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Bus Replacement Modeling and the Impacts of
Budget Constraints, Fleet Cost Variability, and Market Changes on
Fleet Costs and Optimal Bus Replacement Age,
A Case Study

by

Jesse Alexander Boudart

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Civil and Environmental Engineering

Thesis Committee:
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Abstract

Overwhelming evidence throughout the literature has shown that bus overhead and maintenance (O&M) costs increase as buses age. This has implications toward a fleet manager's decision of when one should buy, use, or sell buses to minimize total fleet costs. Unfortunately, there are uncertain market conditions associated with bus fleets that cloud the manager's ability to make appropriate decisions. Using integer programming (IP), O&M trends and changing market conditions are integrated into a model to better analyze bus fleets.

Due to recent budget constraints of transit agencies, needs for a bus fleet replacement model have arisen. King County in Washington State has supplied cost aggregated data of their New Flyer (NF) and NF hybrid buses. These data have been analyzed to create statistical relationships based on rising O&M costs per mile with age, which are then integrated with the IP model to determine the impact of changing diesel prices, potential carbon dioxide (CO₂) emissions costs, uncertain maintenance costs, and bus purchase cost subsidies. The goal is to aid fleet managers to determine the costs of early or delayed suboptimal bus replacement timing and the impacts of market variability on fleet costs and optimal replacement timing.

The optimal replacement age for NF and NF hybrid buses based on King County data and current fuel prices of \$3.99/gal are 16.7 and 18.3 years, respectively. It has been consistently observed that greater expense is incurred when buses are replaced earlier rather than later from optimal. To minimize total CO₂ emissions (including operation and construction emissions), buses should be replaced slightly before the optimal replacement time without considering CO₂ emissions. High diesel prices and CO₂ emissions had little or no effect, on when buses should be replaced. However, higher maintenance costs reduced the optimal replacement time by almost two years.

Although NF hybrid buses have been found to have no economic advantage over conventional buses, this finding may be a consequence of the different costs associated to the different routes operated by hybrid and conventional buses. Due to the lack of detailed King County's route level historical data, a study of the economic competitiveness of NF hybrids against conventional buses is outside the scope of this thesis.

If buses are used less with age, the optimal replacement age is reduced. The optimal replacement age also dropped significantly when the Federal Transit Agency's procurement assistance is applied into the model. The

procurement assistance can be up to 80% of the capital costs and can be considered a purchase subsidy from the transit agency viewpoint. If purchase subsidies decrease bus purchase prices by 1%, the optimal replacement age drops approximately 1.5%. When the bus purchase price is reduced by 80%, the optimal bus replacement age is less than 12 years, the FTA's minimum replacement age.

Dedication

To my grandparents Marina and Michel Boudart and their inspiring stories of love and living the American dream.

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Table of Contents

Abstract	i
Dedication	iv
List of Tables	ix
List of Figures	x
1.0 Introduction	1
1.1 Problem Statement	1
1.2 Research Objectives	3
1.3 Project Scope	3
1.4 Experimental Design	4
1.5 Motivation	4
1.6 Organization	6
2.0 Literature Review	7
2.1 Bus Fleet Characteristics	7
2.1.1 General Bus Fleet Management	8
2.1.2 Bus Maintenance	9
2.1.3 Road Calls	11
2.1.4 Decreased Utilization with Age	14
2.2 Factors Affecting Bus Fleet Management	15
2.2.1 Federal Transit Agency's (FTA) Guidelines	15
2.2.2 Hybrid-Electric Technology	16
2.2.3 Impacts of CO ₂ Emissions	18
2.2.4 Gas and CO ₂ Price Sensitivity	20
2.3 Replacement Model Development	21
2.4 Bus Replacement Modeling Literature Summary	22
3.0 Data	25
3.1 Data Errors	25
3.2 The Bus Fleet	25
3.3 Fleet Records	27
3.4 Fleet General Cost Characteristics	28
3.5 Overhead and Maintenance	30
3.6 Utilization	33
3.7 Fuel Efficiency	34
3.8 Road Calls	35
4.0 Methodology	37
4.1 Tabular Method Summary	37

4.2	The Integer Programming Model.....	39
4.3	Model Formulation.....	40
4.4	Summary of Model Inputs	44
4.5	Model Assumptions	45
4.5.1	Maximum Bus Age and Horizon Time (a & T)	45
4.5.2	Discount Rate (dr)	46
4.5.3	O&M Models ($om(A_j)$).....	46
4.5.4	Fuel Economy Models ($mpg(A_j)$)	48
4.5.5	Road Call Model ($rc(A_j)$).....	50
4.5.6	Utilization ($u(A_j)$).....	52
4.5.7	Procurement Costs (v).....	53
4.5.8	Salvage Value (s & $sf(AT)$)	54
4.5.9	Diesel Price (d)	56
4.5.10	Emission Output and Price ($eps, em(A_j), ec$).....	56
4.5.11	Model and Scenario Setup.....	58
5.0	Results and Analysis	59
5.1	New Flyer (NF)	59
5.1.2	NF Market Impacts.....	64
5.1.3	FTA Capital Assistance and Replacement Age.....	66
5.1.4	Decreasing Utilization and Replacement Age (uA_j)	68
5.1.5	Road Calls Scenario	69
5.2	New Flyer Hybrid	70
5.2.1	NF Hybrid Forced Replacement Age Effects	71
5.2.2	NF Hybrid Market Impacts.....	73
5.3	NF vs. NF Hybrid	75
5.3.1	Cost Comparison	76
5.3.2	Economic Breakpoints for the NF Hybrid	78
5.4	Cost Elasticity	80
5.5	Replacement Age Elasticity.....	82
5.6	Summary of Results	84
5.7	Discussion.....	85
5.7.1	Validity of Assumptions.....	85
5.7.2	Costs	87
5.7.3	FTA Capital Assistance.....	88
5.7.4	Road Calls.....	89
5.7.5	Hybrid Technology	89
5.8	Limitations.....	90

5.8.1	Future Uncertainty	90
5.8.2	O&M costs	91
5.8.3	Road Calls.....	92
5.8.4	Emissions	92
6.0	Conclusion	94
7.0	References	97
8.0	Appendix	100

List of Tables

Table 1: Fleet Data from King County (2009)	26
Table 2: Average Bus Age Converted to the Current 2011 Year Used in this Study	27
Table 3: Aggregated KC Road Call Data from 2,975 Records, March 2011	36
Table 4: Summary of Inputs and Labels	44
Table 5: Statistical O&M vs. Cost Model for the NF	47
Table 6: Statistical O&M vs. Age Model for the NF Hybrid	47
Table 7: Passenger Cost per Road Call	51
Table 8: Percent Cost Increase of Early or Late Replacement from Optimal for NF	63
Table 9: Emissions Cost or Savings from Early or Delayed Vehicle Replacement	63
Table 10: NF's Discounted Sensitivity Analysis from Baseline	64
Table 11: Scenario's Effect on Average Replacement Age for NF	65
Table 12: Discounted Percent Change from Baseline to Road Call Cost Scenario	69
Table 13: Percent Cost Increase of Early or Late Replacement from Optimal for NF Hybrid	72
Table 14: NF Hybrid's Discounted Sensitivity Analysis from Baseline	73
Table 15: Scenarios' Effect on Average Replacement Age for NF Hybrid	75
Table 16: NF and NF Hybrid's Baseline Scenario Comparison of Discounted Average Yearly Costs	76
Table 17: NF and NF Hybrid's Emissions Scenario Comparison of Discounted Average Yearly Costs	77
Table 18: Cost Elasticities for Scenarios	81
Table 19: Replacement Age Elasticities Compared to Baseline Conditions	83
Table 20: Initial Condition Assumption Test	86

List of Figures

Figure 1: Overall Cost Breakdown for Transit Operations of Forty Foot Buses (Chandler & Walkowicz, 1996)	9
Figure 2: Road Calls per mile with age for National Agency Sub-fleets. A figure from Laver et al., 2007	12
Figure 3: US National Average Number of Riders Affected by Road Calls with aging fleet. A figure from Laver et al., 2007	13
Figure 4: Picture of Bus Used in Thesis (KC, 2011)	26
Figure 5: NF and NF hybrid Average Cost Breakdown for Ten & Six years of Operation	29
Figure 6: Maintenance Costs per mile for NF and NF Hybrid	31
Figure 7: Overhead and Maintenance Costs of NF and NF Hybrid	32
Figure 8: Utilization of New Flyer and NF hybrid buses.	33
Figure 9: Fuel Economy of Bus Fleets with Age	35
Figure 10: Statistical O&M Models by Bus Type	48
Figure 11: Fuel Economy Model based on NF and NF Hybrid	50
Figure 12: Total Road Call Cost to a Bus with Age ($rc(A_j)$)	52
Figure 13: Modeled Utilization Functions	53
Figure 14: Final Salvage Value ($sf(AT)$) for NF and NF Hybrid	55
Figure 15: Emissions Production and Salvage Cost of Vehicles with respect to Weight	56
Figure 16: NF Cost Breakdown for Baseline Conditions from Replacement Model for Entire Horizon Time, T	59
Figure 17: Forced Replacement Ages based on Optimal Replacement for NF (B conditions). Star Indicates Optimal Replacement Age.	60
Figure 18: Percent Total Cost Difference of Baseline (B) vs. Extreme (X) Scenarios for NF. Star Indicates Optimal Replacement Age.	62
Figure 19: Percent Cost Difference from Optimal of NF for B, X, and FTA Assistance. Star indicates Optimal Replacement Age.	67
Figure 20: NF Hybrid Cost Breakdown for Baseline Conditions from Model for Entire Horizon Time, T	70
Figure 21: Forced Replacement Ages based on Optimal Replacement for NF Hybrid	71
Figure 22: Average Replacement Age, B and X scenarios for NF Hybrid	72

Figure 23: Average Age of Replacement between NF and NF Hybrid, Baseline conditions. Star Indicates Optimal.	78
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1.0 Introduction

1.1 Problem Statement

Large transit agencies typically own hundreds of buses requiring numerous drivers, mechanics, spare parts, and large facilities to maintain an efficient transportation service. Operation, overhead, and maintenance costs of the bus fleet are expensive for resource-strapped transit agencies, where these costs have been shown to rise with an increasing bus age. Given recent budget shortfalls of many transit agencies (including TriMet)¹, fleet agencies are forced to delay bus replacement. Furthermore, a fleet manager must also deal with market fluctuations, e.g., changing fuel prices, repair costs, labor inflation, and federal policies which complicate bus replacement decisions. The consequences of delayed replacement may incur greater costs affecting service and/or the passenger's fare to ride. To understand the impact of delayed replacement, one must understand bus characteristics, attempt to forecast market changes, and then integrate these factors into a model for the ability to make an optimal bus replacement decision that minimizes overall costs.

¹ http://www.oregonlive.com/politics/index.ssf/2010/11/trimet_bond_election_results_o.html, "Portland-area Rejects Tri-met's Bus Replacement Measure", The Oregonian, published Nov. 2nd, 2001, Accessed April 5th, 2011

There is ample evidence that bus fleets' overhead and maintenance (O&M) costs tend to rise with age. This characteristic of O&M costs implies that there is an optimal time to buy a new vehicle that is a function of 1) purchase price, 2) market conditions and 3) the rate of O&M cost increases. If this optimal replacement age is consistently utilized, fleet managers can minimize their total costs. However, accurately determining this optimal replacement time requires a sophisticated tools and analyses given the uncertainties regarding future market conditions.

Integer programming models can integrate fleet operation characteristics and market factors to calculate the optimal bus replacement age for a given scenario. Results from running the model across many scenarios can help fleet managers make founded assumptions given real market fluctuations, such as gas price volatility and even potential U.S. green house gas legislation².

Without modeling of bus cost variation and market fluctuations, bus managers may be spending tax dollars inappropriately where money could be diverted toward providing better service at a lower cost. This thesis attempts

²<http://www.nytimes.com/2009/03/07/us/politics/07carbon.html>, "House Bill for a Carbon Tax to Cut Emissions Faces a Steep Climb", New York Times, Published March 9th, 2009, Accessed Feb. 10th, 2011.

to aid fleet managers in their bus replacement decisions to minimize fleet costs.

1.2 Research Objectives

This thesis delves into the intricate nature of bus fleets and bus replacement.

The research objectives are to create a bus fleet optimization model and perform data analysis to help a fleet manager make appropriate bus replacement decisions.

1.3 Project Scope

Actual fleet data from King County (KC) in Washington State are used to create operating, overhead, maintenance, and fuel cost assumptions to drive the model. King County Transit serves the Seattle metropolitan area and is one of the larger transit agencies in America, which operates over 1,400 vehicles. KC operates different types of buses; however, only fleets of conventional and hybrid-diesel sixty-foot 'New Flyer' articulated buses are analyzed. Bus fleet characteristics and market fluctuations are modeled to analyze their impacts on total costs and optimal bus replacement timing. A sensitivity analysis of the mentioned parameters brings cost and optimal bus replacement age differences to light.

1.4 Experimental Design

Data analyses are performed to characterize bus costs and how costs change as buses age. Linear regression is used to ensure statistically significance models of costs varying with bus age. These cost models are integrated into an integer programming model that outputs the optimal timing of when to buy, use, and salvage one bus at a time. It is assumed that one bus represents the fleet purchased as a group with average utilization, average operational costs, average bus age, and other fleet characteristic assumptions. The model further provides insight of how market conditions impact optimal bus replacement timing and total costs.

1.5 Motivation

Managing a fleet of buses is complex given varying costs with age, potentially costly CO₂ regulations, volatile diesel prices, and constrained budgets. This research seeks to integrate these four main factors with bus replacement modeling.

Research in replacement models began over 50 years ago with simple series models, where vehicles are replaced in sequence, one at a time. These advanced into replacing multiple vehicles in parallel and included age varying vehicle characteristics. Bus replacement modeling research has been

performed, but not with extensive detail including the previous four bolded factors.

There has been research on operation and maintenance costs with respect to age, but the studies have not been integrated into optimization models extensively. Further, researchers have not helped fleet managers requisite answers of when buses should be replaced.

Budget cuts have forced some transit agencies to delay bus replacement, but with unforeseen consequences to whether this action saves money. Utilizing series optimization models integrating varying costs with age, potential CO₂ regulations, volatile diesel prices, and constrained budgets a manager can determine if early or delayed replacement is justified from a cost or environmental perspective.

Hybrid bus technology holds promise to reduce emissions from higher fuel economy, but its cost competitiveness against conventional internal combustion buses varies depending on future gasoline or CO₂ prices. The breakpoint of when hybrid electric buses (HEB) become economical feasible and more environmental against conventional buses is investigated to aid fleet managers in making appropriate bus investment decisions.

To the best of the author's knowledge there is no published research that simultaneously models the impacts of varying bus costs with age, diesel costs, CO₂ costs, and constrained budgets into a series bus replacement model.

1.6 Organization

First, a review of the literature that deals with fleet characteristics, bus characteristics, emissions, equipment replacement and bus replacement is presented. King County's bus fleet data lays the foundation for creating cost models that drive the integer programming model. The integer programming model is explained followed by the methodology. Assumptions how the integer program models a transit fleet's future operational costs are then discussed and presented. Analyses are then performed based on impacts of changes in bus costs and market conditions and the effects on optimal replacement age, which leads a discussion on the practical uses for this research.

2.0 Literature Review

The literature review encompasses factors related to bus replacement modeling. First, general bus fleet management is discussed. Then, age varying bus characteristics of repair costs, road calls, and utilization are introduced. The importance of these factors to include in bus fleet management is then exemplified. Next, market and federal policy factors as they impact bus fleet management are discussed. Specifically, the FTA's capital assistance program, vehicle technology, environmental emissions, and price sensitivity testing as they relate to bus fleets are explained. The literature review concludes with a discussion of equipment replacement modeling and how it has developed into bus replacement modeling. Finally, a summary of the literature applied toward this thesis is given.

2.1 Bus Fleet Characteristics

Buses require attention as they are driven across the transit network. They require diesel fuel to run the engine, money to pay the driver, and parts to make sure the bus is in good running order. Furthermore, bus costs change as they become older and have more problems. Cost and contemporary issues as they relate to bus fleets are reviewed in the next sections.

2.1.1 General Bus Fleet Management

Beginning in 1975, Wabe and Coles investigated transit fleet costs over time. They observed rising operating and maintenance costs as the fleet aged (Wabe & Coles, 1975). Later studies by Williams (1979) and Berechman and Giuliano (1984) saw similar correlations of rising operating and maintenance costs with fleet age.

Bus costs are attributed to numerous cost factors: capital purchases, vehicle operation, fuel, general administration, facility maintenance, and other, where these contribute a different proportion of total bus costs. A standard forty foot bus operational cost breakdown is illustrated in Figure 1. The pie chart represents an average proportion of total bus operational costs based on a sample of the largest American transit agencies, such as New York Metro (MTA), Washington D.C. Metro (WMTA) and even King County's. The 'vehicle operational' cost is the largest component because it includes the labor cost (driver's salary) needed to operate a bus fleet. However, the driver's and mechanic's salary varies widely between agencies given different wage rates, fringe benefits and overhead costs (Chandler et al., 1996). This may alter the percent contribution of each cost category. For example, an increase of wage

rate would increase the cost contribution of 'vehicle operation' shown in Figure 1.

Figure 1: Overall Cost Breakdown for Transit Operations of Forty Foot Buses (Chandler & Walkowicz, 1996)

Furthermore, the proportion of each of these costs changes depending on agency size, fleet age, fuel costs, overhead costs, labor practices, and other factors. One particular cost of bus maintenance is now discussed in further to better explain bus characteristics.

2.1.2 Bus Maintenance

Simms et al. (1982) has studied optimal bus purchase, operation and replacement policies with respect to preventative maintenance (PM)

schedules. Transit agencies implement PM schedules to keep buses in good operational condition and to decrease the amount of unscheduled breakdowns. However, buses still encounter operational breakdowns.

Rust (1987) integrated average unexpected breakdown and PM costs to help quantify the optimal replacement age of a bus. However, this study mostly dealt with engine issues and did not encompass other feasible bus component problems.

The cost of replacing, refabricating, and rehabilitating buses has been a focus of research by Khasnabis et al. (2000; 2002). He and his colleagues estimated the cost of refabricating major bus components and/or rehabilitating bus frames based on previous studies (Bridgeman et al., 1983). These costs were then integrated into a series replacement model to determine cost minimizing replacement time. Further research by Mishra et al. (2010) integrated similar replacement and refabricating issues, but went one step further for how the Federal Transit Agency (FTA) should best allocate its capital grant funds to transit agencies based on need. These researchers' contributions are to investigate ways to determine optimal bus replacement based on preventative and unscheduled maintenance costs. This thesis' data includes maintenance costs toward the same end as these previous studies,

but also includes an additional unscheduled bus cost not covered widely by the literature.

2.1.3 Road Calls

Research has delved into bus 'Road calls', which is when a bus in regular operation has a severe problem where it must be removed from the roadway. Published equipment breakdown research has been seen as early as 1979 for machines (Lake & Muhlemann), but not for buses. In any case, road calls (RC) are detrimental because of extra waiting staff and resources that are sent out to the broken bus in the field. Further, a RC can result in a bus tow, escalating costs. Road called buses also creates a negative image on the transit agency as riders may think the agency's buses are old and unreliable (Laver et al., 2007).

Even though, there has been little research on total cost of road calls, Laver et al. (2007) has shown that road calls tend to increase as buses become older, shown by the following figure.

Figure 2: Road Calls per mile with age for National Agency Sub-fleets. A figure from Laver et al., 2007

The rising trend line indicates that buses have a greater probability to break down as they age. The cost to service this road called bus is only one component. There may be additional costs borne by passengers.

When a road call occurs, passengers must wait additional time until another bus can collect them and move them to their destination. This extra waiting time cost should be accounted for to better represent the consequences of operating an aging fleet. Commuters using transit value their time differently depending on the segment of their travel. For example, transit passengers tend to value their time more when they are waiting for the bus than sitting in a moving bus (USDOT, 1997).

The scale of this issue is significant by the estimated amount of riders impacted by bus road calls, shown with the following figure.

Figure 3: US National Average Number of Riders Affected by Road Calls with aging fleet. A figure from Laver et al., 2007

The larger the bus fleet, the larger the impact road calls have on passengers as the average fleet age increases.

Both Figure 2 and Figure 3 illustrate estimated impacts of road calls on transit fleet operations and passengers, but do not include dollar value costs. Quantifying these costs is discussed in length in the methodology section of this thesis. Next, another age varying bus characteristic is discussed.

2.1.4 Decreased Utilization with Age

Research observing decreased utilization of buses with age started in the 1960s, with Eilon et al. (1966). Later, buses were modeled with varying utilization levels (Simms et al., 1984). Redmer (2005) calculated the optimal economic life of operating a freight truck using a model that was based off of research using freight truck cost data (Eilon et al., 1966). Buddhakulsomsiri and Parthanadee (2006) have further observed actual fleet trends of decreased utilization with age. Observation of this phenomenon has resulted in more sophisticated research to minimize fleet costs.

Some researchers have focused on the statistical analysis of fleet data and the relationships between age, utilization and costs (Chen and Lin, 2006). Kim et al. (2009) has explored age, annual usage, and cumulative usage to identify whether vehicles' usage decreases over age. He explored if using vehicles at a constant or decreasing amount is the most inexpensive utilization strategy. In this thesis, consideration is made to which utilization strategy saves the most money or emissions for King County.

2.2 Factors Affecting Bus Fleet Management

As fleet managers cope with bus costs and utilization characteristics that vary with age, they are impacted by federal policies and changing market conditions. Studies are now introduced that explain the importance of these factors on bus replacement modeling.

2.2.1 Federal Transit Agency's (FTA) Guidelines

The FTA provides transit agencies grants for up to 80% of bus capital purchases (FTA, 1992). FTA's capital assistance is defined as giving the transit agency money when they purchase buses. But, when agencies are granted funds, they must adhere to certain FTA guidelines: transit agencies are required to keep heavy-duty buses a minimum of 12 years or 500,000 miles, whichever comes first (Laver et al., 2007). Twelve years appears to be a long time to own a bus, but according to a survey of American transit agencies, the average bus retirement age is 15.1 years (Laver et al., 2007) and agencies may have to keep buses longer than average due to budget constraints. In any case, the impact of purchase subsidies on the optimal replacement age is investigated in this thesis. Next, vehicle technology and its impacts on buses is discussed.

2.2.2 Hybrid-Electric Technology

The development of Hybrid-Electric vehicles (HEV) has been a recent innovation to increase fuel economy and decrease CO₂ emissions without a large compromise in vehicle performance. Despite disagreement concerning emissions reductions using HEVs compared with conventional vehicles (Lave & MacLean, 2002), HEVs have been shown to have great benefits in urban environments (Fontaras et al., 2008). These vehicles have regenerative braking and use electric motors to accelerate providing higher levels of torque and efficiency versus internal combustion engines thereby using less gasoline. The same principles that guide HEVs have also spurred innovation with Hybrid-Electric buses (HEB).

Research has shown that HEBs perform well against conventional diesel buses in urban areas with generally low speed transient traffic environments (McKain & Clark, 2000; Wayne et al., 2008). Initial research of HEBs and conventional buses (CB) controlling for bus routes showed no difference in fuel economy (Wayne et al., 2004). However more recent studies have shown that HEBs have better fuel efficiency against CBs in routes with frequent stop and go traffic conditions (Clark et al., 2009). Furthermore, Clark et al. (2009) used data from Seattle's King County, Long Beach's and New York's HEB

fleet to reach this same conclusion. In these urban environments depending on the bus route, pollutant emission rates and bus average speeds have been shown to vary (Hao et al., 2010).

However, HEBs are not without problems. HEBs require batteries, which degenerate over time and require specialized diagnostic and repair equipment. This equipment is costly, and replacing the batteries even more so, which increases total maintenance costs (Clark et al., 2009).

Studies have been performed which modeled bus costs accounting for fuel consumption and emissions output with different bus engine platforms such as conventional and hybrid buses (Chandler & Walkowicz, 2006; Clark et al., 2009). But they do not find optimal replacement of bus replacement through optimization models. Buses have undergone some dynamic programming replacement modeling (Keles & Hartman, 2004); however, minimal attention has included maintenance costs, utilization strategies, vehicle technologies, emissions and impacts of market volatility needed to create a robust replacement model, nor consideration toward finding the optimal replacement age. The literature covering the importance emissions is discussed in the next section.

2.2.3 Impacts of CO₂ Emissions

For each gallon of diesel burned, 22.2 lbs of CO₂ is emitted (EPA, 2011). As each bus burns approximately 30 gallons of diesel fuel per day based on yearly utilization assumptions (Clark et al., 2009), approximately 100 tons of CO₂ are emitted per year, per bus. King County currently owns 1,400 buses equating to an estimated daily CO₂ output of 450 tons. However, in addition to bus usage emissions, CO₂ from fabricating a bus should also be recognized to encompass complete life cycle analysis emissions.

Conventional passenger vehicles have been estimated to create 8-9 tons of CO₂ to produce and salvage an automobile (DeCicco & Thomas, 1999; Samaras & Meisterling, 2008). Buses weigh 10 times more than conventional autos. Their large size inherently requires additional metal and plastics, therefore elevating production and salvage CO₂ emissions. Further, articulated buses (the focus of this thesis), have even more mass and components than standard buses, so are likely to emit more CO₂ emissions during manufacturing. When total utilization, production, and salvage emissions of a single bus are multiplied by the number of buses owned by an agency, and further, American transit agencies, carbon contributions by the public transportation

system become larger than twelve million CO₂ tons per year (Davis & Hale, 2007).

CO₂ has been projected to have a significant impact on the economy because of climate change effects. To emphasize the importance of integrating emissions as a cost, literature has been reviewed to quantify this cost.

One of the most well known studies on climate change is Sir Nicholas Stern's "The Stern Review" released in 2006, which discusses the impact of CO₂ emissions on the economy. Stern argues that if society exhibits a "business as usual" or "do nothing" approach toward carbon mitigation, at least 5% of the global GDP would be lost forever (Stern, 2006). His prescription is to establish a carbon tax (establishing a price of CO₂) that would increase with time, thus financially incentivizing emissions reductions. Despite the recognition and controversy of Stern's claims, a carbon tax has yet to gain political feasibility in America. In Europe, the acceptance of climate change and implementation of mitigation efforts is handled differently.

In 2005, the European community started a cap and trade program, which places an economic value on CO₂; however, they have mostly dealt with power plants or large point emitters, representing about a third of the total European CO₂ emissions. Only recently is Germany taxing vehicles based on

their output of carbon³. If American emissions related-legislation is implemented, it would impact bus investment decisions especially with the competitiveness of hybrid-bus technologies like the following research has shown.

2.2.4 Gas and CO₂ Price Sensitivity

Peet et al. (2009) investigated the cost effectiveness of HEB against (CB) by varying gasoline and carbon prices. The scholars showed that prices of diesel need to be \$7 per gallon for HEB investment to become economical given that HEBs cost more than CBs. Diesel prices have been on the rise as of late⁴, therefore testing when HEB's become economical is timely for fleet managers' decisions to save fleet costs.

When a \$100/ton price of carbon is imposed, HEBs become cost effective compared with CBs. The study's usage of the \$100/ton of carbon price is taken from research performed by Tol's (2005) investigating the social cost of carbon. Tol conducted a meta-study where he averaged other researchers' estimates

³ <http://www.spiegel.de/international/germany/0,1518,603798,00.html>, "Germany Joins EU in Tying Car Fees to Emissions", Der Spiegel, Published Jan. 27th, 2009, Accessed Feb. 10th, 2011

⁴ http://www.logisticsmgmt.com/article/diesel_prices_up_for_eighth_straight_week_according_to_eia/, "Diesel prices up for eighth straight week, according to EIA", Logistics Management, Published Jan. 25, 2011, Accessed May 9th, 2011

on the social cost of CO₂ output. Recognizing that CO₂ has severe economic consequences if ignored, reducing emissions is a logical step forward.

Wayne et al., (2009) has shown that if HEBs have 15% market penetration, HEBs could reduce the transit agency's emissions by 7%. Greater HEB market penetration and fleet manager strategies, such as extending the life of the bus, could provide emissions savings, which the economy and planet would certainly benefit from.

Tying bus fleets, bus characteristics and market conditions are achieved by research performed in the next section: replacement modeling.

2.3 Replacement Model Development

The Management Science and Operations Research literature pioneered the usage of vehicle replacement models to optimize decisions regarding vehicle purchases, scrapping, maintenance, and utilization. A formal optimization model, dealing with a similar but more general topic of equipment replacement models, was first introduced in the 1950's (Bellman, 1955). Rees et al. (1982) and Khasnabis et al. (2003) analyzed problems with fleet equipment replacement. Khasnabis et al. (2003) assumed that inputs such as purchase, usage, and demand were known.

Another important development was the addition of parallel replacement models. The difference between series and parallel models is that series deals with one asset at time and parallel deals with multiple assets, each with potentially different cost models. Research in this topic began with Jones et al. (1991) where he integrated varying operating and maintenance costs of a machine's age. Other models have dealt with machine or vehicle replacement constrained by budget (Karabakal et al., 1994), by parameters with variable utilization (Bethuyne, 1998) and stochastic demands (Hartman, 2001), series against parallel replacement (Chand et al., 2002), and several vehicle types (Hartman, 2004). Kim et al. (2003) has integrated vehicle manufacturing waste factors in a life cycle analysis form, indicating when it is most economical to replace a vehicle.

2.4 Bus Replacement Modeling Literature Summary

First, bus fleet cost trends with age and general characteristics are introduced to give context to fleet management. It was shown that buses cost more, have more breakdowns, and are used less as they age. With greater budget constraints on transit agencies, cost impacts of delayed bus replacement are unclear. Because of this, volatility in bus operating, overhead,

and maintenance costs are investigated further in this thesis as they pertain to total fleet costs and the optimal bus replacement age.

Next, federal policies, technology, and CO₂ emissions are discussed in how they may impact a fleet manager's bus purchase decision. For example, the federal government can subsidize a HEB purchase price by 80% (federal policy). If the HEB is driven in an urban environment, it will save more money and emit less CO₂ compared with a CB (technology). Furthermore, abating CO₂ is good for the earth given studies indicating that high concentrations of CO₂ in the atmosphere increases the severity of climate change which is forecast to harm the economy (CO₂ emissions). Given these three factors of purchase subsidies, Hybrid-Vehicle technology, and potential incentives to decrease CO₂ emissions, their impact on total fleet costs and optimal bus replacement age are tested in this thesis.

However, to find the optimal bus replacement age, a bus replacement model is required. Replacement models have arisen in the literature long ago but have not integrated the intricate nature of bus fleet characteristics, federal policies, and market factors impacting when and which buses should be utilized in the bus fleet. For example, how old does a bus have to be when it should be replaced with a newer bus that is less costly to maintain? Does the

FTA's 80% capital assistance greatly impact the replacement age? Does the extra initial economic and environmental cost of buying a HEB offset the total CO₂ of buying and purchasing a similar CB? Finally, what are the relationships between total fleet cost differences and optimal bus replacement ages? This thesis intends to investigate bus fleet replacement by a case study of King County's bus fleet.

3.0 Data

Data are provided by King County providing fleet information to model year to year bus operational costs. Data were presented using Excel spreadsheets showing a variety of bus characteristics. But first, these data required organization to create usable worksheets.

3.1 Data Errors

These data received from KC consisted of yearly bus costs and aggregated cost information from 1994 to 2009. The Excel spreadsheet containing these data had some errors, when the bus age was not carried over from previous years in some bus types (causing a discontinuity). Also, errors in the total number of buses were noticed as fleet totals were not carried over to future years. These problems prompted a detailed data inventory and were organized by year for accuracy and clarity. All the results shown in this thesis have been obtained after a complete data cleanup.

3.2 The Bus Fleet

King County (KC) owns more than 1,400 buses, vans, and trolleys. Twenty three percent of King County's entire fleet consists of New Flyer (NF) and NF Hybrid sixty foot articulator buses, which are some of the oldest and more rigorously driven buses. These buses were selected for analysis because of

their high quality characteristics accounting and long ownership time period.

A picture of this bus is shown in the following figure.

Figure 4: Picture of Bus Used in Thesis (KC, 2011)

The number of buses and the average age of these buses selected are presented in the following table.

Table 1: Fleet Data from King County (2009)

Bus Type	Age of buses (years)	Number of Units
New Flyer (NF)	10.4	272
NF Hybrid	5.37	213

The number of units and average fleet age represents data from year 2009.

The reason that the age of buses is a fraction is from KC purchasing and selling similar bus types over time. For the purposes of this model, the units have been separated based on when buses were bought and sold. The average fleet age per bus type were converted to integers, recalculated based on date of purchase, and then calibrated to the current 2011 year. This conversion is

necessary given the decision variable constraints of the modeling program which require age in integers. After formatting, these data can then be broken down by age and number of units, presented in the following table.

Table 2: Average Bus Age Converted to the Current 2011 Year Used in this Study

Bus Type	Average Age of Buses	Number of Units
New Flyer (NF)	12	272
NF Hybrid	7	213

The average bus fleet age increases by two years to represent the current 2011 year. Table 2 is the current state of NF and NF hybrid buses. Next, an overview of bus characteristic data is discussed.

3.3 Fleet Records

KC provided yearly (aggregated by fleet) operation, overhead, and maintenance costs the data categories per bus type are as follows:

- Age of bus
- Total units
- Fuel cost
- Diesel gallons consumed
- Maintenance costs (Mechanics' labor plus parts)
- Tire costs

- Administration costs (Manager, supervisor, admins, etc.)
- General costs (Costs not associated to direct labor, facility costs, etc.)
- Total costs

From these data categories, useful performance measures are created on an aggregate level such as:

- Total costs per mile
- Miles per gallon (Fuel Economy)
- Miles per unit
- Maintenance costs per mile
- Total costs per unit

These performance measures aid in characterizing operating, maintenance, and utilization fleet cost models. The raw data used in this thesis can be seen in the Appendix for the NF and NF hybrid. Next, an overview of New Flyer and New Flyer hybrid data are displayed.

3.4 Fleet General Cost Characteristics

Both the New Flyer (NF) and NF hybrid fleets cost significant sums of money to maintain. To operate a fleet of NF or NF hybrids (213 and 272 units, respectively), both fleets cost sixteen million dollars each per year, on average. This means that the total cost magnitudes of the NF and NF hybrid are

similar, however, it is not possible to draw any conclusion when comparing NF and NF hybrid cost data directly because the buses are assigned to different routes. The total costs are disaggregated by type, which differs from the national average cost breakdown presented in Figure 1. KC's data of cost breakdowns are presented in the following figure based on bus type.

Figure 5: NF and NF hybrid Average Cost Breakdown for Ten & Six years of Operation

The repair costs for both buses are at least 11% higher than national average maintenance costs recorded by Chandler and Walkowicz (1996) shown in Figure 1. Unfortunately, the cost category descriptions (General costs, administrative costs, Repair costs, etc.) provided by KC are not identical than the costs covered by Chandler et al., (1996), nor is there information

explaining Figure 1's precise breakdown of vehicle operation costs consisting of 53% of total costs. Despite this inconsistency, the relative cost proportions between the NF and NF hybrid of Figure 5 can still be seen.

Surprisingly, the NF's repair and 'general' costs are of a slightly higher proportion than the NF hybrid's. This is explained by a greater amount of vehicles in the NF fleet. A bigger fleet requires higher 'general' costs (including administration) for regular operation. The fuel cost is a larger percentage of NF hybrid's cost, contrary to the hybrid's expected higher gas mileage. This may be explained from a higher average utilization per unit of 33,500 miles compared with 31,900 of the NF. Unfortunately, the specific reasoning behind the 'other' costs of both bus types cannot be explained because there is not any data on bus average speed, route geography, peak/non peak driving times, etc. To the fullest cost detail that is provided, analyses are performed to help justify operating, overhead and maintenance, utilization, fuel economy and road call cost models described in the following sections.

3.5 Overhead and Maintenance

The maintenance data provided by KC corresponds to the literature's observation for rising maintenance costs with aging buses, shown below.

Figure 6: Maintenance Costs per mile for NF and NF Hybrid

Figure 6 shows rising trend of maintenance costs per mile with age. Notice how the NF's maintenance costs are less than its hybrid counterpart. The NF hybrid's extra cost could be contributed toward: the extra cost of battery repair (Clark et al., 2000) or from the bus route environment or geography. In any case, hybrid buses are known to have higher maintenance costs from the literature (Laver et al., 2007; Clark et al., 2009). The conventional and hybrid repair cost comparison in Figure 6 confirms this observation with King County's data.

Buses have additional operational costs known as overhead costs. These include: labor, administration, tire, and general costs. For the purposes of this model, overhead and maintenance costs are combined and are defined as

overhead and maintenance (O&M) costs from now on. The O&M costs are presented now presented in the following figure.

Figure 7: Overhead and Maintenance Costs of NF and NF Hybrid

Notice that Figure 7's costs are slightly higher than the maintenance costs presented in Figure 6. But in general, rising O&M costs with age is an important observation with the development of the bus replacement model.

3.6 Utilization

The conventional and hybrid NF buses exhibit slightly different utilization characteristics. Bus usage per mile with respect to age has been compiled, which is shown below.

Figure 8: Utilization of New Flyer and NF hybrid buses.

Notice how both buses are seldom used the first year or two of operation, known as the adoption period. Bus operators require time to become acquainted with new controls and vehicle dynamics that may differ from previous bus generations. Maintenance crews must also deal with new systems and may have to use different diagnostic equipment, which is a

requirement to diagnose hybrid-diesels and their more complicated power plants (Clark et al., 2009). After the adoption period, buses are used to their maximum amount at first, and then are driven less with time.

Interestingly, data in Figure 8 suggests that the hybrid does not exhibit decreasing utilization with age. However, there may not be enough data from the hybrid fleet. For example, the NF fleet is seen to noticeably decrease utilization per unit after year five, yet the hybrid's data is only for five years. The main limitation to identify utilization decreasing with age is the lack of long term data. Next, KC's fleet fuel economy data and its variance with age are examined.

3.7 Fuel Efficiency

In general, fuel efficiency is measured by miles per gallon (MPG) and varies with average speed and a bus's route. Hybrid buses tend to have better gas mileage than conventional buses, especially in transient low speed environments (Chandler & Walkowicz, 2006). Working with KC's data, there appears to be a negative MPG correlation with respect to age, shown by the following figure.

Figure 9: Fuel Economy of Bus Fleets with Age

Unfortunately, the average speeds or the environment that these buses operate within are unknown. If speeds are known, better assumptions could be made toward quantifying operating cost and fuel consumption (Clark et al., 2009).

In any case, this downward MPG trend with age is revisited in the methodology. The last data used from KC deal with road calls.

3.8 Road Calls

Due to the lack of long term RC bus data provided by KC, road calls per mile are based on Figure 2 from Laver et al. (2007). The figure has an increasing trend of RCs with age on aggregated data of select agency bus fleets, however the authors did not investigate any cost of road calls. Fortunately, KC

provides cost data corresponding to RCs, which are used to estimate a cost per RC.

Bus fleet repair costs are categorized by type: preventative maintenance, retrofit, [engine or transmission] rebuilds, etc. The data also quantified repair costs due to RCs. Average labor cost, part costs and time used per road call are estimated based on 2,975 records. Averages of these costs are shown in the following table.

Table 3: Aggregated KC Road Call Data from 2,975 Records, March 2011

Category	Averages
Time of Repair (hrs)	1.82
Labor (\$)	96.52
Part Cost (\$)	41.25
Total Cost per RC (\$)	137.78

The labor cost is based on an hourly rate of \$53.10 paid to mechanics. Later, this estimated \$137.78 per RC is combined with number of road calls with age to create a model of RCs.

4.0 Methodology

The bus replacement model is operated by an integer computer program.

With fleet inputs depicting operations, the integer computer program can model fleet costs over many years. Before the model and assumptions are presented, a summary of the methodology is presented in the following tables.

4.1 Tabular Method Summary

Replacement Model Structure	
Purpose	Models total yearly operational costs of a bus fleet. Minimizes costs by finding the optimal replacement vehicle age. Has ability to force early or late bus replacement to determine cost impacts.
General Information	Uses Microsoft Excel's Solver package augmented by Frontline Systems. Objective function to determine which costs to minimize. Decision variables decide when to buy, use or sell a bus, which are constrained by rules to ensure fleet management logic.
Outputs	Performance measurements: <ul style="list-style-type: none">• Total Costs• Total Costs per Mile• Purchase, Usage, and Salvage Costs• Average Replacement Age• Fuel Consumed• CO₂ Emissions Emitted• Emission Costs

Assumptions Held Constant	
Purpose	Sets bounds to model's parameters.
Horizon Time and Bus Maximum Age	On average, buses are replaced at year 15.1. Bus maximum age is set to 30 years. To ensure complete bus ownership cycles, horizon is set to 61 years, where on year 61, all buses are sold.
Discount Rate	9.6%, King County uses this discount rate.
Procurement Costs	New Flyer = \$403,000 New Flyer Hybrid = \$663,000. Based on 'medium' cost of purchasing buses (Clark et al., 2009)
Salvage Values	\$1,000 from conversations with King County (KC, 2011). Final salvage value depends on the age of bus at the horizon time, which minimizes effect of salvage decisions near the horizon time
Emissions	105 CO2 tons are accessed with production and salvage emissions. Usage emissions are based on 0.011 tons of CO2 released by one gallon of diesel.
KC Data Based Model Assumptions	
Purpose	Given empirical data of bus operations, provides bus fleet operational cost predictions. Most cost models vary with bus age.
O&M	Age varying O&M costs depending on NF or NF hybrid bus. The NF has less O&M costs than NF hybrid.
Fuel Economy	Base MPG (Clark et al., 2007) New Flyer = 3.86 New Flyer Hybrid = 4.58 These MPG's are assessed to decrease by 1% per year, observed from KC bus data.
Road Calls (RC)	Transit agency RC cost = \$137.78, based on average time and part cost from road calls. Passenger cost per RC = \$104, based on Average passengers per bus, estimated waiting time, and waiting time cost (Davis et al., 2009; King County Metro Transit, 2008; US DOT, 1997).
Utilization	Yearly utilization = 31,980 From NF total average usage.

Sensitivity Analysis	
Purpose	Determine trends and/or relationships of optimal replacement age, total costs, and emissions.
Gasoline Prices	Low Diesel Price = \$3.99, US national average (May, 2011) High Diesel Price = \$4.85, US national high (September, 2008)
Emissions Prices	No Emissions Price = \$0/CO ₂ -ton High Emissions Price = \$100/CO ₂ -ton High and low emissions price from the social cost of CO ₂ (Tol, 2005).
O&M Costs	Low O&M costs = 0% increase High O&M costs = 25% increase The O&M costs depend on if the NF or NF hybrid maintenance cost functions are used.
Utilization	Average utilization = 31,980, from NF total average. Decreasing utilization function based on maximum and minimum NF figures. Slope found between two, and function applied. All buses have been shown to have decreasing utilization with age.
Bus Capital Assistance	Maximum Capital Assistance = 80% Moderate Capital Assistance = 40% No Capital Assistance = 0% The FTA awards up to 80% capital assistance to purchase buses (FTA, 1992).

More detailed descriptions of costs are described in the following sections.

4.2 The Integer Programming Model

The fleet replacement model described in this section aims to provide answers regarding when to procure/replace or salvage over time as a function of cost.

The purpose of this integer programming model is to 1) account for actual fleet operational costs, 2) determine the optimal time of bus replacement and 3) be able to extend or shorten the bus replacement age. The model should help fleet managers determine the impacts of budget constraints and other economic factors on bus replacement timing.

The bus replacement model utilized incorporates varying costs with age, CO₂ emissions costs, forced replacement at a specified age, and to model buses in series. Decision variables and parameters are denoted as capital and lowercase letters, respectively.

4.3 Model Formulation

Indexes

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

Age of bus at the beginning of year: $A_j \in \mathbf{A} = \{0, 1, 2, \dots, A\}$, A is the maximal age.

Binary Decision Variables

$P_j = 1$ if a bus is procured and salvaged at the end of year j , and 0 otherwise.

Parameters

(a) Constraints

a = maximum or forced salvage age (the bus must be salvaged when reaches this age),

$u(A_j)$ = utilization (miles traveled by an A_j -year old bus),

$mpg(A_j)$ = fuel economy dependent on A_j -year old bus,

(b) Cost or revenue

v = cost of a bus procured,

$om(A_j)$ = overhead and maintenance costs per mile for an A_j -year old bus,

$rc(A_j)$ = cost of road calls per age of an A_j -year old bus,

s = salvage revenue (negative cost) from selling a bus,

$sf(A_T)$ = final salvage revenue (negative cost) from selling a bus only at the final evaluation time period T ,

ec = emissions cost per ton of CO₂ emissions,

d = price of diesel fuel per gallon,

dr = discount rate,

(c) Emissions

eps = production and salvage emissions, in CO₂ tons,

$em(A_j)$ = utilization emissions in CO₂ tons per mile for an A_j -year bus.

Objective Function, minimize:

$$\begin{aligned}
P_0(v + ec \text{ eps}) + \sum_{j=1}^{T-1} P_j(v + ec \text{ eps} - s)(1 + dr)^{-j} - sf(A_T)(1 + dr)^{-T} \\
+ \sum_{j=0}^{T-1} u(A_j)[om(A_j) + mpg(A_j)d + em(A_j)ec](1 + dr)^{-j} \\
+ \sum_{j=0}^{T-1} rc(A_j)(1 + dr)^{-j}
\end{aligned} \tag{1}$$

Subject to:

$$P_0 = 1 \tag{2}$$

$$P_T = 1 \tag{3}$$

$$A_0 = 0 \tag{4}$$

$$A_j \leq a \quad \forall j \in \{1, 2, \dots, T\} \tag{5}$$

$$A_j = (A_{j-1} + 1)(1 - P_j) \quad \forall j \in \{1, 2, \dots, T\} \tag{6}$$

$$P_j \in \mathbf{I} = \{0, 1\} \tag{7}$$

The objective function expression (1) minimizes the sum of purchasing, operating, overhead, maintenance, salvage, emissions, and road call costs over the period of analysis from time zero (present) to the end of year T . At the

first time period, the model purchases a bus without any salvage revenue (2). At the end of the last time period (or horizon time T), the replacement decision is forced where no additional bus is purchased (3) and is sold at the salvage value $sf(A_T)$, shown by the shaded variable. Assume at the first year, the age of the bus is 0 (4). When a bus reaches its forced salvage or maximum age, it is replaced with corresponding costs (5). The bus age increases by one year after each time period if it is not replaced and the age is 0 if the bus is replaced (6). Finally, the decision variables associated to purchasing and salvaging decisions must be binary, expression (7).

Now since the model has been established, a summary of values used are specified in the following tables.

4.4 Summary of Model Inputs

Table 4: Summary of Inputs and Labels

Parameter		Value
Horizon Time, T (Years)		61
Max Bus Age, A (Years)		30, or as specified
Discount Rate, dr (%)		9.6
O&M Cost, $om(A_j)$ (\$)		Function with Age
Road Call Cost, $rc(A_j)$ (\$)		Function with Age
Utilization, $u(A_j)$ (Miles)		31,890 or Function
Production & Salvage Emissions, eps (CO ₂ -ton)		105
Salvage Value, s (\$)		1,000
Bus Type	v (\$)	$mpg(0)$
New Flyer	403,000	3.86
NF Hybrid	663,000	4.58

Scenario	Gasoline Price, d (\$/gal)	Emissions Price, ec (\$/CO ₂ -ton)	O&M increase, $om(A_j)$ (%)
Baseline (B)	3.99	0	0
High Diesel Price (HD)	4.85	0	0
High Emissions (E)	3.99	100	0
High O&M costs (M)	3.99	0	25
HD & E	4.85	100	0
HD & M	4.85	0	25
E & M	3.99	100	25
Extreme (X)	4.85	100	25

The baseline condition is known as B, which utilizes low diesel prices, no emission cost and no increase of O&M costs. The highest priced condition is known as the extreme scenario (X), which includes HD, E, and M elevated

costs. The extreme scenario is performed to illustrate the impacts of what a realistic “worst case” cost scenario may be for a fleet. In between these two conditions, are scenarios consisting of parameter combinations representing the sensitivity analysis.

Details and justifications of these specific inputs into this integer programming model are described in the following section.

4.5 Model Assumptions

The following assumptions are meant to provide context for bus fleet costs and market conditions, described in the following sections.

4.5.1 Maximum Bus Age and Horizon Time (a & T)

Laver et al. (2007) surveyed different agencies to find out that buses were kept an average of 15.1 years before being retired. This retirement age may not be financially optimal. To test this hypothesis, the maximum age of bus ownership was assumed to be twice the average for fleets surveyed of 30 years. To ensure that at least two complete cycles of bus ownership are tested, the horizon time is 60 years of usage. However, the model requires a final period where the bus is sold and no usage costs are evaluated. This salvage period is dedicated to the year after the 60 years of usage. Therefore, in the

61st year, the bus must be sold, which is the reason for the 61 year time horizon.

4.5.2 Discount Rate (dr)

The discount rate greatly influences the importance of saving or spending in cost forecasts. Transit agencies are typically required to use discount rates set by who governs them. To reflect an agency's discount rate requirement, KC has shared the discount rate required of them to use, which is 9.6 percent.

This rate reflects future uncertainty. If there were more certainty with diesel prices, maintenance costs, and other factors, this rate may be lower.

4.5.3 O&M Models ($om(A_j)$)

Sixty-foot articulated buses are analyzed based on operational data of NF and NF hybrids. Each type of bus exhibits different O&M characteristics indicated from the King County cost data illustrated in Figure 6. A regression analysis is performed given bus cost data per individual bus type. Results are shown in the following tables.

Table 5: Statistical O&M vs. Cost Model for the NF

New Flyer				
R Square	0.939			
Standard Error	0.107			
Parameter	Coefficients	Standard Error	t Stat	P-value
Intercept (O&M Cost)	0.950	0.060	15.8	0.000
Age	0.119	0.010	11.7	0.000

Table 6: Statistical O&M vs. Age Model for the NF Hybrid

New Flyer Hybrid				
R Square	0.986			
Standard Error	0.042			
Parameter	Coefficients	Standard Error	t Stat	P-value
Intercept (O&M Cost)	1.162	0.030	38.3	0.000
Age	0.170	0.010	17.0	0.000

There is a strong positive linear correlation between O&M costs per mile and age as shown by the high R^2 and low p values. Utilizing the regression analyses' coefficients, linear O&M cost/mi models are created for buses aged 0 to 30, which is illustrated in the following figure.

Figure 10: Statistical O&M Models by Bus Type

The overhead and maintenance (O&M) cost models used per bus type are illustrated in Figure 10, which forecasts O&M costs to the maximum bus age of 30 years. Since data are not provided for a 30 year old bus, cost values above 12 years are extrapolated. In theory, there comes an optimal replacement age with the model's rising maintenance costs per year. This replacement timing is investigated later in this thesis.

4.5.4 Fuel Economy Models ($mpg(A_j)$)

There is no data regarding average speed and bus route characteristics, therefore it is difficult to determine precise fuel economy calculations.

Standard values are assumed per bus type, where CBs and HEBs have 3.86 and 4.58 MPG, respectively. The fuel economy figures have been obtained

from the literature using an average speed of 12.7 mph (Clark et al., 2007).

Given standard initial values from the literature, an additional MPG assumption based on bus age is made.

Figure 9 shows that the NF and NF hybrid's MPG decreases with age based on raw data. These data show that the NF's fuel economy decreases anywhere from 0 to 11 percent a year. If one calculates the NF's total MPG percent difference from year 0 to 10, the bus fleet loses efficiency by 16%. Similar decreasing fuel economy performance is observed with the NF hybrid. From bus declining fuel economy performance with age, the fuel economy is set to decrease by a conservative 1% per year, yielding the following model,

$$mpg(A_j) = mpg(0) - A_j \cdot 1\%mpg(0)$$

The fuel economy of both NF and NF Hybrid decreases by 1% a year. The decrease in MPG is better illustrated by the following figure.

Figure 11: Fuel Economy Model based on NF and NF Hybrid

4.5.5 Road Call Model ($rc(A_j)$)

The literature review discusses road calls and their impact on transit fleet operations and passengers. Based on Laver's et al. (2007) number of road calls with age, RCs per mile estimates are extrapolated. Figure 2 indicating road calls per mile has been extended to the bus's maximum age of 30 years. The monetary cost of road calls is quantified by King County's data. The last element needed to complete RC quantification is the number of passengers affected per road call.

On average, a bus is driven with 8.8 passengers (Davis et al. 2009). These passengers wait approximately thirty minutes from average headways of KC's transit system (King County Metro Transit, 2008). The passenger's value of transit waiting time applied is \$23.67 per hour based on US DOT (1997) figures and adjusted for inflation (BLS, 2011). When passenger waiting cost is compiled, it is illustrated by the following table.

Table 7: Passenger Cost per Road Call

Category	Value
Number of Passengers per Bus (# of Passengers)	8.8
Waiting Time (hrs)	0.5
Value of Transit Waiting Time (\$/hr)	23.63
Total Cost = Number of Passengers x Waiting Time x Value of Waiting Time	
Total Cost = $8.8 \times 0.5 \times 23.63$	
Total Cost = \$103.97	

Coupled with transit's road call cost of \$137.78 from Table 3, the total cost per RC amounts to \$241.75. This cost is now paired with frequency of road calls with age estimated by Figure 2. The additional cost of road calls to bus fleet operations is seen with the following figure.

Figure 12: Total Road Call Cost to a Bus with Age ($rc(A_j)$)

This road call model is applied to observe the impact on the model's investment decisions.

4.5.6 Utilization ($u(A_j)$)

This model's average utilization is based on the New Flyer's eleven years of data where the conventional bus is driven 31,890 miles. This value is used for the conventional and hybrid vehicles to directly compare total costs. An additional assumption of decreased utilization with age is tested, which has been observed from KC's fleet.

The decreasing utilization function was calculated with KC's maximum and minimum amount of miles traveled with NF data. The slope was calculated from these two extremes using the maximum bus life of 31. This

amounted to $(36,543 - 28,397)/31$ equaling the slope of 263, meaning the utilization decreases by 263 miles per year from the initial 36,543 miles operated per year. For reference, the average utilization of 31,890 used previously is reached at year 18 of the model. This curve is seen in the following figure.

Figure 13: Modeled Utilization Functions

4.5.7 Procurement Costs (v)

The most recent literature that has sixty foot articulated bus prices is TCRP report 132, edited by Clark et al. (2009). The 'medium' cost of purchasing diesel and hybrid buses was shown to be \$403,000 and \$663,000, respectively, therefore, these values are used.

FTA's capital assistance of up to 80% of the capital costs is also applied to test its impact on the average bus replacement age (FTA, 1992; Mathew et al., 2010). 40% and 80% capital cost assistance percentages are applied to the model for the sensitivity analysis.

4.5.8 Salvage Value (s & $sf(A_T)$)

Decommissioning a bus is costly. External markings and internal equipment must be removed which requires time, resources, and money to perform (KC, 2011). Complicating matters, a buyer must be found that wants to purchase a 15 year old bus (on average). The low demand for an old bus greatly reduces any revenue generated from a bus sale. Additionally, the literature highlights that money made from a single bus that exceeds \$5,000 is required to be reimbursed to the FTA if FTA's capital assistance funds were used (Laver et al. 2007), which could make for complicated forms and additional administrative costs. After discussions with KC (2011) and reviewing the literature, a value of \$1,000 is awarded with selling one bus.

However, on year 61 of the model the salvage value of \$1000 may not be a realistic value, especially if a two year old bus is sold. A linear function is used to determine the salvage value based on purchase cost, salvage value,

and the maximum life of a bus. The final salvage value is determined by the following equation.

$$sf(A_T) = v - A_j * (v - s)/31$$

This is graphically represented in the following figure.

Figure 14: Final Salvage Value ($sf(A_T)$) for NF and NF Hybrid

To ensure the validity of the final salvage value assumption, the model is also tested where *any* salvage of the bus is \$1,000. This test requires that the shaded summation is eliminated in the objective function of this replacement model.

4.5.9 Diesel Price (*d*)

The current US diesel price is applied as 'baseline' conditions, which is \$3.99 per diesel-gallon (AAA, 2011). To model a high diesel price, the most recent peak of \$4.85/gallon during the summer of 2008 is used (AAA, 2011).

4.5.10 Emission Output and Price (*eps*, *em*(*A_j*), *ec*)

The life cycle analysis studies estimated a production and salvage emissions of vehicles ranging between 8-9 and 13 CO₂ tons for sedans and sport utility vehicles (SUV), respectively. Their emissions output per weight are illustrated with the following figure.

Figure 15: Emissions Production and Salvage Cost of Vehicles with respect to Weight

To the best of the author's knowledge, there are no bus production emissions studies, therefore, an estimate on the bus manufacturing cost is necessary.

The *eps* estimate of buses is made from a ratio of CO₂ output per weight. The articulated sixty-foot bus weighs 44,000 lbs, where a standard sedan and SUV are 3,500 and 5,400 lbs respectively. The ratio of CO₂ tons per weight of the sedan and SUV are 0.00243 and 0.00239, respectively. Because of the SUV's greater weight and lower ratio implies a greater similarity between the bus and SUV. The SUV's ratio is used to directly calculate the *eps* of the bus. The emissions cost to purchase a bus is 105 tons or

$$eps = 105 \text{ CO}_2 \text{ tons}$$

In addition to *eps*, there are CO₂ emissions associated with bus usage. This value simply equals the CO₂ released when a gallon of diesel is burned. Using standards from the EPA, the combustion emissions of one gallon of diesel fuel is 0.011 CO₂-tons or

$$em(A_j) = 0.011/mpg(A_j)$$

Because CO₂ has been projected to negatively impact the economy, a cost of emitting carbon is applied. Tol (2005) conducted a meta-study on the social cost carbon. Based on numerous publications' estimates, he calculated an average social cost of carbon of \$93/ CO₂-ton. For simplicity, low and high costs of carbon applied in this model are \$0 and \$100/ CO₂-ton, respectively.

4.5.11 Model and Scenario Setup

This bus replacement model intends to minimize costs of replacement over a 61 year time horizon. The model optimizes costs with the integer program using excel's Solver package. Based on cost models such as O&M, utilization, fuel, and other factors, costs are calculated in an excel spreadsheet. Results then provide information how to best manage a bus fleet.

The bus fleet is assumed to consist of the same single bus. Therefore, the best replacement policy is made for this single bus over the 61 year time period. Impacts of market conditions and other factors on total costs and optimal replacement age are tested with a sensitivity analysis. Cost and elasticity differences from the sensitivity analysis are amplified to help fleet managers make optimal replacement decisions.

First the NF, then NF hybrid is analyzed. Within each bus analysis, diesel prices, emissions, and O&M costs are varied to compare economic impacts. Other factors such as FTA's capital assistance program and the decreasing utilization function are also discussed. Then, these two vehicles are directly compared, to identify if hybrids make economic sense like the literature observes in certain situations.

5.0 Results and Analysis

The New Flyer diesel and diesel-hybrid sixty-foot articulated buses are tested as if operating in a real fleet situation using Excel's Solver package augmented by Frontline Systems.

5.1 New Flyer (NF)

First, a breakdown of costs is presented. The costs are calculated from running the model to the horizon period T . Total costs are then summed over the entire period and broken down by type, shown below.

Figure 16: NF Cost Breakdown for Baseline Conditions from Replacement Model for Entire Horizon Time, T

Overhead and Maintenance (O&M) costs represent the largest proportion of total costs. Fuel costs represent the next highest proportion of costs. These

proportions should be kept in mind when analyzing impacts of costs and changes in optimal replacement ages.

5.1.1 NF Forced Replacement Age Effects

First the impacts of constrained budgets are considered, where replacement decisions forced before or after the optimal replacement age.

The forced replacement age a is imposed on the model two, four, and six years before and after that optimal age. The total costs per mile of the forced replacement age are compared with the optimal replacement age given baseline conditions across the horizon time T . These values are calculated and are assembled seen in the following figure.

Figure 17: Forced Replacement Ages based on Optimal Replacement for NF (B conditions). Star Indicates Optimal Replacement Age.

In Figure 17, when the line moves up the y-axis there is a greater total cost difference relative to baseline conditions of modeled total bus operational costs. The x-axis indicates the age of bus replacement age where the star indicates the optimal replacement age under baseline conditions. Figure 17 illustrates the results of forced bus replacement before and after the optimal age, which in this case is 16.7 years. For example, if the forced bus replacement age is 22 years, total costs of fleet operation should increase by ~0.7% relative to the baseline's optimal replacement age.

The most striking feature of the curve's trend is the percent cost differences when the bus is replaced earlier than optimal. The slope of the curve before the optimal replacement age is greater than the slope after. This means that there is a greater cost of replacing earlier than later. For instance, selling the bus earlier requires the model to purchase more expensive buses across the horizon time T . This increased slope before the optimal replacement age illustrates that extending the life of a bus is generally a better economic decision than selling earlier.

Introduction of the extreme or X scenario (high diesel prices of \$4.85/gallon, high CO₂ emissions costs \$100/CO₂-ton, and 25% increased O&M costs) results in significantly higher bus total cost per mile values. When the

baseline (B) and extreme scenario (X) are combined on the same figure, further conclusions are drawn.

Figure 18: Percent Total Cost Difference of Baseline (B) vs. Extreme (X) Scenarios for NF. Star Indicates Optimal Replacement Age.

First, Figure 18 shows that the extreme scenario’s optimal replacement age shifts to the left. This means that with higher market prices and fleet costs, a fleet manager should replace a bus earlier than one would under ‘baseline’ or lower price conditions. Like the previous curve in Figure 17, there is still a greater cost of replacing a bus earlier than is optimal. This point is also illustrated with the percent increase of total cost per mile with respect to the optimal replacement scenario, shown in the following table.

Table 8: Percent Cost Increase of Early or Late Replacement from Optimal for NF.

Scenario	-6	-4	-2	Optimal	2	4	6	Years from Optimal
B	2.38%	0.88%	0.15%	0.0%	0.19%	0.45%	0.89%	% Increase
X	3.23%	1.11%	0.22%	0.0%	0.21%	0.68%	1.18%	of Costs

The percent cost increase from replacing the bus earlier than optimal is more than double that of a delayed replacement, except for two years before and after the optimal time. However, there are small emissions benefits to be had from early bus retirement.

By replacing the bus slightly earlier than optimal, a maximum reduction of 0.23% emissions can be saved. Percent emissions changes shown in Table 9 indicate that when a replacement decision must be made, it is environmentally friendly to replace a bus at its optimal time.

Table 9: Emissions Cost or Savings from Early or Delayed Vehicle Replacement

Average Age of Replacement	% Emissions Change from Optimal
11	0.07%
13	-0.09%
15.0	-0.23%
16.7	0.00%
19	1.30%
21	0.98%
23	1.40%

Forcing the model to replace a bus earlier than optimal results in worse economic conditions, but is more environmentally friendly, while delayed replacement is observed to be the better economically. Now the impacts market changes and policies are modeled.

5.1.2 NF Market Impacts

Changes in market impacts are illustrated by calculating the percent changes of the scenario's summed total costs over the horizon time T relative to the baseline scenario. This is calculated by the formula:

$$\text{Percent change (\%)} = (\text{market impact scenario cost}) / (\text{baseline cost}) - 1$$

The percent change with all scenarios relative to 'baseline' conditions is shown with the following table.

Table 10: NF's Discounted Sensitivity Analysis from Baseline

Cost Category	High Diesel (\$4.85/gal, HD)	High Emissions (\$100/CO ₂ -ton, E)	High O&M (25% O&M cost increase, M)	HD&E	HD&M	E&M	X
Total Cost (\$)	5.4%	7.6%	8.9%	12.3%	13.4%	15.2%	19.1%
Purchase Cost (\$)	0.0%	0.0%	5.0%	0.0%	5.0%	5.0%	5.0%
Salvage Revenue (\$)	0.00%	0.00%	0.34%	0.00%	0.34%	0.34%	0.34%
Fuel Cost (\$)	17.7%	0.0%	-0.6%	17.7%	17.2%	-0.6%	17.2%
O&M Cost (\$)	0.0%	0.0%	16.9%	0.0%	16.9%	16.9%	16.9%
Total Costs per Mile	5.4%	7.6%	8.8%	12.3%	13.3%	15.2%	19.1%

Notice that each scenario imposes higher total costs relative to baseline. The higher positive percent value indicates that the bus is more expensive to

operate. For example, increasing diesel prices by 17.7% (3.99 to \$4.85/gal) in the HD scenario increased fuel costs by 17.7% and total costs by 5.4%. In the M scenario, O&M costs rise by 20.5% and total costs by 8.9%. Even though the O&M and fuel costs increase by a similar percentage of 21.6% and 20.5% respectively, O&M costs represent a more significant piece of total costs impacting the increase of total costs more. When increasing emissions cost from zero to \$100/CO₂ ton in scenario E, the total cost of operating the bus increased by 7.6%, indicating that the social cost of carbon would increase total costs.

There are also observed optimal replacement age differences due to market impacts, shown in the table below.

Table 11: Scenario's Effect on Average Replacement Age for NF

Scenario	High Diesel (\$4.85/gal, HD)	High Emissions (\$100/CO ₂ -ton, E)	High O&M (25% O&M cost increase, M)	HD&E	HD&M	E&M	X
Average Age of Replacement (Years)	16.7	16.7	16.7	15.3	16.7	15.3	15.3

The M scenario moved the optimal replacement age from baseline's 16.7 to 15.3 years. The HD and E scenarios did not change the average replacement age of 16.7 years. The higher diesel prices would push optimal replacement

earlier, but requires diesel prices as high as \$5.40 per gallon. The fuel economy decreases with increased bus age, meaning more fuel must be bought and thus the fuel costs increase.

A cost of emissions has no effect on the optimal replacement age. The increased purchase cost from the purchase/salvage emissions lengthens the time of replacement. However, because the bus has worse fuel economy with age, thereby increasing costs, the production/salvage and operational emission costs offset each other and thus negate any effect on the optimal replacement age. As is shown later, when the purchase price is greatly increased or decreased, there is a large impact on optimal replacement.

5.1.3 FTA Capital Assistance and Replacement Age

Capital assistance also significantly changes the average replacement age. With 40% and 80% capital assistance policies, optimal bus replacement becomes 12.5 and 6.9 years, respectively. These results compared with flat utilization's B and X scenarios show how purchase assistance greatly affects total cost per mile and average age of replacement. Figure 19 shows that the FTA assistance clearly reduces average age of replacement. The optimal replacement age of 12.5 years with the 40% assistance is very close to the FTA's 12 year minimum.

Figure 19: Percent Cost Difference from Optimal of NF for B, X, and FTA Assistance. Star indicates Optimal Replacement Age.

If the FTA used a lower maximum assistance percentage, it is feasible that more agencies could be awarded funds while still meeting minimum replacement age objectives. In any case, it is clear that the 80% capital assistance subsidy pushes the optimal replacement age well before the 12 year minimum.

5.1.4 Decreasing Utilization and Replacement Age ($u(A_j)$)

When the decreasing utilization curve is employed, the replacement age changes significantly. Under baseline conditions, the optimal replacement age for decreasing utilization with age becomes 18 years, as opposed to 16.7 years with flat utilization. Given that most buses are used less over time, fleet agencies may be salvaging buses too early, thus increasing costs. Further, the national average replacement age of buses is 15.1 years. According to this model, agencies are scrapping buses 2.9 years too early. Lastly, it is shown that early replacement costs more than delayed replacement, which adds reasons to why transit agency bus replacement is not optimal. Next the inclusion of road call costs and their impacts are investigated.

5.1.5 Road Calls Scenario

When additional agency and passenger cost of road calls are integrated into the model there are slight cost differences, shown by the following figure.

Table 12: Discounted Percent Change from Baseline to Road Call Cost Scenario

Cost Category	% Change
Total Cost (\$)	0.95%
Purchase Cost (\$)	0.0%
O&M Cost (\$)	2.35%
Fuel Consumption (gallons)	0.00%
Total Costs per Mile	0.95%
CO ₂ Emissions (tons)	0.0%
Average Replacement Age	0.0%

Total costs rise by a percentage point while the O&M cost category rises by 2.35%. There is no change to the optimal replacement age with added costs. The added cost of road calls do not significantly increase total costs. More discussion on this result is in the discussion and limitations sections.

5.2 New Flyer Hybrid

The NF hybrid is tested in a similar fashion as the conventional NF. However, the NF hybrid's different O&M and fuel economy characteristics are applied.

These yield slightly different proportions of costs, presented below.

Figure 20: NF Hybrid Cost Breakdown for Baseline Conditions from Model for Entire Horizon Time, T

The O&M and purchase cost categories are of comparable percentages. The fuel cost proportion is significantly lower the O&M and purchase categories.

Lastly, compared with the NF, this bus type has a significantly higher proportion of purchase costs for the entire horizon period. These cost proportions provide fleet context as budget constraints and market impacts are modeled in the following sections.

5.2.1 NF Hybrid Forced Replacement Age Effects

The replacement curve of the NF hybrid holds a similar trend as the NF, shown below.

Figure 21: Forced Replacement Ages based on Optimal Replacement for NF Hybrid

Again, it is more expensive to replace a bus earlier rather than later from optimal. Therefore, delaying bus replacement because of budget constraints is not as cost intensive as early replacement.

Combining the NF hybrid's B and X scenarios show similar trends as performed in the NF's analysis as are seen in the following figure.

Figure 22: Average Replacement Age, B and X scenarios for NF Hybrid.

Again, replacing a bus earlier or later from optimal results in greater percent cost differences. This can also be seen in tabular form between the B and X scenarios, shown in the following table.

Table 13: Percent Cost Increase of Early or Late Replacement from Optimal for NF Hybrid.

Scenario	-6	-4	-2	Optimal	2	4	6	Years from Optimal
B	2.85%	1.17%	0.32%	0.0%	0.01%	0.17%	0.51%	Increase
X	3.66%	1.44%	0.36%	0.0%	0.11%	0.40%	0.85%	of Costs

With a forced replacement age before optimal, the model must buy more buses in its horizon time, increasing total costs. In any case, there are still

greater cost and emissions advantages toward delaying replacement rather than with early replacement.

5.2.2 NF Hybrid Market Impacts

The percent change from the NF hybrid's baseline based on each scenario is displayed in the following table.

Table 14: NF Hybrid's Discounted Sensitivity Analysis from Baseline

Cost Category	High Diesel (\$4.85/gal, HD)	High Emissions (\$100/CO ₂ - ton, E)	High O&M (25% O&M cost increase, M)	HD&E	HD&M	E&M	X
Total Cost (\$)	3.6%	5.2%	9.2%	8.4%	12.2%	13.5%	16.2%
Purchase Cost (\$)	0.3%	0.0%	4.2%	0.3%	4.6%	4.2%	4.6%
Salvage Revenue (\$)	-2.7%	0.0%	-10.0%	-2.7%	-13.1%	-10.0%	-13.1%
Fuel Cost (\$)	17.7%	0.0%	-0.6%	17.7%	17.2%	-0.6%	17.2%
O&M Cost (\$)	-0.3%	0.0%	16.9%	-0.3%	16.6%	16.9%	16.6%
Total Costs per Mile	3.6%	5.2%	9.2%	8.4%	12.2%	13.5%	16.2%
CO ₂ Emissions (tons)	-0.2%	0.0%	-0.8%	-0.2%	-0.9%	-0.8%	-0.9%

The impact of market and operational changes of the NF hybrid are of similar magnitude to the NF. The M scenario had the largest impact, which is indicated by a 9.2% total cost increase. When maintenance costs increase by 25% in scenario M, the model minimized costs by operating young buses, thus salvaging at an early age. The result of increased replacement decisions with the time horizon T correspond to more frequent purchases decisions indicated by the 4.2% purchase cost rise in the M scenario.

Other observations of the sensitivity analysis show that the NF hybrid is less sensitive to diesel and emissions price increases than the NF. In the HD and E scenarios, total cost differences of the NF hybrid increased by 3.6% and 5.2% compared with the NF's scenarios of 5.4% and 7.6%, respectively. The scenarios show that the NF hybrid's better gas mileage would save more money if prices were to increase.

Lastly, the NF hybrid's CO₂ emissions decrease by 0.8% when O&M costs are elevated, but in the same situation, the NF saw no significant change. The NF hybrid emits less CO₂ from better fuel economy, but 105 CO₂ tons are still emitted when a bus is purchased. If one looks at total emissions across the *T* horizon, the NF hybrid's proportion of procurement emissions is higher than the NF's. Higher maintenance costs increase bus turnover, which releases more CO₂ emissions. But at the same time, replacing the bus earlier means that there are fewer years of operating a low MPG bus. Hence, less operating emissions decreases total emissions by 0.9% relative to baseline. In summary, hybrid bus emission output is sensitive to more frequent replacement.

Higher diesel prices and maintenance costs had an effect on average replacement age, while emissions costs did not. A table of optimal

replacement age with respect to scenarios to show these differences is presented below.

Table 15: Scenarios' Effect on Average Replacement Age for NF Hybrid

Scenario	High Diesel (\$4.85/gal, HD)	High Emissions (\$100/CO ₂ - ton, E)	High O&M (25% O&M cost increase, M)	HD&E	HD&M	E&M	X
Average Age of Replacement (Years)	18.3	18.0	18.3	16.7	18.0	16.3	16.7

When the cost of diesel is incorporated, the bus should be replaced 0.3 years earlier than in baseline conditions.

The relative optimal replacement age difference between B and M scenarios is noticeable when comparing bus types. Inflated O&M costs move optimal ages for NF and NF hybrid from 16.7 to 15.3 and 18.3 to 16.7, respectively. From the higher difference in optimal ages, the NF hybrid optimal replacement age is more sensitive to increased O&M costs.

5.3 NF vs. NF Hybrid

The differences of costs and replacement times between the NF and NF hybrid are now identified and highlighted. However, the following conclusions are made without taking into account route level differences such as average speed, number of stops, passengers carried, and topography among other factors. Hence, since the two bus types are deployed in different routes,

caution should be used when drawing any conclusions from the cost comparison. In particular, the following results should not be used to justify buying conventional instead of hybrid buses.

5.3.1 Cost Comparison

First, the NF and NF hybrid's baseline scenarios are compared for major cost differences of fleet operation, as shown in the following table.

Table 16: NF and NF Hybrid's Baseline Scenario Comparison of Discounted Average Yearly Costs

Cost Category	NF	NF Hybrid	% Difference
Total Cost (\$)	24,676	32,032	23%
Purchase Cost (\$)	8,357	13,177	37%
Fuel Cost (\$)	6,545	5,549	-18%
Fuel Consumption (gallons)	8,938	7,602	-18%
O&M Cost (\$)	9,802	13,349	27%
Total Costs per Mile (\$/mi)	0.77	1.01	23%
CO ₂ Emissions (tons)	106	91	-16%
Average Replacement Age (yrs)	16.7	18.3	12%

The 23% increase in total cost per mile of the NF hybrid is much higher than the NF. NF hybrid outperforms the NF only in the fuel cost category.

However, this cost gain is meager compared to the lower O&M and purchase cost of the NF. The O&M and purchase costs amount to a large percentage of the total costs, shown in

Table 17.

Table 17: NF and NF Hybrid's Emissions Scenario Comparison of Discounted Average Yearly Costs

Cost Category	NF	NF Hybrid	% Difference	NF % of Total Costs	NF Hybrid% of Total Costs
Total Cost (\$)	26,715	33,784	21%	-	-
Purchase Cost (\$)	8,357	13,177	37%	31%	39%
Salvage Revenue (\$)	-29	-43	33%	0%	0%
Fuel Cost (\$)	6,545	5,549	-18%	25%	16%
Fuel Consumption (gallons)	8,938	7,602	-18%	-	-
O&M Cost (\$)	9,802	13,349	27%	37%	40%
Total Costs per Mile (\$/mi)	0.82	1.04	21%	-	-
CO ₂ Emissions (tons)	97	81	-16%	-	-
Emission Cost (\$)	1,892	1,622	-16%	8%	5%

Since the NF hybrid has larger purchase and the O&M costs than the NF, to become cost competitive, any cost advantage of the NF hybrid must be significantly high. However, the hybrid does do well in emissions savings.

The NF hybrid emits 16% less CO₂ emissions, meaning it saves 16% emissions costs shown in Table 17. However, this emission cost savings only equates to a total cost savings of 3%, because the proportion of emissions cost is low. NF hybrid's O&M and purchase costs are too great to economically compete against the NF.

Finally, the total cost per mile figures between the two buses are shown in the following figure.

Figure 23: Average Age of Replacement between NF and NF Hybrid, Baseline conditions. Star Indicates Optimal.

The cost per mile differences show that it is much more economical to operate the NF, regardless of when the buses are salvaged. Is there, however, a point when gasoline costs are high enough to make NF Hybrids economical?

5.3.2 Economic Breakpoints for the NF Hybrid

The comparison between the NF and NF hybrid should be taken with a grain of salt because of lack of route and average speed data. However, this section discusses the breakpoint where the hybrid becomes economical. This is when the NF and NF hybrid's total costs equal each other at some value of a cost parameter. After modifying gas prices using a binary search method, the point where the NF hybrid becomes economical against the NF is when diesel

reaches \$35/gallon! This price is hardly feasible even in terms of the recently higher gas prices. The emissions price must also be outrageously high for the NF hybrid to become economical. Part of the explanation is the relatively high discount rate of 9.6%. However, decreasing the rate to the current US treasury's 20 year yield of 4.27%⁵ only helps the hybrid's economy of scale marginally, in which the breakpoint price of diesel is \$29/gallon.

The purchase price breakpoint for when these vehicles become economical is also investigated. The higher O&M costs of the NF hybrid has a great affect on total costs, therefore the procurement cost had to be significantly lower than its original. The NF hybrid must be \$313,000, 52% lower than its current price to reach the economics of scale. This purchase price is also \$90,000 less than the NF. Next the O&M cost reduction for the NF hybrid to be cost competitive is investigated.

For context, the year 0 O&M costs (baseline conditions) of the hybrid are already 18.5% higher than the NFs. To find the breakpoint, the total O&M costs had to be reduced by 54% for the NF hybrid to become competitive. The hybrid clearly needs purchase incentives and/or better build quality (with

⁵<http://www.treasury.gov/resource-center/data-chart-center/interest-rates/pages/textview.aspx?data=longtermrate>, "Daily Treasury Long Term Rate Data", US Treasury Accessed April 13, 2011.

lower O&M costs) to compete against the conventional diesel bus. There have been recurring discussions where improvements in technology may drop purchase prices (Laver et al., 2007; Chandler & Walkowicz, 2006), which would improve HEB competitiveness. Or if HEB purchase prices become comparable to diesel buses, then hybrid procurement is justified. However, because route information and average speeds are not supplied, the high cost of diesel, decreased maintenance costs, or subsidized purchase cost to justify using a hybrid bus, may be significantly lower than the values found.

5.4 Cost Elasticity

The impact of rising diesel prices, increased emissions costs, and increased maintenance costs on total costs has been shown with the previous sensitivity analysis. These costs relative to each other had different impacts on total costs. One can more precisely forecast the effect of rising prices/costs by calculating the cost elasticity. This is done by comparing the percent change of total costs with the percent change of cost increase.

Cost Elasticity =

[(Increased Cost Scenario Total Cost/ Baseline Total Cost) -1] / [(Increase Cost Amount /Baseline Cost Amount) -1]

Cost Elasticity = %ΔTotal Costs / %ΔParameter Cost

For example, when the diesel prices are increased from 3.99 to 4.85 dollars per gallon, there is a 21.6% increase of price. When comparing the increased diesel price scenario's total costs with the baseline scenario, there is a 5.4% increase. Therefore, the cost elasticity is 0.25. Diesel price, emissions cost, and maintenance cost elasticities are presented in the following table.

Table 18: Cost Elasticities for Scenarios

	High Diesel (3.99 to \$4.85/gal)	High Emissions (0 to \$100/CO ₂ -ton)	High Maintenance (25% increase)
New Flyer	0.25	N/A	0.36
NF Hybrid	0.17	N/A	0.37

These numbers indicate that when prices or costs change, total costs increase by some amount. For example, if diesel prices increase by 1%, total costs of bus operations will increase by 0.25%.

When the diesel elasticities are compared, the NF hybrid is less sensitive to diesel price increases than the NF. The NF hybrid has better gas mileage, therefore when diesel prices increase, the hybrid requires less more expensive fuel to purchase, which results in lower total cost increases compared with the NF.

The maintenance cost elasticities are higher than the diesel's, which means that higher maintenance costs have a greater impact on total costs. This

corresponds to Figure 16 and Figure 20 of the NF and NF hybrid bus cost breakdowns, where the total contribution of maintenance costs are at least 10% higher than that of fuel costs. Essentially, a fleet manager should worry more about increased maintenance costs because they would increase total costs more than higher fuel price.

5.5 Replacement Age Elasticity

The sensitivity analysis presented in the previous sections brings light to how changes in fleet costs affect the optimal replacement age. A sensitivity summary is illustrated with the elasticity of optimal replacement age due to changes in total costs. This is performed by comparing the percentage change in optimal replacement age with the percent cost change with respect to baseline, or

Replacement Age Elasticity =

[(Optimal Scenario Replacement Age / Optimal Baseline Replacement Age)-1] /

[(Scenario Cost / Baseline Cost) - 1]

Replacement Age Elasticity = (%ΔAge / %ΔCost)

By performing these calculations with all scenarios, the following replacement elasticities are calculated.

Table 19: Replacement Age Elasticities Compared to Baseline Conditions

	Bus Type	HD	E	M	Road Call Cost	40% Cap. Assist.	80% Cap. Assist.
Elasticity	NF	0	0	-0.82	0	-1.73	-1.78
(% Δ Age/% Δ Cost)	NF Hybrid	-0.49	0	-0.90	0	-1.51	-1.57

For example, if the NF hybrid's O&M costs force total costs to rise by 1% from baseline, the optimal replacement age should be dropped by 0.9% (M Scenario) to maintain minimum total fleet costs.

Table 19 shows that the NF hybrid is more sensitive to maintenance cost increases than the NF. There is not impact of the cost of RCs the optimal replacement age.

The '40% Cap. Assist.' label means that 40% of the bus purchase price has been subsidized. This corresponding elasticity figure means that if the FTA capital assistance rises by 1% (In other words, decreases purchase price by 1%) the replacement age should decrease by 1.73% to minimize total costs. One can see that the NF's optimal replacement age is more sensitive to capital assistance than the NF hybrid because the hybrid has higher O&M costs. Also, doubling the percentage capital assistance subsidy only marginally increases the optimal replacement age elasticity, meaning that an increased purchase subsidy has a decreasing effect on the change of optimal replacement age.

5.6 Summary of Results

The model has highlighted the impacts of bus cost and market changes that may occur for bus fleet operations.

- The optimal replacement age for baseline conditions of the NF and NF hybrid is 16.7 and 18.3 years, respectively.

- When a bus is replaced earlier or later than optimal, larger total fleet costs result.
- Delayed rather than early bus replacement is less detrimental to total costs. Further, delayed bus replacement results in increased of total CO₂ emissions.
- When O&M costs rise by 25%, the average replacement age to minimize cost should be earlier than the baseline condition's replacement age.
- Increased diesel prices had very minor optimal replacement age effects, significantly less than rises in O&M costs
- Increased emissions costs had no impact on the optimal replacement age.
- When the decreased utilization function is applied to the bus fleet, the bus should be kept longer than baseline's optimal replacement age.
- Purchase subsidies have the greatest effect on the average replacement age. For example, when subsidies decrease the NF hybrid's purchase by 1%, the replacement age should be lower than baseline condition's optimal replacement age by at least 1.5%.

- More information of the route and average speeds are required to justify whether the hybrid bus is more cost effective than the conventional bus.

5.7 Discussion

Specific points of the methodology and analysis are discussed in this section.

Assumptions are tested for validity. O&M costs and potential impacts on this cost category are extrapolated. Lastly, market impacts, federal policies and their implications are discussed.

5.7.1 Validity of Assumptions

The assumption of no initial buses in the fleet requires the model to purchase a bus at time period 0. This initial condition may influence the modeled bus average replacement age. To test this assumption, the initial condition is modified. A 6, 12, and 18 year old bus is assessed at time period 0 and average replacement age changes are observed given baseline conditions for NF and NF hybrid buses. Results in Table 20 show that there is not a significant difference of average replacement ages if the initial condition is modified.

Table 20: Initial Condition Assumption Test

Bus Initial Age (yrs)	Average Replacement Age (yrs)
--------------------------	----------------------------------

	NF	NF Hybrid
0	16.7	18
6	17	18.7
12	16.5	19
18	17.3	19.3

The validity of the final salvage value assumption is also tested. For NF's baseline conditions, the shaded summation expression is removed meaning *all* salvage decisions become a negative cost of \$1,000. When a constant salvage cost assumption is implemented with baseline conditions, the average replacement age is 16.3 years, which is earlier than the baseline scenario's 16.7 year average replacement age. This is explained by bus salvage decisions on the horizon time. Replacing a bus is costly, therefore the model minimizes total costs by shortening or extending the bus life within the bounds of the horizon time. If this final salvage assumption was not implemented, the model would be bias bus replacement. This test shows that the final salvage assumption is valid.

5.7.2 Costs

According to Figure 5, O&M costs represent the largest proportion of KC's total fleet costs, therefore making efforts to reduce these should result in the biggest benefit. Unfortunately, O&M costs are complex.

O&M costs include maintenance costs. Within maintenance costs there are typically two types: preventative maintenance (PM) and unplanned. PM schedules may be performed less frequently to cut costs, but research has shown that this policy may eventually lead toward more road calls, increasing unplanned maintenance costs (Laver et al., 2007). From surveys of American transit agencies, bus fleets with the most rigorous PM schedules showed the lowest bus deterioration and lowest rise in maintenance costs with age (Laver et al., 2007). Implementation of rigorous PM schedules may have numerous positive fleet outcomes and should be heavily considered toward reducing fleet deterioration.

Most of the research to reduce fleet costs has been in rehabilitating buses to extend their life. From previous analyses in this thesis shown in Figure 16 and Figure 20, purchase costs are the second largest contributor to total costs which means there is cost savings potential. Khasnabis et al. (2002) performed an economic analysis to test the cost savings merits of rehabilitation based on a study by Bridgeman (1983). The study found that by performing restoration that extends the bus life, the total life cycle costs are less than purchasing a brand new bus. Since purchase costs make up a significant part of total costs, performing bus restoration may save money for transit agencies overall.

5.7.3 FTA Capital Assistance

Results from the model indicate that agencies may be given too much money to purchase buses. Given baseline conditions, the optimal replacement age for the NF is 16.7 years. If the purchase price drops by 80% with capital assistance, the optimal replacement age drops to 6.9 years, which is even below FTA's 12 year minimum bus retention age. But when 40% is given, the optimal replacement age drops to only 12.5 years. If the FTA reduced their capital assistance to 40%, they could give more money to larger quantity of transit agencies.

However, transit agencies can use money on any 'capital' improvements. They may use the money for additional bus stops, improving their maintenance facility, or other projects. Because the transit agencies must spend money on other improvements besides buses, they may be receiving the right amount of money. More information on how money is allotted for capital improvements is required to confirm whether too much or too little money is given out to transit agencies by the federal government.

5.7.4 Road Calls

Road calls have been examined with an average passenger bus load. If a bus breaks down during peak hours fully loaded with passengers, a greater

sum of passenger's time summed thus resulting in higher costs. If road call data could be distinguished by time of day, a more accurate model could be created based on expected number of passengers effected resulting in better RC cost estimates.

Furthermore, the amount of road calls per bus type may vary. Some buses may be 'lemons', meaning they have more bus repair problems and issues (Laver et al., 2007). This is confirmed by reviewing KC's RC data by bus type. Within these data, some bus fleets have more RCs per miles driven. The variability in RCs by bus type may vary the total costs of bus operation thereby altering the optimal bus replacement age.

5.7.5 Hybrid Technology

Hybrid buses have better gas mileage in transient low speed environments reducing fuel costs, but hybrids have higher O&M costs typically from greater diagnostic equipment to repair the battery systems. In this comparison, it was shown that hybrid bus technology is not effective to reduce total fleet costs. To become economical, hybrids require procurement incentives and/or built with high engineering quality. However, this comparison does not control for the route, elevation change, or average speeds. This comparison between conventional and hybrid buses may not be fair. The literature has shown that

hybrids can have a competitive advantage over conventional buses in certain routing situations. More data is required to make final conclusion on which bus is 'better'. However, hybrids are still effective from an environmental point of view because of their better fuel economy.

5.8 Limitations

Limitations of data used and factors affecting the model's conditions are discussed. Future uncertainty is a large but natural limitation of modeling. Limits in O&M cost data and internalizing all emissions costs of buses are further discussed.

5.8.1 Future Uncertainty

Future uncertainty of market conditions are a large limitation of this model. Diesel prices were assumed to be constant, but prices fluctuate widely based on market or even political factors. Take for example the oil embargo of 1970, which caused widespread American gasoline shortages and large monetary cost increases to citizens and businesses. There is no way to predict these events, but the sensitivity analysis in this thesis helps bring light to market changes.

Hybrid technology is likely to improve over time which would lower purchase costs for hybrid buses. These developments may also improve the

reliability of hybrids, which could reduce maintenance costs. But again, this future uncertainty is difficult to quantify and is disregarded in this study.

5.8.2 O&M costs

Overhead and maintenance costs integrate numerous different factors including administrative, facility, tire, and repair costs, to name a few. Further, maintenance costs vary depending on part warranty that is purchased. Warranty costs are included in the total O&M cost data provided by KC and may mask the actual costs borne to the transit agency.

Furthermore, a warranty is horizon dependent on a bus's age or mileage driven, meaning, at some point the bus repair costs must be borne to the transit agency. Unfortunately, this warranty horizon age and mileage are unknown.

5.8.3 Road Calls

The cost of road calls is estimated for the transit agency and extra passenger waiting time to wait for the next bus. The national average number of passengers per bus is used (8.8 passengers per bus). However, this number is calculated for forty foot conventional buses. Articulated 60' buses may have more passengers on average, and thus would increase the total passenger cost of road calls.

The passenger waiting cost also does not account for the impact of a road call during peak hours. An articulated bus has over 60 seats plus any standing passengers. If a fully loaded bus were to break down, there would be a significant increase of passenger cost due to road calls.

5.8.4 Emissions

Lastly, emissions externalities of buses are not being completely internalized in this thesis. In addition to CO₂, buses emit particulate matter, hydrocarbons, and other gases that harm the human respiratory tract. These gases have been studied to have social costs of ejection (Phelan, 1997) like studied for CO₂ based on inhalation quantities. If the social cost of these pollutants were included in this model, there would be a greater cost associated with burning diesel, thus operating buses. This more complete emissions cost integration may amplify the importance of using fuel efficient buses such as hybrids.

6.0 Conclusion

Transit agency bus fleet costs and characteristics have been shown to vary with age. Specifically, real-world data from King County Transit in Washington state show that overhead, maintenance, and road call costs rise as a bus ages whereas utilization decreases as a bus ages. These characteristics imply that there is an optimal replacement age that minimizes total bus costs. Real-world fleet data have been integrated into an integer programming model to determine this optimal replacement age. Further, the impacts of increased bus maintenance costs and changes in market conditions are also modeled.

It was found that early bus replacement (relative to the optimal replacement age) is more expensive in economic terms than late bus replacement. Delaying bus replacement approximately costs about half as much as an early replacement. This means that transit agencies with budget constraints which are unable to purchase new buses are only marginally increasing total costs in the short term. However, as agencies delay bus replacement, they increase CO₂ emissions emitted, because buses are shown to have decreased fuel economy as they age. To reduce CO₂ emissions, fleet

managers should replace at the optimal time or slightly earlier. In addition, this result assumes that passenger ridership is not affected by bus age.

When sensitivity analyses were performed, certain scenarios altered the optimal bus replacement age. High costs of CO₂ do not affect the optimal replacement time but high diesel prices can impact when buses should be replaced. Higher O&M costs significantly reduce the optimal replacement age. Therefore, if a bus becomes increasingly more costly to repair, it would be advisable to replace it earlier than projected to save money.

Hybrid buses have been compared with conventional buses but a direct comparison is likely to be unfair because cost data is drawn from different routes. Hybrid buses have been shown to be uneconomical despite significant savings in fuel and emission costs. The hybrid's high purchase prices and higher O&M costs relative to conventional buses are too large to make up for any fuel cost savings. But this thesis does not control for route or average speed information, which must be taken into account when making a direct comparison between bus types. However, from an environmental point of view, hybrid buses are better due to their increased fuel economy.

Elasticities have been calculated to provide information regarding how changes in market and fleet conditions impact replacement age and costs. The

hybrid bus is less sensitive to diesel price increases than the conventional bus and maintenance costs have a larger impact on total costs than diesel prices.

When age elasticities are compared, the conventional NF is shown to be less sensitive to higher O&M costs than the NF hybrid. This means that as a NF hybrid's O&M costs rise, the rate of its optimal replacement age decreases faster than the NF optimal replacement age. It was also shown that purchase subsidies have a highly significant effect on reducing optimal replacement age. The conventional NF was shown to be more sensitive to purchase subsidies relative to the NF hybrid.

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

7.0 References

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8.0 Appendix

	Year of Data	Age	Code	Units	Total Miles Driven	Total Fuel Consumption (gallons)	Fuel Economy (mi/gallon)	Fuel Cost (\$)	Fuel (\$/mi)	Mechanic Labor & Parts (\$/mi)	Mechanic Labor & Parts (\$)	Tire Cost (\$)
New Flyer	1999	0	0	185	4,234,915	1,029,310	4.11	545112	0.13	0.33	1,376,609	208,128
	2000	1	23	282	8,992,519	2,423,197	3.71	1747575	0.19	0.42	3,740,265	404,480
	2001	2	23	274	9,976,246	2,834,077	3.52	2361042	0.24	0.26	2,631,588	594,833
	2002	3	23	274	9,863,040	2,745,167	3.59	2165375	0.22	0.50	4,943,652	571,343
	2003	4	23	273	9,976,118	2,760,576	3.61	2976010	0.30	0.55	5,517,391	564,206
	2004	5	23	273	9,607,967	2,603,700	3.69	3843178	0.40	0.65	6,253,891	605,116
	2005	6	23	273	8,851,384	2,405,390	3.68	4647793	0.00	0.71	6,327,908	573,306
	2006	7	23	273	8,632,918	2,505,036	3.45	3256547	0.38	0.84	7,210,286	659,125
	2007	8	23	273	8,382,331	2,544,438	3.29	5881145	0.70	0.95	7,967,087	698,418
	2008	9	23	272	7,810,714	2,268,931	3.44	7089235	0.91	0.98	7,647,729	648,966
	2009	10	23	272	7,724,034	2,243,752	3.44	4683970	0.61	1.14	8,838,293	681,131
Average					8,550,199	2,396,689	3.60	3,563,362	0.37	0.67	5,677,700	564,459

New Flyer	Year of Data	Age	Paint, Body/Upholstery Costs (\$)	Bus Parts (\$)	Administrative Costs (Manager, Supervisors, Admins, Chiefs) (\$)	General Costs (Not Labor) (\$)	Total Costs (\$)	Cost/Mile (\$/mi)	Total Cost per Unit (\$/unit)	Yearly Mileage per Vehicle (mi/yr)
	1999	0	0	0	0	3,032,824	5,162,674	1.22	27,906	22,891
	2000	1	0	0	0	6,346,719	12,239,039	1.36	43,401	31,888
	2001	2	0	0	0	7,719,397	13,306,860	1.33	48,565	36,410
	2002	3	0	0	0	7,706,505	15,386,875	1.56	56,156	35,996
	2003	4	555,125	307,985	1,084,716	4,553,593	15,559,026	1.56	56,993	36,543
	2004	5	0	0	0	6,784,179	17,486,364	1.82	64,053	35,194
	2005	6	0	0	0	3,204,972	14,753,980	2.15	54,044	32,423
	2006	7	2,101,127	317,104	1,545,282	3,236,455	18,325,926	2.12	67,128	31,622
	2007	8	2,149,447	421,504	1,611,260	3,421,154	22,150,015	2.64	81,136	30,705
	2008	9	2,235,737	383,835	1,486,785	3,580,948	23,073,235	2.95	84,828	28,716
	2009	10	2,276,391	120,103	1,505,252	4,084,513	22,189,653	2.87	81,580	28,397
Average			847,075	140,957	657,572	4,879,205	16,330,332	1.96	60,526	31,890

	Year of Data	Age	Code	Units	Total Miles Driven	Total Fuel Consumption (gallons)	Fuel Economy (mi/gallon)	Fuel Cost (\$)	Fuel (\$/mi)	Mechanic Labor & Parts (\$/mi)	Mechanic Labor & Parts (\$)	Tire Cost (\$)
New Flyer Hybrid	2004	0	25	205	2,511,424	653,341	3.84	964,361	0.00	0.38	955,034	158,171
	2005	1	25	212	7,459,882	1,973,808	3.78	3,813,871	0.51	0.50	3,707,553	483,178
	2006	2	25/26	213	7,738,868	2,203,598	3.51	2,864,677	0.37	0.71	5,496,815	590,864
	2007	3	25/26	214	8,264,028	2,410,195	3.43	5,570,859	0.67	0.75	6,169,711	688,561
	2008	4	25/26	213	8,451,373	2,403,738	3.52	7,510,436	0.89	0.92	7,759,593	702,196
	2009	5	25/26	213	8,299,218	2,360,462	3.52	4,927,610	0.59	0.99	8,238,098	731,853
Average					7,120,799	2,000,857	3.60	4,275,302	0.51	0.71	5,387,801	559,137

	Year of Data	Age	Paint, Body/Upholstery Costs (\$)	Bus Parts (\$)	Administrative Costs (Manager, Supervisors, Admins, Chiefs) (\$)	General Costs (Not Labor) (\$)	Total Costs (\$)	Cost/Mile (\$/mi)	Total Cost per Unit (\$/unit)	Yearly Mileage per Vehicle (mi/yr)
New Flyer Hybrid	2004	0	0	0	0	1,773,315	3,850,881	1.53	18,785	12,251
	2005	1	882,175	1,056,061	1,018,459	2,701,127	13,662,426	1.83	64,445	35,188
	2006	2	1,639,341	241,747	1,174,898	2,901,278	14,909,620	1.93	69,998	36,333
	2007	3	1,684,914	326,412	1,225,062	3,372,870	19,038,389	2.30	88,964	38,617
	2008	4	1,750,779	389,450	1,420,084	3,874,668	23,407,206	2.77	109,893	39,678
	2009	5	1,782,615	111,947	1,269,098	4,388,673	21,449,894	2.58	100,704	38,963
Average			1,289,971	354,270	1,017,933	3,168,655	16,053,069	2.16	75,465	33,505