost per Road Call	BASELINE equal to zero
	EXTREME
Gasoline Prices (d)	High projected diesel price = $4.46/gallon, 2011 (*33*)
Emissions Prices (ec)	High emissions price = $100/CO2-ton from (*31*)
O&M Costs (om_i)	High O&M costs = 25% increase over the values obtained King County's study
	OTHER PARAMETERS ANALYZED INDIVIDUALLY
User Cost per Road Call	An average of $103.97 (8.8 passengers) or high of $591.75 (full bus)
Purchase Costs	Decrease total purchase costs by 10%

4.3 SCENARIOS RESULTS

When the model is run under a baseline or average scenario, results show that O&M, purchase and fuel costs 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/salvage replacement decisions are forced

[5] http://www.gpo.gov/fdsys/pkg/USCODE-2008-title49/pdf/USCODE-2008-title49-subtitleIII-chap53-sec5309.pdf

to be two, four and six years before and after the optimal replacement age. The lines in Figure 3 illustrate the percent cost increases over the optimal replacement age.

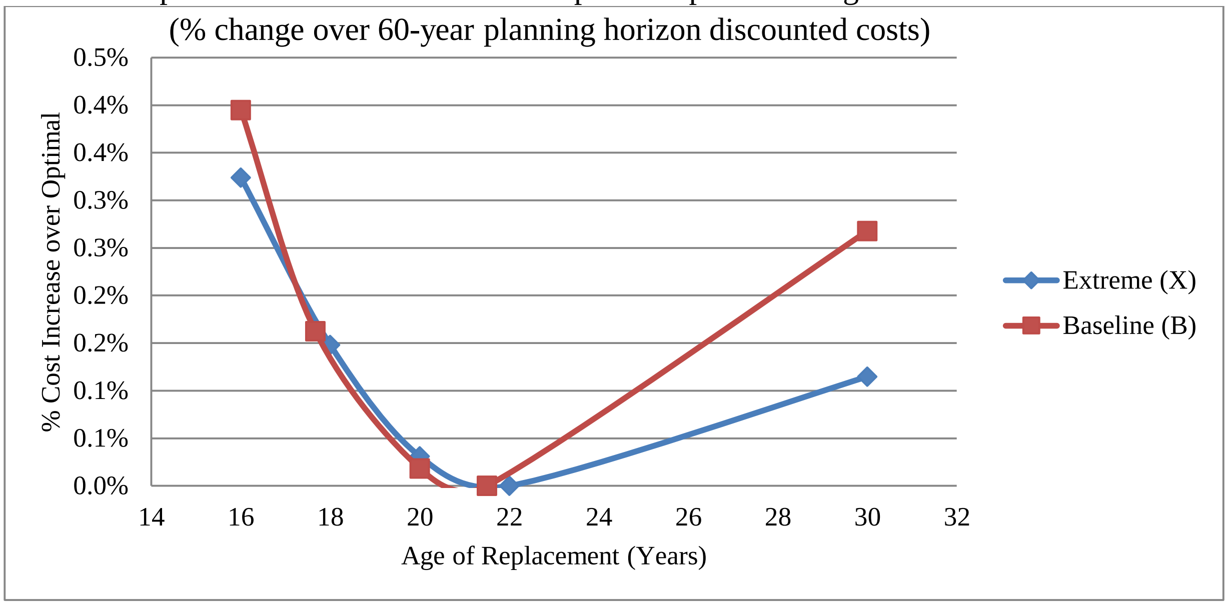


Figure 3. Impact of early and delayed replacement age

Cost changes are relatively small (or flat) around the optimal replacement age. This is in part due to 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. In addition, a small change in bus purchase price results in a significant change in optimal replacement age (see Section 6.4, 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%, whereas 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.

If we assume an extreme scenario (high diesel price forecasts, high CO2 emissions costs of $100/CO2-ton, and a 25% increase in the initial O&M costs), the optimal replacement age increases from 21.5 to 22 years. Additionally, it is less costly to deviate from the optimal bus replacement age; if a bus is replaced six years before, the cost is forecast to increase by 0.32 and 0.4 percent, respectively, in baseline and extreme scenarios. Early and delayed replacement impacts total fleet emissions in a different manner. By replacing the bus six 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 six years later than optimal, the CO2 decreases by 1.59%.

Table 2. Impact of cost increases relative to baseline conditions

Cost Category	High diesel cost	Emissions $100/CO2-ton	O&M 25% cost increase	Purchase cost 10% decrease
Total Cost ($)	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 shows that the difference between low to high diesel price scenarios increased fuel costs by 70.1% and total costs by 34.1%. A 25% increase in O&M costs per mile increased total O&M costs 19.2%, total costs by 13.5% and also affected 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/CO2-ton increases the total costs by 10.5%, which is less than the high diesel price forecast issued by Linwood Capital (Linwood Capital, 2011). Lastly, decreasing the bus's purchase price decreases total costs by 10%, total purchase costs by 8%, and operating and maintenance 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% while the O&M cost category rises by 0.6% and 4%. As a separate scenario we also included the transit agency cost of having additional staff on call from increased road calls. However, we found that the extra cost was insignificant and was therefore ignored.

4.4 SENSITIVITY ANALYSIS

Finally, we perform a sensitivity analysis to understand what factor has the highest impact on the replacement age. We compute the elasticity of costs to each factor using the following arc elasticity formula (10) where η_x^c is the elasticity of per mile cost *c* to parameter *x*:

$$\eta_x^c = \frac{(x_1+x_2)/2}{(c_1+c_2)/2} \cdot \frac{\Delta_c}{\Delta_x} = \frac{(x_1+x_2)}{(c_1+c_2)} \cdot \frac{(c_2-c_1)}{(x_2-x_1)} \qquad (10)$$

We also calculate the elasticity of replacement to each parameter assuming a range shown in Table 3 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 was not affected by a gas price increase or increases in fuel economy.

Table 3. Cost and age elasticity

	Diesel price low to high scenario	O&M 0 to 25% increase	Utilization (miles per 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

Decreasing the purchase price had 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 will also decrease 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 an opposite sign as expected. Among the remaining variables, fuel efficiency turned out to have lower cost elasticity than utilization. This indicates that improvements in fuel efficiency go a long way in terms of reducing costs per mile and justifying investments in more fuel-efficient buses.

5.0 FLEET REPLACEMENT OPTIMIZATION WITH MULTIPLE VEHICLE TYPES

5.1 MODEL FORMULATION

The fleet replacement model described in this section aims to provide answers regarding when and what to purchase/replace or salvage/scrap over time as a function of cost and utilization. The goal is to present a model that is parsimonious yet can evaluate the impacts of new vehicle technologies, operational and maintenance costs, and market conditions.

Indexes

Age of a vehicle type k in years: $i \in \boldsymbol{A_k} = \{0, 1, 2, \ldots, A_k\}$
Time periods, decisions are taken at the end of each year: $j \in \boldsymbol{T} = \{0, 1, 2, \ldots, T\}$
Type of vehicle/engine: $k \in \boldsymbol{K} = \{1, 2, \ldots, K\}$

Decision Variables

X_{ijk} = the number of i-year old, k-type vehicles in use from the end of year j to the end of year $j+1$
Y_{ijk} = the number of i-year old, k-type vehicle salvaged at the end of year j
P_{jk} = the number of k-type vehicles purchased at the end of year j

Parameters

(a) Constraints
A_k = maximum age of vehicle type k (it must be salvaged when a vehicle reaches this age)
u_{ik} = utilization (miles traveled by an i-year old, k-type vehicle in one year)
d_j = demand (miles traveled by all types of vehicle) from the end of year j to the end of year $j+1$
b_j = budget (available for purchasing new vehicles) constraint from the end of year j

(b) Costs or revenue
v_k = purchase cost of a k-type vehicle
f_{ik} = fuel economy (mpg) for an i-year old, k-type vehicle
fc_j = fuel price ($/gallon) in year j
om_{ik} = operation and maintenance costs per mile for an i-year old, k-type vehicle
s_{ik} = salvage revenue (negative cost) from selling an i-old, k-type vehicle
ec = emissions cost per ton of GHG
dr_j = discount rate of year j

(c) Emissions
ep_k = production emissions, in GHG equivalent tons, associated to a k-type vehicle
em_{ik} = utilization emissions in GHG equivalent tons per mile for an i-year old, k-type vehicle

(d) Initial conditions
h_{ik} = the number of i-year old, k-type vehicles available at the beginning

Objective Function, minimize:

$$\sum_{j=0}^{T-1}\sum_{k=1}^{K}\left(v_{jk}+ep_{k}ec\right)P_{jk}\left(1+dr_{j}\right)^{-j}+\sum_{i=0}^{N_k-1}\sum_{j=0}^{T-1}\sum_{k=1}^{K}\left(\frac{fc_{j}u_{ik}}{f_{ik}}\right)X_{ijk}\left(1+dr_{j}\right)^{-j}+ \sum_{i=0}^{N_k-1}\sum_{j=0}^{T-1}\sum_{k=1}^{K}om_{ik}u_{ik}X_{ijk}\left(1+dr_{j}\right)^{-j}-\sum_{i=1}^{N_k}\sum_{j=0}^{T}\sum_{k=1}^{K}s_{ik}Y_{ijk}\left(1+dr_{j}\right)^{-j}+ \sum_{i=0}^{N_k-1}\sum_{j=0}^{T-1}\sum_{k=1}^{K}em_{ik}u_{ik}ecX_{ijk}\left(1+dr_{j}\right)^{-j} \quad (11)$$

Subject to:

$$\sum_{k=1}^{K}v_{jk}\cdot P_{jk}\geq b_{j}\forall j\in\{0,1,2,\text{o: u}T-1\} \quad (12)$$

$$\sum_{i=0}^{N_k-1}\sum_{k=1}^{K}X_{ijk}\cdot u_{ik}\geq d_{j}\forall j\in\{0,1,2,\text{o: u}T-1\} \quad (13)$$

$$P_{jk}=X_{0jk}\forall j\in\{1,2,2,T-1\}\forall k\in\mathbf{K} \quad (14)$$

$$P_{0k}+h_{0k}=X_{00k}\forall k\in\mathbf{K} \quad (15)$$

$$X_{i0k}+Y_{i0k}=h_{ik}\forall i\in\{1,2,2,A_{k}\},\forall k\in\mathbf{K} \quad (16)$$

$$X_{(i-1)(j-1)k}=X_{ijk}+Y_{ijk}\forall i\in\{1,2,2,A_{k}\},2j\in\{1,2,2,T\},2k\in\mathbf{K} \quad (17)$$

$$X_{iTk}=0 \qquad i\in\{0,1,2,\text{o: u}A_{k}-1\}\ \forall k\in\mathbf{K} \quad (18)$$

$$X_{A_{k}jk}=0 \qquad j\in\{0,1,2,\text{o: u}T\}\ \forall k\in\mathbf{K} \quad (19)$$

$$Y_{0jk}=0 \qquad j\in\{0,1,2,\ldots,T\}\ \forall k\in\mathbf{K} \quad (20)$$

$$P_{jk},X_{ijk},Y_{ijk}\in\mathbf{I}=\{0,1,2,\ldots\} \quad (21)$$

The objective function, expression (11), minimizes the sum of purchasing, energy (fuel) cost, O&M costs, salvage, and emissions costs over the period of analysis (i.e., from time zero (present) to the end of year T). Purchase costs cannot exceed the yearly budget, expression (12). The number of vehicles in the fleet at any time must equal or exceed the minimum needed to cover the demand in terms of annual number of buses or annual miles traveled, expression (13). The number of vehicles purchased must equal the number of new vehicles for each vehicle type and year, except for the current time, expression (14). The number of new vehicles utilized during year zero must equal the sum of existing new vehicles plus purchased vehicles, expression (15). Similarly, expression (16) ensures the conservation of vehicles (i.e., the initial vehicles—not 0-age ones—must be either used or sold). The age of any vehicle in use will increase by 1 year after each time period (17). At the end of the last time period, there will be no vehicle in use for any age or type of vehicles (i.e., all vehicles will be sold at the corresponding salvage value, which is a function of vehicle type and age) (18). When a vehicle reaches its allowable maximum age, a function of vehicle type, the vehicle must be sold at the corresponding salvage value (19). A newly purchased vehicle should not be sold before use (20). Finally, the decision variables associated with purchasing, utilization and salvaging decisions must be integer positive numbers, expression (21).

5.2 STUDY SETTINGS AND SCENARIOS

Although the model is able to provide the optimal solution for any given set of inputs, the uncertainty associated with the future value of some factors (e.g., fuel prices and maintenance costs) requires several scenarios to be run and studied. All scenarios are based on the analysis of 60-foot diesel and hybrid buses. The scenarios are also employed to highlight the application of the model and key results obtained.

The baseline scenario economic factors are summarized in Table 4. A long planning time horizon of 100 years ($T = 100$) was used to remove the effect of the last incomplete vehicle life cycle and final resale value on average vehicle replacement age. Emissions costs are not considered in the baseline scenarios but will be analyzed in Section 5.4, Sensitivity Analysis.

Table 4. Baseline scenario economic factors

Planning horizon	Nominal annual discount rate	Base Fuel price ($/gal)			Fuel inflation rate	Emission cost ($/ton)	Budget constraint
		Low	Mid	High			
100 years	9.55%	2.64	3.48	4.46	2.6%	0	No constraint

For simplicity in reporting and comparing results, in this paper only two bus technologies (types) are selected to replace existing buses: New Flyer 60-foot hybrid diesel bus ($k = 1$) and New Flyer 60-foot conventional diesel bus ($k = 2$). There are no budget constraints and detailed vehicular characteristics of the two bus types are summarized in Table 5.

Table 5. Baseline scenario vehicular characteristics

Bus type index	Bus type	Max age (years)	Purchase cost ($)	Salvage value ($) i = age	Annual utilization (miles)	Fuel economy (mpg)	Per-mile O&M costs ($/mile)	Tailpipe emissions (kg/mile)
$k = 1$	Hybrid	$A_1 = 20$	$v_1 = 958{,}000$	$s_{i1} = 1000$	$u_{i1} = 33{,}045$	$f_{i1} = 3.65$	$om_{i1} = 1.458 + 0.0661 \cdot i$	$em_{i1} = 2.504$
$k = 2$	Diesel	$A_2 = 20$	$v_2 = 737{,}000$	$s_{i2} = 1000$	$u_{i2} = 33{,}045$	$f_{i2} = 2.50\ or\ 3.32$	$om_{i2} = 1.706 + 0.0463 \cdot i$	$em_{i2} = 3.407$

Utilization data from King County Metro indicate that the hybrid bus fuel economy (FE) is 3.65 mpg and the diesel bus FE can range from 2.50 mpg to 3.50 mpg on average (see Figure 4). From the data it is not possible to tell the route where buses are operated or the amount of rotation among routes. In general, fuel economy does not significantly vary with age, therefore,$f_{i1} = 3.65$mpg for the hybrid and for the diesel bus two FE values are assumed: $f_{i2} = 2.50$ mpg (fleet #28) and $f_{i2} = 3.32$ mpg (fleet #23).

The maximum age is assumed to be 20 years for both buses ($A_1 = A_2 = 20$), because most transit agencies in the U.S. replace their buses in less than the 20-year cycle (Laver et al., 2007). The purchase costs for the two buses are $v_1 = \$958{,}000$ for hybrid bus and $v_2 = \$737{,}000$ for diesel bus, ordering costs and other related costs already included. Also, transit agencies can receive purchase subsidies from the FTA with additional stipulations that must be met. For example, if an 80% purchase cost subsidy is received the bus must be kept for a minimum of 12 years. The salvage values for the two buses are assumed to be $1,000 regardless of bus type or age according to King County Metro's request ($s_{ik} = \$1{,}000, \forall i \in \{1, 2, \ldots, A_k\}$, $\forall k \in \boldsymbol{K}$).

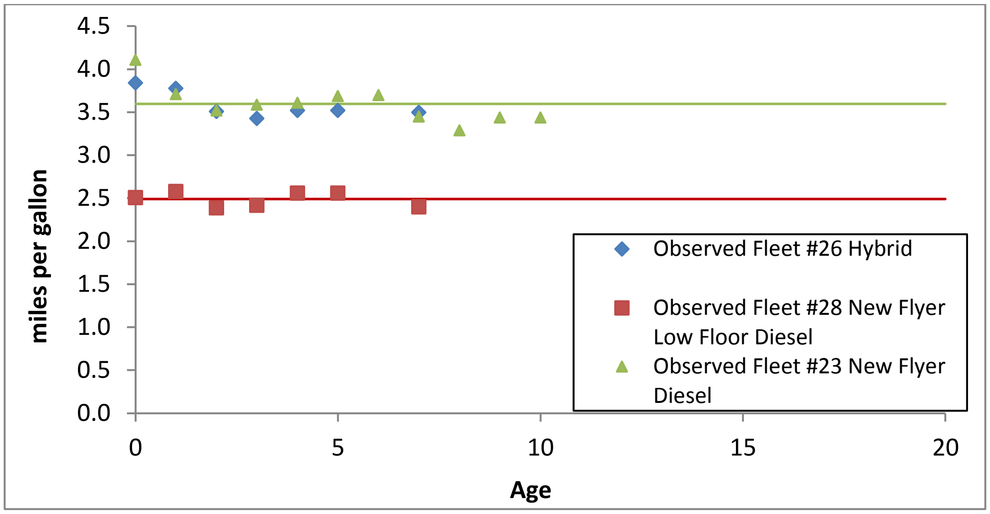


Figure 4. Observed fuel economy

Because the two competing buses are going to serve the same bus routes, their annual utilizations (miles traveled) have to be equal, and this annual utilization does not vary with bus age (u_{ik} =33,045 miles/year according to current fleet data, $\forall i \in \{0, 1, 2, \ldots, A_k - 1\},\ \forall k \in \boldsymbol{K}$). The per-mile O&M costs for the two bus types vary significantly. The baseline scenario uses the per-mile O&M cost functions estimated by King County Metro (2011), $om_{i1} = 1.4580 + 0.0661 \times i$; $om_{i2} = 1.7060 + 0.0463 \times i,\ \forall i \in \{0, 1, 2, \ldots, A_k - 1\}$. Other O&M cost functions will be tested in the Sensitivity Analysis section. Only the tailpipe CO2 emissions are considered in the model, and the generation rates are 2.504 kg/mile for hybrid buses and 3.407 kg/mile for diesel buses, according to Clark et al. (2007). Therefore, $em_{i1} = 2.504\ kg/mi,\ em_{i2} = 3.407\ kg/mi, \forall i \in A_k$.

Initial fleet Composition

It is assumed that in 2014 the existing buses will be replaced with new ones. Therefore, these buses will be salvaged for certain by 2014, and their replacement cycles are not decision variables anymore. The initial fleet composition in year 2014 is equivalent to no initial buses ($h_{ik} = 0, \forall i \in \{0, 1, 2, \ldots, A_k - 1\},\ \forall k \in \boldsymbol{K}$).

Key Research Questions

If it is assumed that in 2014 the existing buses will be replaced with new ones, the problem thus becomes: Should King County Metro buy a 60-foot hybrid bus or a conventional 60-foot diesel bus? What will be the optimal replacement cycle? Also, because King County Metro assumes a homogeneous bus fleet and no budget constraints, a group of buses that are purchased together have to be used and salvaged together. Therefore, instead of optimizing for the actual number of buses in a fleet, a constant number of buses is set to one ($d_j = 1, \forall j \in \{0, 1, 2, \ldots, T - 1\}$), and results are presented on a per-bus basis.

5.3 SCENARIO RESULTS

Baseline scenario results

The baseline scenarios include 12 scenarios: three fuel price functions, two levels of subsidies (0% and 80%), and two diesel bus FE (3.32 and 2.50 mpg); all other parameters are kept constant. The optimal replacement solutions for each of the six baseline scenarios are summarized and shown in Table 6 and Table 7, respectively, for diesel fuel efficiency 3.32 and 2.50 mpg.

The five cost components and their sum (total cost) are shown explicitly as annual costs (average over the first 20 years) with both discounted annualized costs and not-discounted annualized costs; the discounted and not-discounted per-mile costs are also shown. Note that the discounted annualized costs are much smaller than the not-discounted costs due to the impact of the discount rate. Also, the percentage-cost breakdown of the five cost components is different between discounted and not-discounted annualized costs because of the different timing and combined effects of discount rate, fuel inflation rate and planning time horizon. The optimal solutions are to minimize the total discounted sum of all the cost components (minimize net present value). The optimal replacement decisions are shown in the first rows.

If no purchase cost subsidy is received, the optimal solution is to purchase diesel buses and replace them every 20 years (maximum age) with the exception of high fuel costs and low diesel fuel efficiency. If an 80% purchase cost subsidy can be received, the optimal solution switched to purchasing hybrid buses and replacing them every 16 years in all cases. These results indicate that government subsidy levels affect the optimal replacement solution significantly. This is because when no subsidy is received, purchase cost dominates other cost components. The savings from lower fuel costs and O&M costs cannot compensate for the high purchase cost of a hybrid bus. On the other hand, if an 80% purchase subsidy is received, the purchase cost drops significantly and savings in fuel cost and O&M costs from choosing hybrid buses outweigh their higher purchase cost. The subsidy affects the optimal replacement age in a similar way. A low subsidy tends to extend the optimal replacement age whereas low capital cost tends to shorten the replacement cycle. These results also show that fuel price has no effect on the optimal replacement solutions unless there is an scenario that combines low diesel fuel efficiency and high fuel prices. The reduction in CO_2 emissions is proportional to the reduction in fuel consumption.

Table 6. Baseline scenarios optimal replacement results (diesel 3.32 mpg and first 20 years)

Purchase subsidy	0%			80%		
Fuel price	Low	Mid	High	Low	Mid	High
Optimal Bus Type	Diesel	Diesel	Diesel	Hybrid	Hybrid	Hybrid
Hybrid replacement age	-	-	-	16	16	16
Diesel replacement age	20	20	20	-	-	-
Discounted annualized costs						
Total cost($)	83,969	88,782	94,397	54,263	58,641	63,748
Purchase cost($)	36,850	36,850	36,850	11,806	11,806	11,806
Fuel cost($)	15,126	19,939	25,555	13,759	18,137	23,244
O&M cost($)	31,992	31,992	31,992	28,710	28,710	28,710
CO2 cost($)	0	0	0	0	0	0
Salvage revenue($)	0	0	0	-12	-12	-12
Per-mile discounted cost($/mile)	2.541	2.687	2.857	1.642	1.775	1.929
Not-discounted annualized costs						
Total cost($)	141,666	152,453	165,037	111,889	121,701	133,148
Purchase cost($)	36,850	36,850	36,850	19,160	19,160	19,160
Fuel cost($)	33,901	44,688	57,273	30,836	40,648	52,095
O&M cost($)	70,915	70,915	70,915	61,943	61,943	61,943
CO2 cost($)	0	0	0	0	0	0
Salvage revenue($)	0	0	0	-50	-50	-50
Not-discounted per-mile cost($/mile)	4.287	4.613	4.994	3.386	3.683	4.029
Annual fuel (gallons)	9,953	9,953	9,953	9,053	9,053	9,053
Annual CO2 (tons)	110	110	110	100	100	100
Annual miles	33,045	33,045	33,045	33,045	33,045	33,045

Table 7. Baseline scenarios optimal replacement results (diesel 2.5 mpg and first 20 years)

Purchase subsidy	0%			80%		
Fuel price	Low	Mid	High	Low	Mid	High
Optimal Bus Type	Diesel	Diesel	Hybrid	Hybrid	Hybrid	Hybrid
Hybrid replacement age	-	-	20	16	16	16
Diesel replacement age	20	20	-	-	-	-
Discounted annualized costs						
Total cost($)	88,930	95,322	101,278	54,263	58,641	63,748
Purchase cost($)	36,850	36,850	47,900	11,806	11,806	11,806
Fuel cost($)	20,088	26,480	23,244	13,759	18,137	23,244
O&M cost($)	31,992	31,992	30,134	28,710	28,710	28,710
CO2 cost($)	0	0	0	0	0	0
Salvage revenue($)	0	0	0	-12	-12	-12
Per-mile discounted cost($/mile)	2.691	2.885	3.065	1.642	1.775	1.929
Not-discounted annualized costs						
Total cost($)	152,786	167,111	168,927	111,889	121,701	133,148
Purchase cost($)	36,850	36,850	47,900	19,160	19,160	19,160
Fuel cost($)	45,021	59,346	52,095	30,836	40,648	52,095
O&M cost($)	70,915	70,915	68,932	61,943	61,943	61,943
CO2 cost($)	0	0	0	0	0	0
Salvage revenue($)	0	0	0	-50	-50	-50
Not-discounted per-mile cost($/mile)	4.624	5.057	5.112	3.386	3.683	4.029
Annual fuel (gallons)	13,218	13,218	9,053	9,053	9,053	9,053
Annual CO2 (tons)	147	147	147	100	100	100
Annual miles	33,045	33,045	33,045	33,045	33,045	33,045

5.4 SENSITIVITY ANALYSIS

Although the model is able to provide the optimal solution given a set of input variables, the variability and uncertainty of the input variables requires additional sensitivity analysis to understand how optimal solutions are affected by changes in each of the input variables. Holding input variables in the baseline scenarios constant, we evaluate the effects of each input variable on the optimal replacement solution: optimal choice of bus type and replacement age, as well as per-mile net cost, respectively. Only the medium fuel price was used in this sensitivity analysis.

Fuel economy

According to the data provided by King County Metro, the 60-foot New Flyer hybrid bus fuel economy varies slightly between 3.50 mpg and 3.75 mpg. However, the 60-foot New Flyer diesel bus fuel economy varies significantly between 2.40 mpg and 3.40 mpg; the high fuel efficiency is achieved in some routes with favorable conditions such as flat terrain and less congestion or stops. Therefore, to investigate the impact of relative fuel economies between diesel and hybrid buses, different fuel economies for both diesel and hybrid buses were tested within ranges that cover the observed fuel economy records. Sensitivity results are summarized in Table 8 and Table 9. Diesel bus fuel economy ranges from 2.0 mpg to 3.0 mpg with 0.1 mpg interval. Hybrid bus fuel economy ranges from 3.15 mpg to 4.15 mpg with 0.1 mpg interval.

Table 8 and Table 9 show how optimal replacement solutions change with varying diesel and hybrid bus fuel economies in both 0% and 80% subsidy scenarios. The "number+letter" in the table indicates what replacement age and bus type is optimal. For example, "16H" indicates that the optimal solution is to choose a hybrid bus and replace it every 16 years. It is noticeable that in all cases the replacement ages do not change considerably although the bus type can change. There is a frontier or combination of low hybrid fuel efficiency and high diesel fuel efficiency where the optimal bus type changes (and vice versa). For example, if diesel fuel efficiency is lower than 2.4 miles per gallon then hybrids are always the best option (0% subsidy level); if hybrid fuel efficiency is higher than 3.45 miles per gallon then hybrids are always the best option (80% subsidy level).

Table 8. Impacts of diesel bus fuel economy on optimal replacement plan (diesel FE 3.32 mpg)

Diesel FE (mpg) Hybrid FE: 3.65 mpg	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D
80% subsidy	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H
Hybrid FE (mpg) Diesel FE: 3.32 mpg	3.15	3.25	3.35	3.45	3.55	3.65	3.75	3.85	3.95	4.05	4.15
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D
80% subsidy	17D	17D	17D	16H	16H	16H	16H	16H	16H	16H	16H

Table 9. Impacts of diesel bus fuel economy on optimal replacement plan (diesel FE 2.50 mpg)

Diesel FE (mpg) Hybrid FE: 3.65 mpg	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
0% subsidy	20H	20H	20H	20H	20H	20D	20D	20D	20D	20D	20D
80% subsidy	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H
Hybrid FE (mpg) Diesel FE: 2.50 mpg	3.15	3.25	3.35	3.45	3.55	3.65	3.75	3.85	3.95	4.05	4.15
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20H	20H	20H	20H
80% subsidy	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H	16H

Annual utilization

Historical data provided by King County Metro indicated that the average annual utilization ranges between 28,379 miles and 39,679 miles per bus. Therefore, to investigate whether and how annual utilization affects the optimal replacement solutions, 11 different annual utilizations are tested from 28,379 miles/year/bus to 39,679 miles/year/bus with an equal incremental interval of 1,130 miles/year/bus. Results are shown in Table 10.

Table 10. Impacts of annual utilization on optimal replacement plan (diesel FE 3.32 mpg)

Annual utilization (miles/year/bus)	28,379	29,509	30,639	31,769	32,899	34,029	35,159	36,289	37,419	38,549	39,679
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D	20D
80% subsidy	18H	17H	17H	16H	16H	16H	15H	15H	15H	15H	14H

Table 11. Impacts of annual utilization on optimal replacement plan (diesel FE 2.50 mpg)

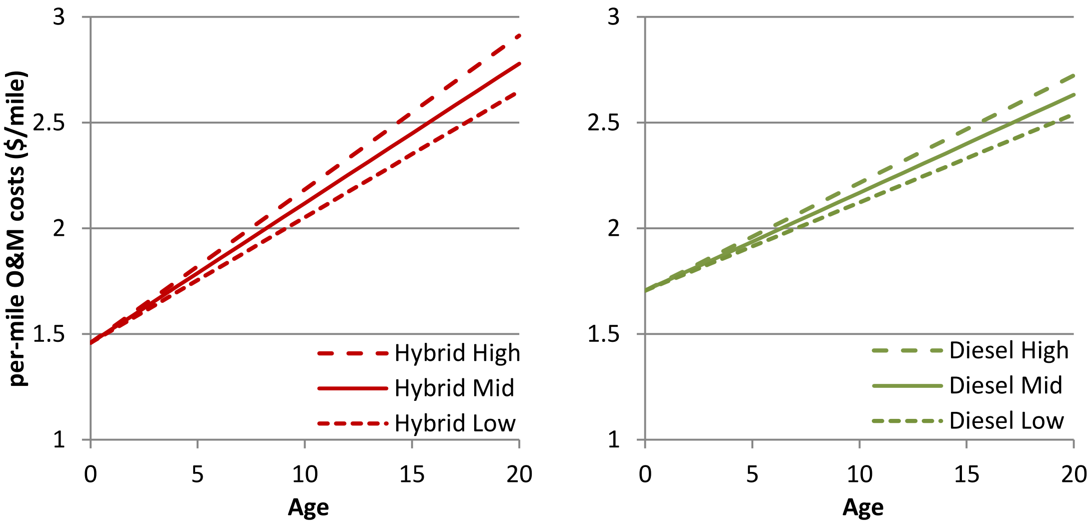
Annual utilization (miles/year/bus)	28,379	29,509	30,639	31,769	32,899	34,029	35,159	36,289	37,419	38,549	39,679
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20H	20H	20H	20H
80% subsidy	18H	17H	17H	16H	16H	16H	15H	15H	15H	15H	14H

Results from Table 10 and Table 11 indicate a general trend that as annual utilization increases hybrid buses are more favorable because savings from fuel and O&M costs compensate for the higher capital costs. In the 80% subsidy scenario the optimal solution is always to buy hybrid buses, but the optimal replacement cycle decreases from 18 years to 14 years as annual utilization increases from 28,375 miles per year to 39,679 miles per year. In the 0% subsidy scenario, the optimal bus choice depends on the annual utilization level and diesel fuel economy. The hybrid bus becomes the best option with utilization levels above 36,000 miles and low diesel fuel economy.

Linear O&M Costs

Per-mile O&M costs as a function of age are the most difficult cost functions to estimate or forecast because of the high variance among buses and the lack of data for older buses (more than 12 years old). Therefore, average values for hybrid and diesel buses are used and linear extrapolations are assumed to predict the per-mile O&M costs as a function of age. Although the historical data has shown a linear behavior so far on the aggregate (see Appendixes A, B, and C) it is essential to ensure that the linearity assumptions hold into the future.

The variance between buses is represented by two additional per-mile O&M cost functions that are lower and higher than their average functions. As shown in Figure 5 (a) and (b), the solid lines represent the "Mid" functions, which are the baseline per-mile O&M cost functions. The two dashed lines represent "High" and "Low" per-mile O&M cost functions. In the sensitivity analysis the intercepts for the three functions are the same for each bus type, but the slopes of "Low" and "High" functions are 10% lower and higher than their "Mid" per-mile O&M cost function slopes. This generates nine scenarios. Each of the nine scenarios for each diesel bus fuel economy (18 scenarios total) is tested to investigate the impact of relative per-mile O&M cost functions on the optimal replacement solution. Results are shown in Table 12 and Table 13.



(a) Hybrid bus **(b) Diesel bus**

Figure 5. Per-mile O&M cost functions

Without subsidies, the optimal replacement solution is to always choose diesel buses and replace them every 20 years except for the one combination of low hybrid O&M and high diesel per-mile O&M (for both high and low diesel fuel economy). On the other hand, when the 80% purchase subsidy is received the optimal candidate is always the hybrid bus and the optimal replacement cycle increases from 15 years to 17 years as the per-mile O&M cost function slope decreases (negative correlation). The results indicate that within these ranges of per-mile O&M, the relative slopes affect the optimal bus type choice but not the optimal replacement cycle in the 0% subsidy scenario. On the other hand, the relative slopes affect the optimal replacement cycle but not the optimal bus type in the 80% subsidy scenario.

Table 12. Impacts of O&M cost function slopes (diesel FE 3.32 mpg)

Hybrid slope	High	High	High	Mid	Mid	Mid	Low	Low	Low
Diesel slope	Low	Mid	High	Low	Mid	High	Low	Mid	High
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20D	20H
80% subsidy	15H	15H	15H	16H	16H	16H	17H	17H	17H

Table 13. Impacts of O&M cost function slopes (diesel FE 2.50 mpg)

Hybrid slope	High	High	High	Mid	Mid	Mid	Low	Low	Low
Diesel slope	Low	Mid	High	Low	Mid	High	Low	Mid	High
0% subsidy	20D	20D	20D	20D	20D	20D	20D	20D	20H
80% subsidy	15H	15H	15H	16H	16H	16H	17H	17H	17H

Non-Linear O&M Costs

To test the impact of more concentrated major maintenance costs distributions we follow the distribution curves provided by a FTA report (Laver et al., 2007), which are shown in Figure 6 (unfortunately, there is more information for 40-foot buses). These two additional, combined, nonlinear, per-mile, maintenance cost functions are shown in Figure 7 as the dotted blue and black lines. Only a diesel bus with 3.32 mpg and medium fuel prices is analyzed in this section.

Results indicated that without FTA support, different shapes of maintenance cost functions have no impact on the optimal replacement age. When the 80% FTA support is applied, the optimal replacement time does change. Diesel bus optimal replacement age varies across different maintenance cost functions. In both cases, the concentrated peaks and optimal replacement ages are close to each other (17 and 13 years, respectively). This indicated that with an 80% subsidy, it is very important to determine the maintenance cost peaks since they do impact the optimal replacement age.

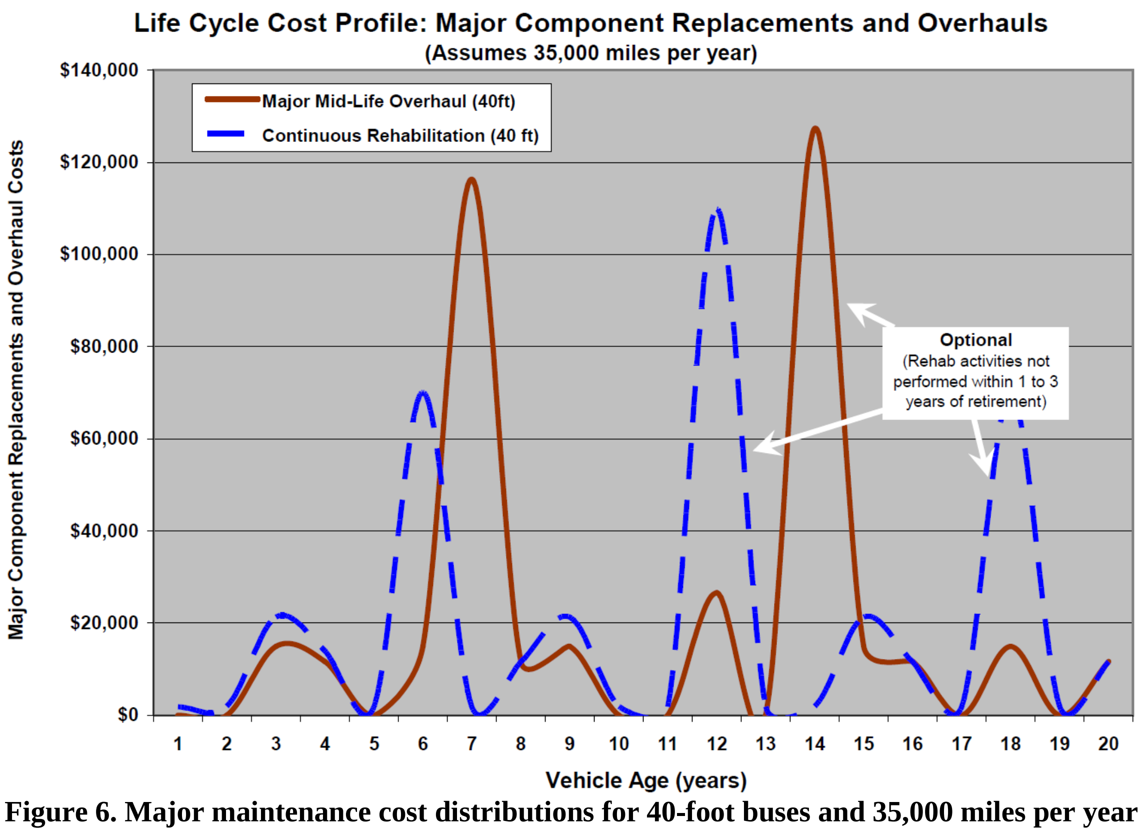


Figure 6. Major maintenance cost distributions for 40-foot buses and 35,000 miles per year utilization

Source: Laver et al., 2007

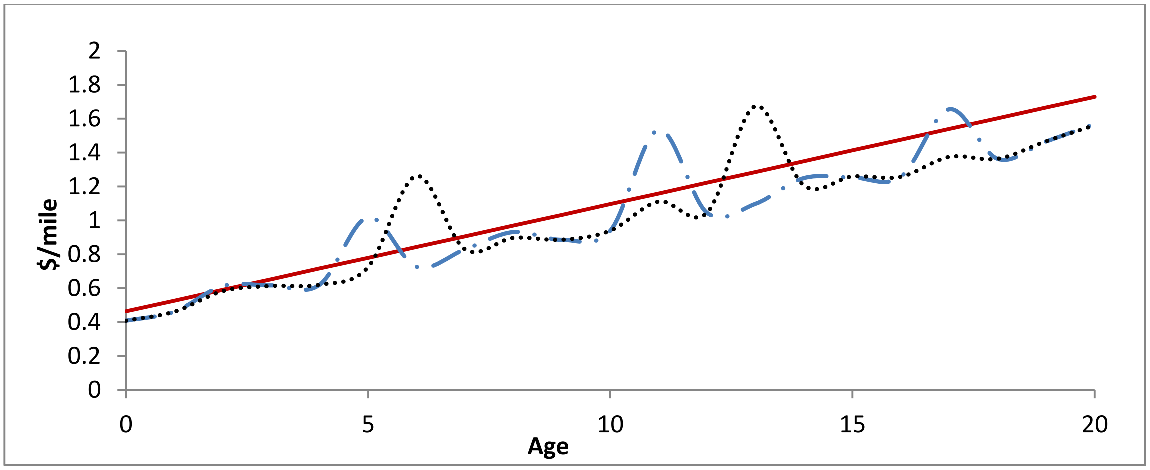


Figure 7. Nonlinear, per-mile, maintenance cost functions

Capital purchase cost

The capital cost of purchasing new buses may vary due to market fluctuations, technology improvements and purchase quantity. It has also been shown in the baseline scenario results (Table 6) that purchase costs share a large percentage of the total life cycle costs. Therefore, it is necessary to evaluate how sensitive the optimal replacement plan is in response to varying capital purchase costs. Twenty percent under and over the current purchase cost for diesel and hybrid buses is tested, and results are shown in Table 14 and Table 15.

Results are consistent. With no purchase cost subsidy the replacement age is always 20 years, but a 10% reduction in prices tips the balance. If purchase costs for *both* hybrid and diesel buses are reduced by at least 10%, hybrid buses are the best choice. With an 80% subsidy level, the optimal bus is always the hybrid bus but the replacement age is reduced as the purchase price decreases.

Table 14. Impacts of capital purchase cost on optimal replacement plan (diesel FE 3.32 mpg)

Capital cost percent change	-20%	-15%	-10%	-5%	0%	5%	10%	15%	20%
0% subsidy	20H	20H	20H	20D	20D	20D	20D	20D	20D
80% subsidy	14H	15H	15H	16H	16H	16H	17H	18H	18H

Table 15. Impacts of capital purchase cost on optimal replacement plan (diesel FE 2.50 mpg)

Capital cost percent change	-20%	-15%	-10%	-5%	0%	5%	10%	15%	20%
0% subsidy	20H	20H	20H	20D	20D	20D	20D	20D	20D
80% subsidy	14H	15H	15H	16H	16H	16H	17H	18H	18H

CO2 emissions

The CO2 emissions costs are not considered in the baseline scenarios. In order to test whether CO2 emissions have a significant impact on optimal solutions, a $30/ton CO2 emissions cost (suggested by King County Metro) was added to the model objective functions. Results are shown in Table 16 and Table 17. Results show that CO2 emissions costs are a small part of total costs in both 0% and 80% scenarios. With a $30/ton CO2 emissions cost, the optimal bus candidate and replacement cycle are the same as in the baseline scenario where CO2 emissions penalty costs are not considered. Results indicate that this CO_2 emissions cost has no impact on optimal replacement policies.

However, with a $100/ton CO_2 emissions cost plus low diesel FE, it is optimal to buy hybrids with the same replacement cycle as in the baseline scenario where CO_2 emissions penalty costs are not considered. As mentioned later in the breakeven analysis section, a $60/ton or higher CO_2 emissions cost tips the balance in favor of hybrid buses.

Table 16. First 20-year results after including CO2 emissions costs (diesel FE 3.32 mpg)

Subsidy	0%		80%	
CO2 penalty cost ($/ton)	100	30	100	30
Discounted annualized				
Total cost ($)	90,371	94,027	60,072	63,410
Purchase cost ($)	36,850	36,850	11,806	11,806
Fuel cost ($)	19,939	19,939	18,137	18,137
O&M cost ($)	31,992	31,992	28,710	28,710
CO2 cost ($)	1,590	5,245	1,431	4,769
Salvage revenue ($)	0	0	-12	-12
Per-mile net cost ($/mile)	2.735	2.845	1.818	1.919
Not discounted annualized				
Total cost ($)	155,757	163,358	124,675	131,614
Purchase cost ($)	36,850	36,850	19,160	19,160
Fuel cost ($)	44,688	44,688	40,648	40,648
O&M cost ($)	70,915	70,915	61,943	61,943
CO2 cost ($)	3,305	10,905	2,974	9,914
Salvage revenue ($)	0	0	-50	-50
Not discounted per-mile cost ($/mile)	4.713	4.943	3.773	3.983
Fuel (gallons)	9,953	9,953	9,053	9,053
CO2 (tons)	110	110	100	100
Miles	33,045	33,045	33,045	33,045
Hybrid replacement age	-	-	16	16
Diesel replacement age	20	20	-	-

Table 17. First 20-year results after including CO2 emissions costs (diesel FE 2.50 mpg)

Subsidy	0%		80%	
CO2 penalty cost ($/ton)	100	30	100	30
Discounted annualized				
Total cost ($)	97,388	100,939	60,072	63,410
Purchase cost ($)	36,850	47,900	11,806	11,806
Fuel cost ($)	26,480	18,137	18,137	18,137
O&M cost ($)	31,992	30,134	28,710	28,710
CO2 cost ($)	2,066	4,769	1,431	4,769
Salvage revenue ($)	0	0	-12	-12
Per-mile net cost ($/mile)	2.947	3.055	1.818	1.919
Not discounted annualized				
Total cost ($)	171,406	167,393	124,675	131,614
Purchase cost ($)	36,850	47,900	19,160	19,160
Fuel cost ($)	59,346	40,648	40,648	40,648
O&M cost ($)	70,915	68,932	61,943	61,943
CO2 cost ($)	4,296	9,914	2,974	9,914
Salvage revenue ($)	0	-50	0	-50
Not discounted per-mile cost ($/mile)	5.187	5.066	3.773	3.983
Fuel (gallons)	13,218	9,053	9,053	9,053
CO2 (tons)	147	100	100	100
Miles	33,045	33,045	33,045	33,045
Hybrid replacement age	-	20	16	16
Diesel replacement age	20	-	-	-

Initial age and bus type

The baseline scenarios assume that there are no existing buses. However, it is interesting to evaluate scenarios with an existing fleet of buses of different ages. Scenarios with different initial fleet compositions (types and ages) are also tested. The initial fleet composition is assumed to be one bus, hybrid or diesel bus, with any of the following six ages: 3, 6, 9, 12, 15, and 18. Results for the 24 scenarios are shown in Table 18 and Table 19.

Results indicate that initial age has little impact on replacement age or optimal bus type. In the 80% subsidy scenario, if the initial bus is a hybrid, the optimal solution will be to keep using the hybrid bus and replace it every 16 years. If the initial bus is diesel, the optimal solution will be to keep using the diesel bus until it reaches age 12 (or age 15 or 18 if the initial diesel bus age is already 15 or 18), and then replace it with a hybrid bus every 16 years in all future years in the time horizon. In the 80% subsidy case, the optimal bus is the hybrid; even if the initial bus is a diesel, there is always a reversion towards the optimal policy. In the 0% subsidy scenario the opposite takes place.

Table 18. Impacts of initial fleet composition on optimal replacement plan (80% subsidy)

Diesel FE (mpg)	2.50 mpg						3.32 mpg					
Initial bus age (Hybrid)	3	6	9	12	15	18	3	6	9	12	15	18
Hybrid replacement age	16	16	16	16	16	18	16	16	16	16	16	18
Diesel replacement age	-	-	-	-	-	-	-	-	-	-	-	-
Initial bus age (Diesel)	3	6	9	12	15	18	3	6	9	12	15	18
Hybrid replacement age	16	16	16	16	16	18	16	16	16	16	16	18
Diesel replacement age	*12*	*12*	*12*	*12*	*15*	*18*	*15*	*15*	*15*	*15*	*15*	*18*

(in *italics* a one-time replacement)

Table 19. Impacts of initial fleet configuration on optimal replacement plan (0% subsidy)

Diesel FE (mpg)	2.50 mpg						3.32 mpg					
Initial bus age (Hybrid)	3	6	9	12	15	18	3	6	9	12	15	18
Hybrid replacement age	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*
Diesel replacement age	20	20	20	20	20	20	20	20	20	20	20	20
Initial bus age (Diesel)	3	6	9	12	15	18	3	6	9	12	15	18
Hybrid replacement age	-	-	-	-	-	-	-	-	-	-	-	-
Diesel replacement age	20	20	20	20	20	20	20	20	20	20	20	20

(in *italics* a one-time replacement)

Elasticity

The previous section focuses on the impacts of fuel economy, annual utilization, O&M costs, capital purchase costs, CO2 emissions costs and initial age and bus type on the optimal replacement plan. It is also necessary to analyze which input variable has the highest impact on the optimal per-mile net cost. Elasticity of per-mile net cost to each of the above input factors was calculated according to formula 12.

Elasticity values for the cost per miles are summarized in Table 20. For example, with an annual utilization range between 28,379 miles/year/bus and 39,679 miles/year/bus, each additional 1% increase in annual utilization decreases 0.41% per-mile net cost (0% subsidy scenario) or decreases 0.17% (80% subsidy scenario). Results show that a nominal annual discount rate and a utilization rate have the highest absolute cost-per-mile elasticity values. Elasticity values for the Net Present Value (NPV) are summarized in Table 21. For example, with an annual utilization range between 28,379 miles/year/bus and 39,679 miles/year/bus, each additional 1% increase in annual utilization increases the NPV 0.59% per-mile net cost (0% subsidy scenario) and 0.78% (80% subsidy scenario). Results show that annual utilization, nominal annual discount rate, and vehicle purchase price have the highest absolute NPV elasticity values.

An elasticity value is significant when the output variable changes significantly (in this case, the output variables are cost per mile and net present value).

Table 20. Elasticity between various input variables and per-mile net cost (diesel 3.32 mpg)

Factors	0% subsidy	80% subsidy
Vehicle Factors		
Diesel bus mpg (2.5 – 3.3)	-0.24	0.00
Hybrid bus mpg (3.15 – 4.15)	0.00	-0.26
Diesel bus O&M cost function slope ($0.0417/mi/year – $0.0509/mi/year)	0.06	0.00
Hybrid bus O&M cost function slope ($0.0595/mi/year – $0.0727/mi/year)	0.00	0.09
Diesel bus price ($589,600 – $737,000)	0.38	0.00
Hybrid bus price ($766,400 – $958,000)	0.13	0.17
General Factors		
Annual utilization (28,379 miles/year – 39,679 miles/year)	-0.41	-0.17
CO2 emissions penalty cost ($0/ton – $100/ton)	0.03	0.03
Fuel price ($2.64/gallon – $4.46/gallon)	0.25	0.35
Fuel inflation rate (0% – 5%)	0.09	0.13
Nominal annual discount rate (5% – 15%)	-0.85	-1.01

Table 21. Elasticity between various input variables and 20-year NPV (diesel 2.50 mpg)

Factors	0% subsidy	80% subsidy
Vehicle Factors		
Diesel bus mpg (2.0 – 3.0)	0.00	-0.16
Hybrid bus mpg (3.15 – 4.15)	-0.05	-0.31
Diesel bus O&M cost function slope ($0.0417/mi/year – $0.0509/mi/year)	0.01	0.02
Hybrid bus O&M cost function slope ($0.0595/mi/year – $0.0727/mi/year)	0.01	0.03
Diesel bus price ($589,600 – $737,000)	0.36	0.00
Hybrid bus price ($766,400 – $958,000)	0.43	0.21
General Factors		
Annual utilization (28,379 miles/year – 39,679 miles/year)	0.59	0.78
CO2 emissions penalty cost ($0/ton – $30/ton)	0.01	0.01
Fuel price ($2.64/gallon – $4.46/gallon)	0.25	0.31
Fuel inflation rate (0% – 5%)	0.05	0.06
Nominal annual discount rate (5% – 15%)	-0.38	-0.55

Breakeven analysis

With an 80% FTA subsidy the best policy is to buy hybrid buses. However, there is a breakeven value for each subsidy level and a combination fuel price-diesel FE. The breakeven subsidy values are calculated for the three fuel price scenarios and two diesel fuel efficiencies. Results are shown in Table 22 and Table 23. For example, with the mid fuel price forecast functions (initial value $3.48/gal), it is more economical to buy a hybrid bus if the purchase cost subsidy is more than 7% and the diesel bus fuel economy is 2.50 mpg. It is more economical to buy a diesel bus if the subsidy is less than 7%, with all other variables held constant as in the baseline scenario. Results show that higher fuel prices favor the hybrid bus and, therefore, fewer subsidies are required to break even, especially if the diesel fuel economy is low. When the fuel price is $4.46/gallon and diesel FE is 2.50 mpg, even without a subsidy the hybrid bus is the best option.

Since diesel buses are the best option without the government subsidy, the breakeven values in Table 24 and Table 25 indicate what condition or value must be reached. For example, with 0% subsidy, if the diesel bus fuel economy is less than or equal to 2.43 mpg compared to the hybrid bus baseline fuel economy of 3.65 mpg, the optimal solution will be to choose the hybrid bus. If the bus annual utilization is higher than 35,794 miles/year/bus, it will be cost effective to adopt hybrid buses. All of these breakeven values are also consistent with the findings shown in previous subsections. These breakeven values are not too far from the baseline values, indicating that the two bus technologies are very competitive without a government subsidy.

Table 22. Breakeven values of government subsidies (diesel FE 3.32 mpg)

fuel price ($/gallon)	2.64	3.48	4.46
subsidy breakeven value	72%	69%	66%

Table 23. Breakeven values of government subsidies (diesel FE 2.50 mpg)

fuel price ($/gallon)	2.64	3.48	4.46
subsidy breakeven value	26%	7%	0%

Table 24. Breakeven values for 0% subsidy scenario (diesel FE 3.32 mpg)

Factors	Baseline values	Breakeven values
Vehicular factors		
Diesel bus mpg	3.32	≤ 2.43
Hybrid bus mpg	3.65	≥ 6.16
Diesel bus per-mile O&M cost function slope	0.0436	≥ 0.1155
Hybrid bus per-mile O&M cost function slope	0.0661	≤ inf.
Diesel bus purchase cost ($)	737,000	≥ 882,784
Hybrid bus purchase cost ($)	958,000	≤ 812,215
General factors		
Annual utilization (miles/bus)	33,045	≥ 97,093
Fuel price ($/gal)	3.48	≥ 17.88
Fuel inflation rate	2.6%	≥ 20.9%
CO2 emissions penalty cost ($/ton)	0	≥ 506
Nominal annual discount rate	9.55%	≤ inf.
Planning time horizon (years)	100	≥ inf.

inf. means infeasible, there is no realistic value of the parameter that can change the optimal solution

Table 25. Breakeven values for 0% subsidy scenario (diesel FE 2.50 mpg)

Factors	Baseline values	Breakeven values
Vehicular factors		
Diesel bus mpg	2.5	≤ 2.43
Hybrid bus mpg	3.65	≥ 3.83
Diesel bus per-mile O&M cost function slope	0.0436	≥ 0.0543
Hybrid bus per-mile O&M cost function slope	0.0661	≤ 0.058
Diesel bus purchase cost ($)	737,000	≥ 753,972
Hybrid bus purchase cost ($)	958,000	≤ 941,028
General factors		
Annual utilization (miles/bus)	33,045	≥ 35,794
Fuel price ($/gal)	3.48	≥ 3.83
Fuel inflation rate	2.6%	≥ 4%
CO2 emissions penalty cost ($/ton)	0	≥ 60
Nominal annual discount rate	9.55%	≤ 8.22%
Planning time horizon (years)	100	≥ inf.

Table 26. Breakeven values for 80% subsidy support scenario (diesel FE 3.32 mpg)

Factors	Baseline values	Breakeven values
Vehicular factors		
Diesel bus mpg	3.32	≥ 3.60
Hybrid bus mpg	3.65	≤ 3.36
Diesel bus per-mile O&M cost function slope	0.0436	≤ 0.0299
Hybrid bus per-mile O&M cost function slope	0.0661	≥ 0.0852
Diesel bus purchase cost ($)	737,000	≤ 593,075
Hybrid bus purchase cost ($)	958,000	≥ 1,107,625
General factors		
Annual utilization (miles/bus)	33,045	≤ 19,418
Fuel price ($/gal)	3.48	≤ inf.
Fuel inflation rate	2.6%	≤ inf.
CO2 emissions penalty cost ($/ton)	0	≤ inf.
Nominal annual discount rate	9.55%	≥ 27.25%
Planning time horizon (years)	100	≤ 2

Table 27. Breakeven values for 80% subsidy support scenario (diesel FE 2.50 mpg)

Factors	Baseline values	Breakeven values
Vehicular factors		
Diesel bus mpg	2.5	≥ 3.59
Hybrid bus mpg	3.65	≤ 2.52
Diesel bus per-mile O&M cost function slope	0.0436	≤ inf.
Hybrid bus per-mile O&M cost function slope	0.0661	≥ 0.1724
Diesel bus purchase cost ($)	737,000	≤ 106,193
Hybrid bus purchase cost ($)	958,000	≥ 1,724,808
General factors		
Annual utilization (miles/bus)	33,045	≤ inf.
Fuel price ($/gal)	3.48	≤ inf.
Fuel inflation rate	2.6%	≤ inf.
CO2 emissions penalty cost ($/ton)	0	≤ inf.
Nominal annual discount rate	9.55%	≥ inf.
Planning time horizon (years)	100	≤ inf.

As shown in Table 26 and Table 27, with an 80% subsidy the hybrid bus easily dominates and the breakeven values are hard to achieve or are mostly unrealistic. For example, diesel bus fuel economy should be greater than 3.59 mpg when the hybrid bus fuel economy is 3.65 mpg. If the annual utilization is less than 19,418 miles/year/bus (unrealistically low), it will be cost effective to adopt diesel buses. Even if the fuel price is as low as 0, the diesel bus will not be chosen in the optimal solution. These results indicate that hybrid buses clearly outperform diesel buses if an 80% subsidy can be received. The breakeven values above indicate to what extent each factor itself can change optimal vehicle type. When breakeven values are unrealistic or infeasible, the optimal solution for this scenario is highly stable and robust (in this case 80% subsidy level and 2.50 mpg diesel FE).

6.0 CONCLUSIONS

Budget-constrained transit agencies have challenges to minimize total fleet costs. 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.

Changing vehicle prices, utilization levels, and operations and maintenance costs have been shown to not only change total per mile costs of fleet operation, but also 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 importance or even the necessity of transit agencies to receive FTA's bus purchase subsidy. Diesel prices and internalizing CO_2 emissions costs have significant impacts on total costs but not on 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 of less frequent emissions costs associated with manufacturing. In addition, elasticities are useful to understand how changes in market and fleet conditions impact 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.

The case study of hybrid diesel vs. conventional diesel indicates that the bus purchase cost subsidy has a significant impact on optimal bus type choice and its replacement age. Without a purchase cost subsidy, the optimal solution is to choose diesel buses and replace them every 20 years. Sensitivity and breakeven analyses results indicate that the optimal solution is not sensitive to any of the input parameters within the evaluated ranges except when the relative purchase cost difference between diesel and hybrid bus is larger than 10%. With the maximum purchase cost subsidy allowed in the USA (80%), the optimal solution is to choose hybrid buses and replace them every 14 years. In addition, in the 80% subsidy case the optimal solution is more sensitive to input parameters. Several findings from the sensitivity and breakeven analyses include: 1) when the base-year fuel price is less than $2.79/gal, or hybrid bus fuel economy is more than 35% higher than the diesel bus, the optimal solution is the diesel bus; 2) annual utilization, annual discount rate, fuel inflation rate and CO2 emissions penalty cost have no impact on the optimal solution within realistic ranges; and 3) higher utilizations or hybrid bus purchase cost decreases with optimal replacement ages from 15 years to 12 years. The breakeven value of the government subsidy indicates that hybrid buses will not be selected by optimal policies unless the subsidy is equal to or greater than 63%, holding all other input parameters constant.

Although the models are general and can be applied to any transit agency, the data utilized is valid for King County Metro and the years of data provided (11 years of data for fleet 23 and seven years of data for fleets 26 and 28). King County Transit, or any agency that wants to make fleet replacement decisions, must annually update fuel price forecasts, utilization, fuel economy, and maintenance cost data records and forecasts. Hybrid and diesel bus fuel economy must be representative of the type of route and operating conditions. A wide range of fuel economies was observed in the historical data.

It is particularly important to keep track or forecast major maintenance cost distributions and their peaks. The following codes were detected: engine system, transmission, exhaust system, climate control and hybrid propulsion; however, more codes may appear in the future. Similarly, the validity of linear functions to predict future operating and maintenance costs must be supported by maintenance cost records, company experience, and the schedule of preventive maintenance jobs. Finally, it must be said that presented models are valid to compare bus technologies of similar capacity and performance (e.g., 60-foot buses that are hybrid diesel, conventional diesel, etc.), but not to compare 60- and 40-foot buses even if they share the same technology (e.g., conventional diesel).

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