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Sustainability Issues in Benchmarking of Advanced Transit Bus Technologies

By

Tim S. Wong

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive, and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

2014

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Sustainability Issues in Benchmarking of Advanced Transit Bus Technologies

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Author's Declaration of Originality

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Abstract

From reduced costs to improved efficiency, fleet managers are constantly striving to improve their operations in their transit bus systems. Hybrid electric buses have gained prominence among transit agencies due of their potential for improving fuel economy, reducing costs and increasing reliability over the traditional diesel bus. The question which must be asked is, are hybrid electric buses the best choice for every city? Are there single or multiple solutions which can satisfy the current and future requirements of the transit bus industry? This thesis aims to combine previous research, statistical data and survey results into a multiobjective analysis to determine an answer to these questions. Current and future technologies will be compared with each benefit and downside discussed and scored. For transit agencies looking to justify the significant capital cost increase for new technologies, this research will form the basis for an informed decision.

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During the completion of this thesis, many thanks are owed to my supervisor, Dr. Edwin Tam for supporting me, my research, and my ostentatious ideas. Through my many years of musing, pondering, as well as discombobulated days in the University of Windsor, Dr. Tam has been consistent in his direction and funding when I have been paradoxical and impecunious.

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List of Abbreviations

APU: Auxiliary Power Unit

BAE Systems: British Aerospace Systems

BYD: Build Your Dreams

CARB: California Air Resources Board

CNG: Compressed Natural Gas

CW: Curb Weight

EV: Electric Vehicle

EGR: Exhaust Gas Recirculation

EPA: US Environmental Protection Agency

GVW: Gross Vehicle Weight

HEV: Hybrid electric Vehicle

KC: King City Metro

LCA: Lifecycle Analysis

LCC: Lifecycle Cost

LRT: Light Rail Transit

MBRC: Miles Between Road calls

MPG: Miles Per Gallon

NiMh: Nickel Metal Hydride

NiCd: Nickel Cadmium

NREL: National Renewable Energy Laboratory

NSW: New South Wales

NYCT: New York City Transit Authority

QC - Quality Control

STURAA: Surface Transportation and Uniform Relocation Assistance Act of 1987

SLW: Seated Load Weight

TTC: Toronto Transit Commission

USLCI: U.S. Lifecycle Inventory

ULSD: Ultra Low Sulfur Diesel

1 Introduction

The global trend of increasing oil prices has impacted many transit agencies. Over the past 5 years alone, the price of gasoline has increased almost 40 percent. This particularly affects transit agencies as fuel costs can represent 40% or more of the total operating costs per bus. In addition, transit as a transportation alternative is often perceived to be a preferred, sustainable means of travel. Moreover, transit systems often serve as a platform for new and emerging transit technologies and their applications. However, the benefits of various transit technologies, particularly from an environmental perspective, are often assumed to be preferable. Recent developments in some major transit authorities suggest that this might not be the case, or at least, the benefits must be traded off against other relevant factors. It is critical then to examine how bus technologies, both current and emerging, can affect transit operations in terms of sustainability, environmental, social and economic performance.

An example of the situation is the emergence of hybrid technologies for buses. These include battery-based hybrid buses, capacitor-based hybrid buses, as well as series and parallel hybrid powertrains. The Federal Transit Agency (FTA) and the National Renewable Energy Laboratory (NREL), among other independent researchers, have composed reports comparing their own fleets before, after, and during operation with and without hybrid buses. For some transit agencies, the choice of technology was clear but for many others, there are many factors which present a significant challenge in choosing the appropriate technology.

1.1 Hypothesis

The overall questions that arise from this research are:

1. Were buses implemented properly in their respective environments to maximize the benefits related to their technology?
2. What other factors are involved in the operation of a bus containing advanced technologies?
3. Are there novel or advanced technologies available today which can improve transit bus operations?

These questions are answered by comparing research and measured data of currently operating transit buses to other novel or advanced technologies such as electric buses. The hybrid bus has been used in many transit agencies thanks to their benefits, as well as their availability. In one case, the New York City Transit Authority (NYCT) directly compared their newly acquired

Daimler Orion VII Hybrid electric buses to their existing diesel buses and found significant cost savings within their operations (Barnitt, 2008). Multiple transit agencies had similar results as the NYCT and ordered hybrid buses as well.

Those who do not see the hybrid bus as an end solution can point to multiple cases where hybrid buses do not perform as expected. Most recently, hybrid buses have fallen out of favour with both the Toronto Transit Commission and the NYCT after experiencing major issues with their initial purchases. The TTC has gone so far as to remove the hybrid powertrain entirely from some of their buses, electing to operate them as diesel-only buses.

A transition from hybrid bus technology to fully electric buses may be a solution. This most recent development has buses running on electric power from its own batteries, charging up either every night or in-route. Electric buses have the potential for significant cost savings and social benefits.

Using measured data, past literature, and an analysis of available technologies, it is possible to determine the preferred, rational choice of technology for fleet upgrades. Whether the hybrid bus is the end solution, a stopgap technology to fully electric buses, or even other technology, it involves a rational decision making process to determine the preferred transit solution. This thesis demonstrates how to arrive at such a solution using an integrated decision making approach based on a multiobjective analysis with critical insights and assessments from the literature, industry and engineering reports, and expert survey results.

1.2 Research Thesis Structure

The remainder of this thesis contains:

1. A literature review in which past research papers and results were analysed and empirical data from transit agency pilot test programs were investigated.
2. An analysis of advanced transit bus technologies to find viable and important developments which can help transit agencies in their need to operate a fleet efficiently and cost-effectively.
3. The development of a multiobjective analysis utilizing linear scoring and weighting to determine the best combination of technologies.

The multiobjective analysis sought to answer which technology or combination of technologies is preferred in a public transit environment based on:

1. Financial costs associated with the operation, purchase and maintenance of transit buses.
2. Environmental emissions from different types of powertrain technologies, both from in-use and production emissions.
3. Feasibility of implementing a new transit bus technology from a time-cost and social perspective
4. Operations of each bus from the perspective of bus drivers and passengers on performance, noise and comfort.

The principle behind this analysis is to more objectively compare different technologies such that lesser-known or less well-measured impacts from these technologies are not biased against when compared to the overall circumstances involving multiple issues, such as cost, operational efficiency, and so on. As an example of this comparison, Table 1 shows the projected fuel costs of five different bus types. The Proterra BE35 electric bus has lifetime fuel costs 80% less than the worst performing diesel bus. This cost difference alone is significant to warrant further investigation into the challenges of implementing such a technology. However, looking further into electric bus technology, we see the initial purchase price can be a significant hurdle.

Table 1 - Transit Bus Lifetime Fuel Costs

Bus Type	Fuel Costs ($3.50/gallon), or Electricity Costs ($0.10/kwh) over 500,000 miles
Diesel (including clean diesel and regular diesel)	$430,398.43
Diesel-electric Hybrid Battery-based (both series and parallel)	$370,135.36
Diesel-electric Hybrid Capacitor Based	$350,560.90
Proterra BE35 Electric Bus	$85,500.00
BYD electric Bus	$94,890.17

Table 2 below, displays the additional training hours needed for different technologies shows a cost of $1000 to hybrid and electric buses. A score is given on a scale of 1 to 10. Further explanation about scoring will be discussed later in this thesis. In a traditional cost-benefit analysis, this factor would not have a significant effect on the final outcome as the total costs for operating a traditional transit bus during its lifetime are easily over $1 million. Instead, by including this cost as part of the multiobjective analysis, the importance is highlighted. There may additionally be a time-cost or an implementation issue to deal with, in addition to the monetary costs.

Table 2 – Personnel Training Scores

Item	**Diesel Bus**	**Hybrid Bus**	**Electric Bus**
Additional training Cost ($50/hour)	None	20 hours or $1000	20 hours, or $1000
Score	10	1	1

Using 20 different categories, the multiobjective analysis concludes new and emerging technologies are viable solutions while relatively older technologies can still be implemented in an efficient and cost-saving manner. Although a specific technology may not score well in the final tally, by considering the overall picture, such technologies may not be dismissed on conventional parameters, such as cost alone, and may provide other tangible values to transit agencies looking to implement new technologies.

1.3 Applicability of Research

A fleet manager using this data can compare buses from many different aspects to see which bus would most benefit their own transit system. This research has bolstered the ever-improving technology trend in the transit industry and gives value by helping assess performance and fuel economy improvements. Furthermore, it can guide the industry and give comparative values to performance, environmental, social and economic impacts of advanced transit bus technologies for fleet managers to use in their bus purchasing decisions.

To assess the applicability of this research, a survey on advanced transit bus technologies was sent to transit managers in multiple cities and organizations in North America regarding the state of their own fleet, improvements that should be done, as well as opinions about hybrid buses and other novel technologies. The available data revealed the opinions of a few operators, on advanced transit bus technologies, as well as their experience with hybrid buses, both negative and positive.

The potential exists for any one of these technologies to excel, given the appropriate circumstances and proper operational environment. This thesis has been able to identify sustainability, environmental, financial, and social issues through the benchmarking and comparing of advanced transit bus technologies.

2 Literature Review

As the transit industry moves forward, there is a greater push to both reduce greenhouse gas emissions and reduce costs. There are a number of different cases where transit authorities have added new buses to their transit system, comparing the resulting benefits and downsides. Every transit agency is looking to reduce costs, and purchasing hybrid buses was seen as a popular route. In addition, other transit agencies have researched into electric buses and capacitor-based hybrid buses and found results to be favourable. This literature review summarizes and examines many of these research studies.

2.1 New York City Transit (MTA)

The New York City Transit Authority (Chandler, Walkowicz, & Eudy, New York City Transit Diesel Hybrid-Electric Buses: Final Results, 2002) currently has over 1700 hybrid buses and conducted a number of research comparisons with their traditional diesel buses to assess the benefits of HEV buses in their fleet. This research is the most extensive research conducted on comparing hybrid buses to diesel buses. Table 3 is a summary of the buses being compared in this 2002 study. Please note: MBRC (Miles Between Road Calls) is a standard average used in industry to measure reliability.

Table 3 - MTA Bus Type Comparison

Item	NYCT Daimler Orion VII 40-foot Hybrid (Next Generation)	NYCT Daimler Orion VII 40-foot CNG	NYCT Daimler Orion V 40-foot Diesel
Model Year	2004	2002	1998
Engine	Cummins ISB	DDC S50G	DDC S50
Hybrid Drive	BAE HybriDrive	N/A	N/A
Batteries	Lead Acid	N/A	N/A
Average MPG	3.00	1.70	2.17
Miles/Million BTU	23.1[1]	13.1	N/A
Most common wear item	Hybrid Powertrain	Non-lighting electrical	Body-exterior

[1] Assuming 1 gallon of diesel fuel contains 129,500 BTU of energy.

MBRC	5000	6000	2166
Total Distance travelled (miles)	28,440	27,540	29,091
Initial Purchase Cost	$385,000	$313,000	$290,000

R.Barnitt and the National Renewable Energy Laboratory (Barnitt, 2008) focused on comparing Generation 1 (Gen 1), Generation 2 (Gen 2), compressed natural gas (CNG), and existing diesel buses in the NYCT fleet. Both generations operated on similar duty cycles over a period of 1 year, with Gen 1 hybrids measured over two years due to them being in operation longer. Table 4 highlights the different buses being compared as part of the fleet.

Table 4: NYCT Hybrid bus specification comparison

	Gen 2 Hybrid	**Gen 1 Hybrid Bus**	**CNG**
Bus Manufacturer and model	Daimler Orion VII	Daimler Orion VII	Daimler Orion VII
Model year	2004	2002	2002
Rated HP	270 hp@ 2500 RPM	270 HP @ 2500 RPM	275 HP@ 2100 RPM
Rated Torque	660 lb-ft @1600 RPM	660 lb-ft @ 1600 RPM	900 lb-ft @ 1200 RPM
GVWR	42,540 lbs	42,540 lbs	42,540 lbs
Powertrain	Cummins ISB	Cummins ISB	DDC S50G
Purchase Cost	$385,000	$385,000	$313,000

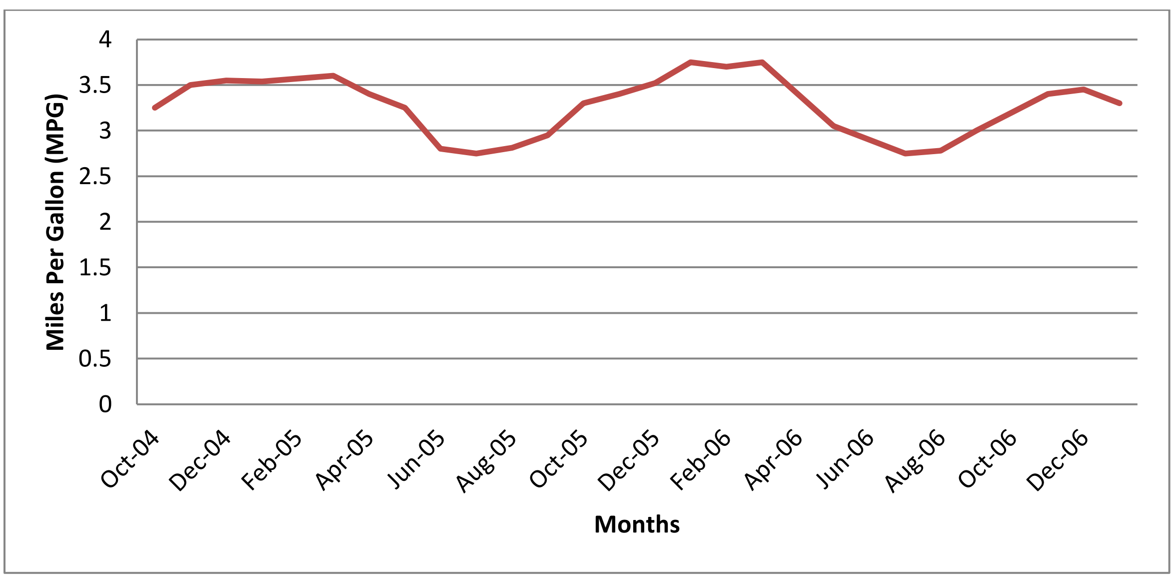
The 12 month average miles per bus for Gen 2 hybrids were approximately 10% lower than for Gen 1 hybrids because of the different bus routes and depot size. As bus routes are determined and used many years previously to the arrival of new buses, the actual bus routes would not change. It would be too costly from both a municipal and transit agency perspective. If a transit agency were to decide to optimize a route for a hybrid bus, they would simply find an existing route which best fit the technology as opposed to creating a new route or rerouting an existing one. Table 5 summarizes the performance of hybrid, compressed natural gas (CNG) and diesel buses that were evaluated.

Table 5: NYCT bus performance comparison

Bus Study Group	Evaluation year #	Mileage	Gallons consumed	MPG	Average speed
Gen 2 Hybrid	1	246,926	82,213	3	6.07 mph
Gen 1 Hybrid	1	258,826	81,104	3.19	6.13 mph
Gen 1 Hybrid	2	263,130	81,677	3.22	5.70 mph
CNG	1	259,083	152,016*	1.70	---
Diesel	1	436,672	187,157	2.33	---

The Gen 1 hybrid bus in evaluation year two performed the best among the buses compared (Barnitt, 2008). The fuel economy was reduced in the summer months of June and August due to increased usage of air conditioning systems as illustrated in Figure 1. In addition, if the battery packs get too hot, the hybrid control system shuts down regenerative braking to help the batteries cool down and recover. Consequently, the hybrid system would be operating at a reduced efficiency due to a lack of recharging of the batteries when braking. The newer Orion VII hybrid buses should not experience these same problems due to an improved design. As Gen 1 hybrid batteries are reaching their 3-year life expectancy with no apparent decrease in MPG, they seem to be able to achieve their rated life expectancy.

Figure 1: NYCT Average Fuel Economy



At a labour rate of $50/hour, average total maintenance costs for Gen 2 buses was $0.75/mile which was 39% lower than Gen 1 hybrids ($1.23/mile) during both groups year 1. The summary of costs can be seen in Table 6. It should be noted that the Gen 2 Hybrid bus did not accumulate enough miles to warrant a brake reline during the evaluation period, which accounts for a partial decrease in maintenance costs per mile.

Table 6: NYCT bus maintenance comparison

Bus Group Study	**Evaluation year #**	**Miles (Maintenance base**	**Parts ($)**	**Labour hours**	**Cost ($/mile)**
Gen 2 Hybrid	1	250,460	32,389	3,096	0.75
Gen 1 Hybrid	1	285,349	61,408	5,793	1.23
Gen 1 Hybrid	2	268,750	86,918	5,869	1.42
CNG	1	275,444	99,980	5,133	1.29

Brakes and brake relining are major expenses for transit companies. Because hybrid buses use regenerative braking, material and labour costs to reline brake pads are greatly reduced. Gen 1 hybrid buses accumulated twice as many miles (55,067 miles) before requiring a brake reline compared to CNG buses. Non-hybrid buses usually have a 4-wheel brake reline every 18,000 miles on average. Hybrids weigh 440 lbs more than CNG buses so weight is not the determining factor in brake relining. Unlike passenger vehicles, the majority of braking is applied to the rear wheels where the motor is connected to; consequently, relining of the rear wheels occurs more frequently than the front wheels. Being able to operate for twice as long without scheduled brake maintenance is a significant advantage in reducing costs.

A further breakdown of propulsion related maintenance costs are summarized in Table 7. Thanks to improved changes, the Gen 2 hybrid bus more than halved the maintenance costs of the Gen 1 hybrid in its first evaluation year.

Table 7: NYCT Propulsion related maintenance costs

Vehicle System	Gen 2 Hybrid ($/mile)	Gen 1 Hybrid ($/mile)	Gen 1 Hybrid ($/mile)
Evaluation Year Number	1	1	2
Total propulsion-related	0.162	0.359	0.335
Exhaust	0.0169	0.0241	0.0174
Fuel	0.0176	0.0150	0.0150
Engine	0.0331	0.0609	0.0367
Electric Propulsion	0.0387	0.1765	0.1266
Non-lighting electrical	0.0278	0.0416	0.0613
Air Intake	0.0087	0.0056	0.0054
Cooling	0.0181	0.0309	0.0689
Transmission	0.0008	0.0044	0.0039

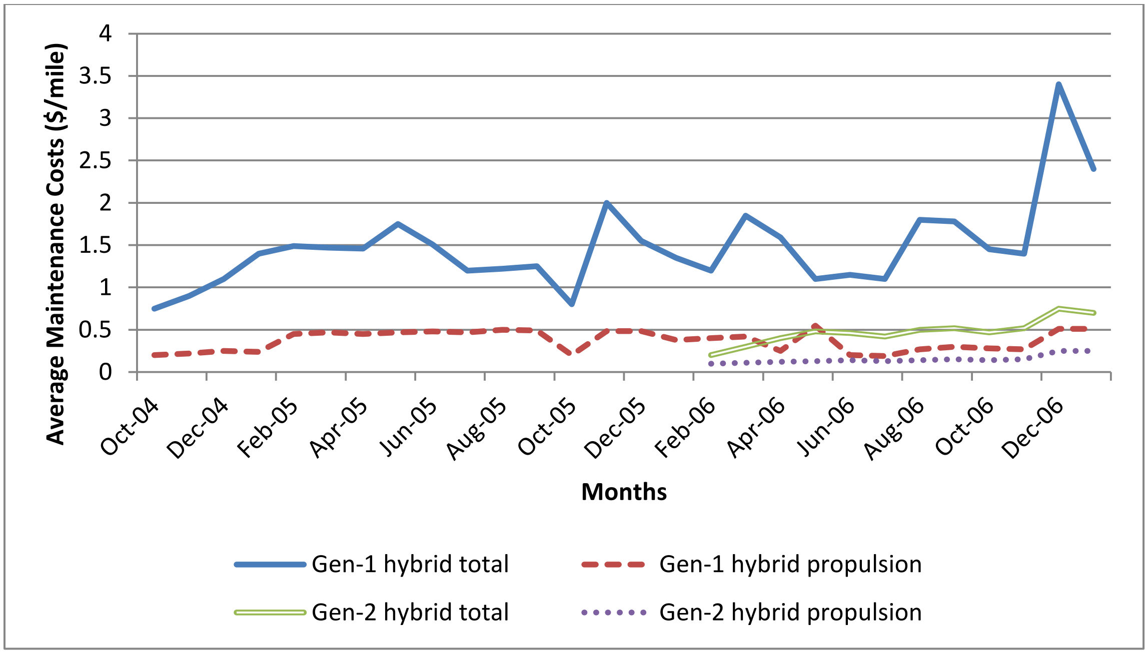
Each traction battery had a per-unit cost of $70,000. Battery conditioning was performed in 6-month intervals. During evaluation year 1, Gen 2 hybrid buses had zero battery failures. In the months prior to evaluation, there were 13 single battery failures (assumed related to quality control issues). Gen 1 hybrids experienced 4.8% failure per year during evaluation year 1 and 3.3% failure rate during evaluation year 2. Software changes made battery failure identification less sensitive to reduce number of indicated failures though the battery. In essence, this did not resolve the problem but instead adjusted the point at which a problem would appear on the computer.

Figure 2 illustrates the increasing maintenance costs of the buses versus time. Both the Gen 1 hybrid propulsion and total costs saw steadily increasing maintenance costs, with no large increase in the average over two years relating to the propulsion. However, the total maintenance costs were erratic and costly. The Gen 2 Bus also saw increasing maintenance costs, but not to the same extent. The difference in Gen 1 and Gen 2 buses can be attributed to a number of reasons:

- Mechanics became more familiar with hybrid systems, performing maintenance quicker.
- Basic improvements between Gen 1 and Gen 2 buses.

- Software changes to the battery control system in Gen 2, which were tuned to be less sensitive, allowing for a larger margin of error.

Figure 2: NYCT average monthly total and propulsion-related maintenance costs



Road calls are on-road failures of in-service buses. NYCT buses should meet or exceed 4000 MBRC for all buses. Gen 2 hybrids had nearly 5,445 MBRC while Gen 1 had about 5,188 miles during their evaluation year. For road calls relating purely to the hybrid propulsion system, Gen 2 hybrids had 8,678 MBRC and Gen 1 hybrids had 8,153 MBRC. Simply put, the Gen 2 buses were more reliable than Gen 1 buses. For comparison, the total MBRC of CNG buses was 5783 miles whereas the propulsion only MBRC was 8885 miles.

The research done by the NYCT showed that hybrid buses had 2.6 times the reliability of the rest of the fleet. Maintenance costs of their Gen 2 hybrid buses were calculated at $0.75/mile compared to Compressed Natural Gas (CNG) buses which were calculated at $1.29/mile. For Gen 2 buses this represents a 24% lower total maintenance cost than Gen 1 hybrids, and 39% lower than CNG buses. The length between brake relines of hybrid buses was also twice that of CNG buses. There was a noticeable reliability increase from Gen 1 to Gen 2 buses.

The Gen 1 hybrid buses exhibited 88% and 37% higher fuel economy than CNG and conventional diesel buses, respectively. Gen 2 buses showed a 5.9% reduction in fuel economy compared to

Gen 1 hybrids, further widening the fuel economy gap to CNG and Diesel buses. With the implementation of hybrid buses, the NYCT was able to drastically reduce running costs and will see even more savings in the future.

Table 8 summarizes the EPA emissions requirements through the years (EMBARQ, 2012). As we can see, the emissions requirements have not changed significantly since 1991. This is important to note as there does not seem to be a large push by the government to improve transit bus emissions. Without a push by the government, there is little incentive for manufacturers to improve the environmental performance of the buses.

Table 8 - EPA Emissions Requirements For Transit Buses

Model Years	CO (g/bhp-hr)	HC (g/bhp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)
1990	15.5	1.3	6	0.6
1991-1992	15.5	1.3	5	.25
1993	15.5	1.3	5	0.1
1994-1995	15.5	1.3	5	0.07
1996-1997	15.5	1.3	5	0.05
1998-2003	15.5	1.3	4	0.05
2004-2006	15.5	2.4 combined or 2.5 with a limit of 0.5 for NMHC		0.05
2007-2010	15.5	0.14	0.2	0.01

2.2 Long Beach Transit Authority

The Long Beach Transit authority decided to evaluate their new fleet of hybrid buses, purchased in 2005 from New Flyer industries (Lammert, 2008). The buses use a series hybrid-electric powertrain with a gasoline engine acting as a generator. Instead of typical batteries used in hybrid buses, the New Flyer buses were equipped with the new ThunderVolt Hybrid Drive system which incorporates ultra-capacitors to capture regenerative braking energy. Ultra capacitors have a 12-year life expectancy as opposed to a three to six year expectancy for batteries, making them more reliable and potentially cheaper over their lifetime to operate. Table 9 shows the two different bus types in the Long Beach Transit Study.

Table 9 - Long Beach Transit Bus Type Comparison

Item	Long Beach New Flyer GE40LF	Long Beach New Flyer D40LF
Model Year	2004,2005	2002
Engine	Ford Triton V10	Cummins ISC
Hybrid Drive	ThunderVolt Hybrid	N/A
Batteries	Ultra Capacitors	N/A
Average MPG	3.78	3.50
Most Common wear item	Engine, Electrical	Engine, Transmission
MBRC (MBRC Propulsion only)	9000 (15000)	11040 (19000)
Total Distance travelled (miles)	15,000	19,118
Purchase cost	$462,379	$268,051

The new hybrid buses were compared with traditional diesel powered buses over a 24-month period from July 2005 to June 2007. 10 vehicles from each of the two evaluation groups were randomly selected out of a total of 47 and 138 hybrid and diesel buses, respectively. They found improvements in fuel economy and maintenance costs compared to the diesel buses

The emissions of the hybrid bus were measured by the California Air Resources Board (CARB). While NOx emissions are significantly lower in the hybrid bus due to the gasoline engine, the CO value is higher, as shown in Table 10 .

Table 10: Long Beach Transit Hybrid versus Diesel emissions comparison

Study Group	NOx (g/bHp-hr)	PM (g/bHp-hr)	CO (g/bHp-hr)
Hybrid	0.6	N/A	3.7
Diesel	40	0.05	0.5

Table 11 compares the diesel and hybrid buses across various metrics.

Table 11: Long Beach Transit Hybrid versus Diesel comparision

Bus	MPG	Fuel Cost/Mile ($)	Maintenance Cost/mile	Propulsion related maintenance cost/mile	Brake Maintenance costs/mile	MBRC	Total cost /mile
Diesel	3.50	0.65	$0.5392	$0.1906	$0.0356	11,040	$1.19
Hybrid	3.35	0.74	$0.3124	$0.0782	$0.0036	9000	$1.05

Over the evaluation period, the fuel economy of hybrid buses at 3.35 MPG was 4.3% lower than the diesel buses. The hybrid bus is cheaper to operate than the diesel bus in fuel costs. Taking into account the different energy contents of gasoline and diesel, the hybrid buses would have delivered an 8.5% higher MPG diesel gallon equivalent than the diesel buses.

The hybrid bus was also cheaper to maintain as a whole when considering specific propulsion-related costs and brake system cost. At $0.31 per mile in the hybrid, compared to the diesel bus at $0.54 per mile, the hybrid showed a 42% lower maintenance cost. When comparing the specific costs of brakes, the hybrid bus was approximately 10 times cheaper to operate due to the regenerative braking system allowing a much reduced frequency of brake relining. Despite being cheaper to maintain, the MBRC was notably lower in hybrid buses than diesel buses. This suggests that the hybrid buses required more maintenance than diesel buses, but saved money in the long run.

The Long Beach Transit authority was very pleased with their hybrid buses and purchased more buses following the conclusion of the trial period which found the hybrid buses being less costly to operate over their diesel counterpart.

2.3 King City Metro

King City Metro (Chandler & Walkowicz, 2006) concluded that their hybrid bus acquisition provided them with better reliability with no significant issues with the technology. Newly acquired hybrid electric and diesel articulated 60 foot buses in 2004 to replace their older fleet of dual mode breda articulated buses were evaluated. The dual mode buses operated in electric mode from overhead catenary lines inside tunnels and used its diesel propulsion outside the tunnel. The buses themselves were becoming expensive to maintain and were at the end of their lifetime after being in operation for 16 years. The decision was then made to find a replacement. In total, 30 buses were selected for the study; 10 new diesel buses from the Ryerson base, 10 new hybrid buses from the Atlantic base, and 10 new hybrid buses from the South base.

The new hybrid buses made by New Flyer incorporated the *GM Allison E50 parallel hybrid system*. It incorporated two motors which could also be used as generators for regenerative braking. The batteries used were Nickel Metal Hydride (NiMh). Table 12 is a breakdown of the buses used in this comparison.

Table 12 - KC Metro Bus Comparison

Item	**KC Metro New Flyer D60LF Diesel**	**KC Metro New Flyer DE60LF Hybrid**
Model Year	2004	2004
Engine	Caterpillar C9	Caterpillar C9
Hybrid Drive	N/A	GM Allison E50
Batteries	N/A	NiMh
Average MPG	2.50	3.17
Most common wear item	Propulsion related, HVAC[2]	Propulsion related, HVAC
Total Distance travelled (miles)	35388	37152
MBRC (MBRC Propulsion only)	5896 (12,199)	4954 (10,616)
Purchase Cost	$445,000	$645,000

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[2] Not including cab, body and accessories, which required more maintenance due to outside factors such as accidents, vandalism and common wear.

Overall, the reliability of the new buses were satisfactory. KC Metro reported no significant issues in the new technology. Warranty work was performed on the buses but most work was due to unexpected operating conditions.

When comparing the buses, the duty cycle between their Ryerson base and the Atlantic base were very similar. This allowed a very credible comparison between the performance of diesel and hybrid buses. Table 13 is a summary of the results.

Table 13: King City Metro Diesel versus Hybrid bus cost comparison

Category	Diesel Ryerson Base	Hybrid Atlantic Base
Monthly average miles per bus	2,949	3,096
Fuel Economy (MPG)	2.50	3.17
Fuel Cost per mile	$0.79	$0.62
Total Maintenance cost per mile	$0.46	$0.44
Total Operating Cost per mile	$1.25	$1.06
MBRC	5,896	4,954
MBRC (propulsion related)	12,199	10,616

The fuel economy of hybrid buses was 3.17 MPG versus 2.50 MPG of the Diesel buses. It must be noted that, due to the prototype nature of the buses that King City Metro (KC Metro) had acquired, the comparatively lower Miles Between Road Call (MBRC) is not necessarily representative of the technology. The fuel cost per mile was slightly lower with the hybrid buses while the maintenance costs were much more similar to the diesel buses. Overall, KC metro was more satisfied than originally expected with their new hybrid buses which showed the potential for long term cost savings and better reliability.

2.4 Connecticut Transit

The Connecticut Department of Transportation (Warren & Warhola, 2005) evaluated Hybrid-electric diesel buses over the course of 18 months. The new buses were 2003 model year New

Flyer Allison Hybrid-electric buses. The buses being compared to, were clean diesel buses also made by New Flyer in 2002. The two bus types were tested along the same routes, making for extremely similar driving conditions and equipment which are vital to identifying performance differences between Hybrid and traditional diesel powertrains. The fuel economy seen by hybrid buses over the testing period was around 10%. This 10% improvement of hybrids over diesel buses is similar to the improvement in passenger cars of their gasoline and hybrid counterparts. Table 14 highlights the buses used in this research study.

Table 14 - Connecticut Transit Bus Comparison

Item	**Connecticut Transit New Flyer D40LF**	**Connecticut Transit DE40 LF Hybrid**
Model Year	2002	2003
Engine	Detroit Diesel 40E	Cummins ISL
Hybrid Drive	N/A	GM Allison E40
Batteries	N/A	NiMh
Average MPG	4.20	4.60
MBRC	9,800	12,000
Total Distance travelled (miles)	34,400	23,700
Purchase cost	$320,000	$500,000

The reliability for both diesel and hybrid buses were much lower than the fleet average directly affecting the lower maintenance costs per mile. They were surprised with the reliability of new and unproven hybrid technology.

The Table 15 is a summary of the costs CTTransit encountered when operating diesel buses and hybrid buses.

Table 15 - CTTransit Bus Costs Comparison

Cost Item (CTTransit)	Total Diesel Bus Costs	Total Hybrid Bus Costs
Purchase Cost	$320,000	$500,000
Engine Rebuild	$50,000	$25,000
Transmission Rebuild	$30,000	$10,000
Battery Replacement	0	$20,000
Fuel Costs	$171,429	$156,522
Brake Maintenance	$18,000	$12,000
DPF Maintenance	$12,000	$6,000
Other Misc Maintenance	$150,000	$150,000
Totals	$751,429	$879,522

Emissions were also measured onboard the buses during operation. It was found that the diesel and hybrid buses exhibited few differences in the emissions of CO_2, NO_x, CO and HC. A large decrease in emissions was observed from the introduction of a *diesel particulate filter*, showing that the simplest technology can sometimes make the most significant difference.

2.5 Edmonton Transit System

Comparing diesel electric buses and diesel buses to trolley buses yielded interesting comparisons at the University of Alberta (Checkel, 2008). Data was collected over one year and cost and emissions estimates were done in order to assess the abilities of a hybrid bus. Table 16 is a summary of buses compared by the University of Alberta.

Table 16: U of A Diesel, Hybrid, and trolley bus comparison

Item	**Clean Diesel**	**Hybrid 1 (Allison)**	**Hybrid 2 (Orion BAE)**	**Trolley Bus**
Bus Cost (2010)	$425,000	$650,000	$650,000	$950,000
Average fuel economy (L/100km)	70.86	62.17	56.96	202.84 (KW.hr/100km)
Total Maintenance Costs per km	$0.54	$0.55	$0.55	$0.86
Total Cost per km	$2.25	$2.552	$2.516	$10.267
Total cost per year	$59,470	$65,393	$65,743	$216,834
GHG emissions (kg.km)	1.966	1.725	1.581	1.93

Diesel buses and hybrid buses maintenance costs were very similar at $2.25/km and $2.53/km, respectively. Trolley buses were pegged at $10.26/km. It should be noted that the majority of maintenance costs can be attributed to the maintenance of the overhead wires specific to trolley buses in addition to the buses themselves. Even without these extra maintenance costs, hybrid-electric buses would need to see a number of improvements in order for their purchases to be financially viable:

- Purchase price dropped to $545,000 from $650,000
- Hybrid life was extended to 21.5 years while diesels lasted 18
- buses averaged twice as many kilometers
- diesel fuel prices averaged $2.70/liter over the next 18 years

From an emissions aspect, the 15-20% fuel economy benefit of hybrid buses relates directly to a 15-20% reduction in CO_2 emissions. When converting electrical power from the grid, trolley buses fall above diesel buses but below hybrid buses from emissions. In their conclusion, D.

Checkel states that while operating on short-distance heavy duty cycles, the initial bus and system capital costs are the most significant transit bus operational costs.

2.6 Indianapolis and Knoxville Area Transit

An evaluation by NREL (Barnitt, 2006) focused on the demonstration of hybrid electric 22 foot buses manufactured by Ebus, Inc. The two municipalities which participated in the study were the Indianapolis Transportation Corporation (IndyGo) and Knoxville Area Transit (KAT).

Both hybrid-electric buses used Nickel Cadmium (NiCd) batteries for energy storage. They are exactly the same, apart from the fuel used to power the microturbine. A 30 kW Capstone micro turbine auxiliary power unit is used in place of a traditional diesel engine. The auxiliary power unit (APU) can operate on many types of gas including CNG, LPG, and diesel. These hybrid buses operate on a charge sustaining principle whereas the batteries will only have power if the APU has fuel. This is opposed to the majority of hybrids in which the battery charge is independent of how much fuel the generator has. The batteries can be charged overnight to give the batteries a 100% charge before the start of every day. Table 17 highlights the data of the two microturbine hybrid buses after half a year of testing.

Table 17: IndyGo Hybrid versus Trolley bus comparison

Item	Indygo Diesel Hybrid bus	KAT LPG hybrid bus
Total Passenger Capacity	29	29
Maintenance Cost/mile	$0.66	$0.62
Overall Operating Costs/mile	$1.04	$0.97
MPG	4.37	3.22 (Equiv. Diesel)
Cost	$280,000	$280,000

Operating costs and maintenance costs are very similar between the two over the evaluation period. Fuel economy is comparatively lower for the LPG Ebus, keeping in mind it is a diesel equivalent calculation.

The LPG buses were found to be very reliable and were available to be used at any time with little to no downtime. With the LPG buses, KAT found it was extremely important to match the drive cycle and route with the appropriate bus. It was also important to train the maintenance personnel as well as the drivers so that road calls will be less often and maintenance handled correctly. Indygo had many issues with the reliability of their buses and it was difficult to keep two out of five buses on the road at a time. In addition, training was very important in the operation of theses buses as improper operation caused a number of road calls that would have been otherwise unneeded.

2.7 Comparisons of Hybrid buses over Diesel Buses

By comparing hybrid and diesel buses on a dynamometer (Hallmark, Qui, Wang, & Sperry, 2012), researchers at Iowa State University concluded that hybrids have a clear advantage in all aspects of performance. However, these tests were compared to very old diesel buses, not newly purchased ones so the perceived performance gap is greater than one would expect. According to researchers in a study by Battelle (Chandler & Walkowicz, 2006), the buses were tested on dynamometers and returned a fuel economy 54% higher than regular diesel buses. Another study performed by Transport Canada evaluated hybrid buses in 2010 (CrossChasm, 2010) and found their fuel economy to be up to 36% higher. With the routes the buses took, as average speed increased, the difference in fuel consumption went down.

Although the prices of replacement battery packs are known to the industry, not many hybrid buses have been in service long enough to warrant an out of warranty battery replacement. Thus, long term maintenance costs are not yet fully understood. Early nickel cadmium batteries had a short lifespan of about 3-6 years while the new generation of lithium batteries are understood to last the lifetime of the vehicle.

Interestingly, researchers found that even with the cost reductions and improved efficiencies; it is difficult to recuperate the initial capital costs associated with the acquisition of hybrid buses (Williamson, 2012). This points to hybrid buses not necessarily being an economically sustainable purchasing decision at the time of this research, and suggests there might be other reasons, such as environmental objectives, for their purchase.

Intercity Transit has provided public transport for people living and working around Olympia, in the state of Washington. They concluded that hybrid buses significantly reduce emissions, reduces maintenance and running costs, in addition to a few more benefits (Intercity Transit, 2013). Despite costing more per bus, the approximate fuel savings per year is $138,000 over the life of the bus.

Transport for New South Wales commissioned a trial of urban hybrid bus technology for routes in Sydney, Australia (Williamson, 2012). Two comparisons were performed between hybrid buses and diesel buses. The two comparisons compared the current hybrid bus technology to both the current diesel bus, and a diesel bus with the latest enhancements and technology.

Four major topics were covered:

- Commissioning effort: how easy were these buses to incorporate into city transit.
- Operational Factors: Driveability, downtime, fuel efficiency.
- Economic factors: Fixed cost, fuel costs, variable costs, vehicle-life-costs.
- Environmental factors: Air quality, GHGs.

The hybrid bus technology was developed by BAE systems using a Cummins 4-cylinder engine and a 120 kW motor. The diesel buses were both developed by Volvo. The hybrid bus cost $610,000 AUD to procure. The results were as follows, in Table 18:

Table 18: NSW hybrid versus diesel performance comparison

Topic	**Results**
Commissioning	Hybrid buses returned a fuel consumption about 15% higher than the older diesel buses, but only 4% higher than the newer diesels. Hybrid buses also experienced more downtime than the diesel buses, which were mostly associated with the electrical system. The best diesel bus returned a fuel economy of 53.19 L/100km while the hybrid bus achieved 55.24 L/100km.
Environmental Performance	GHG emissions of the hybrid bus were reduced by 15% compared to the old style diesel bus. The newer diesel bus however, had a lower output of GHG emissions by 4%. An economic analysis concluded that the procurement of hybrid buses would deliver a negative economic outcome with a potential loss of $113,950 AUD compared to the newer diesel bus.
Other notes:	Vehicle noise was reported to be lower in hybrid buses.

This research conducted on hybrid buses in Sydney concluded that hybrid buses are very much a work in progress and a substantial improvement of hybrid buses is needed if they are to compete directly with diesel buses. As it stands, the Volvo ULSD bus would be cheaper to operate over its lifetime.

The benefits of implementing hybrid buses in the UK would only make financial sense if a number of changes happen (Emes, Smith, Tyler, Bucknall, Westcott, & Broatch, 2009). Fuel costs and hybrid efficiency need to increase, in addition to the lowering of hybrid bus manufacturing costs as well as an increased social awareness of hybrid buses. At the moment with current technology, there does not seem to be any significant increase in performance of hybrid buses compared to the latest clean diesel buses. Maintenance for hybrids may be considerably less, but data has not been available for a sufficient period of time, hence the inability to provide solid calculations and assumptions. The most significant unknown is the price of fuel. If fuel prices increase dramatically, then there will be a clearer benefit of hybrid buses. Hybrid buses currently *seem* like a sound financial investment, and the benefits are anticipated to increase over time.

2.8 LCA analysis

A lifecycle cost analysis was performed between an Ultra-Low Sulfur Diesel (ULSD) bus and a diesel hybrid bus. With a 12-year, 100-bus lifecycle cost, hybrid buses cost more at $90,819,202 compared to ULSD buses at $67,709,015. The hybrid buses obtained better fuel economy, but the cost savings was offset by the cost of a replacement battery every three years (Clark, Zhen, Wayne, & Lyons, 2007). Table 19 is a summary of the findings from this research.

Table 19: FTA ULSD Diesel versus Hybrid bus comparison

Item	ULSD bus	Diesel Hybrid bus
Vehicle Cost	$319,709	$531,605
Fuel costs	$268,830	$226,629
MPG (Manhattan cycle)	2.82	3.86
Battery Replacement cost	N/A	$67,500
Propulsion-related maintenance costs	$66,394	$63,589
100-bus Life Cycle Cost	$67,709,015	$90,819,202

This paper concluded that hybrid buses have a much higher capital cost than current diesel buses. Operationally, the cost was very similar. Although hybrid buses offered the best fuel economy, this was offset by the cost of replacing the battery every 3 years for lead acid batteries or 5-7 years for NiMh batteries. The cost for lead acid batteries is $25,000 per pack while NiMh batteries cost $35,000-$40,000 per pack. In their calculations, they assumed every bus would need a battery replacement every three years over a 12 year life. When selecting buses, it is important to recognize that costs will vary depending on the route operating conditions: costs can be minimized by choosing the appropriate technology for each route.

An LCA was performed comparing battery powered transit buses with electric and hybrid powered buses (Cooney, 2005). The study used databases from the *USLCI* and *EcoInvent v2.2* in order to determine final global warming potential values. The following were important points of this study:

- The environmental impacts associated with battery production are significant. When combining production and in-use operation, the electric bus had 28 g/vehicle km of SOx compared to a diesel bus which had an SOx value of 3.6 g/vehicle km. If battery energy density was increased and the efficiency increased, a best case scenario could see a decrease of 11% of global warming potential.
- Examining the carbon intensity for each state proved that there are large variations, based on which state an electric bus operates in. Overall, there are only eight states

where using an electric bus would reduce GHG emissions compared to a diesel bus. Generally, states which depend on renewable energy and nuclear energy for a large percentage of their power would be better suited for electric bus operations when trying to reduce GHG emissions.

Gregory A. Cooney concluded that diesel buses are favoured over diesel-electric and electric buses when comparing global warming potentials. The large battery packs in hybrid buses constituted a significant impact in the increased global warming potential. However, if battery technology matures, its global warming potential can be reduced and electric buses can find favor in transit agencies seeking to reduce their GHG emissions output.

2.9 Government Funding and Regulations

The transit bus is not a highly regulated industry, unlike passenger vehicles. Through time, even though technology has evolved, the standards for emissions have not changed much. As such, there is little drive by manufacturers to improve their emissions for the sake of passing tests.

Instead, the drive to improve the efficiency of buses comes from transit operators demanding lower costs. The government's role is to provide money for transit agencies to purchase new buses. As seen in the advanced transit bus technologies survey, only about 10%-20% of funding for new buses comes from the government. The majority of their funding come from customer sales.

For government regulations to have any effect on the purchasing of buses, they would need to enforce emissions regulations or give financial incentives for advanced technologies. Some governments have previously and continue to fund pilot projects for testing of hybrid buses and electric buses. In fact, many of the research documents completed on hybrid buses were done in partnership with the United States Federal Transportation Administration who provided both expertise and funding. Unfortunately, there does not exist standard incentives or rebates as there are with electric passenger vehicles. Additional funding from the government is seen on a case-by-case basis with no set rule on whether one agency will receive funding for the purchase of an electric bus or not.

Larger transit agencies, such as the New York City MTA rely less on government funding in making their purchasing decisions. Smaller agencies like the Coast Mountain Bus Company have on-going funding issues which prevent them from acquiring extra buses needed in their operations. For these smaller cities, more government funding would be a significant factor in their purchasing ability and subsequent transit bus choice.

Due to the varying nature and inability to isolate trends linking government regulations and funding to the acquisition or operation of advanced transit bus technologies, an analysis of government regulations as part of the multiobjective analysis will not be part of this research.

2.10 Advanced Transit bus Technologies

The following is a compilation of a number of different buses and technologies which are available to the market today. The Daimler Orion VII has proven to be the most popular in-use hybrid bus, partially due to the use of this bus in some of the largest transit fleets in North America. There are also a number of other manufacturers and technologies with different offerings which have their own benefits.

2.10.1 Electric Buses

The Proterra BE35 has a fully charged range of 40 miles. The BYD electric bus boasts a range of over 155 miles. The large difference in range is simply attributed to how the buses were designed. A summary of the important specifications of each bus is seen in Table 20.

Table 20 - Comparison of Electric Bus Types

Specifications	**Proterra BE35**	**BYD eBus**
Length (feet)	35	39
Curb Weight (lbs)	27,680	30,423
Seats	38	32
Passenger Capacity	65	69
Brakes (F/R)	Disc/Disc	Disc/Disc
Motor Type	2 x Permanent Magnet Motor (UQM Powerphase 150)	1 x AC Permanent Magnet Synchronous Motor (BYDTYC90A)
Battery Type	54-72 kWh Lithium Titanate	324 kWh Iron Phosphate
Charging Time	<10 mins	5 hours@ 60kw /1.6h @ 200kw
Estimated Range (miles)	40	155+
Average Energy Consumption	1.73 kWh/mi	1.92 kWh/mi
Expected Life Expectancy	18-25 years	up to 20
Cost	$950,000	$850,000

The BYD ebus is designed to charge fully after a day of use, taking into account that roughly 80% of large city transit daily service routes are less than 150 miles. The BE35 has a design which would require it to be charged at every few stops along its route. Its batteries can be rapidly charged in under 10 minutes, enabling this operation.

Table 21 compares the BYD and Proterra electric buses.

Table 21 - Comparison of Electric Motor Types

Item	BYD eBus	Proterra BE35
Motor Type	180 KW or 90 KW AC Permanent Magnet Synchronous Motor	150 KW Permanent Magnet
Quantity	2 (one per drive wheel)	1
Cost	[3]$150/KW	
Total	$54,000 or $27,000	$22,500
[4]**Maintenance Cost per mile calculation (assume 500,000 miles)**	$0.108/mile or $0.216/mile	$0.045/mile
Maintenance Cost per mile including assumed similar brake costs to hybrid buses.	$0.1116/mile or $0.2196/mile	$.0486/mile

The BE35 is shorter at 35 feet versus the BYD bus at 39 feet. Despite the shorter length, the BE35 sacrifices only 4 passengers in capacity. This is again because of the design where the BE35 carries less batteries and the BYD bus has more batteries which take up space which would normally be used for additional seats or standing room.

For both electric buses, and for electric buses in general, a route which involves more stop-and-go is beneficial to its operation. These buses rely heavily on their regenerative braking capabilities to extend their range so more stops equal more regenerative braking.

[3] (Geiras & Bianchi, 2004)
[4] Calculated by dividing the cost of the electric motor over an estimated 500,000 mile lifetime.

2.10.2 Hydraulic-Hybrid

The Altair Hydraulic hybrid bus definitely shows promise with its fuel costs, initial purchase costs and maintenance costs. The technology itself is not new. Hydraulic power systems have been in use in construction vehicles like excavators and heavy duty trucks. However, implementing the technology in a transit bus as a main propulsion device has only been done on a small number of vehicles. However, there are potential downsides to the technology. It does not yet have proven reliability in a transit bus application. A transit bus duty cycle involves many stop and go events and operation in many varying climates. Whether the technology will hold up to the stresses of transit duty is unknown. Conversely, it benefits through the simplicity of a hydraulic hybrid system. Unlike hybrid-electric vehicles, there are not many electronics or batteries to worry about.

If there is any indication that Hydraulic Hybrids technology is ready for transit buses, we can examine the use of the technology in UPS delivery vans. UPS has expanded their fleet after an initial test run in 2009. They have been reported to improve fuel economy by up to 35%. The hydraulic system in these vans were designed by Parker Hannefin, the same company who provided the technology for the Altair Hybrid Hydraulic bus (Barry, 2012). Over the lifespan of each delivery van, UPS could potentially save $50,000.

Automation Alley, Altair ProductDesign, and the Federal Transit Administration jointly created a prototype of a hydraulic-hybrid series bus (Heskitt, Smith, & Hopkins, 2012). The goal was developing a heavy-duty, lightweight bus which would perform better than what the market had to offer in fuel economy and lifecycle costs. This bus is shown in figure 5. The bus has already completed its testing phase and the results are promising in terms of both financial and environmental aspects. Some benefits to the hydraulic hybrid bus as mentioned by Altair are:

- Lightest bus structure in the industry.
- Extremely rigid structure which takes advantage of the benefits of an aluminum body and chassis.
- Increased seating capacity.
- High capacity, low maintenance cooling system.
- 30% better mileage and 30% lower cost of ownership compared to today's “Best” diesel-electric hybrid bus.

- 110% higher fuel economy at 6.9 MPG on the industry standard ADB duty cycle.
- 10% lighter than other buses on the market.
- 20% less ownership costs than conventional diesel bus and 30% less than hybrid electric buses.
- Requires no infrastructure additions to operate.
- High power density compared to electric batteries. Hydraulic energy recovery system also operates at a 75% efficiency compared to a 30% efficiency for electric hybrid buses.
- Diesel engine drives hydraulic pumps, which in turn drive the bus. There does not exist a direct link between the engine and the wheels due to series hydraulic system.

Altair fully developed the bus from the ground up using extensive research that their engineers undertook. They found that despite new technology being available on the market, bus manufacturers were constrained by the market itself due to the entry cost being so high. Transit agencies need a significant amount of capital investment to buy new buses, and in the majority of cases, this is not possible without government funding The entire structure was built out of aluminum to save weight and also increase the rigidity. The overall weight gain was 700 pounds compared to a diesel drivetrain, but the extra weight does not reduce the overall efficiency. Table 22 outlines the benefits of the Altair Hydraulic Hybrid bus.

Table 22: Comparison of Altair hydraulic hybrid bus compared to other leading bus technologies

Item	Compressed Natural Gas	Ultra Low Sulfur Diesel	Diesel Electric Hybrid	BusSolutions Diesel Hydraulic Hybrid
Compression Electricity	$19,003	$0	$0	$0
Facility Maintenance	$24,433	$20,723	$17,470	$17,470
Propulsion-Related Maintenance	$62,588	$66,394	$63,589	$63,589
Battery or Bladder Replacement	$0	$0	$67,500	$0
Fuel Costs	$444,145	$488,979	$305,612	$233,961
Emissions Equipment	$0	$1,434	$0	$0
Depot Modification	$8,750	$0	$1,400	$0
Refueling Station	$20,000	$0	$0	$0
Vehicle Cost	$342,366	$319,709	$531,605	$410,000

Life Cycle Cost	$921,285	$897,239	$987,176	$725,020

2.10.3 Flywheel Energy Storage

Another promising but unproven technology is seen in Flywheel energy storage. Similar to hydraulic hybrid technology, flywheel hybrid technology has been used in other applications, but not yet in transit buses.

The Porsche 911 GT3 Hybrid R is a hybrid race car which uses flywheel hybrid technology. By utilizing a flywheel spinning up to 40,000 RPM, it can store up to 120 KW of energy which can then be used to directly spin an electric motor/generator. In a racing application, the energy is then channeled to the front wheels by a pair of motors allowing the car greater power.

The flywheel energy storage concept is still in development and has not been used in a production bus. The Flybus consortium designed a flywheel energy storage system to capture wasted kinetic energy in the braking process and store it in a spinning flywheel (Phys.org, 2011). The CVT transmission transfers energy from the wheels directly into a flywheel, spinning it up to 60,000 rpm. As the bus starts moving again, the CVT reverses the flow of energy and uses the energy stored in the flywheel to move the bus.

This system is claimed to transfer over 60KW of power. As the entire package weighs around 10 kg, there is a small weight penalty associated with this technology, especially compared to typical hybrid or electric buses. Research done by Dean Flanagan from Flywheel Energy Systems (Flanagan, 2011) shows that flywheel energy storage have the potential to, compared to battery-based energy storage:

- Higher power density
- Higher energy density
- Higher efficiency
- Smaller volume
- Lower cost

2.10.4 Battery packs and Ultracapacitors

Batteries are the most commonly used type of energy storage in hybrid buses. The major types of batteries in use today are lithium-ion and nickel-metal hydride, with the latter being phased out for lithium-based batteries. Appendix C details the positives and negatives for Li-ion, NiMh and Ultracapacitors (Battery University, 2010).

Among bus manufacturers, a sub-type of lithium ion battery that is proving popular is the lithium iron phosphate battery. The BYD electric bus uses lithium iron phosphate batteries. The advantages include higher power density, longer lifetime, and inherently safer due to the materials being used. The batteries can therefore be lighter to achieve the same energy capacity as typical lithium ion batteries, which can be advantageous for hybrid and electric buses.

The costs of maintaining battery packs is only related to electric and hybrid buses. The electric battery packs are by far the most expensive maintenance item. Multiple transit agencies report that every 5-7 years, a new replacement will be needed at a cost of $50,000. In-use maintenance costs over the lifetime of the battery are not significant as they used to be. Old Nickel-based batteries required battery conditioners and special charging systems as well as the need to replace cells more often. Lithium batteries solved most of these issues and thus will only need to be replaced when problems appear.

Ultracapacitors present another energy storage method. Instead of having large and heavy battery packs, ultracapacitors are much lighter, cheaper, and also much more durable. Ultracapacitors can only store about 5% of the energy of lithium batteries but makes up for it in lower costs, much higher durability, and significantly increased charge and discharge rate. For example, the New Flyer GE40LF which uses ultracapacitors costs about 20% less than a battery-pack based hybrid bus (Lammert, 2008). Ultracapacitors are expected to last the life of the vehicle and thus would not represent any additional costs to the operator for maintenance.

2.10.5 Fuel Cell Buses

Fuel cell buses are one of the newest emerging technologies in transit. As of 2012, there were 10 transit agencies operating 25 demonstration fuel cell buses from 6 different manufacturers (Eudy, Chandler, & Gikakis, 2012) in the USA. All of these buses are demonstration vehicles used to determine the viability and applicability of the technology. The fuel cell systems are either from UTC power, Ballard Power Systems, or Hydrogenics using hydrogen. Each of the manufacturers use existing chassis outfitted with a fuel cell powertrain. as an example, Proterra, manufacturer of the BE35 electric bus uses the same chassis for both electric and fuel cell buses.

One benefit includes potentially higher fuel economy, as shown by demonstration vehicles. One bus has a tested fuel economy twice as high as a standard diesel bus in the same fleet.

Unfortunately, the average propulsion-only MBRC is much lower than the average diesel bus at 3329 miles. Although it is low, it should not be unexpected for a prototype application.

Research was also done with BC Transit in British Columbia, Canada with New Flyer Fuel Cell Electric Buses (Eudy & Post, 2014). 20 demonstration buses were introduced during the 2010 Winter Olympics, making them one of the oldest fleets of fuel cell buses. Reliability and subsequent maintenance costs were seen to be highest in the propulsion system, falling well below the average of diesel buses.

It is clear there are a number of obstacles to overcome in order for hydrogen fuel cell transit technology to become a viable alternative. If these obstacles can be overcome, there is potential for low-cost operations from fuel cell buses.

2.10.6 Ultra-lightweight Bus Chassis

Light weighting a bus is surprisingly not a common theme among bus manufacturers; instead, most buses available for purchase are implementing newer technologies in relation to the powertrain.

Altair designed their bus to be lightweight and the structure optimized from the beginning. By starting from a clean-sheet design, the Altair bus and its all-aluminum structure has a very strong and corrosion resistant base. In addition to the structure, for further light-weighting, the Altair bus uses balsa wood for the floor and roofing, lightweight seating and carbon fiber hand rails. The Altair Hydraulic Hybrid bus is a model design study for a new way of lightweight bus manufacturing. The all-aluminum structure allowed a gross vehicle weight of 40,500 lbs, similar to a competing hybrid bus, despite the hydraulic-hybrid powertrain weighing about double of a hybrid-electric powertrain application. Even if its hydraulic drivetrain proves to be unsuccessful in the transit bus market, the underlying structure has many benefits and technology that should be passed down into greater use (Heskitt, Smith, & Hopkins, 2012).

The optimization of structural members for specific locations may be slightly more expensive during manufacture, but from a lifecycle perspective, it has the potential to save more money and reduce emissions through improved fuel efficiency.

Bruce Emmons from Autokinetics developed a transit bus structure with the goal of light weighting to improve fuel efficiency (Emmons, 2006). They set out to 'develop and demonstrate a heavy hybrid technology that achieves a 60% improvement in fuel economy, on a representative urban driving cycle'. By using computer simulations they were able to design a lightweight bus with a hybrid powertrain.

They used the NREL advisor program to determine the potential fuel economy of their proposed design. Their calculations showed a potential 16.1 MPG fuel economy rating in a plugin hybrid bus with a 5-battery pack. A competing Orion VI hybrid bus was calculated to have a fuel economy of only 4 MPG.

As part of their research, the following components in Table 23 were chosen by Autokinetics to be a starting point for their lightweight bus :

Table 23 - Lightweight Bus Motor Choice

Item	Specification	Reasoning
Traction Motor	UQM SR128, 30kW.	High specific power, appropriate size.
Battery	Zebra Z37 Nickel Chloride batteries, 20kWh	High specific energy, deep cycle capabilities
Diesel generator	Hatz 1.4L	Not specified

After constructing the chassis and estimating the weights of each subsystem, they expect their bus to meet their goals with the following improvements:

- 14,700 lb curb weight with 10 battery packs
- 20% increase in payload capacity
- 50% reduction in curb weight
- 300% increase in fuel economy
- 32% cost reduction (structure)

2.11 Currently Available technologies

Currently available hybrid buses include the Daimler Orion VII, Novabus LFS HEV, and the Nabi BRT hybrid, among others. Each of these buses have their own set of benefits and capabilities including but not limited to reduced emissions, increased fuel economy and lower maintenance costs. The Daimler Orion VII has the advantage of being used in the largest transit fleet in North America, in New York.

Bus Rapid Transit (BRT) systems were compared with Light Rail Transit systems in a number of municipalities and BRT systems can cost 4-10 times less than LRT systems and 10-100 times less than metro systems (Barbosa, 2011). A bus based system (infrastructure notwithstanding) can therefore offer significant savings while providing a credible transportation alternative. Fuel cell hybrid buses were examined and were shown to be a promising technology in various trials conducted by the United States Fuel Cell Bus Program. In this research, it was found that the single, most influential factor contributing to higher lifecycle costs in fuel cell hybrid buses was the initial purchase and infrastructure costs, which totalled to 48%. Comparing the capital costs of 15% of its LCC in diesel buses, it is stressed that government incentives play a large part in the adoption of new technologies.

There are many currently available buses in both hybrid, diesel, and electric powertrains. Novabus is a Canadian manufacturer of buses owned by Volvo Buses, based out of Quebec, Canada (Novabus, 2014). They manufacture both hybrid and traditional diesel buses. Their *LFS Smart bus* and hybrid bus incorporates many energy saving technologies:

- eCooling technology improves fuel economy 18% on a Manhattan duty cycle. This incorporates an electric engine cooling system with an absence of a hydraulic oil cooler to reduce engine load.
- Hybrid LFS HEV bus adds approximately 900 lbs of batteries to the roof of the bus to allow the use of low floors.
- At an average speed between 9 and 18 MPH, fuel consumption on the Hybrid LFS is reduced by 30-40%. Emissions are also substantially reduced during hybrid operation.
- The powertrain used in the hybrid bus is the *Allison EP 40 hybrid* propulsion system

Daimler buses corporation produced the Orion VII hybrid bus (Daimler Buses North America, 2009). Over 1300 units have been delivered, with more than 1500 on order. The Orion VII is used in 3 of 4 of the world's largest fleets accumulating a total of over 50 million miles. Orion buses have since gone out of business.

The energy storage is designed to be:

- Long lived
- Lightweight
- High efficiency
- Low maintenance
- Better in fuel economy

These buses have been provided to fleets in Toronto, New York City, and San Francisco. The Orion VII Saved 2,000,000 gallons of diesel fuel over first 20 million miles. It also saved 26,000 tons of CO_2 in the same timeframe.

In New York City, Orion Hybrid buses achieved 2.6 times higher reliability than the rest of NYCT fleet of buses. The Orion 2007 hybrid average Mean Distance Before Failure (MDBF) of 10,343 miles was significantly better than the NYCT Fleet average of 3,966 miles (Chandler, Walkowicz, & Eudy, 2002). The batteries in the Orion buses have less weight (over 3000lbs less than previous design), improved carrying capacity and fuel economy. They also have a 6-year design life, which is twice as long as previous design. They are backed by 2 year standard warranty and a 5 year extended warranty. Batteries have reduced maintenance, with no battery conditioning needed. Lower lifecycle costs and lower operating costs are also realized (fuel, brake life, maintenance, replacement costs).

The TTC ordered 560 Orion hybrid buses. The hybrid bus fleet launched with many difficulties and even until now, are not fully satisfied with their performance, converting some of the buses back to diesel-only buses (Toronto Transit Commission, 2008).

At San Francisco Transit 86 units are in service and their hybrid buses are the cleanest and quietest after trolley buses. In the unique topography of the city, the hybrid buses were deemed as best hill climber in fleet (Papandreou, 2010).

A new entrant to the transit bus market, the Proterra BE35 35-foot fully electric bus is a new entrant into the transit bus industry (Proterra, 2014). In order to be used optimally, the bus is designed to be charged quickly at every stop. By stopping for 10 minutes each hour, the bus can operate up to 20 hours per day. Each 10-minute charge allows the bus to travel for 30 miles. Some notable aspects of the BE35 are as follows:

- Achieved between 17.5 to 29 MPG diesel equivalent according to the Altoona Bus Research Center (Altoona Bus Testing and Research Center, 2012).
- An estimated $300,000 in fuel savings assuming a price of $3.00/gallon of diesel fuel and a 12-year operating lifespan.
- Maintenance costs can be reduced by $75,000 to $150,000 due to the BE35's composite body, durable electric motor, and less requirements for brake relining thanks to an advanced brake regeneration system that converts braking energy into electrical energy.
- The BE35 has been used by the Foothill transit agency since 2011. After being extremely pleased with the performance of the bus, the transit agency has recently ordered 12 more BE35 buses in addition to its 314 bus fleet.
- At 35 feet long, the BE35 was designed to be a lower capacity, but a lighter bus to operate.

BYD is another company who manufactures and sells an all-electric 40 foot bus (BYD, 2014). The BYD electric bus has a single-charge range of 155 miles, almost 4 times that of the Proterra BE35. This is enabled with a larger number of batteries in the BYD electric bus, with a similar battery type being used in the BE35. The BYD bus has a number of features such as:

- A 3-hour fast charge or a 5-hour overnight charger can be used.
- 100 kWh of electricity are used to move the bus 60 miles.
- Solar cells can be mounted on the roof of the bus to aid in charging of the batteries while the bus is in use.

2.12 Altoona Bus Testing Facility

The Altoona bus testing facility tests and documents all new buses which are slated for sale in North America (Pennsylvania State University, 2014). It is operated by the FTA and the University of Pennsylvania. Most buses are tested according to the guidelines of the 500,000

Mile Surface Transportation and Uniform Relocation and Assistance Act (STURAA) test. This test is standardized among all bus types and simulates the conditions of a 12-year, 500,000 mile lifetime of the bus. The STURAA test allows buses to be evaluated on:

- Maintenance costs
- Durability and reliability
- Operational capacity
- Dynamic safety
- Acceleration performance
- Fuel economy
- Tailpipe emissions
- Structural integrity and noise

There are two types of testing available to the bus manufacturers:

- Full STURAA test
- Partial STURAA test

The full STURAA test is required when a brand new bus model has not been previously tested. A partial STURAA test can be performed when a bus has been previously tested, returns with specific changes where test data would be expected to be significantly different from the original test. A partial test includes all aspects of the full STURAA test, excluding the durability and structural tests.

2.13 Critique of Literature

The literature review revealed a number of similarities in the performance of hybrid buses in public transit. Despite differences in the manufacturers and operational location, the consensus among transit agencies points to a noticeable improvement of performance in most metrics, valuable to transit agencies. Tellingly, the NYCT, one of the earliest adopters of hybrid-electric bus, has increased their hybrid bus operations. As of 2007, the NYCT has about 6250 buses in their fleet with 825 of them being hybrid-electric. The large purchases of hybrid buses were fueled by the need to reduce emissions, reduce costs, and increase operational performance. By most metrics, the hybrid buses performed better than their diesel and CNG counterparts.

Although the test recorded only two years of operation, at the conclusion of the test, the NYCT were satisfied and confident in purchasing more hybrid buses.

The same pattern was seen among other transit agencies whose reports were covered in this literature review including KC Metro, Knoxvlle transit, IndyGo, CTTransit and Long Beach Transit. All of these agencies either made steps with the intention, or placed orders to purchase more hybrid-electric buses.

When examining the fuel economy improvement among transit agencies, we see an average improvement of 30% with the adoption of hybrid powertrains, with no cases of the hybrid powertrain exhibiting lower fuel economy than the diesel buses. The largest improvement was seen in New York with a 76% better overall fuel economy in the hybrid buses. The smallest improvement was seen in Long Beach with only an 8% improvement. This suggests that hybrid powertrain technology has a wide range of applications where it can perform well. Obviously, it performs better in certain situations than others.

Another performance correlation is to compare the average speed observed by the buses in their driving routes and the average fuel economy. The speeds and fuel economy observed in the following cases studies for hybrid buses are seen in Table 24:

Table 24 - Transit Agency Speed and MPG Comparison

Transit Agency	**Hybrid Bus Type**	**Average Speed of route**	**Hybrid Fuel Economy**	**Diesel bus Fuel Economy comparison**	**Average distance before brake reline**
New York	Daimler Orion VII 40 ft	6.10 mph	3.00	2.17	55,000 miles
King City Metro	New Flyer DE60 LF 60 ft.	11.70 mph	3.17	2.50	N/A
Indianapolis Transit	Ebus Diesel-Hybrid Microturbine 22ft	12.30 mph	4.37	N/A	N/A

Knoxville Area Transit	Ebus LPG-hybrid Microturbine 22 ft	8.50 mph	2.09 (Diesel Equivalent)	N/A	N/A
Long Beach Transit	New Flyer GE40LF 40 ft.	13.80 mph	3.78 (Diesel Equivalent)	3.50	76,000+ miles

Starting from the New Flyer GE40LF at Long beach transit, the highest average speed route, the fuel economy was only 8% better than the comparable diesel bus. KC Metro hybrid buses were 26% better while hybrid buses at the NYCT were 38% better. This snapshot shows that in real-world situations, the lower the average speed, the better hybrid buses perform compared to diesel buses. Examining the operation of the hybrid buses in New York, heavy stop and go traffic is well suited to the unique properties of hybrid powertrains. Simply stated, where the diesel engine is least efficient at low RPMs, the electric motor assists the most, increasing the overall fuel economy.

During the winter months, the fuel economy was noticeably lower in both buses. Looking at the Gen 2 bus, the fuel economy fluctuated from a low of 2.6 MPG in the peak summer months, to a high of around 3.25 MPG in the winter months. This represents a difference of 20% from winter and summer months. As mentioned previously, this is due to the use of air conditioning in the summer months. If the efficiency of air conditioning was improved, it would be possible to realize a significant improvement of fuel economy.

If we compare overall maintenance costs on hybrid buses, they average about 20% lower than diesel buses. The powertrain of Hybrid buses were seen to be marginally better, and in some cases worse than diesel buses. The majority of the savings were realized from much reduced brake relining costs. In most cases, the frequency of relining the brakes was reduced by half. At Long Beach Transit, the brakes were 10 times cheaper to maintain in hybrid buses in most part due to the regenerative braking.

Comparing powertrain specific costs, the average from three transit agencies shows diesel buses to be 0.5% cheaper to operate. Looking into the powertrain maintenance costs for hybrid buses at KC Metro where the hybrid buses were slightly more expensive, it was observed that exhaust system maintenance was the most expensive in this category, mainly due to having more expensive parts. Battery replacements were not an issue, but there were significant labour costs associated with troubleshooting the problems. Other categories of propulsion maintenance costs were similar between hybrid and diesel buses.

The NYCT also observed slightly higher propulsion only maintenance costs in their hybrid buses. The engine system specifically saw a 34% lower maintenance cost than the diesel buses. Where the costs became significant for the hybrid were the electric motor, generator, and battery pack repairs. These three components added up to 24% of the total propulsion related costs of the Gen 2 hybrid bus and 49% of total for Gen 1 hybrid buses. The costs have decreased substantially due to improvements made to the hybrid technology and would be assumed that there is further improvements that can be made.

At Long Beach transit, they used a hybrid-electric bus which incorporated ultra-capacitors as their energy storage system. The hybrid buses had a lower fuel economy to the diesel buses, but due to the higher average speeds on the driving route, the difference was lower than at NYCT with their buses.

With maintenance costs, the diesel bus was twice as expensive to maintain as the hybrid bus. If we compare the Long Beach hybrid bus to that of the NYCT hybrid Gen 2 bus, we see 0.0782 $/mile and 0.367 $/mile for propulsion-only maintenance costs, respectively. Looking at these costs at face value, the ultra-capacity based buses are about 360% cheaper to maintain. Ultra-capacitors are more reliable than batteries, but both transit agencies did not experience significant issues with the batteries/capacitors.

The route observed by Long Beach transit had an average speed twice that of the NYCT hybrid bus. This higher speed would therefore mean less stops and less overall wear and tear. This can be seen in the lower costs of the diesel bus on the same route. At $0.1906/mile, the diesel bus is still significantly cheaper to operate than the bus in New York City. The demands of the different routes are also seen in the distance the respective buses can travel before needing a brake reline. The hybrid buses at NYCT could travel on average for 55,000 miles before needing a reline. The diesel buses on the same NYCT routes needed a reline every 18,000 miles, whereas the Long Beach Transit hybrid buses could travel more than 76,000 miles, and the diesel buses could travel about 35-40,000 miles. Therefore, we conclude that the lower the average speed on the route these buses are placed on, the greater the difference in performance between hybrids and diesel buses.

The Appendix D is a summary comparing the buses used by the different transit agencies on:

- Total Maintenance Costs
- Propulsion-only maintenance costs
- Calculated MPG
- Purchase Cost of bus
- Purchase consensus

The Altoona Bus Testing database is extremely comprehensive and has information from most buses on the road in North America today. Surprisingly, little research has been done to examine the patterns and impact of this data. The Penn State University mentions that all of the STURAA tests have a degree of variability and the numbers will not correspond exactly to how the buses will perform in the real world. On the other hand, because the testing is done very precisely, with as many variables as possible standardized, these numbers can serve as a baseline comparison between buses.

Fuel economy tests are conducted under controlled conditions. The economy test is performed immediately after the durability test, as time and weather permits. The rigorous standardization of these tests presents a uniform baseline. There are three duty cycles the bus is driven through, to simulate three different route/traffic scenarios. The fuel economy test is measured from multiple runs in different combinations of cycles.

a. Central Business District (CBD) Cycle: This cycle simulates a stop and go heavy-traffic situation in a Central Business District type area. This phase contains a distance of 2 miles with 7 stops per mile, with a top speed of 20 MPH
b. Arterial (ART): This phase covers 2 miles with 2 stops per mile. The top speed is 40 MPH.
c. Commuter (COM): This phase covers 4 miles with 1 stop. The maximum speed is the maximum governed speed.

Each phase, designed to represent a range of actual traffic and municipal scenarios, allows direct comparisons of different technologies of buses. For each driving cycle, the top performers among the 40-foot buses compared are as follows:

- CBD Cycle: New Flyer XDE40 Diesel-Electric Hybrid (5.46 MPG)

- ART Cycle: New Flyer XDE40 Diesel-Electric Hybrid (5.11 MPG)
- COM Cycle: New Flyer D40LF Diesel (8.93 MPG)

The averages for different fuel economy metrics among nine diesel buses and ten hybrid buses are summarized in Table 25. Values underlined indicate the better performer.

Table 25 - Fuel Economy Cycle Averages for Diesel and Hybrid Buses

Metric	**Diesel Average (9 buses)**	**Hybrid Average (10 buses)**
CBD Cycle (MPG)	3.28	<u>4.28</u>
ART Cycle (MPG)	3.74	<u>4.22</u>
COM Cycle (MPG)	<u>6.75</u>	6.58
Idle Fuel Consumption (Gallons/hr)	.91	<u>.85</u>
Overall Fuel Consumption (MPG)	4.00	<u>4.70</u>
Overall Fuel Consumption (Miles/million BTU)	29.40	<u>34.32</u>

Examining the above values, the hybrid bus seems to outperform the diesel buses in fuel consumption. The CBD cycle shows the largest difference with the hybrid buses averaging better than the diesel buses. With a total of 14 stops and a top speed of 20 MPH, it would make sense as hybrid buses are best suited to slow speeds and more stop and go traffic.

In the ART cycle, the difference is smaller. Because this driving cycle has a faster top speed of 40 MPH and only four total stops, the improvement of the hybrids over the diesel bus is much less pronounced.

With the COM cycle, the diesel bus proves to be the better choice with better average fuel economy. The commuter cycle has a faster speed (limited by the governor on the bus) and has only one stop, thus negating the advantage hybrids have in stop and go traffic. The average diesel bus curb weight, being less than the hybrid buses, would contribute to this difference.

Overall, the hybrid buses have an advantage in fuel economy. This is in no doubt due to the better performance in the CBD and ART cycle, which covers 50% of the travelled distance during the fuel economy tests. The idle fuel consumption figures are surprisingly exactly the same. This shows that most hybrid buses don't idle much less than diesel buses, despite having an electric motor and battery pack. Without exception, all of the hybrid buses listed here have a serial hybrid system which does not allow the engine to deactivate at low speeds. If the engine was able to turn off at stops, the idle and overall fuel consumption could be reduced.

Although not a perfect representation of the real world, this selection of data from the Altoona Bus Testing Facility shows that with current hybrid technology, its improvements are not significantly better than the average diesel bus. As noted in the COM cycle, the diesel bus can outperform newer hybrid technology under certain situations. Diesel buses still have a long lifespan, and it would be important to find more reasons to replace diesel technology than fuel economy alone.

The maintenance data collected during the testing is difficult to examine. The data reveals there is a disproportionally large number of suspension failures for the majority of buses tested. Because of the nature of the test, which is designed to simulate 500,000 miles of testing, it is difficult to discern between manufacturer defects or simply an extremely demanding durability test track which pushes suspension to its boundaries. For a bus which travels 2000 miles every month, a 500,000 mile durability test represents a 21 year lifespan. When we look at the drivetrain aspect of durability, there are a number of reported failures for both hybrid buses and diesel buses. When comparing testing failures related to the engine/transmission only, over 5 different diesel buses there were an average 7.5 failures. Over 5 diesel-electric hybrid buses, there were an average 8.5 failures. The lone electric bus tested with the STURAA durability test, the Proterra BE35, had 16 failures related to its electric motor/transmission. Each failure was defined as a failure of the part related to the engine/transmissions that would prevent proper operation of the bus and required a fix in order to continue the test. The low, average 1.0 difference between diesel and hybrid buses is surprising, and suggests similar reliability between diesel-electric powertrains and diesel powertrains.

Appendix B is a summary of the information available in the Altoona database that will be used in this research. Most of the buses were chosen based on the following criteria:

- Must be 40ft in length. Proterra BE35 is an exception
- Particularly outstanding in performance.
- Matched a bus which was evaluated in a city
- Particularly notable use of technology e.g. Hybrid, electric, capacitor, etc.

3 Method

From this literature critique, we can see there is likely an optimal technology or combination of technologies which bus manufacturers and municipalities can implement. The newness of some proposed bus technologies, combined with sometimes questionable performance, would lead transit agencies to question the value of implementing new technologies.

A multiobjective analysis was undertaken to determine what might be the preferred technology(s). As discussed previously it was seen from the reports by the FTA (Barnitt, 2008) that the NYCT had been very satisifed with their hybrid-electric buses during initial tests. Later however, it was then seen that the NYCT has fallen out of favour with their original purchase of hybrid buses (Gartland, 2013) and are seeking different technologies to replace them.

This disconnect between pilot test results and experience is one every transit agency attempts to avoid. The multiobjective analysis will analyse each component and assign a weighted value based on its perceived importance, allowing a comparison between technologies in key categories which may have been missed making a transit bus purchasing decision. For example, capacitor-based propulsion systems will be compared to battery-based hybrid propulsion systems, but the final scoring will also take into account commonality between the two buses such as driving performance and noise.

As part of the multiobjective analysis, the fuel economy of different buses and respective technologies will be analysed, discussed and weighted. As seen in the literature critique, fuel economy performance numbers vary wildly, depending on different routes. Hybrid buses operate most efficiently in low-speed stop and go traffic, but do not show a significant difference in performance on high-speed routes compared to diesel buses. Due to the different driving routes of different cities, which renders city-specific data relatively incomparable, the Altoona bus testing database and respective standardized test reports were utilized. The data from these reports was used in the final weighting.

In order to determine the weighting of different categories, a survey was sent out to transit agency personnel across North America. The purpose of this survey was to gauge the industry on financial trends, current operational performance and emerging technologies. Unfortunately, the response rate was low, and thus the results do not have sufficient statistical significance. The weightings were instead determined from multiple reports and through rational discussion.

A predominant trend in the transit industry is a reduction of costs across the board. As has been seen in many transit agency reports, saving money with minimal disruption to their operations is key. Costs therefore, have been given an overall higher weighting. The specific reasoning will be discussed later in this research.

This section outlines in detail the method for completing the multiobjective analysis; the weighting of the fuel economy for overall scoring; and a review of the Advanced Transit Bus Technologies Survey.

3.1 Multiobjective Analysis.

The multiobjective analysis will be broken up into four main components. Their respective subcomponents are also listed. A more comprehensive explanation of each component will be discussed in Chapter 4:

1. Financial Cost
    a. Bus Purchase Cost
    b. Infrastructure Capital Cost
    c. Propulsion Maintenance Cost
    d. Brake Maintenance Cost
    e. Fuel Costs
    f. Personnel Training Costs
    g. Engine and Transmission Replacement and Maintenance
    h. Electrical Subsystems Maintenance
    i. Unforeseen Costs
2. Environmental Impact
    a. Operational Emissions
    b. Emissions From Production
3. Feasibility of Implementation
    a. Infrastructure
    b. Acceptance by Bus Drivers
    c. Acceptance by Maintenance Personnel
    d. Acceptance by the Public and Awareness of Technology
4. Operational Performance
    a. Driving Performance – Perception
    b. Driving Performance - Statistical
    c. Noise – Exterior
    d. Noise – Interior
    e. Reliability

For the majority of categories, there will be measured values used in the scoring. The bus with the perceived best performance will receive 10 points while the lowest performer will receive 1.

All the other scores will be scaled linearly between 1 and 10. Similarly, for some of the above parameters, there are no direct measurable values. In these cases, in the absence of strict quantitative measures, the scores will also be divided equally on a linear scale with the perceived best performer receiving 10 points and the worst performer receiving 1 point. For example, in a linear scale involving three different bus types, the scores will be assigned as 1, 5.5, and 10. For a linear scale involving four different bus types, the scores assigned will be 1, 4, 7 and 10.

3.1.1 Financial Cost

The financial value associated with a particular category will be examined. If a sub-category has impacts which cross over into one of the other three categories, they will be re-evaluated from that specific perspective. The sub-categories are seen in Table 26:

Table 26 - Financial Cost Scoring Explanation

Subcategory	Specific Items to be scored	Unit of scoring
Bus purchase cost	Financial cost to acquire a transit bus	Dollars ($) Lower cost = higher score
Infrastructure capital cost	Financial cost to implement a new transit bus, excluding the cost of the bus itself. Infrastructure costs include modifications to existing facilities and/or additional equipment.	Dollars ($) Lower cost = higher score
Propulsion Maintenance costs	Financial cost to maintain a transit bus	Cost per mile ($/mile) Lower cost = higher score
Fuel costs	Financial cost for fuel to operate a bus over a distance of 500,000 miles. Diesel buses will use a diesel price of $3.50/gallon while electricity will be charged at $0.10/kwh. Costs will correspond to rated fuel economy in the Altoona Bus Tests.	Dollars ($) Lower cost = higher score
Personnel training costs	Financial cost to train employees when implementing a new technology. This will be scored based on the estimated number of hours needed to train an employee.	Hours (h) Lower hours = higher score
Engine and Transmission Replacement and Maintenance	Financial cost to replace an engine and transmission. The amount of time needed to replace an engine and transmission will be considered.	Hours (h) Lower hours = higher score
Electrical Subsystems Maintenance	Financial cost to maintain electrical subsystems	Dollars ($) Lower cost = higher score
Unforeseen costs	The potential for additional costs unknown by the transit agency will be evaluated. Testing issues during the Altoona STURAA were averaged and evaluated	Number of testing issues(#) Lower # of issues = Higher Score

3.1.2 Environmental Emissions

Emissions from both the operation as well as the production of the buses will be considered. For all intents and purposes, the only emissions to be considered and scored will be CO_2 emissions. As will be discussed later, CO_2 is the prevailing emission in the measurement of greenhouse gases. In addition, as measured from the tailpipe of a transit bus, 99.95% of tailpipe emissions are CO_2 emissions. The sub-categories are listed here in Table 27:

Table 27 - Environmental Emissions Scoring Explanation

Subcategory	Specific Items to be scored	Unit of Scoring
Operational Emissions	Emissions from the use of transit buses will be scored. For diesel buses, an engineering calculation for CO_2 emissions per gallon of fuel was used. For electric buses, equivalent CO_2 emissions were calculated for each kwh of electricity used.	Diesel bus – grams CO_2/mile Electric bus – grams CO2e/mile Lower CO_2 = Higher Score
Emissions from Production	The emissions from the production of batteries and ultra-capacitors were scored. As bus structures are similarly constructed, they will be considered equal.	Tons CO_2. Lower CO_2 = higher score

3.1.3 Feasibility of Implementation

By scoring the feasibility of implementation, we will take into account both the reluctance of acceptance as well as the time-cost needed to implement a new technology. Financial costs will not be considered but rather, the acceptance by various parties including operators, maintenance personnel as well as passengers. The time-cost in implementing a new technology will also be examined through the need of building new infrastructure. Each subcategory is listed in Table 28:

Table 28 - Feasibility of Implementation Scoring Explanation

Subcategory	Specific Items to be scored	Unit of scoring
Infrastructure	The time-cost to implement a new technology will be scored.	Logical reasoning for time-cost advantage and disadvantages. Greater advantages = higher scores.
Acceptance by Bus Drivers	The opinions of bus drivers from various sources and surveys were examined and scored.	Scoring based on surveys. Better opinions = higher scores
Acceptance by Maintenance Personnel	The opinions of maintenance personnel were extrapolated from the idea that a simpler bus to work on is one that a maintenance worker would enjoy more.	Scoring based on perceived acceptance of maintenance personnel from literature review. Better opinions = higher scores.
Acceptance by the Public and Awareness of Technology	Opinions of the public on different bus technologies were scored.	Scoring based on surveys. Better bus = higher scores.

3.1.4 Operational Performance

The driving performance and noise comfort for passengers and pedestrians will be scored and issues identified. The overall reliability was also scored based on MBRC. Each item and explanation for operational performance is seen here in Table 29.

Table 29 - Operational Performance Scoring Explanation

Subcategory	Specific Items to be scored	Unit of scoring
Driving Performance - Perception	The perception from bus drivers on different bus technologies relating specifically to the driving performance will be scored	Scoring based on surveys of bus drivers. Better opinion = higher scores.
Driving Performance - Statistical	Test data from the Altoona Bus Testing database will be used.	0-30 MPH time (s) Lower time = higher score
Noise - Exterior	Noise measurements from the exterior of the bus were scored.	Noise Level (dB) Lower noise level = higher scores.
Noise - Interior	Noise measurements from the interior of the bus were scored.	Noise Level (dB) Lower noise level = higher scores.
Reliability	The reliability of different bus technologies was examined. Data was used from multiple reports compiled by the FTA. The full list of reports can be found in the references.	Miles Between Road Calls (MBRC) Higher MBRC = higher scores.

3.2 Overall Weighting

This analysis will consider the following types of bus powertrains:

- Regular Diesel
- Ultra Low Sulfur Diesel
- Diesel-electric hybrid (Battery-based, series)
- Diesel-electric hybrid (Battery-based, parallel)
- Diesel-electric hybrid (Capacitor-based energy storage)
- Diesel-electric hybrid (Battery-based Microturbine generator)
- Electric Bus (Proterra BE35)
- Electric Bus (BYD eBus)

The bus powertrains above were chosen because of the availability of data and therefore the ability to compare metrics to determine a best possible scenario.

In adjusting the weighting to best represent the industry, each category was analysed and weighted. Each sub-category was given a specific weight. The following scoring rubric in Table 30 was developed.

Table 30 - Category Weighting

Weight	Reasoning
1	Low-importance
2	Average Importance
3	High Importance
4	Very High importance

The goal of this research was to create a multiobjective analysis that would not only include major factors in transit bus technologies, but also recognize categories or topics that would have been otherwise missed or conventionally underweighted. In order to capture the lesser known impacts that have not been addressed in previous literature, a weighting scale out of four was implemented. A much smaller range scale would have allowed lesser known impacts to have a greater influence on the final results. Conversely, these same impacts would have been lost in a larger scale. As is the nature of a multiobjective scoring, the weighting scheme can be highly variable and make a significant difference when adjusted in this case. For this research, each category was given a score out of 4.

There are two arguments to be made, for and against this weighting scheme. When comparing fuel costs and personnel training costs, this weighting strategy becomes skewed. When comparing dollar values, personnel training costs can be over 400 times less than fuel costs, yet can only be weighted 4 times less. Indeed, for a cost-benefit analysis, it may be beneficial to examine a result where all costs are weighted according to actual dollar values. If this was done, personnel training costs may become inconsequential while bus purchase costs may be the most dominant factor.

However, for this multiobjective scoring where there are also environmental, feasibility, and operational performance factors to consider, a dollar-value weighted scheme would not allow for a proper comparison. Instead, by choosing a more straightforward weighting scheme, issues that may have initially seemed inconsequential become more important factors to consider in choosing transit bus technology. Thus, this weighting scheme is a reasonable compromise which will allow all factors to be considered while reducing the change of losing or overemphasizing specific factors.

For a weight of 1 to be assigned, the category has to be minimally important to a transit agency. The factors affecting the score of the specific category will not have a significant impact on the long-term operations of the transit agency. Most of the impacts will be short term.

A weight of 2 will be assigned to categories which are important enough for transit agencies to consider when making their decision of purchasing a bus. The factors affecting the score of the specific category will directly affect operations of a transit agency over the lifetime of the vehicle.

A category assessed with a weight of 3 is of high-importance to transit agencies making decisions on purchasing buses. This category will be important to consider in smooth-running and low-cost operations over the lifetime of the vehicle.

Finally, a weight of 4 will be given to categories of very high importance in transit bus purchasing decisions. These categories are very important to transit bus operations due to their high overall lifetime impact. There are major differences between the best performer and worst performer in this category and will fundamentally affect the operations of your transit agency.

Once each subcategory has been weighted, the final weighting of each of the four main categories will be used to represent the overall total score.

3.3 Fuel Economy Weighting

In order to accurately determine the weighting of each fuel economy score, we need to reference the APTA fact book (2014) which contains key metrics for transit agencies across the USA. From vehicle revenue miles and hours recorded, we can calculate the average speed of the buses in service. The highest average speed of municipalities with 10 or more buses was seen in New-York-Newark, with 40.4 MPH and a population of 18,351,295. The lowest average speed of municipalities with 10 or more buses was seen in Aguadilla-isabela-San Sebastian, PR with 5.2 MPH and a population of 306,196. The overall average speed of municipalities with 10 or more buses is 15.1 MPH.

Unfortunately, the correlation between population and average speed cannot be used for our purposes. For example, Bonita Springs, FL has a population of 310,298 yet has an average speed of 18.3 MPH, significantly different than Aguadilla-isabela-San Sebastian with a similar population. As each municipality has widely varying driving routes, instead of weighting fuel costs in terms of population, we will use average speeds as our determining metric.

Table 31 is a summary of average speeds of cities in the APTA fact book. They were divided in 10 mph increments except for speeds between 10 mph and 20 mph. This was needed to better differentiate the spread of average speeds.

Table 31 - Average Speed of City Buses in USA

Average Speed	0-9.9 mph	10-12.49 mph	12.5-14.9 mph	15-19.9 mph	20-29.9 mph	30-39.9 mph	40+ mph
# of cities in category	14	83	187	119	42	15	5
% of total cities	3.0	17.8	40.2	25.6	9.0	3.2	1.1

It is interesting to note that 40% of cities have an average speed between 12.5-14.9 MPH. An average speed below 20 MPH represents 87% of cities, suggesting that for a large percentage of transit agencies, a bus which has the best fuel economy at low speeds would be the best choice.

Taking into account the average speeds of different cities, each speed category was finally determined by analyzing performance tests completed by the Altoona bus testing database. Over an average of twenty hybrid and diesel 40-ft buses, the acceleration times were averaged. From these average times, a single bus whose acceleration numbers closely matched the average times would be used as a representative average-speed bus. The Daimler Orion VII EPA 10 Hybrid 40-ft bus was chosen as the representative bus. From using the data from a bus which is close to the average performance of all the buses, we can then find the average speed in each of the fuel economy tests. The average accelerations were are listed in Table 32:

Table 32 - Average time to Complete Acceleration Runs

Acceleration metric	Average time (twenty 40-ft buses, diesel and hybrid), seconds	Daimler Orion VII EPA 10 Hybrid-electric 40-ft, seconds.
0-10 MPH	4.6	4.6
0-20 MPH	8.9	8.8
0-30 MPH	13.6	13.7
0-40 MPH	22.5	23.1
0-50 MPH	36.5	37.1

The data from each of the fuel economy tests for the Daimler Orion VII EPA 10 hybrid is summarized in the Table 33.

Table 33 - Average Time to Complete ADB Fuel Economy Cycle

Test	**Run # 1, time (min:sec)**	**Run # 2, time (min:sec)**	**Run # 3, time (min:sec)**	**Average, time (min:sec)**
CBD # 1	9:15	9:09	8:46	9:03
ART # 1	4:12	4:11	4:06	4:09
CBD # 2	9:07	8:50	8:47	8:54
ART # 2	4:30	4:13	4:06	4:16
CBD # 3	9:14	8:56	9:06	9:05
Commuter	5:57	5:58	6:06	6:00
Total				41:27

The average time taken for each phase of the fuel economy tests, and subsequent average speed is calculated in Table 34:

Table 34 - Average Speed Calculations

Test	**Average Time**	**Distance Travelled**	**Average Speed**
CBD	9:01	2 miles	13.2 mph
ART	4:13	2 miles	28.5 mph
Commuter	6:00	4 miles	40 mph
Overall	41:29	14 miles	20.3 mph

In the overall ADB fuel economy cycle, there are three segments run in the CBD cycle, two in the ART cycle and one in the Commuter cycle. The overall fuel economy in the standardized ADB cycle is weighted through total distance travelled:

- 42% in the CBD cycle

- 29% in the ART cycle
- 29% in the Commuter cycle.

61% of cities have average speeds below 15 mph, and a full 87% of cities have average speeds below 20 MPH. We will not use the ADB overall fuel economy for our weighting as this does not represent a majority of the cities. Instead, to best represent the transit agencies, there will be four separate categories that will be weighted separately. The weighted average speed to be used is calculated from weighting the average speed of each cycle, CBD, ART, and Commuter. For transit operators looking to optimize this analysis for different driving routes, they can decide which category their route best fits in.

The weighting for each route-type was calculated to better represent average speeds in cities as seen in Table 31. The target speeds for each route was 15, 20, and 30 MPH for low, medium, and high-speed routes, respectively. The weight for each fuel economy cycle was not to be below 5%, but there was no upper limit. Using a trial and error method to achieve these target average speeds, the weights are displayed in Table 35.

In weighting the overall fuel economy, the target was to have a weighted average speed of 20 MPH or below. Using the fuel economy test distances and speeds as a reference, the CBD, ART and COM routes were weighted at 60, 20, and 20 percent, respectively using a trial and error method. These combined to have an overall weighting of 21.6 MPH.

Table 35 - Fuel Economy Weighting and Speeds

Item	Overall Weighting	Low-Speed route Weighting	Medium-speed route weighting	High-speed route weighting
CBD	60%	90%	50%	25%
ART	20%	5%	35%	25%
Commuter	20%	5%	15%	50%
Target Speed	N/A	15 MPH	20 MPH	30 MPH
Weighted Average speed	21.6 MPH	15.3 MPH	22.6 MPH	30.4 MPH

The electric bus costs will be calculated from the Altoona Bus test of the Proterra BE35. As the BYD electric bus has not been tested by Altoona, its costs will be scaled according to the estimated overall energy efficiency of 2 kWh/mile versus the Proterra bus at 1.73 kWh/mile.

Each score will be relative to the calculated fuel costs over 500,000 miles. The cost of diesel is assumed to be $3.50 per gallon while the cost of electricity is assumed to be $0.10/kWh.

As you can observe in Appendix E, the difference between fuel economy of low, medium and high speed route weighting was negligible. The difference was small enough that in the final scoring, there was no difference in the ranking of buses, depending on the route speed weighting. As such, low, medium and high speed weightings were not used. Only the overall weighting was used in the multiobjective analysis.

3.4 Advanced Transit Bus Technologies Survey

A survey was conducted to poll participants on their opinions of the current and future transit bus industry. It included questions asking about transit bus performance, transit operations and what they thought were useful technologies. The survey was completed through Fluidsurveys and invitations were sent to 35 different contacts in the transit bus industry.

The questions in the survey were vetted by both faculty members and different transit industry and fleet insiders, with significant input and approval by the University's Research Ethics Board (REB). The questions were deemed appropriate for the purpose of the survey. It was designed with the intention to give a broad view of the transit bus industry and gather the opinions of those who worked closely with buses. Once multiple opinions were recorded, a picture of the industry as viewed by those with the expertise was to be acknowledged and analysed.

Unfortunately, despite the survey being sent out to 35 people from various transit agencies and companies in North America, only two recipients responded and completed the survey. Because of this low response rate, the survey results to not have statistical significance. However, the results can be used as a guide to inform the research and to help support or refute the conclusions from this research. The two participants were experienced professionals in the industry each with over 10 years of experience.

Table 36 is a summary of a select number of responses. The full survey can be found in Appendix F.

Table 36 - Advanced Transit Bus Technologies Survey Selected Responses

Survey Question	Participant A	Participant B
Experience with powertrain type	Diesel, Hybrid-electric	Diesel, Hybrid-electric
How would you rate the reliability of your bus fleet?	Unsatisfactory (Hybrid-electric)	Good (Diesel)
How do you rate the reliability of diesel buses	Excellent	Good
How do you rate the reliability of hybrid-electric buses	Average	Unsatisfactory
How do you rate the reliability of Electric buses	Average	Unsatisfactory
How do you rate the reliability of CNG or alternative fueled buses	Good	Unsatisfactory
Where does the majority of funding come from? (Percentage)		
Private Funding	20	0
Customer Sales	100	80
Government Funding	10	20
Other	50	50
What is the largest cost associated with transit bus operations?	Fuel	Fuel
The use of hybrid buses improves the efficiency of performance versus	Agree	Disagree

cost.		
The use of electric buses improves the efficiency of performance versus cost.	Strongly Agree	Choose not to answer
The use of advanced clean diesel buses improves the efficiency of performance versus cost.	Disagree	Agree
The use of CNG or alternative fuel buses improves the efficiency of performance versus cost.	Agree	Agree
The availability of funding would influence our timeline in the purchase of new buses.	Strongly Agree	Agree
Battery failures and unforeseen maintenance issues are an important consideration when purchasing hybrid or electric buses.	Strongly Agree	Strongly Agree
Fuel economy is an important consideration when choosing a transit bus.	Strongly Agree	Agree
Low maintenance costs and high reliability are important considerations when choosing a transit bus.	Strongly Agree	Strongly Agree
The environmental impact of our buses in operation is an important consideration when operating our fleet.	Strongly Agree	Agree
Hybrid-hydraulic buses are a promising technology.	Neutral	Neutral
Bus route optimization is important	Strongly Agree	Agree

part of maintaining the efficiency of our fleet.		
Introducing a set of voluntary benchmarks would improve our fleet's *economic performance and reduce costs.*	Agree	Disagree
Introducing a set of voluntary benchmarks would improve our fleet's *environmental performance and reduce emissions.*	Strongly Agree	Disagree
Factors which influence your decision on purchasing new buses	Funding, Age of fleet, Reliability of current fleet, Growth/need for expansion, Environmental concerns, Public opinion, Government	Funding, Age of fleet, Reliability of current fleet, Growth/need for expansion, Government
Top three most important factors in deciding to purchase new buses	1. Funding 2. Growth/need for expansion 3. Government	1. Funding 2. Age of fleet 3. Government
Do you believe there are current novel or experimental technologies that would be beneficial to fleet operations?	Yes, Hybrid Buses.	No.

Although limited, the survey results provide critical insights into the operations of bus fleets and the opinions of some of their operators.

Diesel buses, as they have been used in the transit industry for a long while, are still percieved as a very good bus for transit operations. New technologies such as hybrid buses and electric buses are not yet universally accepted and still have many questions surrounding them. Indeed, Participant A, who rated the reliability of hybrid-electric buses and electric buses as average, strongly agrees that battery failures and unforeseen maintenance issues are an important consideration in purchasing hybrid or electric buses. The two respondents disagree on the performance of clean diesel buses and hybrid buses, with participant B preferring clean diesel buses over hybrid electric buses. The difference in opinion on these issues suggests either not having enough information available for transit authorities to make informed decisions, or having a poor, anecdotal experience with certain technologies. A larger survey return would have provided more information to come to a conclusion.

The understanding of hybrid-hydraulic buses as designed by Altair is also most likely very low. Because these buses have not been purchased or marketed for sale to any transit agencies, it is more than likely the neutral answers about this technology simply stem from a lack of knowledge. If hybrid-hydraulic transit bus technology moves away from the prototype stage and into full-scale production, we would likely see an increase of awareness.

Bus route optimization is the basis to an efficient bus. As we have seen from the research earlier in this paper, a hybrid electric bus will show their improved performance on slower routes with more stop and go traffic. The two participants both agree on route optimization, although disagree to which optimization is important differs.

Of the three most important factors in deciding to purchase new buses, two key identified were funding and the role of government. These two are generally interrelated because both new government policies and government budgets given to municipalities. If we look back at where the majority of funding comes from, both participants have customer sales as their number one source of funding, with government funding in the bottom half.

Finally, while one participant stated that hybrid buses have the potential to be beneficial to fleet operations, the other did not think there was anything new that could help.

While the survey did not produce statistically significant results, it supported the main objective of this thesis: a critical evaluation of the benefits and difficulties of advanced transit bus technologies is both timely and needed.

4 Multiobjective analysis

The multiobjective analysis incorporates all the data from the analysis. Again, based on the literature reviewed, there are four main categories which a transit agency may wish to optimize their operations for:

1. Financial costs
2. Environmental emissions
3. Feasibility of implementation
4. Operational performance

Within each category, there are certain points that will overlap each other. These overlapping categories will not necessarily be graded the same, but will instead be graded according to the specific category in which it is being considered. Technologies which are entirely unproven, yet hold promise will only be considered in a bonus category, and not as part of the main analysis. Technologies which have been proven but do not have specific information for, will be included as part of the analysis with an explanation given for the reasoning of the given weighting.

For example, if a transit agency were to target a better, more environmentally friendly transit bus operation, they would look to the environmental friendliness category and see what transit technologies fit their requirements.

The main bus types and their variants to be considered in this analysis are:

1. Diesel
2. Diesel-electric Hybrid Series
3. Diesel-electric Hybrid Parallel
4. Diesel-electric Hybrid Microturbine
5. Full Electric (BYD)
6. Full Electric (Proterra)

Between the different variants of diesel buses and hybrid buses, significant differences will be noted and weighted differently. Given the fundamental differences between the BYD electric bus and the Proterra BE35 electric bus, the differences will be noted in calculations where necessary.

Fuel cell buses were not covered in this analysis as there was no directly comparable data available. There are a few studies done by NREL on fuel cell buses in municipal operation, but the data was not comprehensive enough for use in this multiobjective analysis. The Altoona Bus Testing Center also did not test a fuel cell bus as of the writing of this thesis. As a number of categories used data collected from the Altoona bus testing database, it would be very difficult to accurately score a fuel cell bus. Fuel cell buses could be included in future research if more data becomes available.

Within each category, each alternative will be scored from “1” (lowest performing) to “10” (highest performing) as to how well they meet that category. Alternatives scoring between 1 and 10 will be linearly interpolated. Later, the categories will be weighted according to their relative importance. The downside to linear scoring is that to maintain inter-category consistency, the lowest and highest scoring options must be assigned to an extreme (value 1 or value 10), even if the actual differences between these extremes and other alternatives in some categories is much less. For example, for the emissions category, the highest emitter emits 2112 grams CO2/mile while the lowest emits 1378 grams CO2/mile. Even though the difference is about 1100 grams, the higher emitter will be given a full 9 points less, which will negatively impact that specific bus technology more than it should. In addition, the weightings for each category will be closely examined and discussed and where discrepancies are found.

4.1 Financial Cost

This category will compare the costs associated with transit bus operation. The subcategories to be discussed and compared are:

1. Bus Purchase Cost
2. Infrastructure Capital Cost
3. Propulsion Maintenance Cost
4. Brake Maintenance Cost
5. Fuel Costs
6. Personnel Training Costs
7. Engine and Transmission Replacement and Maintenance
8. Electrical Subsystems Maintenance
9. Unforeseen Costs

4.1.1 Bus Purchase Cost

The initial purchase cost is usually the first hurdle for transit agencies. All other factors being equal, less costly technology is preferred, or "cheaper is better". In the case with transit buses, agencies have to carefully weigh the short term costs versus long term benefits. The diesel bus is by far the least expensive to purchase, typically three times less up front in terms of purchase cost than an electric bus. If transit agencies are in need of more buses and have limited funding available, it would very difficult to justify the purchase of an electric bus. On the other hand, if a transit agency has less worried about up-front costs and quantity of buses, electric buses can prove to be a sound investment. Table 37 is a summary and scoring results of each alternative bus based on the purchase prices.

Table 37 - Bus Purchase Cost Scorest

Item	Diesel	ULSD Clean Diesel	Diesel-electric Hybrid (Ultracapacitor)	Diesel-electric Hybrid (Series)	Diesel-Electric Hybrid (Parallel)	Microturbin e Hybrid	Full Electric Bus (BYD)	Full Electric Bus Proterra
Purchas e Price	$300,00 0	$450,00 0	$462,000	$590,00 0	$630,00 0	$325,000	$520,00 0	$900,00 0
Score	10	7.8	7.6	5.7	5.1	9.6	6.7	1

4.1.2 Infrastructure Capital Cost

As infrastructure is essential to the operation of transit buses. Diesel buses and hybrid buses only need minimal, if any additional infrastructure. The status quo as represented by diesel buses utilized current routes and infrastructure for many years and continue to do so. Thus, the diesel bus will score the highest points. Older hybrid buses that used NiCd and MiMh batteries special battery conditioners to maintain their battery packs. Without these supplemental systems, the batteries would quickly lose their ability to hold a charge. The new generation of lithium batteries do not need additional facilities to maintain their charge. As we are dealing with the new generation of hybrid buses in this research, we will score hybrid bus technology the same as diesel buses. Electric buses will be scored according to their estimated capital costs per bus as discussed below. With normal use, the batteries in both hybrid and electric buses will be limited only by their projected lifetimes. Scores are shown in Table 38.

Table 38 - Infrastructure Capital Costs Scores

Item	Diesel bus	Hybrid Bus	Proterra Electric Bus	BYD Electric Bus
Facilities Capital Cost	$0	$0	$432,000	$35,166
Score	10	10	1	9.2

Electric buses, as they operate fundamentally differently from hybrid and diesel buses, need special chargers and facility improvements. The Proterra BE35 constantly charges it batteries throughout its daily operations instead of charging once during the day, to be ready for the next day. This advantage allows less on-board batteries and higher operational efficiency, at the lower cost of initial infrastructure. The capital costs are averaged by an estimated purchase of three buses (Foothill Transit, 2013). The more expensive Proterra BE35 requires three different systems:

- On-route charger
- Charging station control
- Slow charger

The charger costs are seen in Table 39 for the Proterra BE35 and in Table 40 for the BYD Ebus:

Table 39 - Proterra BE35 Infrastructure Costs

Item	Proterra Infrastructure Costs
"Slow charge" Stop Charger and installation	$70,000
Charge Station Control	$44,000
One "Fast Charger" placed on-route and installation	$1,182,000
Estimated total cost for 3-bus acquisition[5]	$432,000

[5] One fast charger, one charge station control, one slow charger

In an estimated three-bus acquisition, the BYD bus will need:

- 2 x slow chargers
- 1 x fast charges

The BYD eBus costs and infrastructure costs are as follows (Tiberiu, 2013):

Table 40 - BYD E-Bus Infrastructure Costs

Item	BYD Infrastructure Costs
3-hour "Fast" Charger	$72,500
5-hour "slow" charger	$16,500
Estimated total cost for 3-bus Acquisition ***One fast charger and two slow chargers**	$105,500*

4.1.3 Propulsion Maintenance Costs

Propulsion-only maintenance costs of hybrid buses are averaged from reports done by the FTA. Hybrid buses which underwent testing with different transit agencies fared worse in maintenance costs compared to their diesel counterparts. Since there is no published data on the differences between series and parallel hybrid maintenance costs, they will be considered one and the same. The ultra-capacitor New Flyer GE40 LF hybrid bus proved to be more significantly more reliable than other hybrid buses during testing and will scored independently. The microturbine based eBus hybrids are also scored separately due to the availability of data.

In order to score propulsion maintenance costs for electric buses, one replacement of the electric motor will be assumed needed over the lifetime of the vehicle. With regards to the batteries, the battery system in the Proterra BE35 is projected to last up to 15 years while the BYD bus projects their batteries to last up to 12 years. As each of these buses are also expected to last approximately 12 years, we can assume no battery replacement will be necessary over the lifetime of these buses. If a transit bus operator wishes to extend the lifetime of their bus with a replacement battery pack, it would have to be determined separately in a cost-benefit analysis. The Propulsion Maintenance Costs Scores are in Table 41.

Table 41 - Propulsion Maintenance Costs Scores

Item	Diesel (including clean diesel and regular diesel)	Diesel-electric Hybrid Battery-based (both series and parallel)	Diesel-electric Hybrid Capacitor Based	Diesel-electric Hybrid Microturbine-based	Electric Bus (Proterra BE35)	BYD electric Bus
Propulsion-only Maintenance costs /mile	$0.13	$0.266	$0.0782	$0.29	$.045	$0.108
Score	6.9	1.9	8.8	1	10	7.7

4.1.4 Brake Maintenance Costs

The brake maintenance costs are also taken from research done by the FTA. Hybrid buses are seen to outperform diesel buses in every report regarding braking. The electric motor allows regenerative braking which converts a significant amount of kinetic energy into electrical energy, taking the load off of the main friction brakes.

The brake costs represented in this scoring category will be taken from the FTA report from research done with New York City Transit. This city represents a heavy-traffic urban cycle and would put more stress on the brakes than average. By taking costs from a single location, we can better compare the different technologies. The braking costs for electric buses are assumed to be same costs as seen in the hybrid-battery based bus. Both of these buses use the same fundamental system of brake regeneration and battery energy storage.

Since the GE40LF showed a significantly lower brake maintenance cost to a comparable diesel bus, the costs will be calculated separately. The capacitor pack allows for more efficient use of regenerative braking due to capacitors having a larger power handling capacity. This allows the brakes on the GE40LF to last longer than a conventional hybrid-electric battery powered bus. To accommodate the difference between driving routes in New York and Long Beach, the cost will be scaled to the costs seen in in the NYCT report. In Long beach, they compared the capacitor based hybrid bus to a diesel bus.

A factor between diesel bus costs was used to normalize the hybrid bus in NYCT to that of the capacitor-based bus. This was needed to be able to compare the data more equally. The New York City diesel bus undergoes a more severe duty cycle with much more stop and go traffic. This is evidenced by the average speed of New York routes of 6.4 MPH compared to Long Beach transit average speeds of 13.8 MPH. The Diesel bus in Long Beach was found to have brake maintenance costs 2.03 times lower than in New York. This cost factor seems to be directly related to the respective average speeds. Similarly, the brake maintenance cost for the capacitor based hybrid bus, also tested by Long Beach Transit will be multiplied by the same factor of 2.03. The Ebus Microturbine brake system costs are assumed to have the same brake maintenance costs as a hybrid-battery based bus.

When estimating the brake maintenance costs for electric buses, we are estimating similar costs as battery-based hybrid buses. The regenerative braking system should operate at the same level based on similar technologies being utilized. Scoring is done in Table 42.

Table 42 - Brake Maintenance Costs Scores

Item	**Diesel (including clean diesel and regular diesel)**	**Diesel-electric Hybrid Battery-based (both series and parallel)**	**Diesel-electric Hybrid Capacitor Based**	**Electric Bus**
Brake Maintenance costs/mile	$0.05	0.02	0.0073	$0.02
Score	1	7.3	10	7.3

4.1.5 Fuel Costs

From the critique of literature, we found that there was an average improvement of 15% with the adoption of hybrid powertrains. As commented upon in the literature critique, this suggests that overall, hybrid powertrains can have a better fuel economy than diesel buses. The New York City transit bus route is especially well suited to hybrid buses, consisting of many stops along its route with the lowest average speed of every route of 6.1 MPH. Hybrid buses returned a fuel economy 38% better than diesel buses. From this reasoning, there are two conclusions:

1. In low to moderate speed arterial routes, hybrid buses return better fuel economy.
2. In higher speed commuter routes, the hybrid bus does not show a definitive advantage. It may or may not be beneficial to use hybrid buses over diesel buses, and if there is an advantage, the advantage is likely much lower.

The savings of using hybrid buses compared to diesel buses will depend on the price of diesel. Higher prices of diesel will give a greater emphasis on fuel savings.

As the cost of fuel varies between cities and the given information was compiled at different times under different conditions, it is difficult to directly compare buses. Fuel costs in this analysis will be compared through the Altoona bus tests. These tests present a standardized drive cycle and environment to allow accurate direct comparisons. Each test cycle has the following characteristics:

- CBD – 2 miles with 7 stops per mile and a top speed of 20 MPH
- ART – 2 miles with 2 stops per mile and a top speed of 40 MPH
- COM – 4 miles with 1 stop and a maximum speed of 40 MPH

Until the bus reaches the maximum cruising speed, each bus is accelerated at full throttle. By using the previously mentioned fuel economy weighting scheme in chapter 3.3, we are able to better fit the fuel economy scores of the buses to better represent the speed of buses in cities. Fuel economies were also scored using a low, medium, and high-speed fuel economy weighting scheme. It was found that even by weighting the scores based on route speeds, the overall scoring did not change the outcome. This could be because the difference was not significant enough to be seen in this multiobjective scoring method. The technologies were scored using the 500,000 mile equivalent fuel costs as shown in Table 43.

Table 43 - Fuel Costs Scores

Item	Diesel (including clean diesel and regular diesel)	Diesel-electric Hybrid Battery-based (both series and parallel)	Diesel-electric Hybrid Capacitor Based	Electric Bus (Proterra BE35)	[6]BYD electric Bus
Fuel Economy (CBD)	3.28	4.28	4.5	1.70	1.89
Fuel Economy (ART)	3.74	4.22	4.34	2.07	2.30
Fuel Economy (COM)	6.75	6.58	7.12	1.38	1.53
Overall Fuel Economy	4.00 MPG	4.70 MPG	4.97 MPG	1.73 kWh/mile	1.92 kWh/mile
Fuel Costs ($3.50/gallon), $0.10/kwh over 500,000 miles	$430,398.43	$370,135.36	$350,560.90	$85,500.00	$94,890.17
Score	1	2.7	3.2	10	9.8

[6] Extrapolated values from Proterra BE35 Values multiplied by a common factor of 1.11, found through overall fuel economy.

4.1.6 Personnel Training

When implementing a new bus, personnel need to be trained to operate and maintain them. According to the FTA (TRCP Report 132, 2009), hybrid bus operators will require additional training costs for both their maintenance personnel and operators. The additional training hours quoted below include both training hours for mechanics and drivers/operators. As electric buses share many similar electric powertrain components with hybrid buses, it will be assumed that the electric bus will require the same number of training hours. Scores are displayed in Table 44.

Table 44 - Personnel Training Scores

Item	Diesel Bus	Hybrid Bus	Electric Bus
Additional training hours needed	None	20	20
Score	10	1	1

4.1.7 Engine and Transmission Replacement and Maintenance

With the onset of electric buses, they are generally simpler to work on. As evidenced by the Altoona bus testing facility, the electric bus required significantly less hours to perform an equivalent component replacement. Using a worst-case scenario, to remove an engine from a diesel or hybrid bus required 14 hours compared to an electric bus's 4 hours. To remove and replace a transmission required up to 20 hours for a Diesel bus, 18 hours for a hybrid bus and a significantly lower 8 hours for the electric bus.

In addition, diesel buses require regular inspections and maintenance approximately every 1-1/2 months that electric buses do not require (Chambers, 2012). All-electric buses also do not require oil changes like diesel and hybrid buses. This saves both cost of the oil and labour for required maintenance, which is summarized in Table 45.

Table 45 - Engine and Transmission Replacement and Maintenance Scores

Item	Diesel Bus	Hybrid Bus (Battery Based)	Hybrid Bus Capacitor Based	Electric Bus
Engine/motor Removal (hours)	14	14	4	4
Transmission Replacement (hours)	20	18	18	8
Total hours for engine and transmission	34	32	22	12
Score	10	1	5.9	10

4.1.8 Electrical Subsystems Maintenance

Because there are much more comprehensive electrical subsystems in hybrid and electric buses, we will include electrical system labour costs. The labour costs score will be estimated comparing electrical system maintenance costs. The averages are taken from city-collected data compiled by the FTA. Interestingly, the capacitor-based New Flyer GE40LF exhibited lower electrical system maintenance costs than the diesel bus, differing significantly from the hybrid bus average.

There is little reliable data for electrical-based maintenance for electric buses. The cost has been estimated to be between that of the hybrid-capacitor based and the hybrid-battery based bus. The electric bus has a battery-based energy storage system, which is more prone to failure than capacitor-based systems. However, it lacks the additional IC engine drivetrain and transmission that both hybrids have, further reducing maintenance costs. The electrical subsystems maintenance scores are seen in Table 46.

Table 46 - Electrical Subsystems Maintenance Scores

Item	Diesel Bus	Hybrid Bus (Battery Based)	Hybrid Bus Capacitor Based	Electric Bus
Electrical Maintenance Costs ($/mile)	0.02	0.045	0.0176	0.0313
Score	9.2	1	10	5.5

4.1.9 Unforeseen Costs

Unforeseen costs are extremely variable and depend on a number of factors. To attempt to normalize these costs, we will again use the Altoona bus testing database. During each test, they recorded the number of issues related to every subsystem of the bus, in two phases. The first phase is the testing phase, and the second phase is the durability phase. We will average out the number of issues seen in the propulsion system of diesel, hybrid, and electric buses.

An issue is defined as a failure of any component of the bus to the extent that if the component itself seized normal operation or failed, then there may be other unintended failures in the bus. Regular wear items such as tires and brakes were not excluded.

The only electric bus tested to date which has been through the STURAA bus test is the Proterra BE35, so the score for the BYD eBus will be estimated to be the same as the Proterra BE35. Table 47 shows these scores.

Table 47 - Unforeseen Costs Scores

Item	Diesel Bus	Hybrid Bus	Electric Bus (Proterra BE35)	Electric Bus (BYD eBus)
Propulsion System Issues during testing	6.67	7.50	16	N/A
Propulsion System issues during durability testing	4.67	6.58	5	N/A
Total test issues	11.34	14.08	21	N/A
Score	10	7.4	1	1

4.2 Environmental Emissions

Emissions from operation of the bus vastly outweigh emissions from every other aspect of operation. As such, the focus will be on operational emissions and production emissions. As the basic bus structure is mostly the same between buses, the manufacture and associated emission from the structure will not be considered. The parts being considered are the individual battery packs and capacitor packs that differentiate hybrid buses and electric buses. The subcategories are:

1. Operational Emissions
2. Emissions From Production

4.2.1 Operational Emissions

There have not been many studies on the in-use emissions of transit buses. The varying nature of transit bus operations makes it very difficult to directly compare tailpipe emissions. Weather conditions, fuel composition, and exhaust after-treatment all contribute to the complexity of comparing tailpipe emissions. Therefore, instead of using tailpipe emissions, we will use the calculated emissions from consuming diesel fuel. The CO2 emissions from operations over a 500,000 mile period will be used in the scoring. The fuel consumption data is taken directly from the overall fuel economy category in the Altoona Bus tests. Emissions will be estimated by an engineering calculation. An emissions rate of 10,180 grams CO2/gallon was used (US EPA, 2010).

When calculating emissions for electric buses, eGrid was used to determine the emissions from consuming electricity in the USA (US Environmental Protection Agency, 2009) and research by High Performance Solutions was used for Canada (2009). For the sake of simplicity, though there are different emissions for each different region, the CO_2 emissions used will be the average of all the regions in the country. Electric bus emissions were calculated from an estimated kWh usage over 500,000 miles. For Canada, grams CO_2e/kWh was calculated to be 164. In the USA, it was 554.42 g/kwh. This large discrepancy can be attributed to a ‘dirtier’ mix of electrical generation in the USA which includes more coal and gas plants as opposed to Canada’s nuclear and renewable energy.

Other emissions that would be seen from the operation of diesel and hybrid buses include CO, THC, NHMC, NOx and PPM. Using a chassis dynamometer, the Altoona bus testing facility has recently recorded emissions of buses over different driving cycles. The Table 48 is an emissions test for the Daimler Orion VII EPA10 diesel-electric hybrid bus:

Table 48 - Tailpipe Emissions from Transit Bus

Driving Cycle	**Manhattan**	**Orange County Bus**	**UDDS**	**Average % of total emissions**
CO2, gm/mi	2365	1832	1993	99.95%
CO, gm/mi	.20	.14	.12	0.008%
THC, gm/mi	.013	.008	.008	0.0005%
NHMC, gm/mi	N/A	N/A	N/A	N/A
NOx, gm/mi	.88	.682	.654	.04%
Particulates, gm/mi	.004	.008	.005	.0003%

We can see from this chart that CO2 represents 99.95% of total emissions. Because other emissions constitute up to .05%, for the purposes of this multiobjective analysis, we will only consider CO2 emissions for our scoring. In addition, because the differences between hybrid bus types are small, there would be little distinction in terms of emissions between the variations of hybrid buses. These scores are listed in Table 49.

Table 49 - Operational Emissions Scores

Bus Type	Diesel	Hybrid-electric	Electric Bus (Proterra)	Electric Bus (BYD)
Grams CO_2/ mile	2112	1783	N/A	N/A
Grams CO_2 equivalent/mile (Canada)	N/A	N/A	283.7	314.9
Grams CO_2 equivalent/mile (USA)	N/A	N/A	959.1	1064.5
Score	1	4	10	9

4.2.2 Emissions from Production

In this category, the emissions from the manufacturing of different energy storage systems were examined. Because diesel buses are the most well-known bus type and the manufacturing of these buses are so streamlined, this will be given a calculated battery weight of zero kg. As such, the diesel bus will score the highest of 10 points. Note that the structure of the bus (e.g., frame, tires, exteriors, etc.) and the associated impacts and emissions from its manufacture are not included as currently, they are essentially the same for any bus drivetrain technology.

The remaining technologies will be scored using CO_2 emissions from the manufacture of specific components. The battery packs will be the only difference considered in this scoring. Every bus will have different control systems, electric motors, wiring, and other electrical based subsystems. For this scoring, it is not unreasonable to assume such systems are similar and so all hybrid and electric buses under consideration will contain a similar number of these electrical subsystems.

According to the Argonne National Laboratory (Burnham, Wang, & Wu, 2006), lithium batteries emit an average of 12.5 kg CO_2 per kg of battery weight. The following chart includes estimates for the CO_2 emitted from the production of electric bus battery packs.

The rebuild costs for diesel engines are more labour-based than material based. Even a full engine rebuild would not involve a significant amount of replacement parts or waste. As this process has minimal cost to the environment, we will not quantify a CO2 equivalent emissions rate associated with an engine rebuild. An electric motor requires even less parts and labour for a full rebuild and therefore, we will also not quantify a CO2 equivalent emissions rate for electric motors. The linear scores are seen in Table 50.

Table 50 – Emissions From Production Scores

Item	Diesel Engine	Hybrid Battery	Ultracapacitor pack	Proterra BE35 Battery	BYD eBus Battery
[7]**Battery Type**	N/A	200 kwh Lithium Iron Phosphate	[8]Maxwell Boostcap	72 kWh Lithium Titanate	324 kWh Lithium Iron Phosphate
[9]**Energy Density**	N/A	90-115 Wh/Kg	3.22 Wh/kg	60-75 Wh/kg	90-115 Wh/Kg
Calculated battery weight	N/A	1739 kg	200 kg	960 kg	2817 kg
[10]**CO2 emissions**	N/A	21.7 metric tons	[11]0.64 metric tons	12 metric tons	35.21 metric tons
Score	10	4.5	9.8	6.9	1

[7] (Transit Bus Applications of Lithium Batteries: progress and Prospects. FTA Report No. 0024)
[8] (Product Information Sheet - Boostcap Ultracapacitors, 2003)
[9] Burke, Andrew et. al. Performance Characteristics of Lithium-ion batteries
[10] Assumed maximum energy density
[11] Assumed similar production emissions as Lead-acid Batteries at 3.2 kg/kg

4.3 Feasibility of Implementation

This section will assess the ease to implement a new technology. The subcategories are:

1. Infrastructure
2. Acceptance by Bus Drivers
3. Acceptance by Maintenance Personnel
4. Acceptance by the Public and Awareness of Technology

4.3.1 Infrastructure

How quickly and easily can a transit agency implement a new bus technology? Assuming the different buses themselves have similar delivery times, the main comparison will be on infrastructure modifications. Diesel buses can use existing infrastructure in almost every transit agency without exception. If a transit agency is in need of a new bus, they can implement a new diesel bus immediately with minimal, if any upgrades to their facilities with the only wait being order time. Existing routes and facilities have already been used for diesel buses for many years as they represent the status quo. However, electric buses will need new infrastructure.

Hybrid buses operate similar to diesel buses and to implement them requires very little time. According to a hybrid bus implementation plan by the City of Ottawa (Gray, 2003), hybrid buses will still need new tooling and spare parts to maintain hybrid powertrain and electrical subsystems. Because additional tooling and spare parts for the hybrid powertrain are needed, these buses will score lower than diesel buses.

The Proterra BE35 electric bus needs significantly more infrastructure. In addition to charging facilities inside the transit depot, it will need an in-route charging station. The in-route charging station, depending on the location and existing infrastructure can take time to install, in addition to causing disruptions in the immediate area of the charger installation. The Proterra BE35 will score the lowest.

The BYD Ebus will score below the hybrid bus but above the Proterra bus. The BYD bus requires new chargers inside the transit depot. In some depots, additional modifications may be needed to deal with the increased electrical load. However, it does not need additional on-route chargers like the Proterra and once the additional chargers are installed, the buses operate similarly to hybrid buses.

The scores will scale linearly between 1 and 10, shown in Table 51.

Table 51 - Infrastructure Scores

Item	Diesel Bus	Hybrid	Electric Bus (Proterra)	Electric Bus (BYD)
Score	10	7	1	4

4.3.2 Acceptance by Bus Drivers

According to a survey of operators by the Baltimore region hybrid bus tour on their 40-foot hybrid buses, drivers were very positive about the smooth and strong acceleration and braking (New West Technologies, 2006). Overall visibility, ingress/egress, and control were very good. Some drivers disliked the feel of the regenerative braking and one driver thought the bus lagged around 35 mph. Another driver thought the bus was top-heavy in corners. In a survey by CTTtransit drivers some of the negatives were similar, but the complaints were relatively minor such as the back door closing slower or climbing into the driver's seat (Warren, 2004).

The scores for hybrid buses will be based on the following survey question (Warren, 2004): which bus do you prefer driving? Of 28 participants in Baltimore, 3.5% preferred the standard diesel bus, 32% preferred the hybrid, while 64.5% had no preference. In another survey by CTTransit, drivers were asked the same question. 80% of drivers preferred driving a hybrid and only 20% preferred a diesel bus.

In addition to these questions, it is seen from the two surveys that the hybrid bus is universally preferred to drive than diesel buses. Diesel buses will be scored the lowest. Other questions include noise level, vibration, acceleration, defroster, HVAC, braking performance, and how difficult it is to get used to a hybrid bus.

To score the electric bus we need to consider the Altoona bus tests. Many positive attributes of the hybrid bus are even more pronounced in the electric bus. Electric buses are quieter, as seen in the lower levels in the Altoona testing noise tests. Without an engine, the vibrations will also be reduced. They also drive very similarly, and the braking performance would be similar.

From our technological analysis, an electric bus should perform better in the eyes of a driver than a hybrid bus. We can also compare the benefits of electric buses to those of electric cars which operate fundamentally on the same technology. According to a review of the Tesla Model S electric car, (Jalopnik, 2013) the Model S has a fun driving experience with a "rush of torque" that is not subdued by any turbo lag or downshifting necessary. Even on everyday electric cars with significantly lower performance like the Nissan Leaf, the availability of torque from a standstill is a great feature (Honest John, 2014) and gives the driver confidence in driving. In a recent demo of the Proterra BE35, drivers preferred the quiet, smooth and clean ride the all-electric bus provided (Abed, 2013).

With these above comparisons, we assume that the electric bus will be preferred by drivers over the hybrid bus. The electric bus will score the highest points, followed by the hybrid bus and finally the diesel bus. These scores will be scaled linearly, and not according to the survey percentages because the electric bus has no common scale in the same survey. These scores are shown below in Table 52.

Table 52 - Acceptance by Bus Drivers Scores

Item	Diesel Bus	Hybrid	Electric Bus
Baltimore Survey question	3.5%	32%	N/A
Score	1	5.2	10

4.3.3 Acceptance by Maintenance Personnel

This category will be based on the complexity of each technology. The easier it is to maintain, the higher the score for that alternative. Hybrid buses and electric buses will be compared to the diesel bus.

Hybrid buses have electrified components like motors and batteries. Taking into account the many hours needed to remove an engine and transmission, in addition to extra training and no doubt more work required to learn about the new technology, hybrid buses will score below the diesel bus.

The electric buses are potentially easier to work on, but will eventually require fixes on the electrical powertrain that maintenance personnel are not used to. It will take time for them to learn the electrical systems. However, it is expected that these initial challenges will be short lived given that electric buses are simpler to work on. As seen in the Altoona bus tests, to replace the engine/motor only requires 4 hours in the electric bus compared to the diesel bus's 14 hours. After maintenance personnel become more familiar to electric buses, we predict it will most certainly will be easier to work on.

Fewer hours to perform maintenance also potentially mean the reduction of spare buses in a fleet. An engine/transmission replacement requirement of 14 hours will need at least two full days in the shop to repair. An electric bus with an 8 hour replacement may only need one day, significantly reducing the downtime of the bus. The respective scores are here in Table 53.

Table 53 - Acceptance By Maintenance Personnel Scores

Item	**Diesel Bus**	**Hybrid**	**Electric Bus**
Score	5.5	1	10

4.3.4 Acceptance by the Public and Awareness of Technology

Having your transit agency projecting a 'green' image can be very important for environmentally conscious riders and equally important for politicians. In addition to the 'green' image, passengers would be happier if the bus they are riding on is more comfortable. As such, each bus is rated based on the public perception of each technology.

Based on the Baltimore survey of hybrid buses where passengers were surveyed, 76.5% said they would prefer to ride in a hybrid bus and 23.5 had no preference. None preferred to ride in a diesel bus. They were also asked about ride comfort, interior noise, and performance. Overwhelmingly, participants preferred the hybrid bus with the only category where hybrid buses were perceived as worse than diesel buses was in air conditioning performance. In a survey done by Ballard power with a fuel cell hybrid-electric bus, passengers noted the bus being quiet, smooth, no vibrations, and clean and odourless.

To examine public interest of electric buses, we can reference a survey completed by Accenture (2011) on the public perception of plug-in electric vehicles for private transport. Although the survey specifically pertains to personal transportation, it sheds light on the general perception of electric vehicles. A total of 7003 people from 13 countries were surveyed. 500 were from Canada and 1000 were from the USA. 58% of participants were in favour of electric vehicles replacing conventional cars over time. It was also asked if participants cared how the electricity used to charge the vehicles was generated. 45% said it would impact their buying decision, 35% said they cared, but it would not impact their decision, and finally, 20% did not care at all.

In addition, the city of Montreal surveyed passengers about their ride on newly acquired BYD electric buses. The overall appreciation of the bus was “very good” and the majority of respondents believe the transit agency should favour electric or hybrid buses even if they are more expensive (Robillard-Cardinal, 2013).

From the examining of the surveys, the general perception of new technologies are as follows:

- Hybrid buses are preferred due to better overall comfort
- Electric vehicles are a favoured technology over conventional vehicles.
- Most consumers are concerned about where the electricity used to charge electric vehicles comes from

As the public universally preferred hybrid buses over diesel buses, diesel buses will score the lowest. Electric buses have all the benefits of hybrid buses, but are even more pronounced. Similarly to drivers, passengers can also appreciate the added comfort of a fully electric bus. A survey by Société de transport de l'Outaouais (BYD, 2014) on their trials of the BYD electric bus was completed by passengers. The overall appreciation of passengers was very good and the majority of participants thought electric buses should be preferred over hybrid buses although they are more expensive to buy than conventional buses. "Riders favour fostering the development of sustainable transportation and the reduction of Gatineau's carbon footprint." (Robillard-Cardinal, 2013).

Electric buses will score the highest points and the hybrid bus will score in the middle, shown in Table 54.

Table 54 - Acceptance by the Public and Awareness of Technology Scores

Item	Diesel	Hybrid	Electric
Score	1	5.5	10

4.4 Operational Performance

The operational performance is analysed and scored to determine which bus technology is preferred among transit operators, drivers and users. The categories are:

1. Driving Performance – Perception
2. Driving Performance - Statistical
3. Noise – Exterior
4. Noise – Interior
5. Reliability

4.4.1 Driving performance - Perception

Some bus drivers demand more from their buses, while others simply drive whatever they are given. This category will be scored from an acceleration and braking performance viewpoint. From the aforementioned survey about hybrid buses, drivers overall preferred hybrid buses to diesel buses. Among the reasons was improved acceleration and braking performance. 73% preferred hybrid buses over diesel buses. Only 2% thought hybrid buses were worse while 25% did not have any preference. A hybrid bus survey by CTTransit also showed that drivers enjoyed the improved acceleration and power. Many drivers liked the regenerative braking of the buses, but some drivers noted it was difficult to get used to.

The performance of electric buses has not been surveyed by drivers, but there are a few, published opinions by those who have driven the BYD electric bus. One driver in California (Xinhua, 2013) found the BYD electric bus to, “...ride a lot smoother, cleaner; they feel a lot lighter, and the driver area is more comfortable."

When comparing the importance of measured data versus perceptive data, the perceptive data could be argued to be a more important consideration and therefore carry more weight. A bus driver needs to feel more confident in their bus as opposed to the bus being just measured as superior. We draw this conclusion based on reviews of the Nissan Leaf and the Tesla Model S electric cars. In these instances, drivers prefer to react and gauge a vehicle by how it feels over how it performs on a sheet of paper. As will be discussed later in chapter 4.5.4, the final weighting of statistical data is less compared to the perceptive data.

Hybrid buses with a majority of positive comments about their acceleration will score the highest; diesel buses will score the lowest. From a technology standpoint and the information reviewed, we can further assume electric buses to perform at least the same level as hybrid buses as perceived by drivers, with even lower noise and lower emissions. Accordingly, the electric bus will score the highest and the diesel bus the lowest with the hybrid bus scoring in-between, seen in Table 55.

Table 55 - Driving Performance, Perception Scores

Bus	**Diesel**	**Hybrid**	**Electric**
Score	1	5.5	10

4.4.2 Driving performance – Measured

The Altoona bus testing center performs acceleration tests on its buses. We can directly use these acceleration numbers to form a score for different bus technologies. The tests are performed at full throttle from a stop and once the target speed is reached, a time is recorded.

The buses are tested from a standstill to a maximum speed of 50 MPH with the time being recorded at 10 MPH intervals. The median measured speed is used as the highest acceleration of 0-50 MPH was much farther out of the range of average city speeds, in Table 31. It would be uncommon for a bus would reach 50 MPH. An acceleration of 0-10 MPH did not cover enough of the average city speed spectrum. Therefore, the time from 0 -30 MPH, the median measured speed will be used as seen in Table 56.

Table 56 - Driving Performance, Statistical Scores

Bus	**Diesel**	**Hybrid (battery Based)**	**Hybrid (Capacitor Based)**	**Electric**
0-30 MPH (s)	14.07	13.16	15.64	17.83
Score	8.2	10	5.2	1

4.4.3 Noise - Exterior

Not only do passengers and drivers on the bus appreciate lower noise levels, so do pedestrians and residents living next to bus routes. In multiple cases, home owners complained about the noise of buses on the streets (Westmiller, 2014). Some transit agencies have also tried rerouting buses to reduce the noise complaints by neighborhoods during nighttime hours (Rwema, 2012).

Noise test values conducted by the Altoona bus testing facility will be used. All three noise tests are listed below but for the purpose of scoring comparison only the acceleration from a standstill will be used. Acceleration from a standstill was chosen because this was deemed to be the most noticeable noise, as well as the most common. It is uncommon for buses to undergo hard acceleration while at a constant speed. When the bus is stationary, the noise levels are also low. The bus with the lowest noise, representing the quietest bus, will score 10 points. The loudest bus with the highest noise level will score 1 point. The remaining buses will score linearly between the two.

The exterior noise test values are recorded from both the road side and the curbside of the bus. In the different cases of acceleration, the tests are performed at full throttle. The three different tests are:

- From a constant speed, the bus is accelerated with full throttle just before a transmission upshift. The highest recorded decibel level is listed.
- Acceleration from a standstill. The highest decibel is listed.
- Stationary with the engine on low idle, high idle, and wide open throttle. The highest decibel level from all three cases is listed.

The scores and noise levels are summarized in Table 57. Note: Acceleration from a standstill was the only noise level used in the scoring as it was determined to be the most frequent and commonly heard noise from a transit bus.

Table 57 - Noise, Exterior Scores

Noise	Diesel	Hybrid	Electric
Acceleration (constant speed)	75.6 db	72.9 db	60 db
Acceleration (from standstill)	76.2 db	71.9 db	57.4 db
Stationary	68.2 db	65.2 db	43.1 db
Score (Acceleration from standstill)	1	2.5	10

4.4.4 Noise – Interior

The noise from a bus can affect the customer as well as the driver. Surveys of passengers on hybrid buses have shown passengers appreciate the reduced noise. Optimally, a bus would make minimal noise at all phases of operation; while stationary, while accelerating, and while cruising at a constant speed.

This is an important metric for the passengers of the bus. In the case of a survey of passengers by Baltimore Transit (2006) as well as CTTransit (2004), the lower noise level of hybrid buses was noticeable and appreciated. Among other reasons, noise was a factor in passengers stating their preference in riding hybrid buses over diesel buses.

The interior noise acceleration tests are measured from various points within the bus. The noise level is measured while the bus is accelerating from a standstill to 35 MPH at full throttle on level pavement. All openings in the bus are closed. The noise level from the rear seats was used for the scoring as this location was generally the loudest location in recorded test data, apart from the electric bus. These scores are listed in Table 58.

Table 58 - Noise, Interior Scores

Noise	Diesel	Hybrid	Electric
Driver's seat	73.4	75	72.9
Front Passenger Seat	73.7	75	71.9
Rear Seats	78.2	78.2	72
Score (Rear seats)	**1**	**1**	**10**

4.4.5 Reliability

For an operator, a bus must be reliable. It should not break down while in service. The transit industry uses a standard measure, Miles Between Road Calls (MBRC), to estimate the reliability of a bus. The higher this value, the more reliable the bus.

For the case of electric buses, there are a few reported values for MBRC. In a study performed by NREL with fuel-cell electric buses (Chandler, 2012) in different cities, the data collected was from testing these buses in regular operations. Although we are referring to electric buses non-fuel cell buses in this research, the data compiled by NREL can be used for a clearer picture of electric powertrains. As the main difference between fuel cell buses and battery or capacitor based buses is the energy storage system, the rest of the powertrain can be reliably compared.

The average propulsion-only MBRC from 19 buses was 5801 miles, the lowest of all the buses compared in this research. The reasons could be from the infancy of the technology. Although electric buses have a drivetrain that is simpler than a hybrid bus, they are not as well understood as diesel buses. In practice then, electric powertrains may cause – or be at least perceived to cause - problems than hybrid buses.

Early hybrid bus electric motors, despite their simplicity, did not last as long as many people believed. According to a report done by the auditor general on the operations at the TTC, diesel buses currently have an 18 year service life compared to hybrid buses with a 15 year service life. Many aspects of maintenance are covered by warranty including the hybrid motor units. As the warranty expires, the TTC will need to absorb the costs, which will dramatically increase. This maintenance cost will double after 10 years of service according to estimates by the TTC (Toronto Transit Commission, 2014). The current yearly maintenance for a hybrid bus is about $45,000. In the future, this cost will be more than $90,000.

The TTC is not the only transit agency to experience these problems. The NYCT is also suffering similarly from their early hybrid bus acquisitions (Young, 2013). As the warranty is about to expire, the costs for maintaining hybrid buses are going to increase significantly. The MTA reports that their electric motors are burning out and it would be cheaper to convert these buses to diesel buses than to replace the electric motors.

It is generally accepted that a diesel engine will require a rebuild every 300,000 to 500,000 miles (M.J. Bradley & Associates, 2000). Buses undergoing more stop and go traffic will need to be rebuilt in shorter intervals. A 500,000 mile interval is generally accepted as a 12-year interval. The new generation of electric motors however, are reported to have a longer lifetime of up to 25 years, about double what a diesel engine is expected to last. Since the new generation of electric buses and traction motors have not been on the market for a very long time, it remains to be seen whether these motors will live up to its manufacturers claims.

The capacitor-based hybrid bus exhibited a Propulsion-only MBRC significantly higher than the average battery-based hybrid bus, and will be scored separately. The bus with the highest MBRC will receive the highest score with the others scoring linearly between, as shown in Table 59

Table 59 - Reliability Scores

Item	**Diesel**	**HEV Battery-based**	**HEV Capacitor Based**	**Electric Bus**
Powertrain-only MBRC	17,391	8,415	15,000	5,801
Score	10	3	8.1	1

*Average between Diesel and HEV Battery-based MBRC

4.5 Overall Scoring Weighting

The overall weighting of the subcategories are determined on a scale of 1 to 4 with 4 bring the highest score and 1 the lowest. As discussed in Chapter 3, each category was weighted according to the data available and through rational argument. The reasoning behind each category is detailed in the following discussion.

4.5.1 Financial Costs Weighting

Starting with Financial Costs, according to a survey of 180 fleet managers and directors in North America (Accenture, 2011), participants were asked to rank four different categories, depending on how much they influenced their purchasing decision of alternative fuelled vehicles. The top three reasons were:

1. Lower acquisition cost
2. Lower operating expenses
3. Lower infrastructure costs

Acquisition cost is the most important cost to transit agencies. Operating expenses follows second and lower infrastructure costs comes third. Using these survey results, the bus purchase price will be weighted the highest of 4, with all maintenance costs being weighted 3.

Infrastructure costs will be weighted 3 as the cost is not insignificant when implementing electric buses. When the survey was conducted, it was did not take into account the increased infrastructure cost for implementing electric buses.

As seen from the two participants in the Advanced Transit bus technologies survey, fuel costs are currently the highest operating costs for transit operators. This is also reflected in multiple hybrid bus comparison reports from the FTA. As fuel costs are so significant, this will be weighted as 4.

Personnel training, being a one-time cost during the introduction of the buses should not affect any purchasing decisions or long-term costs for buses, but it is nevertheless something that should be considered. This will be given a weight of 1

Replacing an engine and transmission should not happen often in buses. However, when they happen, they will put a bus out of service and increase the overall costs of the vehicle. The NYC MTA has decided to convert a number of their hybrid buses into pure diesel buses due to warranties expiring and the cost of replacing an electric motor was enough to warrant a retrofit to diesel-only which would be significantly cheaper (Gartland, 2013). Due to the infrequent nature, but significant costs associated with a replacement engine and transmission, this will be weighted as a 3.

Finally, unforeseen difficulties are always concerns for transit managers when selecting a new technology. They will have to adapt to new parts, new systems, and new maintenance schedules. On top of that, there may be problems which appear unexpectedly and cause major issues. This category is scored using the number of propulsion-only issues recorded during testing at the Altoona bus testing center. The buses driven through the STURAA test are usually first-generation buses with higher than average durability issues. However, the number of issues can be a proxy indicator of the durability of the powertrain and what potential issues may occur during operations. This category is weighted a 2 for affecting the bus operations over the lifetime of the vehicle.

Many of the costs were heavily weighted due to the importance of cost in transit bus operations. In the Advanced Transit Bus Technologies survey, both respondents listed funding as the most important factor in their decision to buy buses. Naturally, the need for funding parallels the need for reduced costs. Personnel training was weighted as a 1 due to the low cost needed to train employees compared to other costs. These weights are listed in Table 60.

Table 60 - Financial Costs Weighting

Category	Weight
Bus Purchase Price	4
Infrastructure Capital	3
Propulsion Maintenance	3
Brake Maintenance	3
Electrical Subsystems	3
Fuel Costs	4
Personnel Training	1
Engine and Transmission Replacement	3
Unforeseen Difficulties	2

4.5.2 Environmental Emissions Weighting

Operational emissions significantly outweigh the emissions from production. Using the BYD Ebus as an example, during production, it was calculated to emit 35.2 metric tons of CO_2 from the production of its batteries. During operation, it was calculated to emit 314.9 gCO_2e/mile. Over a 500,000 mile lifetime, this represents 157 metric tons of CO_2e. Going further and estimating the equivalent emissions from the production of electricity in the USA, we see the difference even greater at 532 metric tons of CO_2e.

This worst-case scenario of the BYD Ebus has the highest pollution during bus production and the lowest pollution during operation in Canada, minimizing the ratio of production to operational emissions. Production emissions represent 18% of total electric bus emissions in

Canada. Although this number seems high, in the larger picture, the production emissions for the worst electric bus represent only 3% of total emissions from an average diesel bus. Because of the dirtier mix of electrical generation, production emissions of electric buses in the USA drop to only 6% of total electric bus emissions.

Operational emissions will be weighted as a 3 and production emissions as a 1. Operational emissions were deemed to have a lower impact than bus purchase price and fuel costs (weight of 4) because most transit agencies seem to prioritize costs as a more important factor to operations than the environment. At present, transit agencies appear to improve environmental emissions chiefly when there is a financial benefit. Transit agencies with a greater importance on emissions, may choose to weight operational emissions a 4. In this higher-weighted environmental emissions case, there would not be a difference in the order of preferred alternatives, but rather a greater spread between electric buses and other bus technologies. These weights are listed in Table 61.

Table 61 - Environmental Emissions Weighting

Item	**Total Weight**
Operational Emissions	3
Emissions from production	1

4.5.3 Feasibility of Implementation

The infrastructure needed for new technologies such as electric generally do not exist. The BYD eBus has less required infrastructure to install than the Proterra, which involves on-route chargers. From an overall context, purchasing diesel buses and having infrastructure that is already available or easily implemented allows for faster adoption of new buses with minimal cost. Due to large differences in the implementation of electric and diesel buses affecting long-term operations, this will be weighted a 3.

The information presented to date indicates bus drivers enjoy driving the newer hybrid buses. They are quieter and ride better, which the drivers enjoy. Presumably, if drivers enjoy a new technology, they will complain less and thus will aid in the implementation of new technology. The acceptance of new technology by maintenance personnel is similarly important. In either case, they are both short term issues. Employees are trained to adapt to new environments and new technologies and the transit industry is no exception. According to the University of Tennessee Chattanooga, maintenance and driver training is very important (2014). Although electric buses are not any more complicated to work on, they are different, necessitating training. There may be a steep learning curve for maintenance personnel, but they will eventually learn to work well with the new buses. Both of these categories will be weighted as a 2.

The opinion of the general public and their awareness of new technologies are significant to ensuring customer satisfaction. Satisfied customers are important for any business, and transit agencies can help cities and politicians in projecting a greener image. Customers in general prefer riding in hybrid buses and as reported by the Bulletin d'Aylmer (Robillard-Cardinal, 2013), "Riders favour fostering the development of sustainable transportation…".

In a study by Brian Taylor and Camille Fink (Taylor & Fink, 2012) examining factors to improve transit ridership, they concluded that transit ridership is largely a product of factors outside the control of the transit agency itself. The quality, service, and pricing are the most influential factors within the control of the agency and since the choice of powertrain can directly affect the quality and pricing, weighting a 2 shows that this category has a degree of influence on transit bus purchasing decisions which may affect their operations during their lifetime. Additionally, where respondents were asked to rank the most important factors in bus purchase decisions, public opinion ranked the lowest in both responses completed in the Advanced Transit Bus Technologies survey. The weights for these sub-categories are listed in Table 62.

Table 62 - Feasibility of Implementation Weighting

Category	**Total Weight**
Infrastructure	3
Acceptance by bus drivers	2
Acceptance my Maintenance Personnel	2
Acceptance by the Public and Awareness of Technology	2

4.5.4 Operational Performance Weighting

For driving performance, there are two categories, perception and statistical. According to the Altoona bus testing, the diesel bus is faster. In a survey from drivers, they preferred the feel of hybrid buses, despite them being slower than diesel buses. The driving performance of the bus as felt by the drivers is important, and transit bus drivers have been shown to be able to adapt quickly to most new bus technologies. As seen in an all-electric Nissan Leaf passenger car review, the feel of power from the electric motor is strong, outweighing its relatively slow acceleration performance numbers (Honest John, 2014). Since the feel of the bus behind the driver does not affect costs significantly, driving performance-perception will be weighted at 2. As driving performance-measured does not hold as much importance compared to perceptive driving performance, it will be weighted as a 1.

For noise, it is equally important for passengers as it is for those outside of the bus. Passengers enjoy less noise on the bus for a more pleasant trip while those outside the bus such as pedestrians and homeowners would prefer not to be bothered by the noise of buses. By and large, official noise complaints are made by residents along bus routes as opposed to passengers. One of the loudest diesel buses as tested by the Altoona Bus Testing facility was the New Flyer D40 LF with a measured rating of 80 db when accelerating at full throttle from a stop. For comparison, a typical passenger vehicle will register around 65 db, approximately 3 times quieter than a loud diesel transit bus (Transport Canada, 2000).

The New York City MTA responded to residential complaints about their buses by installing mufflers on their city buses (Donohue & Goldsmith, 2010). Around 6000 buses will be modified to reduce the noise on the streets of New York at an estimated cost of around $1 million: the cost per bus could potentially be $170/bus. This is a very minor cost compared to other costs, but shows that noise complaints can be taken seriously enough by transit agencies for them to invest time and money to mitigate the issues. Both interior and exterior noise scores will be equally weighted at 2 for affecting the long term operations of their buses but not significantly affect the cost of the buses.

Mechanical reliability is extremely important for transit agencies, and using a reliable metric such as MBRC allows us to rate the different bus technologies. In a survey by RLTS Market Review, participants were asked about the importance of attributes with their specific mode of transit. Of those who responded, 90% stated that the '*reliability of journey time*' was either very important or quite important (Ian Wallis Associates Ltd., 2013). In a previously mentioned study by Taylor and Fink (2012), the quality of service including reliability and on-time performance are among the most important aspects of public transit as viewed by regular passengers. This category will be weighted at 3 because having a reliable bus over the lifetime of operations can affect ridership and customer satisfaction.

The final operational performance weighting for all the subcategories are listed in Table 63:

Table 63 - Operational Performance Weighting

Item	**Total Weight**
Driving Performance, perception	2
Driving performance, statistical	1
Noise, Exterior	2
Noise, Interior	2
Reliability	3

4.6 Final Scores

After comparing every subcategory, and determining the scoring and the individual weighting, the weighted total scores for the different technologies are seen in Table 63. For a full breakdown of individual scores, please refer to Appendix E.

According to the overall weighting scheme, the buses in order of preference from the highest score to lowest score are seen in Table 64:

Table 64 - Final Overall Weighted Scores

Bus Type	Weighted Total Score	Scoring Position
Electric Bus (BYD)	352.7	1
Electric Bus (Proterra)	312.4	2
HEV (Capacitor)	305.8	3
Regular Diesel Bus	260.5	4
ULSD Diesel Bus	251.5	5
HEV (Microturbine)	225.3	6
HEV (Series)	212.1	7
HEV (Parallel)	209.7	8

As seen in the multiobjective analysis, electric buses from Proterra and BYD both present a promising future for the transit industry. The multiobjective analysis placed the BYD Ebus first, with the Proterra BE35 in second. High capital costs aside, the technology and performance of electric buses can significantly help transit agencies who have the purchasing ability to introduce them to their fleet. The BYD electric bus has a lower cost entry, and a fundamental difference of operation compared to the Proterra BE35. Where the BE35 will top up its charge through the day, the BYD buses charge throughout the night.

The advantage of the Proterra BE35 is its higher efficiency and lower operating costs. Some bus routes may be best suited for in-route charging while others are not. With the BYD bus, transit operators will have to determine if they have the ability to charge all of their buses at once. This can be a space issue or even an electrical issue. The most significant reason disadvantaging electric buses in the analysis is from the high capital costs, infrastructure, and low MBRC reliability. The lower capital costs of the BYD bus allowed it to score higher.

The second best performing bus was the New Flyer GE40LF, which uses ultracapacitors instead of batteries for its hybrid energy storage system. It performed extremely well in many aspects of transit bus operations. Although the GE40LF did not have the lowest capital cost or highest reliability, it was also rarely the worst performer. Its fuel economy was the best among hybrid and diesel buses, as well as having low maintenance costs. Ultracapacitors are extremely durable, cheaper than batteries, and are expected to last the life of the vehicle. For any transit agency looking to purchase hybrid buses, a capacitor-based hybrid bus could potentially a preferred alternative.

Interestingly, ranking above other hybrid buses in fourth place is the traditional diesel bus. The initial capital costs are simply cheaper than the competitors, and to transit agencies who need new buses without a large budget, this cost differential is significant. Transit agencies are familiar with the diesel bus and require no additional training or infrastructure. Environmentally, the lack of large electrical energy storage of any sort and the familiarity and robustness of diesel technology gives it an advantage in production emissions and reliability. The traditional diesel bus fares poorly where human perception is involved. Drivers and passengers a like much prefer cleaner and quieter technologies to diesel buses. If diesel buses can be designed to be quieter and cleaner, then there exists potential for them to excel. Its cleaner counterpart, the ULSD diesel performed similarly but ranked one place below because of increased capital cost.

In sixth place is the microturbine hybrid bus. These buses when implemented with IndyGo and KAT transit performed reasonably well. The microturbine buses excelled in the multiobjective analysis in the categories of purchase cost, infrastructure capital costs, acceptance by bus drivers, and measured driving performance. The scores for the bus were not as high because of its poor fuel economy, propulsion maintenance costs, engine and transmission maintenance costs, and acceptance by maintenance personnel. Tellingly, both KAT transit and IndyGo, two transit agencies who performed trials did not expand their fleet with microturbine buses, instead choosing LPG-fueled trolleys and Allison Hybrid buses, respectively.

In 7th and 8th place are the battery-based series and parallel hybrid buses, respectively. Due to a lack of significant information available, the only differentiator between these buses is the purchase cost, with the series bus being cheaper. These buses present the most basic hybrid systems which in many transit agencies, has been seen to outperform the diesel bus. What is clear in this analysis however, is that the small improvement of fuel economy does not compensate for the shortfalls of this type of bus. The increased purchase costs and increased complexity leading to lower reliability and maintenance scores result in a lower category score. The reduced brake maintenance costs also cannot compensate that hybrid buses are expensive relative to the performance they return.

A final observation ties together an initial hypothesis of this thesis is: Were buses implemented properly in their respective environments to maximize the benefits related to their technology? As demonstrated in this analysis, given the assumptions, the issues experienced by the TTC and the NYCT were not isolated issues. Their dissatisfaction and desire to return to diesel buses is supported by the shortfalls of the implementation of the technology.

5 Conclusion

Significant research has been undertaken on hybrid buses. Overall, without exception, every transit agency that implemented hybrid bus technology and underwent a study to compare them to diesel buses found hybrid buses to be preferred. Although the capital costs were higher, the agencies were satisfied with their performance. The New York City MTA, whose study was the most comprehensive, is the best example of this. Through their research, they have placed over 1700 hybrid buses in operation throughout their fleet.

Other transit agencies have also upgraded their fleet to hybrid buses as well including IndyGo, Long Beach Transit, and CTTransit, among many others. The primary reasons for this are:

- Hybrid buses are simple to implement without significant additional infrastructure costs.
- The capital purchase cost increase is justified by the improved performance and their perceived environmental benefits and image.
- There are many models available from manufacturers who have many years of experience in bus manufacturing, as well as interchangeable parts between existing diesel buses.

Having hybrid buses is seen as a win-win situation for both the customer and transit operator. They are cheaper to run, seem to be more reliable, are generally more comfortable, and provide the consumer and politicians the satisfaction about helping the environment. Unfortunately, this outcome is not universally the case.

In recent years, the two largest fleet operators of hybrid buses in North America are reducing hybrid bus operations. The New York City MTA has begun a study to convert some of their hybrid buses into diesel buses. The reasoning is ultimately about costs. With warranties expiring, the transit agency will have to absorb the major repair costs. At $50,000 for a battery pack and similar cost for a new electric motor, it is cheaper to convert their buses to diesel buses. The TTC has already undergone modifications to many of their buses for the exact same reason. Interestingly, neither transit agency has purchased new hybrid buses since their initial acquisition. Furthermore, the bus manufacturer, Orion Buses North America, have since gone bankrupt, which prevents any improvements to the technology already used in the TTC and the NYC MTA.

However, these two situations do not represent definitive reasons for pronouncing the failure of hybrid bus technology. Hybrid bus technology is improving all the time, and does show much promise. Indeed, the third best performing bus according to the multiobjective analysis is the HEV bus using ultra-capacitors. As a stopgap technology between diesel and fully electric buses, a combination of high reliability and low overall costs helped this diesel-electric combination of technologies to succeed.

Electric powertrain technology, when implemented properly has the potential to significantly reduce operational costs of transit agencies as well as reducing greenhouse gas emissions compared to diesel and battery-based hybrid technology. There are two directions for a transit agency to take should they decide on electric buses. With the BYD bus, they can have lower capital costs but reduced efficiency over the long term. With the Proterra solution, higher capital costs are offset by a higher efficiency. Although the multiobjective analysis rated the BYD bus higher, it is not due to a *better* implementation of the technology, but rather a *fundamentally different* implementation using the same basic technology. The choice on which electric bus to choose must be weighed carefully for an optimized end solution.

As technology matures and battery technology improves, it would further widen the gap between electric buses and other technologies. As some of the lowest points for electric buses were scored in capital cost-based categories, as the technology presumably becomes cheaper, it will be more accessible to the average transit agency. Furthermore, as reliability increases and if more transit agencies adopt electric bus technology, additional benefits and methods of maximizing the technology will be found. Along with more advanced electric buses, hybrid-battery based buses may also have an increased presence in fleets if their overall performance and reliability are similarly improved.

The ideal bus for any transit agency would combine the best in terms of cost, environmental performance, ease of implementation, and operational superiority. However, no such bus actually exists because buses must operate in different circumstances. Instead, the technologies that allow transit buses to perform optimally in different scenarios are important to examine. This research allows transit agencies to comprehensively assess the impacts and benefits different technologies have on bus operations using the most current industry and research literature available combined with a rational decision method.

Based on these conclusions, for transit agencies with the capital funding to allow it, the purchase of an electric bus, from Proterra or BYD will be beneficial in the long term, with an even greater potential for savings if a transit agency decides to extend the lifetime of the bus. These buses will also give greater comfort to the passengers and drivers, in addition to their green image. For transit agencies with less funding available, a preferred choice would be a capacitor-based hybrid bus, which performs exceptionally well for the price and with a proven dependability. Its hybrid credentials and powertrain should arguably satisfy both operators and passengers.

5.1 Recommended further research:

The recommendations for further research include:

1. Hybrid hydraulic buses were only briefly examined in this research. It is an extremely promising technology with the potential to both reduce emissions, and reduce costs. Altair Product Design has built a fully functional concept which has the ability to be implemented in a transit agency. This hybrid-hydraulic bus should be tested in actual applications and service environments. Additionally, research into fuel cell buses as more data becomes available could shed insight into this emerging technology.

2. The implementation of lightweight bus structures is extremely important. By lowering the weight of the structures, and even accessories and seats inside the bus, the fuel efficiency of any transit bus can be improved regardless of the powertrain. Passenger vehicle lightweighting is constantly being examined, but the same scrutiny has yet to be applied to transit buses. Further research should be undertaken to realize the full potential of lightweight bus structures.

3. Much of the time spent on the road for buses is spent idling. If idling can be reduced through the use of a mild-hybrid system or a stop-start system as implemented in passenger vehicles, the fuel consumption can be reduced. Research should be done to compare the impacts of idling a bus and operating a start-stop system. Electric buses have the advantage where they can essentially turn off their system while stopped. Apart from the load from accessories, the energy consumption could be greatly reduced. This system is commonly used in passenger vehicles and research into the similarities and applicability could be beneficial.

4. This multiobjective analysis can be utilized in many different ways. With the implementation of future research and specific city-data, the analysis and weighting can be further refined to be tailored to specific goals of the transit agencies. Furthermore, different stakeholders would likely weight the various evaluation categories differently. Running this analysis with different weighting schemes could demonstrate how alternatives might change, provided there was sufficient data to accurately reflect

different preferences.

5. Given the pace at which technology progresses, it would be valuable to include data about further technological advances and improvements to existing technology.

6. If more comprehensive data was available, a sensitivity analysis could be completed. This would require more measured data than was available in this thesis.

7. Knowing that electric and hybrid buses require batteries, what effect would the improvement of battery technology have on the performance of these transit buses? If the reliability and durability were improved, would the hybrid bus be more desirable?

8. As seen in figure 1, there are differences in fuel economy due to varying weather conditions. Further research could include other environmental and geographical conditions such as seasonal weather, location, altitude and flat versus hilly terrain. Doing so would allow the multiobjective analysis to be tailored specifically to individual municipalities and their circumstances.

6 Appendices

Appendix A

This table is from a recent transit bus bid (Abel, 2013). Here is a snapshot of prices for Clean Diesel and Hybrid parallel and series buses from different manufacturers:

Bus Manufacturer	Clean Diesel	Hybrid
Gillig	$412,662	$579,227 (Series) $604,081 (Parallel)
New Flyer	$439,990	$585,681 (Series) $626,951 (Parallel)
NOVAbus	$429,950	$595,270 (Series) $627,600 (Parallel)
NABI	$473,066	$665,570 (Parallel)
Average Price	$447,668	$586,726 (Series) $631,050 (Parallel)

Appendix B

The following table is a summary of information on the buses used from the Altoona Bus Testing Database.

Bus Model	Year of test	Fuel Type	# of seats (Seated, Standing, total)	Engine/Transmission	Bus Length (feet)	CBD MPG	ART MPG	COM MPG	Overall MPG	Idle	Overall (Miles/Million BTU)
[12] **Daimler Orion VII EPA10**	2012	Diesel	43,37,80	Cummins ISL/ ZF Ecolife	40	3.86	4.1	7.09	4.53	1.1	32.55
[13] **Daimler Orion VII EPA10 Hybrid**	2010	Diesel-electric Hybrid	43,37,80	Cummins ISB/BAE HybriDrive	40	4.64	4.37	6.8	5	0.79	36.38
[14] **New Flyer D40 LF**	1995	Diesel	40,28,68	Detroit Diesel Series 50/Interstate	40	3.44	4.29	**8.93**	4.47	0.60	7.09
[15] **New Flyer D40LF**	2006	Diesel	40,41,81	Cummins ISM/ZF Ecomat 2	40	2.61	2.96	4.38	3.07	1.16	22.48

[12] (Daimler Orion VII EPA10 Diesel. PTI-BT-R2012-P, 2012)
[13] (Daimler Orion VII EPA10. PTI-BT-R1007, 2010)
[14] (New Flyer Model D40LF. PTI-BT-R9508-20, 1995)
[15] (New Flyer Model D40LF. PTI-BT-R0607, 2006)

Bus Model	Year of test	Fuel Type	# of seats (Seated, Standing, total)	Engine/Transmission	Bus Length (feet)	CBD MPG	ART MPG	COM MPG	Overall MPG	Idle	Overall (Miles/Million BTU)
[16]**New Flyer DE40LF**	2006	Diesel-Electric Hybrid	40,40,80	Cummins ISB, ISE ThunderVolt	40	4.42	4.44	7.24	4.98	1.01	36.48
[17]**New Flyer XD40**	2012	Diesel	36, 45, 81	Cummins ISL9/Allison B400R	40	3.94	4.48	8.2	4.82	.63	35.08
[18]**New Flyer GE40LF**	2004	Gasoline	39,37,76	Ford Triton V10/ Ford	40	4.5	4.34	7.12	4.97	0.12	39.63
[19]**New Flyer XDE40**	2010	Diesel-Electric Hybrid	42,34,76	Cummins ISB/BAE HybriDrive	40	**5.46**	**5.11**	**7.79**	5.84	.67	42.50
[20]**Novabus LFS40**	2008	Diesel	36, 30, 66	Cummins ISL/Voith DIWA.5	40	2.41	2.75	5.2	2.97	1.01	22.43
[21]**Gillig 40' Low Floow**	2012	Diesel-electric Hybrid	40, 32, 72	Cummins ISB/ BAE HybriDrive	40	**4.66**	3.87	5.76	4.64	0.86	32.8

[16] (New Flyer DE40LF. PTI-BT-R0611, 2006)
[17] (New Flyer Model XDE40. PTI-BT-R1015, 2011)
[18] (New Flyer Model GE40LF. PTI-BT-R0401, 2004)
[19] (New Flyer Model XDE40. PTI-BT-R0913, 2010)
[20] (Nova Bus Model LFS-40. PTI-BT-R0810, 2008)
[21] (Gillig LLC Model 40' Low Floor BAE Hybrid. PTI-BT-R1206-P, 2012)

Bus Model	Year of test	Fuel Type	# of seats (Seated, Standing, total)	Engine/Transmission	Bus Length (feet)	CBD MPG	ART MPG	COM MPG	Overall MPG	Idle	Overall (Miles/Million BTU)
[22]**NABI Bus**	2012	Diesel	43, 29, 72	Cummins ISL 280/ZF Ecolife	40	3.74	4.1	7.07	4.45	1.29	32.36
[23]**Proterra BE35**	2011	Electric	36, 30, 66	UQM Technologies SRM286-149-2	35	22.16 (MPGe)	18.20 (MPGe)	27.21 (MPGe)	21.72 (MPGe)	N/A	Not Specified

[22] (North American Bus Industries, Inc. Model 416.15. PTI-BT-R1011, 2011)
[23] (Proterra, Inc. Model BE-35. PTI-BT-R1107, 2012)

Appendix C

This Chart is a summary of advantages, disadvantages and specifications of different battery and capacitor types.

	Advantage	**Disadvantage**	**Usable Specific Energy (Wh/kg)**	**Recyclability**
Lithium-Ion	- High energy per unit mass and lightweight - Good high-temperature performance; - Low self-discharge rate. - No memory effect	- Fragile and requires protection circuits. - Expensive - Moderate discharge current	100-250	- Easily disposed and able to be reused for other purposes - Extremely environmentally friendly
Nickel-Metal Hydride	- Safe to operate and tolerant to abuse - Contains no toxic metals. - Low cost compared to Li-ion	- High self-discharge rate - High heat generation during - High temperature operation; - Low discharge current - Very Heavy	60-120	- Low amount of toxic chemicals are used - Easily recycled.
Ultracapacitors	- Fast charge/discharge cycle. - Lightweight - Extremely long lifetime - Large operating temperature range - High discharge current	- Low power storage - High self-discharge rate - Complex electronics are needed	0.5-15	- Extremely clean, do not contain hazardous materials.

Appendix D

This chart is a summary of all the compiled data used in this research from NYCT, KC Metro, CTTransit, Long Beach Transit, TTC, Knoxville Transit and IndyGo.

Transit Agency/City	Model Year	Hybrid or Diesel	Bus Length (feet)	Bus Type	Total Maintenance cost, propulsion only ($)/mile (% compared to Diesel/CNG)	Calculated MPG (% compared to Diesel)	Purchase Cost	Purchasing consensus
NYCT	2004	Hybrid-Diesel	40	Daimler Orion VII (Gen 1 and 2)	1.0850 (4.6%), 0.266 (-4.9%)	3.11 (+38%)	$385,000	Very satisfied. Purchased more hybrid buses
	2002	CNG	40	Daimler Orion VII	1.29 (-4.6%), 0.349 (+4.9%)	1.70 (-76%)	$313,000	
	1999	Diesel	40	Daimler Orion V	0.6150, 0.0757	2.17	$290,000	
KC Metro	2004	Hybrid-Diesel	60	New Flyer DE60LF	0.44 (+4.3%), 0.13 (-7.6%)	3.17 (+26%)	$645,000	RFP to purchase more
	2004	Diesel	60	New Flyer D60LF	0.46(-4.3%), 0.12 (+7.6%)	2.50 (-26%)	$445,000	

CTTransit	2003	Hybrid-Diesel	40	New Flyer DE40LF	0.16 (+29%)	4.60(+9.5%)	$500,000	Research group suggests purchase of more hybrids
	2004	Diesel	40	New Flyer D40LF	0.24 (-29%)	4.20 (-9.5%)	$320,000	
Long Beach	2004	Hybrid-Diesel	40	New Flyer GE40LF	0.3124 (+42%), 0.0782 (+11%)	3.78(8%)	$462,379	Taken delivery of more buses, plan to purchase more
	2002	Diesel	40	New Flyer D40LF	0.5392(-42%), 0.1906 (-11%)	3.50 (-8%)	$268,051	
TTC		Hybrid-Diesel	40	Daimler Orion VIII				Very unhappy, removing hybrid buses from service[24]
		Diesel	40	Daimler Orion VII				
IndyGo	2003	Hybrid-Diesel	40	Ebus Hybrid	0.66, 0.46	4.37	$280,000	Purchased more hybrid buses
Knoxville	2003	Hybrid-LPG		Ebus Hybrid	0.62, 0.12	2.09	$280,000	Purchase more Hybrids
Diesel Averages			40ft		0.46, 0.13	2.84	$292,684	
Hybrid Averages			40ft		0.65, 0.24	3.77	$387,500	

[24] (Kalinowski, 2014)

Appendix E

This is the Chart used to calculate the final scores for the Multiobjective analysis. The scores out of ten are highlighted in the blue column.

Chapter	Category	Diesel		Diesel-electric Hybrid				Electric Bus		Weighted	Low-speed	Med-speed	High-speed
		Regular Diesel	ULSD Diesel	Battery-based Series	Battery-based Parallel	Capacitor based	Microturbine-based	Proterra BE35	BYD Ebus	Weight case 1	Weight case 2	Weight Case 3	Weight Case 4
4.1	**Financial Cost**												
4.1.1	**Bus Purchase Cost**	**10.0**	**7.8**	**5.7**	**5.1**	**7.6**	**9.6**	**1.0**	**6.7**	**4**	**4**	**4**	**4**
	Cost ($)	300000	450000	590000	630000	462000	325000	900000	520000				
4.1.2	**Infrastructure Capital Cost**	**10**	**10**	**10**	**10**	**10**	**10**	**1**	**9.267375**	**3**	**3**	**3**	**3**
	Cost	0	0	0	0	0	0	432000	35166				
4.1.3	**Propulsion Maintenance Costs**	**6.9**	**6.9**	**1.9**	**1.9**	**8.8**	**1.0**	**10.0**	**7.7**	**3**	**3**	**3**	**3**
	Cost ($/mile)	0.13	0.13	0.266	0.266	0.0782	0.29	0.045	0.108				
4.1.4	**Brake Maintenance Costs**	**1.0**	**1.0**	**7.3**	**7.3**	**10.0**	**7.3**	**7.3**	**7.3**	**3**	**3**	**3**	**3**
	Cost ($/mile)	0.05	0.05	0.02	0.02	0.0073	0.02	0.02	0.02				
4.1.5	Fuel Costs									**4**	**4**	**4**	**4**
	CBD Cycle	3.28	3.28	4.28	4.28	4.5	4.28	1.7	1.89				
	CBD Fuel Costs	$ 533,536.59	$ 533,536.59	$ 408,878.50	$ 408,878.50	$ 388,888.89	$ 408,878.50	$ 85,000.00	$ 94,335.26				
	CBD Score	**1.0**	**1.0**	**3.5**	**3.5**	**3.9**	**3.5**	**10.0**	**9.8**				
	ART Cycle	3.74	3.74	4.22	4.22	4.34	4.22	2.07	2.30				
	ART Fuel Costs	$ 467,914.44	$ 467,914.44	$ 414,691.94	$ 414,691.94	$ 403,225.81	$ 414,691.94	$ 103,500.00	$ 114,867.05				
	ART Score	**1.0**	**1.0**	**2.3**	**2.3**	**2.6**	**2.3**	**10.0**	**9.7**				

	COM Cycle	6.75	6.75	6.58	6.58	7.12	6.58	1.38	1.53				
	COM Fuel Costs	$ 259,259.26	$ 259,259.26	$ 265,957.45	$ 265,957.45	$ 245,786.52	$ 265,957.45	$ 69,000.00	$ 76,578.03				
	COM Score	**1.3**	**1.3**	**1.0**	**1.0**	**1.9**	**1.0**	**10.0**	**9.7**				
	Overall Fuel Economy	4	4	4.7	4.7	4.97	4.7	1.73	1.92				
	Fuel Costs	$ 437,500.00	$ 437,500.00	$ 372,340.43	$ 372,340.43	$ 352,112.68	$ 372,340.43	$ 86,500.00	$ 96,000.00				
	Weighted Overall Fuel Economy	**1.0**	**1.0**	**2.7**	**2.7**	**3.2**	**2.7**	**10.0**	**9.8**				
		4.1	4.1	4.7	4.7	5.0	4.7	1.7	1.9				
		$ 430,398.43	$ 430,398.43	$ 370,135.36	$ 370,135.36	$ 350,560.90	$ 370,135.36	$ 85,500.00	$ 94,890.17				
	Low-speed Fuel Economy	**1.0**	**1.0**	**2.6**	**2.6**	**3.1**	**2.6**	**10.0**	**9.8**				
		3.5	3.5	4.4	4.4	4.6	4.4	1.7	1.9				
		$ 503,379.84	$ 503,379.84	$ 398,451.73	$ 398,451.73	$ 378,542.07	$ 398,451.73	$ 85,125.00	$ 94,473.99				
	Medium-speed Fuel Economy	**1.0**	**1.0**	**3.3**	**3.3**	**3.7**	**3.3**	**10.0**	**9.8**				
		2.5	2.5	2.7	2.7	2.8	2.7	1.0	1.1				
		$ 704,083.69	$ 704,083.69	$ 653,472.74	$ 653,472.74	$ 622,332.86	$ 653,472.74	$ 50,825.00	$ 56,406.94				
	High Speed Fuel Economy	**1.0**	**1.0**	**1.7**	**1.7**	**2.1**	**1.7**	**10.0**	**9.9**				
		5.1	5.1	5.4	5.4	5.8	5.4	1.6	1.8				
		$ 341,130.60	$ 341,130.60	$ 323,176.36	$ 323,176.36	$ 303,292.89	$ 323,176.36	$ 81,625.00	$ 90,589.60				
4.1.6	**Personnel Training**	**10.0**	**10.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1**	**1**	**1**	**1**
	Hours needed	0	0	20	20	20	20	20	20				
4.1.7	**Engine and Transmission Replacement**	**1.0**	**1.0**	**1.8**	**1.8**	**5.9**	**1.8**	**10.0**	**10.0**	**3**	**3**	**3**	**3**
	Engine/motor removal (hours)	14	14	14	14	4	14	4	4				

	Transmission Replacement (hours)	20	20	18	18	18	18	8	8				
	Total Hours)	34	34	32	32	22	32	12	12				
4.1.8	**Electrical Maintenance**	**9.2**	**9.2**	**1.0**	**1.0**	**10.0**	**1.0**	**5.5**	**5.5**	**3**	**3**	**3**	**3**
	Costs ($/mile)	0.02	0.02	0.045	0.045	0.0176	0.045	0.0313	0.0313				
4.1.9	**Unforeseen Costs**	**10.0**	**10.0**	**7.4**	**7.4**	**7.4**	**7.4**	**1.0**	**1.0**	**2**	**2**	**2**	**2**
	Propulsion System issues during testing (#)	6.67	6.67	7.5	7.5	7.5	7.5	16	16				
	Propulsion system issues during durability testing (#)	4.67	4.67	6.58	6.58	6.58	6.58	5	5				
	Total	11.34	11.34	14.08	14.08	14.08	14.08	21	21				
4.2	**Environmental Emissions**												
4.2.1	**Operational Emissions**	**1**	**1**	**4**	**4**	**4**	**4**	**10**	**9**	**3**	**3**	**3**	**3**
	Grams CO2/mile	2112	2112	1783	1783	1783	1783	959.1	1064.5				
	Grams CO2e/mile (Canada)	n/a	n/a	n/a	n/a	n/a	n/a	283.7	314.9				
	Grams CO2e/mile (USA)	n/a	n/a	n/a	n/a	n/a	n/a	959.1	1064.5				
	Score												
4.2.2	**Emissions from Production**	**10**	**10**	**4.5**	**4.5**	**9.8**	**4.5**	**6.9**	**1.0**	**1**	**1**	**1**	**1**
	CO2 Emissions (metric tons)	0	0	21.7	21.7	0.64	21.7	12	35.21				
4.3	**Feasability of Implementation**												
4.3.1	**Infrastructure**	**10**	**10**	**7**	**7**	**7**	**7**	**1**	**4**	**3**	**3**	**3**	**3**

4.3.2	**Acceptance by Bus Drivers**	**1.0**	**1.0**	**5.2**	**5.2**	**5.2**	**5.2**	**10.0**	**10.0**	**2**	**2**	**2**	**2**
	Baltimore Survey Question	3.50%	3.50%	32%	32%	32%	32%	64%	64%				
4.3.3	**Acceptance by Maintenance Personnel**	**5.5**	**5.5**	**1**	**1**	**1**	**1**	**10**	**10**	**2**	**2**	**2**	**2**
4.3.4	**Acceptance by the Public and Awareness of Technology**	**1**	**1**	**5.5**	**5.5**	**5.5**	**5.5**	**10**	**10**	**2**	**2**	**2**	**2**
4.4	**Operational Performance**												
4.4.1	**Driving Performance - Perception**	**1**	**1**	**5**	**5**	**5**	**5**	**10**	**10**	**2**	**2**	**2**	**2**
4.4.2	**Driving Performance - Statistical**	**8.2**	**8.2**	**10.0**	**10.0**	**5.2**	**10.0**	**1.0**	**1.0**	**1**	**1**	**1**	**1**
	0-30 mph (s)	14.07	14.07	13.16	13.16	15.64	13.16	17.83	17.83				
4.4.3	**Noise - Exterior**	**1.0**	**1.0**	**3.1**	**3.1**	**3.1**	**3.1**	**10.0**	**10.0**	**2**	**2**	**2**	**2**
	Acceleration (constant speed)	75.6	75.6	72.9	72.9	72.9	72.9	60	60				
	Acceleration (from standstill)	76.2	76.2	71.9	71.9	71.9	71.9	57.4	57.4				
	Stationary	68.2	68.2	65.2	65.2	65.2	65.2	43.1	43.1				
4.4.4	**Noise - Interior**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**10.0**	**10.0**	**2**	**2**	**2**	**2**
	Driver's Seat	73.4	73.4	75	75	75	75	72.9	72.9				
	Front Passenger	73.7	73.7	75	75	75	75	71.9	71.9				
	Rear Seats	78.2	78.2	78.2	78.2	78.2	78.2	72	72				
4.4.5	**Reliability**	**10.0**	**10.0**	**3.0**	**3.0**	**8.1**	**3.0**	**1.0**	**1.0**	**3**	**3**	**3**	**3**
	Powertrain-only MBRC	17391	17391	8415	8415	15000	8415	5801	5801				

Case 1	**Overall Fuel Economy Weighted**	**260.5**	**251.5**	**212.1**	**209.7**	**305.8**	**225.3**	**312.4**	**352.7**				
Case 2	Low-Speed Route	**260.5**	**251.5**	**211.7**	**209.3**	**305.4**	**225.0**	**312.4**	**352.7**				
Case 3	Medium-Speed Route	**260.5**	**251.5**	**214.4**	**212.0**	**307.8**	**227.7**	**312.4**	**352.9**				
Case 4	High-Speed Route	**260.5**	**251.5**	**208.2**	**205.8**	**301.5**	**221.5**	**312.4**	**353.4**				

Appendix F

This is a copy of the Advanced Transit Bus Technologies Survey.

A Survey on the Future of Urban Transit Bus Technologies

Thank you for taking the time to complete our survey. Your opinion will not be shared directly with any other parties, but will be used for the purpose of aiding in the research of *Sustainability issues in Benchmarking of Advanced Transit Bus Technology.* Thank you for taking your time and completing this survey.

Section 1: Fleet and personal information

Your position: ____

# of years of experience in the transit industry: ________________

City or transit agency: _____________________________________

Approximate fleet size: ______________________________

Approximate age of fleet: ______________________________

Total # of buses: ______________________________

What bus types do you currently operate? Circle all that apply:

Diesel CNG Full-electric Diesel-electric hybrid Trolley
other (please specify):

If applicable, please fill in the following information:

# of hybrid diesel-electric buses: ____ Model year of first hybrid bus? __________

Hybrid bus model (s): ____

____

____

____

# of electric buses: ____ Model year of first electric bus?
____

Electric bus model (s):
____

____

____

____

# of trolley buses: ________

# of diesel or CNG buses: ________

Section 2: Specific Bus information

Choose up to three buses which best represent your fleet. Use your best judgement to assess how each bus performs. When outlining a bus, please state whether it represents your fleet average, best performance or poorest performance for the costs. If you have hybrid buses or electric buses in your fleet, please provide information about these particular buses.

Bus type 1 (circle one) : Hybrid-electric Full Electric Diesel CNG

Length (circle one) 35' or less 40' 60'

Performance Type: Best Performing Fleet Average Poor performing

Additional comments
____

on bus performance:
____

Maintenance Cost ($/mile):
____

Fuel Cost ($/mile): ____

Average distance travelled (miles) /year: ____

Route type (circle one): Urban Rural

Bus type 2 (circle one) : Hybrid-electric Full Electric Diesel CNG

Length (circle one) 35' or less 40' 60'

Performance Type: Best Performing Fleet Average Poor performing

Additional comments ____

on bus performance: ____

Maintenance Cost ($/mile): ____

Fuel Cost ($/mile): ____

Average distance travelled/year: ____

Route type (circle one): Urban Rural

Bus type 3 (circle one) : Hybrid-electric Full Electric Diesel CNG

Length (circle one) 35' or less 40' 60'

Performance Type: Best Performing Fleet Average Poor performing

Additional comments ____ on bus performance:

____

Maintenance Cost ($/mile):

____

Fuel Cost ($/mile):

____

Average distance travelled/year:

____

Route type (circle one): Urban Rural

General Bus Fleet Questions:

The following questions are intended to gather additional information about your bus fleet. Please use the following scale when answering the questions:

1 – Poor
2 – Unsatisfactory
3 – Average
4 – Good
5 – Excellent

Question	Rating (where 5 is Excellent)
How would you rate the reliability of your bus fleet?	1 2 3 4 5
I would consider the on-time performance of my bus fleet as:	1 2 3 4 5
If a bus breaks down, the ability of the maintenance crews to fix it quickly and cost effectively is:	1 2 3 4 5
During inclement weather, how would you rate your transit agency's ability to cope and prevent delays of operation?	1 2 3 4 5
The ability of our transit agency to control costs is:	1 2 3 4 5
How do you rate the reliability of diesel buses?	1 2 3 4 5
How do you rate the reliability of hybrid-electric buses?	1 2 3 4 5
How do you rate the reliability of electric buses?	1 2 3 4 5
How do you rate the reliability of CNG or alternative fuel buses?	1 2 3 4 5

If you would like to further comment on any question, please leave any additional comments below:

____
____
____
____

Opinion Questions

We would like to get your opinion about the following statements. Please use the following rating scale when answering the questions:

1 – Strongly disagree
2 – Disagree
3 – Neutral
4 – Agree
5 – Strongly Agree

Statement	**Rating (Where 5 is Strongly Agree)**
The use of hybrid buses is an effective way to reduce costs and improve performance.	1 2 3 4 5
The use of electric buses is an effective way to reduce costs and improve performance.	1 2 3 4 5
The use of advanced clean diesel buses is an effective way to reduce costs and improve performance.	1 2 3 4 5
The use of CNG or alternative fuel buses is an effective way to reduce costs and improve performance.	1 2 3 4 5
The availability of funding would influence our timeline in the purchase of new buses.	1 2 3 4 5
Battery failures and unforeseen maintenance issues are an important consideration when purchasing hybrid or electric buses.	1 2 3 4 5
Fuel economy is an important consideration when choosing a transit bus.	1 2 3 4 5
Low maintenance costs and high reliability are important considerations when choosing a transit bus.	1 2 3 4 5
The environmental impact of our buses in operation is an important consideration when operating our fleet.	1 2 3 4 5
Hybrid-hydraulic buses are a promising technology.	1 2 3 4 5
The opinions of our passengers are important when deciding how to improve our buses and/or bus service.	1 2 3 4 5
Our buses and their respective performance meet the needs of our bus drivers	1 2 3 4 5
Bus route optimization is important part of maintaining the efficiency of our fleet.	1 2 3 4 5
Introducing a set of voluntary benchmarks would improve our fleet's *economic* performance and reduce costs.	1 2 3 4 5
Introducing a set of voluntary benchmarks would improve our fleet's *environmental* performance and reduce emissions.	1 2 3 4 5

It would be useful if transit agencies shared more information with each other regarding new bus acquisitions or operational improvements.	1 2 3 4 5

If you would like to further comment on any question, please leave any additional comments below:

____
____
____
____

Yes or No questions and comment questions

Please answer the following by clicking either yes or no. Please expand on your decision in the comments section.

1. a) Please circle any factors that apply in influencing you to purchase new buses

Funding Age of fleet Reliability of current fleet Growth/need for expansion Other

If you answered other, please specify: ____

1 b) For the previous four factors, please rank them from the most important to the least important factor with 1 being the most important and 5 the least important

Funding
Age of fleet
Reliability of current fleet
Growth/need for expansion
other

1 c) Among these choices, where does the majority of your funding come from?

Public funding Private funding other (please specify):_____________

2. When do you expect to make a major purchase of new buses (years)?

0-3 4-8 9-14 15-19 20+

3. We have taken steps to 'green' our fleet.

Yes No

If you have answered yes, what steps have you taken, and have you received green fleet accreditation?

Comments:
____

4. Do you believe there current novel or experimental technologies that would be beneficial to fleet operations?

Yes No

If you answered yes, then what technologies are they?

Comments:
____

5. What is the largest cost associated with transit bus operation?

____

6. Would you be interested in being contacted again for further information and/or questions?

Yes No

7. Would you be interested in having a digital copy of this research when it is completed?

Yes No

Thank you very much for your time and co-operation with this survey!

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