Appendix 1: A Review of Trolley Bus Potential

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Summary

Concerns about global warming have stimulated renewed interest in alternatives to standard diesel buses used by most transit properties throughout North America. Although the use of electric trolley buses declined significantly during the 1960s, decisions to re-introduce or modernize this form of transit service have been taken in a number of U.S. and Canadian cities, including Vancouver, as an important means of achieving more sustainable transportation.

This report reviews the potential for trolley bus applications in the delivery of TTC service.

Trolley buses are quieter and environmentally friendlier than fossil-fuel vehicles. At street level, greenhouse gas (GHG) emissions are essentially zero. (Overall, emission benefits depend upon how electrical energy is produced at source.) Trolley buses are also capable of higher acceleration, particularly on grades.

The main disadvantages of trolley bus service pertain to capital costs and service flexibility. Significant capital investment is required for electrification, namely, substations required to convert high voltage alternating current to low voltage direct current, as well as overhead wires and structural supports. The purchase price of vehicles is also considerably higher than for comparable size conventional buses but economic service lives are also much higher. In addition, there is generally less flexibility to extend trolley bus routes into new transit service areas in the short term.

At its peak, the TTC operated a fleet of 153 trolley buses on 9 routes. The service enjoyed considerable popularity but, following a number of studies in the early 1990s, and faced with a declining fleet of serviceable trolley buses, the need for major rehabilitation of electric power distribution infrastructure, and reductions in operating subsidies, all TTC trolley bus service was eventually discontinued in 1993.

Recognizing today's environmental imperative, this report assesses the benefits and costs of re-introducing trolley bus service in Toronto by considering a representative hypothetical network of 4 routes (the 29 Dufferin, 63 Ossington, 52 Lawrence West, and 90 Vaughan bus services) that focus on the Wilson bus garage (which already has access to electric power supply) as a maintenance and storage facility.

The same number of 'clean' diesel, hybrid, and trolley buses has been assumed for all four routes. The same labour costs for operation, as well as unit bus maintenance costs have also been assumed for all three technologies. In addition, the analysis assumes that most electrical energy will derive from sources of energy supply (solar, wind etc.) that have zero GHG emissions for the trolley bus alternative.

For this hypothetical network, service levels and capacity are assumed to be the same. Costs and emissions are compared for diesel, hybrid, and trolley bus service in Table S.1 and Figure S.1.

Table S.1 – Comparison of Diesel, Hybrid and Trolley Bus Costs (excluding costs of bus maintenance and labour operation)

Item	Units	Bus Technology		
		Diesel	Hybrid	Trolley
Route length (1 way)	km	41.8	41.8	41.8
No. of Buses		77	77	77
Annual Vehicle-km	veh-km (1000s)	6,193	6,193	6,193
Capital Costs	$1,000			
Vehicles		38,577	54,131	70,840
Electrification				303,555
Maintenance Facility				15,000
Total		38,577	54,131	389,395
Incremental (relative to diesel)			15,554	350,818
Annual Costs	$1,000			
Energy		4,469	3,799	1,325
Overhead Maintenance				1,254
Sub Total (Operation)		4,469	3,799	2,579
Debt service				
Buses		3,300	4,631	4,608
Electrification				19,747
Maintenance Facility				976
Sub Total (Amortization)		3,300	4,631	25,331
Total Annual Costs	$1,000	**7,769**	**8,429**	**27,910**
Unit Costs	$/passenger	0.29	0.31	1.03
Total Annual GHG	tonnes	10,969	9,324	0
Implied Value of GHG	$1,000/tonne	0	401	1,836

Table S.1 also shows the value per tonne of GHG emissions 'implied' by the trolley bus selection. As the analysis shows, the benefits of reduced GHG emissions are achieved at an average cost of about $1840 per tonne (when compared with diesel buses), well above the $40 per tonne now used in various *Metrolinx* studies.

By comparison, the purchase and operation of hybrid buses in Toronto implies a considerably lower cost per tonne ($401) for GHG reductions. Relative to expectations, however, hybrid buses appear to be underperforming in Toronto. As originally anticipated, with fuel saving of about 30 percent, the cost of GHG reductions would approximate $200 per tonne.

Due to the significance of capital costs associated with electrification, a sensitivity analysis was undertaken comparing two cases, namely, a doubling of the real costs of diesel fuel, and a doubling of frequency of service (thereby reducing the average cost per passenger associated with the fixed costs of electrification).

Figure S.1 – Comparative Costs for Alternative Bus Technologies

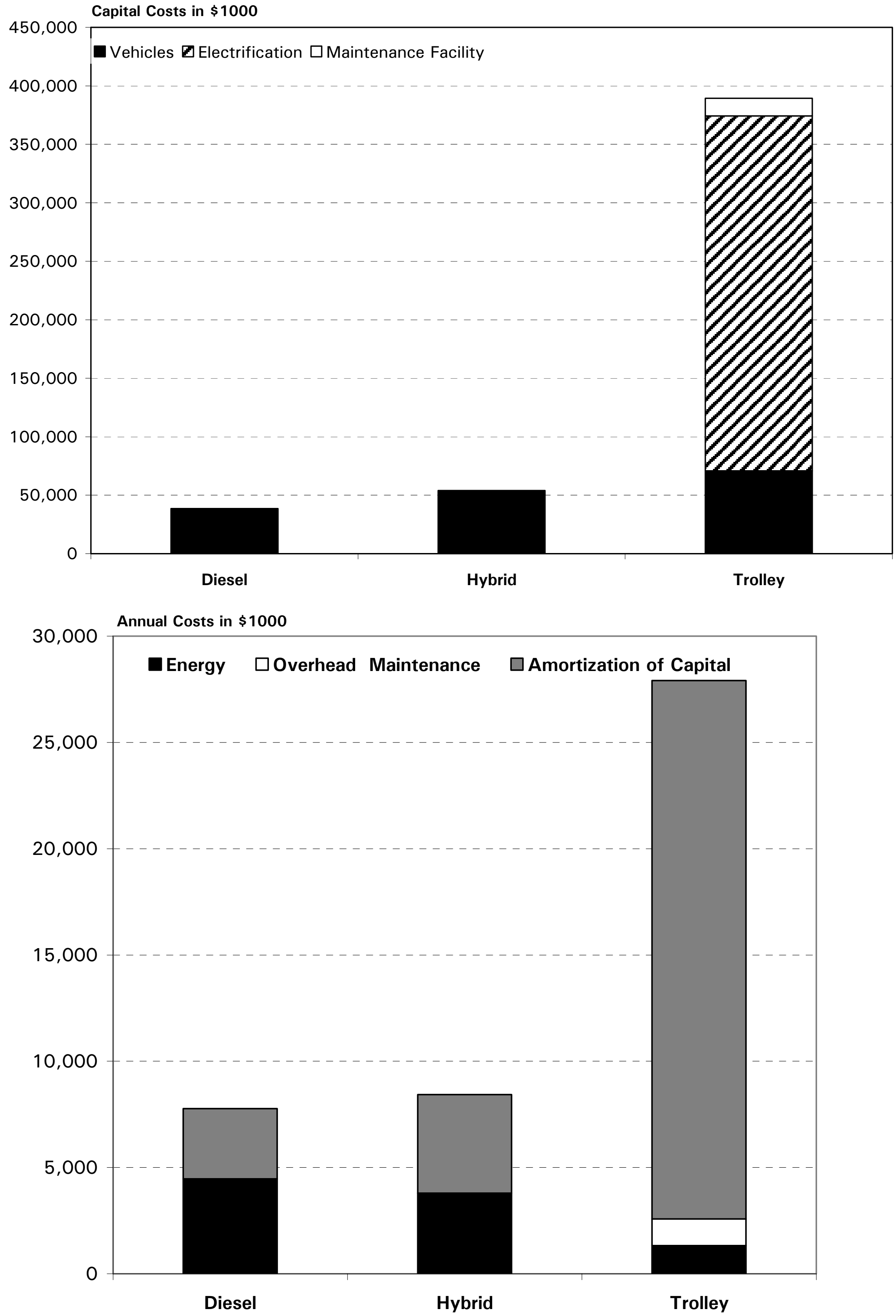
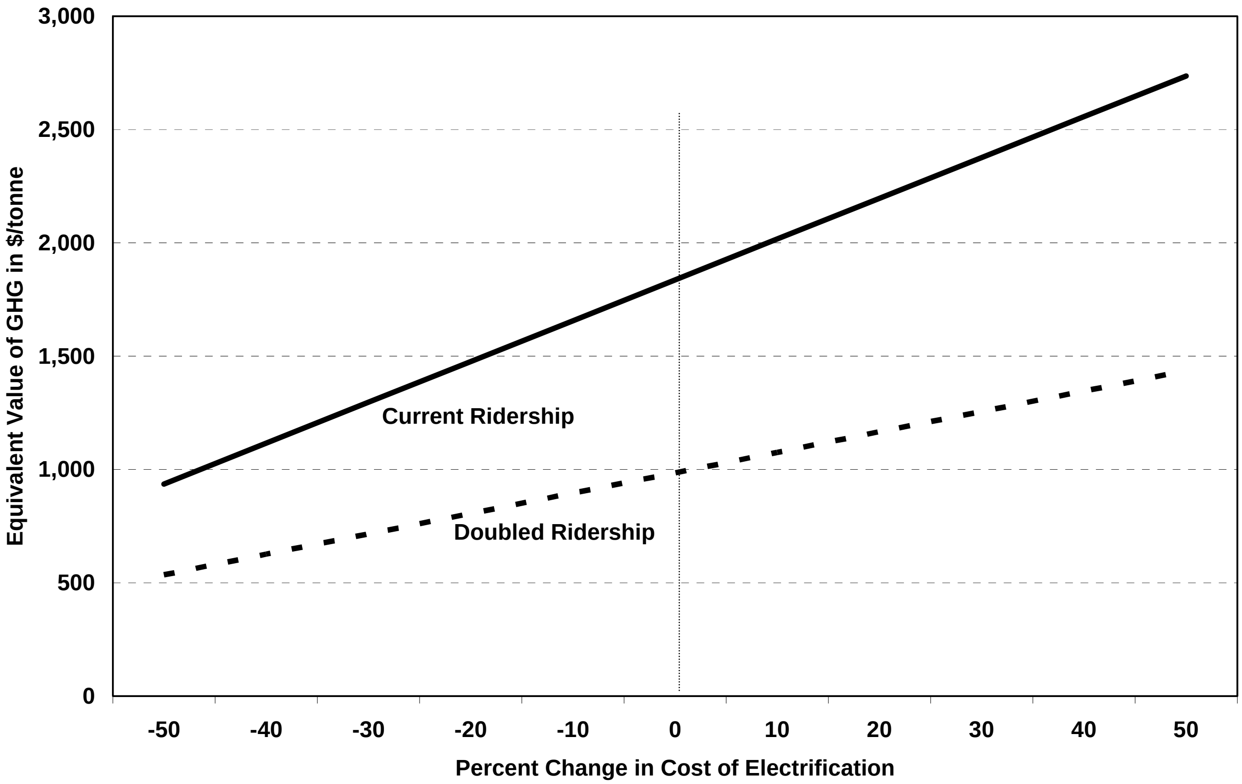


Figure S.2, for example, compares the implied value of GHG reductions for a hypothetical network of total comparable length against changes in the cost of electrification with double the service density. In both cases the implied value of GHG emissions remains quite high, even for large reductions in the costs of electrification.

Figure S.2– Implied Value of GHG Emissions for Variation in Electrification Estimates and Service Level Compared to Diesel Bus Service



The main conclusions of this initial evaluation of electric trolley buses are as follows.

First, trolley buses consume less energy and produce lower emissions than either diesel or hybrid buses. They are also more attractive from the standpoint of air quality, noise, acceleration (notably in heavy traffic), and opportunities provided by central power generation to negotiate steeper grades.

Second, overall, the unit costs of service delivery are much higher than for either diesel or hybrid buses. Even if diesel fuel costs were to double, the incremental cost estimates of converting the sample network to trolley bus operation still remain very high.

Third, the main cost disadvantages of trolley buses derive from the need for investment in electrification infrastructure (sub-stations and power transmission structures). In fact, the annual cost of electrification accounts for more than two-thirds of the total cost differential when compared to diesel bus operation.

Fourth, trolley buses offer less flexibility to both alter and extend routes to serve entirely new areas.

Fifth, the implied value per tonne of GHG emissions ($1,840) achieved through the operation of trolley buses is considerably higher than values currently assumed for GHG reductions (about $40 per tonne). Even a doubling of service still results in an implied value per tonne of about $985.

Sixth, for the large differences in capital investment (or the difference in total annual costs), the high implied cost per tonne for reducing GHG emissions raises an issue of the relative efficiency of reducing GHG emissions from transit by other means. Theses include:

- achieving the anticipated performance benefits of hybrid buses,
- the emergence of more cost effective fuel cell buses,
- development, within the foreseeable future, of all electric buses, possibly as a by product of initiatives driven by restructuring of the automotive industry with respect to electric automobiles, and
- expansion of bus services to new markets.

Finally, the high cost of trolley bus service derives primarily from the fact that, in Toronto, entirely new infrastructure is required for electrification as opposed to a situation (as in Vancouver) in which there is an existing electrification network in need of refurbishment. In this situation, although it is difficult to justify the large capital investment in electrification required for new trolley bus service from the standpoint of the TTC's finances alone, such investment may be considered by City Council as a separate initiative, under the Sustainable Transportation Initiative for achieving its GHG emissions reduction goals.

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1. Introduction

Concerns about global warming, as well as the contribution made by urban transportation to greenhouse gas (GHG) emissions, has stimulated renewed interest in alternatives to the standard diesel buses used by most transit properties throughout North America. These alternatives include hybrid, electric trolley, and fuel cell buses.

While the jury is still out on hybrid buses (which appear to be underperforming relative to initial claims of relative fuel efficiency), and while the economics (though improving) of fuel cell buses remains in doubt, electric trolley buses are a proven technology that have enjoyed varying degrees of popularity over time, even though the use of this technology declined significantly during the 1960s.

Given the current emphasis on sustainability as a major criteria for all aspects of urban planning, including transportation, the purpose of this report is to review the potential for trolley bus applications in the delivery of TTC service.

2. Background

Still widely used in many cities of the world, trolley buses in both Canada and the U.S. have been replaced in the majority of cities by diesel buses, particularly wherever major rehabilitation of the electrification system was needed or new fleet acquisitions were necessary.

Following World War II, electric trolley buses replaced many existing trams and streetcars, probably for two main reasons.

First, with the end of the war, fuel rationing disappeared, the availability of private automobiles increased, and much of urban transportation planning focussed on increasing road capacity to parallel the high increase in motorization. During this period, urban transportation planning was dominated by the goal of accommodating private automobiles and reducing road congestion (except in Toronto where the 1948 decision to build the Yonge Street subway was made when most north American cities were mesmerized by the concept of freeways and expressways).

Under the prevailing values of the day, with their fixed and less flexible guideways, trams and streetcars were perceived as barriers to efficient automobile traffic. This perception was probably more prevalent in Canada and the U.S. than in Europe and developing countries where economic recovery and automobile ownership rates lagged behind North American. As a result, buses were generally viewed as a technology that was more compatible with the objectives of transportation planning of the day.

Second, many cities, as well as electric utility companies, retained an interest in maximizing the use of the existing power transmission infrastructure while eliminating track structure in the process of road widening and/or repaving. Electric trolley buses were viewed as a means of reducing the inflexibility of the streetcar and its impact on road capacity, while still serving as a market for sales of electricity.[1]

'Trackless' trolley buses also had more (though limited) flexibility to circumvent road obstacles such as accidents and illegal parking than streetcars. New generation trolley buses can be equipped with battery-powered or diesel supplementary units (APU) that allow them to manoeuvre around obstructions or operate 'off wire' over limited distances.

Over time, however, trolley bus fleets in many Canadian cities were replaced by standard diesel buses which:

- were viewed to interfere even less with automobile and truck traffic,
- could be used for new routes without the need to invest in capital intensive electrification infrastructure (sub-stations and overhead wires), and
- were being aggressively marketed by the automotive industry.

In addition, there were few suppliers of electric trolley buses relative to the number, size, and diversity of fossil fuelled buses (e.g., standard city buses, as well as inter-city, school, and special purpose buses).

As trolley bus fleets required replacement, a number of Canadian transit operators and municipalities used the opportunity to reassess continuation of this technology versus replacement by diesel bus service.

In Toronto, for example:

- trolleys were first introduced in 1922 on Mount Pleasant Road (subsequently replaced by an extended streetcar service in 1925),
- new trolley buses were acquired in 1947,
- by 1963, the TTC owned a fleet of 153 vehicles operating on 9 routes,
- all of the original trolley buses were rebuilt in during the period 1968-72,
- used trolley buses were leased from Edmonton in 1990, and
- service was discontinued between January 1992 and July 1993.

At present, all trolley bus overhead wires have been removed. Some residual substation capacity remains (which may or may not form part of the power supply and distribution systems for new *Transit City* LRT services). Low voltage electricity is still available at the Wilson bus garage, which could serve as a terminal in the event trolley bus service were to be re-introduced.[2]

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[1] In Halifax, for example, public transit (tram) service was operated by Nova Scotia Light and Power as a profitable enterprise.

[2] TTC substations for both the subways and streetcars presently deliver 600 volt DC current. Consistent with current practice in Europe, new LRVs may be selected that require 750 volt DC or AC, thereby reducing flexibility to take advantage of LRT substations to produce power for any new trolley bus services.

In Hamilton, as well, decisions were taken at the same time as in Toronto to discontinue trolley bus operations.

In Canada, Vancouver and Edmonton still operate trolley buses. Although the City of Edmonton plans to phase out remaining services by 2010, *Translink* (Vancouver) acquired a new fleet of trolley buses (180 rigid and 48 articulated New Flyer buses) beginning in 2003. In the U.S., trolley buses are operated in Boston, Dayton, San Francisco, Seattle, and Philadelphia (where SEPTA recently decided to restore service on three of its original five routes). In all five U.S. cities, new or rebuilt trolley buses have been introduced since the 1990s and, as noted above, many trolley bus services continue to operate elsewhere in the world.

3. Trolley Bus Technology

Trolleybuses, or trackless trolleys, derive power from low voltage (600 to 750 volts) direct current (DC) electric motors. Unlike streetcars or LRVs that use one of the rails to conduct the return current through contact with steel wheels, for non-conducting rubber tires, electricity is drawn from two overhead wires supported by an overhead contact system comprised of supports, poles, and wire cable.

Examples of Vancouver and San Francisco trolley buses are shown in Figure 3.1.

Figure 3.2 shows that in addition to the power distribution wires, sub-stations are required at periodic intervals (usually 1.5 to 2 km, depending upon service density and electrical load) first, to transform high voltage current to low voltage and second, to rectify alternating current (AC) to direct current (DC).

Due to the unique characteristics of vehicle maintenance and storage, generally speaking, it is advantageous to combine trolley bus routes that can be served efficiently by common servicing terminals in order to achieve economies of scale. According to earlier studies by the TTC, for example, efficiency is maximized for terminal facilities (storage and maintenance) capable of accommodating approximately 250 trolley buses. About 150 vehicles are considered as a minimum fleet size.[3]

In general, electric trolley buses are quieter and environmentally friendlier than fossil-fuel vehicles. At street level, for example, greenhouse gas (GHG) emissions are essentially zero. (Overall, emission benefits depend upon how electrical energy is produced at source.) Trolley buses are also capable of higher acceleration (notably on grades) since electric motors draw power from central plants that can be overloaded for short periods.

Energy efficiency depends upon the basic costs of electricity, transmission losses from the source of electrical supply to the actual application, and whether energy can be recaptured effectively through regenerative braking.

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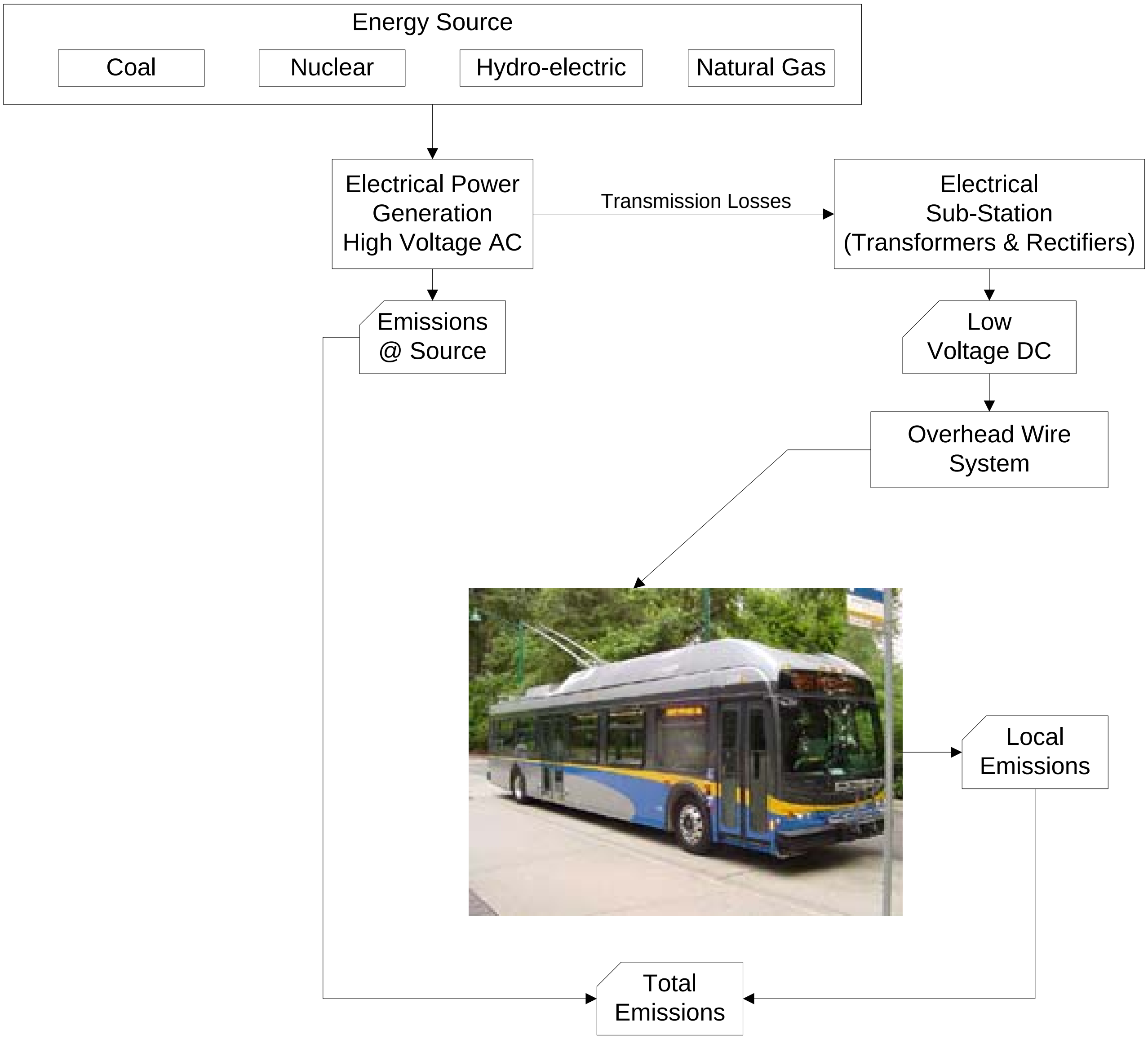
[3] "An Information Report on Trolley Coaches", presented to the Toronto Transit Commission, 17 March 1992.

Figure 3.1 –Trolley Bus Examples

These benefits, of course, are most evident in areas characterized by low electricity rates and non-fossil fuel generation of electricity, as is the case both in Vancouver and Seattle.

The main disadvantages of trolley bus service concern capital costs and service flexibility. The unit cost of purchasing a trolley bus is considerably higher than for a comparable size diesel or hybrid bus (but economic service lives are also much higher). In addition, significant capital investment is required for electrification – substations and overhead wires. Other than for relatively short segments where APUs can be used, there is generally less flexibility to extend trolley bus routes into new transit service areas in the short term.

Figure 3.2 – Trolley Bus Power Generation, Transmission, and Distribution



Since the early 1990s, comparative studies of electric trolley buses, 'cleaner' diesel buses, compressed natural gas (CNG) powered transit coaches, and hybrid buses have been carried out in a number of jurisdictions. These studies show considerable variation in unit estimates of pollution and emissions, as well as the relative capital costs associated with vehicle procurement, the power supply and distribution systems, and the average costs of vehicle maintenance**.**

Although most comparative analyses show higher average unit costs for trolley bus than for other types of bus service (when total capital investment is taken into account), there is an increasing body of opinion that, over the long term, cities will require more transit service based on the use of 'tethered' vehicles (LRT or trolley bus) from the standpoint of reducing reliance on fossil fuels, lowering GHG emissions, and improving air quality. Centralizing the source of energy for transit operations enhances these benefits in ways that cannot always be quantified in monetary units. (Most comparisons ignore GHG emissions related to construction activity itself, that is, the supply and installation of power supply and distribution systems, which can be significant.)

4. Previous Studies of Trolley Bus Applications

Comparative analyses of electric trolley buses and other non-electric vehicles were carried out by the TTC (in the 1980s and 1990s) and, more recently, in Edmonton and Vancouver, usually when decisions were required regarding replacement of existing fleets and/or rehabilitation of overhead wire systems.

TTC Studies
Faced with a declining fleet of serviceable trolley buses, the need for major rehabilitation of electric power distribution infrastructure, and reductions in operating subsidies, trolley bus studies were carried out by the TTC during 1991/92. Those studies essentially involved assessing tradeoffs among community preferences, cost differences, and environmental impacts with respect to air quality and GHG emissions. At the time, it was recognized that continuation of existing services would require major capital investment in rehabilitation of the overhead wire structures, as well as the acquisition of new or refurbished buses.

During that period, as an interim measure, the TTC leased 40 trolley buses from Edmonton Transit in order continue service on a more limited basis. In the various studies and analyses, the impact of continued trolley bus operation on Metropolitan Toronto's annual budget received special attention from the Municipality.

The major study by TTC staff concluded that[4]:

- on a life cycle basis, trolley buses are more expensive than either diesel or compressed natural gas (CNG) buses,
- trolley buses are quieter than diesel or CNG buses and cause no local air pollution,
- overhead wire support systems involve some degree of objectionable visual intrusion,
- routing for trolley buses is far less flexible when compared to non-electric buses,
- new vehicles and upgraded overhead wires would be required to retain service, and
- for a representative trolley coach scenario, equipping the Landsdowne division with 160 new trolley buses would require a marginal capital investment of between $95 million and $140 million.

[4] "An Information Report on Trolley Coaches", presented to the TTC on 24 March 1992.

At that time, CNG buses received considerable attention and, of course, hybrid buses were yet to be considered seriously as commercially viable.

To some extent, these conclusions derived from a report of the Hamilton Peer Review Group which estimated unit costs per vehicle–km of $2.15, $1.20, and $0.95 for electric trolley buses, diesel buses, and CNG buses, respectively.[5] An earlier study by the Ontario Ministry of Transportation (March 1991) concluded that the environmental benefits of electric trolley buses relative to modern transit buses had declined substantially. The MTO study also concluded that the unit life cycle costs for trolley buses were higher than for diesel or CNG buses.

Nevertheless, in view of strong public interest in electric bus service (somewhat analogous to the strong public lobby that successfully reversed TTC decisions to eliminate streetcar services some years earlier), as well as the fact that the Edmonton trolley bus lease could not be renegotiated, the Commission authorized management to reinstate trolley bus services (principally on Bay Street) in the Fall of 1992. All trolley bus service was finally suspended at the end of the Edmonton lease in June 1993.

In 1994, the TTC authorized a major bus technology study to revisit the question of trolley buses in view of considerable public criticism of the decision to suspend service.[6] Six bus technology scenarios were assessed ranging from one with all bus service based on 'clean' diesel through various combinations involving mixes of clean diesel, CNG, and trolley buses, to a final scenario based on CNG buses and an 'optimized' network of trolley bus routes.

Selective data from the 1995 RGP study are shown in Table 4.1

Table 4.1 – TTC Electric Trolley Bus, Diesel Bus, and Natural Gas Bus Comparisons*

Item	Units	Type of Vehicle		
		Electric Trolley	Diesel	Natural Gas
Vehicles				
Unit costs	$1000	775	350	410
Vehicle life	years	36	18	18
Major upgrade	years	18	na	na
Energy consumption	Per km	2.175 kwh	0.538 litres	0.722 m^3
Emissions	grams/veh-km			
CO_2 Carbon dioxide		765	1470	1460
SO_2 Sulphur dioxide		3.13	0.45	0.35
HC Hydrocarbons		na	0.26	0.58
CO Carbon monoxide		0.56	3.42	1.17
NO_x Nitrogen oxides		1.15	12.90	5.26
PM Particulate matter		0.20	0.16	0.06

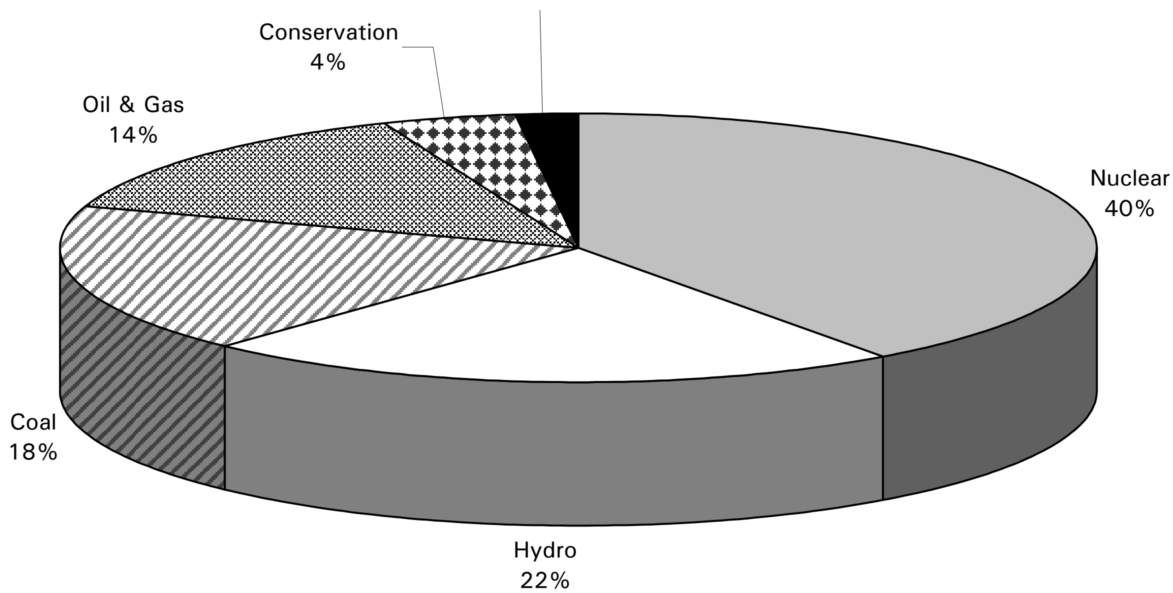
* RGP Transtech Inc. and others, *Bus Technology Study*, March, 1995

[5] Hamilton Street Railway Company, "Alternative Vehicle Technology Investigation", Peer Review Group Report, January 1992.
[6] RGP Transtech Inc. and others, *Bus Technology Study*, March, 1995

The estimates for trolley bus emissions, notably, carbon dioxide (CO_2) allowed for the energy mix applicable to the generation of electricity, at that time For new services, that mix is expected to be comprised almost, if not entirely, of renewable sources of energy or nuclear power, both of which eliminate CO_2 at source.

In 2008, for example, as shown in Figure 4.1, about 32 percent of Ontario's electrical energy was produced by fossil fuels. However, the Ontario government is committed to phasing out coal-fired plants, the energy system's largest polluters, by 2014.[7] For purposes of this study, it has been assumed that all electrical power generation for any new trolley bus service would derive from emission free power generation.

Figure 4.1 – 2008 Ontario Electricity Generation



The RGP Transtech study concluded that "Clean Diesel and CNG are the logical and appropriate technologies for the TTC to consider at this time, for the majority of the fleet".[8] The study also recommended that if a decision were to be made provide trolley bus service, presumably for environmental reasons, then,

- an ideal system should be based on a confined network of high density routes, frequent stops, high passenger loads, and short headways,
- an assessment of the community acceptability of trolley bus garages would be required, and
- a minimum fleet size of 125 and a maximum of 300 vehicles should be considered for garages.

[7] Ontario Ministry of Energy and Infrastructure, *Cleaner, Greener Energy*, News Release, 2008.

[8] Members of a TTC appointed Peer Review Committee expressed concerns about "inadequate analysis, discussion and presentation of the trade-offs between the three technologies in terms of monetary and non-monetary effects," notably "between the additional capital investment…and more benign environmental impacts at the local level".

It should be noted that, during the period when the TTC was deciding the fate of trolley bus service, there appeared to be little appetite for retaining this technology due to cost considerations, in general, and the expected impact on Metro's annual budgets, in particular.

Edmonton

In 2004, Edmonton City Council directed Edmonton Transit to continue operation of a number of trolley bus routes and to undertake a comparison of trolley bus and hybrid bus technologies. On grounds that the existing trolley system is outdated and expensive to maintain and operate, the Edmonton transit study recommended phasing out of the trolley bus fleet and decommissioning of the electrification infrastructure by 2010 in favour of new services to be provided by hybrid buses.[9]

The main arguments supporting the recommended course of action were:

- with the elimination of restrictions imposed by overhead electrification, hybrids or clean diesel buses offer more flexibility to introduce service efficiencies through changes in route design,
- there are no differences in direct bus maintenance costs that favour trolley bus service, and
- although energy costs for trolley bus are about 50 percent less than diesel buses, total costs of operating trolley buses (including depreciation) are about twice those of either diesel or hybrid.

The Edmonton study includes cost estimates for rehabilitation of the existing overhead wire support structure and electrical substations that are fairly substantial and contribute to the unit costs of trolley bus service. These rehabilitation costs, however, are site specific to the Edmonton system and cannot readily be used for comparisons of trolley bus service in Toronto.

The Edmonton study also notes that from a route perspective, trolley bus operation is emission free since the buses themselves produce none of the main emissions that are of community concern. From a regional perspective, however, emissions are higher since electricity is produced by coal fired generating stations.

In addition, the Edmonton study is based on a common service life of 18 years for all bus technologies, contrary to the more common view that trolley bus service lives are closer to 30 years. As well, amortization of vehicle costs is based on straight line depreciation (that is, a constant annual costs based on service life) with no allowance for interest. As a result, in comparing the total life cycle costs of a fleet of 47 vehicles, relative estimates are $173 million for the trolley bus fleet and $64 million for clean diesel buses (that is, a ratio of 2.7 times). (The comparative figure for hybrid buses is $73 million.)

Selected data from the Edmonton studies (including a consultant study)[10]are shown in Table 4.2. For trolley bus emissions, those attributable to electric power generation are excluded

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[9] Edmonton Transit, Transportation Department, *Transit Vehicle (Trolley) Technology Review*, May, 2008.
[10] Booz/Allen/Hamilton, *Alternative Scenarios for Trolley Bus Replacement*, Edmonton Transit, March 2008.

based on the assumption that future power generation in the GTA will derive predominantly from renewable or nuclear sources of energy.

Table 4.2- Selected Trolley Bus, Hybrid Bus and Clean Diesel Bus Characteristics For Edmonton*

Item	Units	Type of Vehicle		
		Electric Trolley	Diesel	Hybrid
Vehicles				
Unit costs	$1000	950	425	650
Vehicle life	years	18	18	18
Energy consumption	per km	2.89 kwh	1.68 litres	na
Emissions**	grams/veh-km			
CO_2 Carbon dioxide		0	1822	1472
SO_2 Sulphur dioxide		0		
HC Hydrocarbons		0	0.442	0.360
CO Carbon monoxide		0	0.704	0.574
NO_x Nitrogen oxides		0	1.504	1.241
PM10 Particulate matter		0	0.245	0.205
PM2.5 Particulate matter		0	0.101	0.084

* Sources: Edmonton Transit and Booz/Allen/Hamilton
** excludes emissions at source

Vancouver (Translink)
In August 2008, *Translink* reported on a demonstration project concerned with bus technology and alternative fuels. The draft final report summarizes findings on emissions and performance tests of seven standard buses including 'clean diesel', CNG, and hybrid buses.[11] A separate report compares baseline clean diesel buses and trolley buses based on tests of two newly acquired trolley buses conducted over a four week period.

This Translink study suggests that both particulate and GHG emissions for trolley buses are far below those of other bus technologies studied, even for the relatively small proportion of electricity generated by fossil fuel plants (about 6 percent).

In contrast to findings of the Edmonton studies, *Translink* concludes that "the superiority of trolley buses to internal combustion engine-powered buses is undeniable and maximum use of trolley buses will yield substantial reductions in energy use and cost." Overall, the study argues that:

> to achieve *TransLink's* objectives of reduced emissions, cost effectiveness, performance (safety) and reliability (customer service), trolley and hybrid technology are the best choices.

This *Translink* conclusion relates to *both* trolley bus and hybrid buses and presumably derives from the fact that trolley bus services are already provided using an existing electrification

[11] M.J.Bradley and Associates, *Bus Technology and Alternative Fuels Demonstration Project, Phase 2 Draft Final Test Report*, Translink, August 2008.

system that can be considered as a ‘sunk’ cost. In other words, given the infrastructure now in place, the marginal costs of providing trolley bus service are considerably lower than would be the case if entirely new substations and overhead transmission systems would have to be constructed, as would be the case in Toronto.

In the *Translink* demonstration project, net energy consumption for the two buses averaged 2.14 kwh per km (somewhat lower than in the Edmonton study), or an average cost of $0.14 per km at current electricity rates.

When comparing the TTC, Edmonton, and Vancouver findings, differences in the air quality and emissions estimates should be noted. From the standpoint of air quality, NO_x and particulate emissions are of most concern whereas CO_2 emissions are most relevant from the standpoint of GHG and climate change. Although the differences in NO_x estimates are not easily explained (but may derive from different definitions of measures), the CO_2 emission estimates in grams/veh-km for diesel buses, namely 1,470 in Toronto (1995), 1,822 in Edmonton (2008), and 1,400 in Vancouver (2008) are of the same order of magnitude. The most recent TTC estimate for diesel bus GHG emissions is 1,771 grams per km.

5. Case Study

In comparing trolley bus and other bus technologies for application in Toronto, the major criteria pertain to:

- Capital costs for vehicles, electrification infrastructure, and bus maintenance facilities,
- Operating costs for vehicle maintenance, energy, and labour,
- Maintenance of sub-stations and overhead wires, and
- Emissions

As noted previously, the initial costs of trolley buses are higher than for other buses. Capital investment for sub-stations is influenced by service density and, for the overhead wire system, by route length. In the current studies of new *Transit City* LRT routes, a ‘blended’ average cost per km is used for the combination of sub-station and overhead costs, an approach that is adequate for this preliminary assessment of trolley bus service. (Some adjustment, of the order of 10 to 20 percent might be appropriate to allow for the second trolley bus overhead wire and the use of two curb lane rather than one centre lane overhead wire supports.)

Although both Edmonton and *Translink* studies place considerable emphasis on diesel/electric hybrid buses, recent experience in Toronto with hybrid buses raise some uncertainty as to the extent to which these vehicles, once in service, actually achieve expectations.

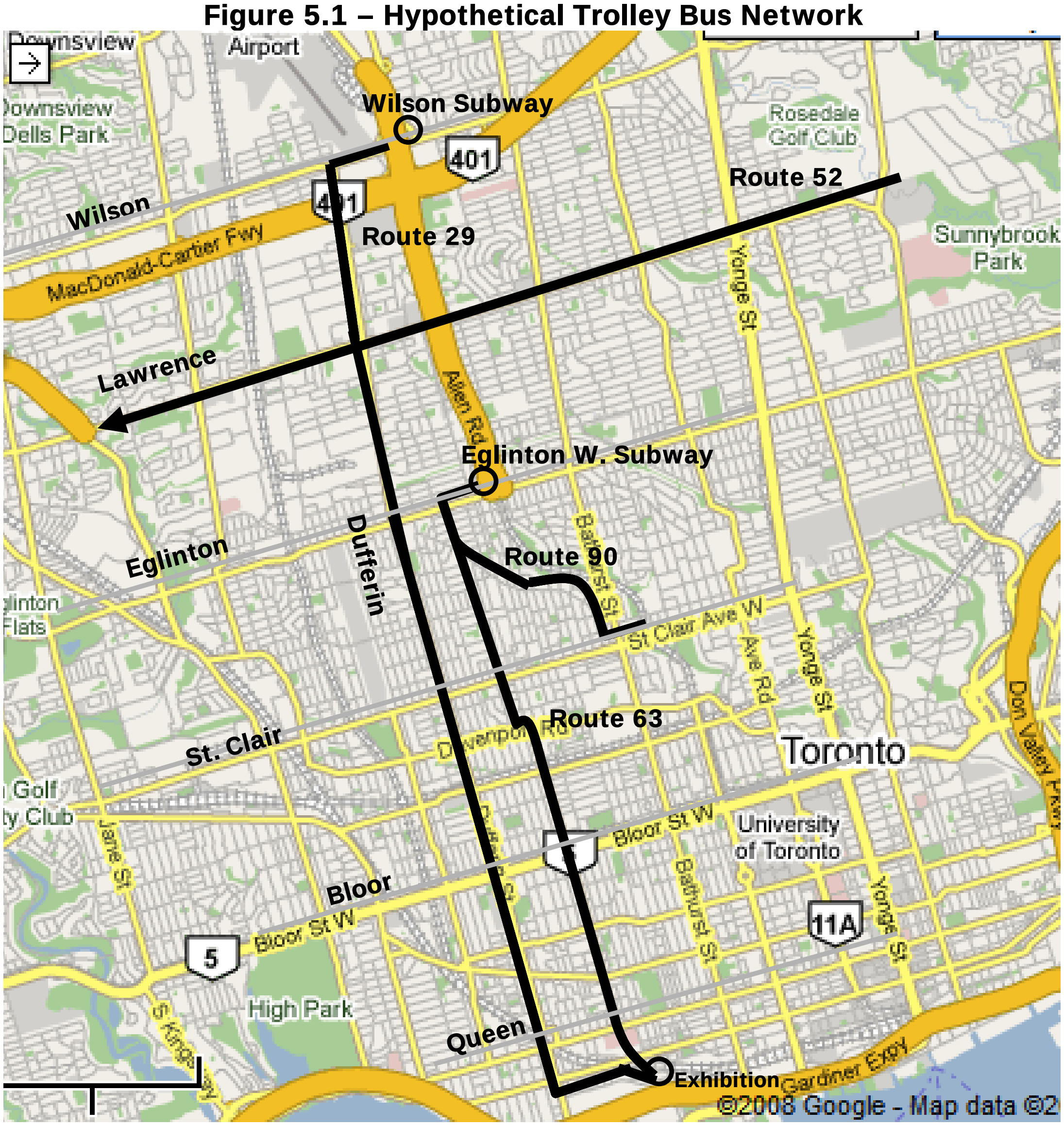
In order to examine trolley bus service in a preliminary manner relative to modern diesel buses (that is, ‘clean’ diesel) and hybrid, a sample network of potential trolley bus service has been developed, shown in Figure 5.1.

This network includes the 29 Dufferin, 63 Ossington, 52 Lawrence West, and 90 Vaughan bus services. Current route information is summarized in Table 5.1. These routes were selected for purposes of illustration primarily because they could all use the existing Wilson garage, suitably modified to provide trolley bus storage and maintenance facilities.

Table 5.1 – Hypothetical Trolley Bus Network

Route	Route Length One-way km	AM Peak Buses	2008 Daily Ridership 1000s	Annual Veh-km 1000s
29Dufferin	13.56	35	43.65	3,053
52Lawrence West	15.31	21	22.19	1,666
63Ossington	9.63	15	16.94	1,174
90Vaughan	3.30	6	6.19	299
Total	**41.80**	**77**	**88.97**	**6,193**

Figure 5.1 – Hypothetical Trolley Bus Network



Major capital cost items include:

- Fleet acquisition,
- Construction and installation of power substations and overhead wires, and
- Construction and equipment of a trolley bus maintenance facility.

For purposes of comparison, the same fleet size has been maintained for trolley buses, equivalent to the total number of buses now allocated to the current 29 Dufferin, 63 Ossington, 52 Lawrence West, and 90 Vaughan services.

Capital costs for the electrification system are more complicated. TTC estimates for substations are $2.7 million each with an average substation spacing of 1.5 km. Unit costs for the installation of overhead wires depend upon the configuration of trolley lanes (essentially two curb lanes or adjacent lanes served by central support poles). Estimates shown in Table 5.2 are based on an average unit cost of $2 million per km with a supplementary cost of $50,000 per intersection to allow for special treatment.

Both the substation and overhead wire unit cost estimates are subject to the usual TTC allowances for contract changes (10 percent), design and engineering (25 percent), and contingencies (30 percent), on a cumulative basis. For the four hypothetical routes, these assumptions lead to an average 'blended' (both substations and overhead wires) unit cost estimate of $7.3 million per km.

Recognizing technical differences between LRT and trolley bus electrification (one less overhead wire and central lane configuration in the case of LRT) this estimate is somewhat higher than the blended average unit costs now being assumed in the EAs for the Finch West and Sheppard East LRT routes.[12]

Although no estimates have yet been prepared for new trolley bus maintenance facilities, an incremental allowance of $15 million has been made for this preliminary comparison.

Recent estimates for a trolley bus electrification project in Vancouver are somewhat lower than the estimates included in this case study but, as previously noted, Vancouver already has a considerable sunk investment in existing electrification infrastructure.[13] However, the potential impact of lower electrification costs is treated below as part of a sensitivity analysis.

Operating costs include labour, vehicle maintenance, energy, and infrastructure maintenance (in this case, maintenance of the trolley bus wires). Labour costs are excluded because they are common to all three bus technologies considered.

Although one analysis by the Coast Mountain Bus Company (part of *Translink*) concludes that trolley bus maintenance is more costly than for diesel buses, both the recent Edmonton and

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[12] Overhead wire design (basically cable diameter) depends upon estimated electrical loads that, in turn, vary with vehicle weight and rolling resistance. LRVs are considerably heavier than trolley buses but rolling resistance (per tonne) for a steel wheel on rail is significantly lower than for rubber wheeled vehicles.

[13] City of Vancouver, Engineering Services, Report A19, 10 July 2007

Translink studies suggest no difference of any consequence. Intuitively, trolley bus maintenance costs could be expected to be less than those of diesel buses due to simpler propulsion and transmission components. For this reason, differences in vehicle maintenance costs are also excluded.

Table 5.2 – Components of Electrification Estimates

Item	Units	Estimate
Route length		42
Substations	$1000	2,700
Spacing	km	1.5
Unit Costs	$1000/km	1,800
Contract changes	%	10
Engineering	%	25
Contingencies	%	30
Substation Total	**$1000/km**	**3,218**
Overhead Wires		
Overhead	$1000/km	2,000
No. of Intersections		220
Intersection Adjustment	$1000	50
Intersection Cost	$1000/km	263
Sub Total	$1000/km	2,263
Allowances		
Contract changes	percent	10
Engineering		25
Contingencies		30
Overhead sub total	$1000/km	**4,045**
Total Electrification	**$1000/km**	**7,263**

In amortizing capital costs, although there is always some disagreement on the discount rate to be used by public authorities, some interest rate is appropriate to reflect the opportunity cost of capital from the standpoint of taxpayers. *Metrolinx* currently uses a 5 percent discount rate in its benefits case analyses. (At the federal government level, Treasury Board evaluates projects using a 10 percent discount rate.)

Table 5.3 summarizes the unit cost estimates, as well as other assumptions used for diesel, hybrid, and trolley bus service on the hypothetical network. GHG estimates are based on recent TTC calculations for GHG per litre of diesel fuel and fuel consumption rates. For hybrid buses, a 15 percent improvement in fuel efficiency is assumed (which, as noted, below, is about one-half the anticipated fuel saving).

Total capital and operating costs are shown in Table 5.4 and Figure 5.2.

Table 5.3 – Comparison of Diesel, Hybrid and Trolley Bus Input Assumptions

Item	Units	Bus Technology		
		Diesel	Hybrid	Trolley
Bus Purchase Price	$1,000	501	703	920
Electrification	$1000/km			7,263
Service Life	years			
Buses		18	18	30
Electrification		na	na	30
Maintenance Facility				30
Discount Rate (interest)	percent	5	5	5
Overhead Maintenance	$1000/km/year			30
Energy consumption	litres or kwh/km	0.66	0.56	2.14
Energy Cost	$/litre or kwh	1.10	1.10	0.10
GHG (CO2) Estimates				
	grams/litre	2,700	2,700	na
	grams/bus-km	1,771	1,506	0

Overall, the analysis shows GHG emission reductions are achieved at an implied average cost of about $1,840 per tonne, considerably above the average normally used in benefit-cost analyses of this type. (*Metrolinx* benefits case analyses currently use a value of $40 per tonne.) By comparison, current operation of hybrid buses in Toronto implies a considerably lower cost per tonne ($401) for GHG reductions.

Relative to expectations, however, hybrid buses appear to be underperforming in Toronto, a fact that may derive from the routes on which they are used. As originally anticipated, with fuel savings of about 30 percent, the cost of GHG reductions would approximate $200 per tonne. Moreover, given the restructuring now under way in the North American automotive industry, it may be reasonable to anticipate the development of electric buses within the foreseeable future, paralleling the planned introduction of General Motors' electric car in 2010, which would eliminate GHG emissions without the need for investment in trolley bus electrification infrastructure.

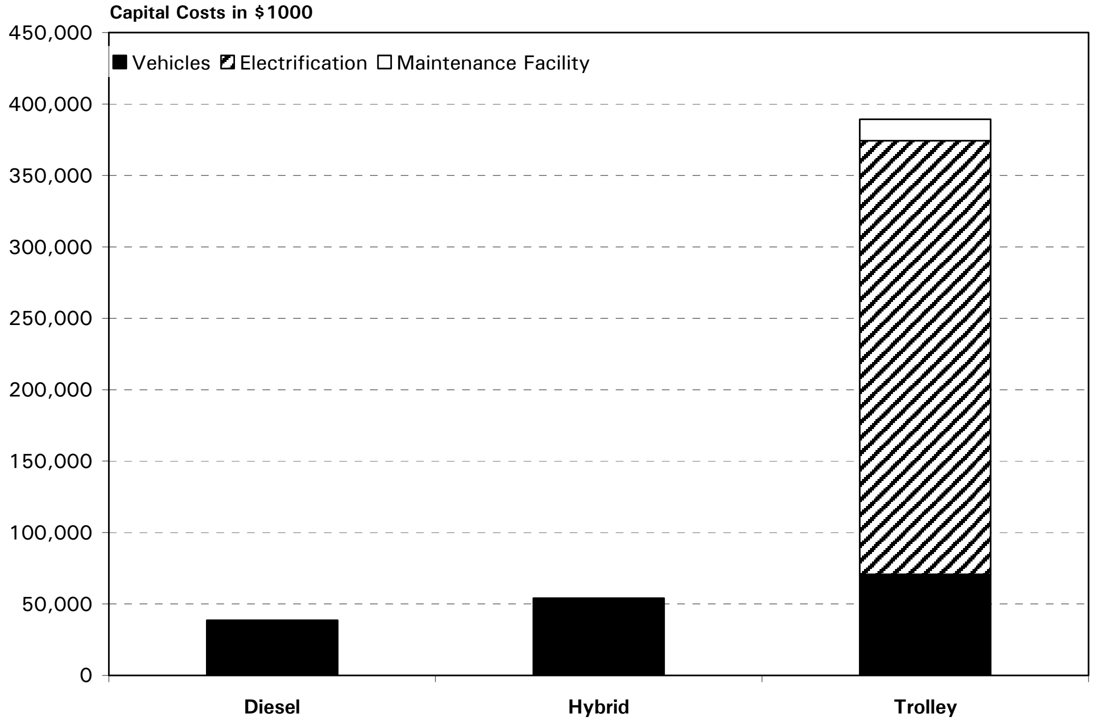
Table 5.4 – Comparison of Diesel, Hybrid and Trolley Bus Costs (excluding costs of bus maintenance and labour operation)

Item	Units	Bus Technology		
		Diesel	Hybrid	Trolley
Route length (1 way)	km	41.8	41.8	41.8
No. of Buses		77	77	77
Annual Vehicle-km	veh-km (1000s)	6,193	6,193	6,193
Capital Costs	$1,000			
Vehicles		38,577	54,131	70,840
Electrification				303,555
Maintenance Facility				15,000
Total		38,577	54,131	389,395
Incremental (relative to diesel)			15,554	350,818
Annual Costs	$1,000			
Energy		4,469	3,799	1,325
Overhead Maintenance				1,254
Sub Total (Operation)		4,469	3,799	2,579
Debt service				
Buses		3,300	4,631	4,608
Electrification				19,747
Maintenance Facility				976
Sub Total (Amortization)		3,300	4,631	25,331
Total Annual Costs	$1,000	**7,769**	**8,429**	**27,910**
Unit Costs	$/passenger	0.29	0.31	1.03
Total Annual GHG	tonnes	10,969	9,324	0
Implied Value of GHG	$1,000/tonne	0	401	1,836

The dominance of capital investment in electrification (about 71 percent) is illustrated in Figure 5.3. Given the preliminary nature of the electrification estimates, Figure 5.4 compares the sensitivity of differences in total annual costs to changes in the unit cost estimates for electrification. For purposes of illustration, the effect of doubling the real cost of diesel fuel is also shown. As this figure shows, even with a substantial reduction in the capital costs of electrification, the trolley bus alternative remains considerably more costly than diesel bus service.

Consistent with the generally held view that trolley bus service is most effective on more intensively used routes, Figure 5.5 compares the impact of higher density service on a comparable network (in terms of total length) of trolley bus service with twice the ridership and fleet size. In the higher density service network, the implied value per tonne of GHG (about $985) is roughly half that estimated in the case study, a value that still exceeds Metrolinx's $40, by far. Even with considerable reductions in the costs of electrification, the implied values for GHG reductions remain high.

Figure 5.2 – Comparative Costs for Alternative Bus Technologies



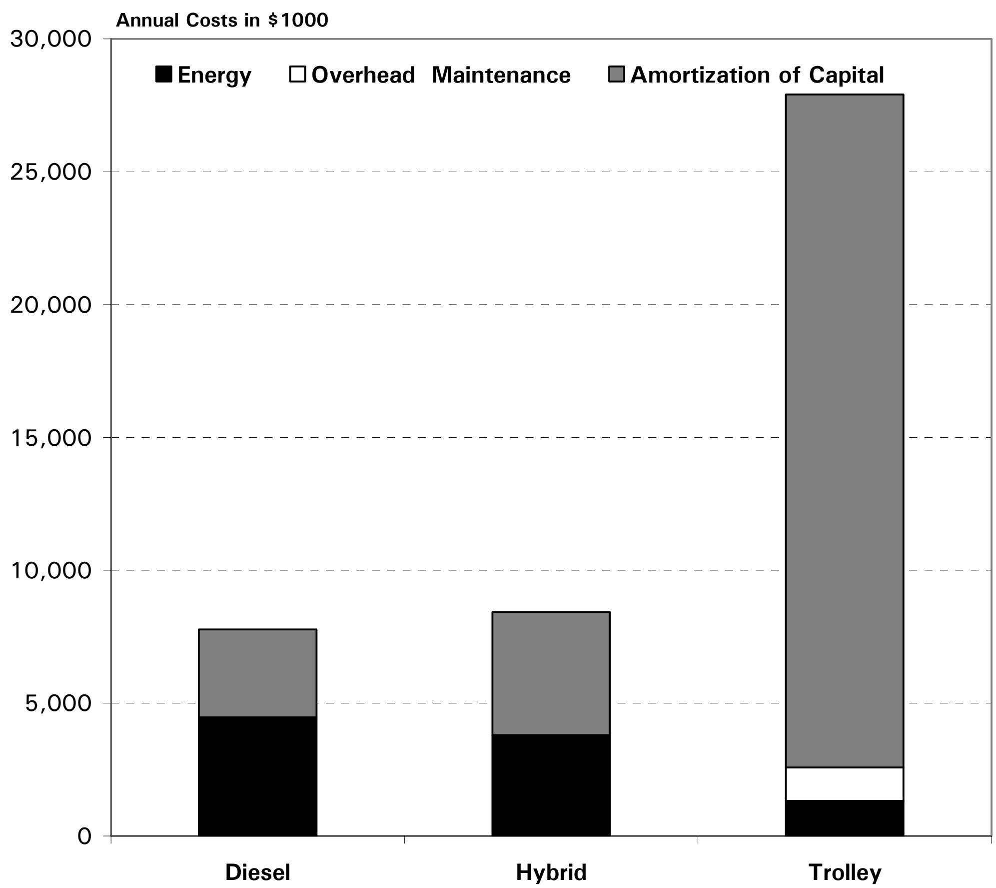


Figure 5.3 – Annual Cost Distribution for Trolley Buses

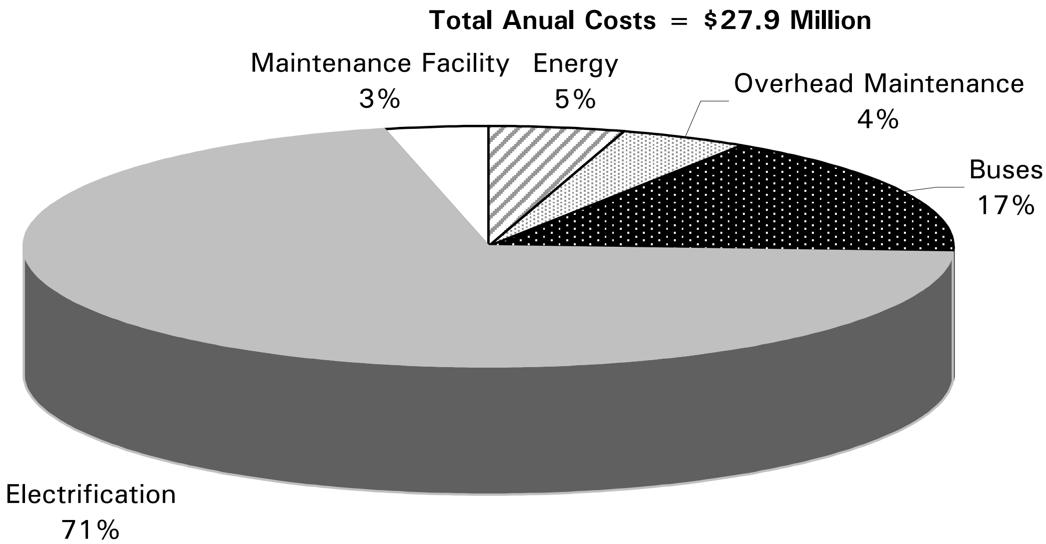


Figure 5.4– Difference in Annual Costs for Variation in Electrification Estimates

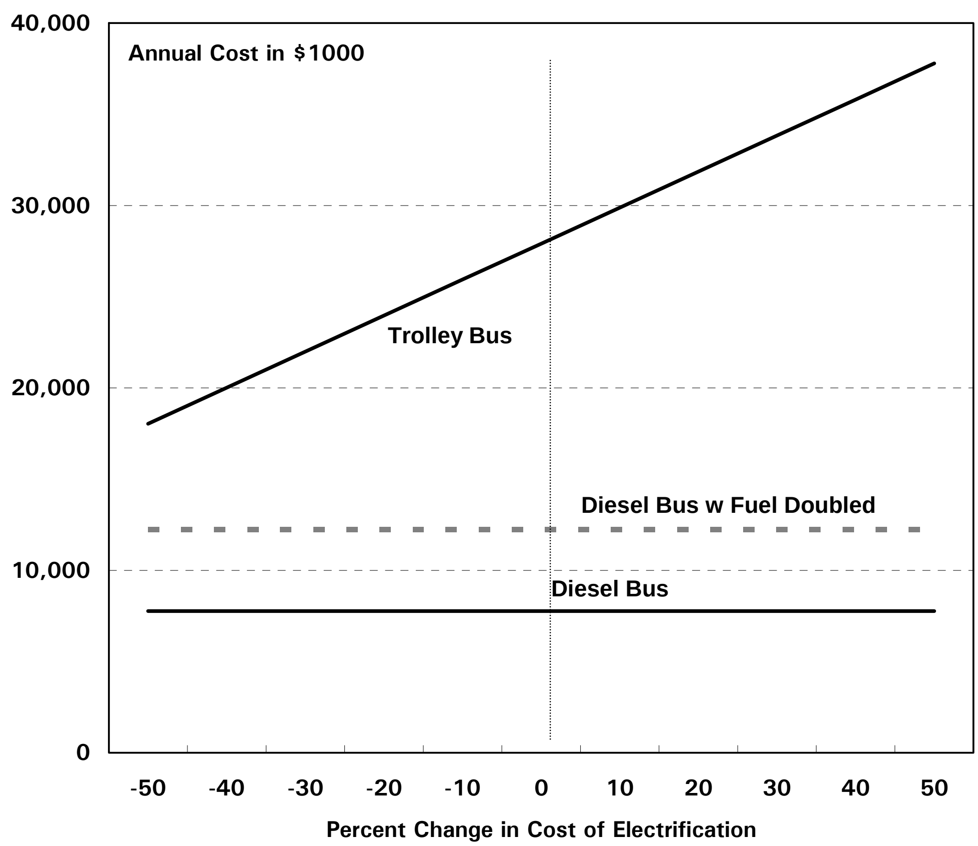
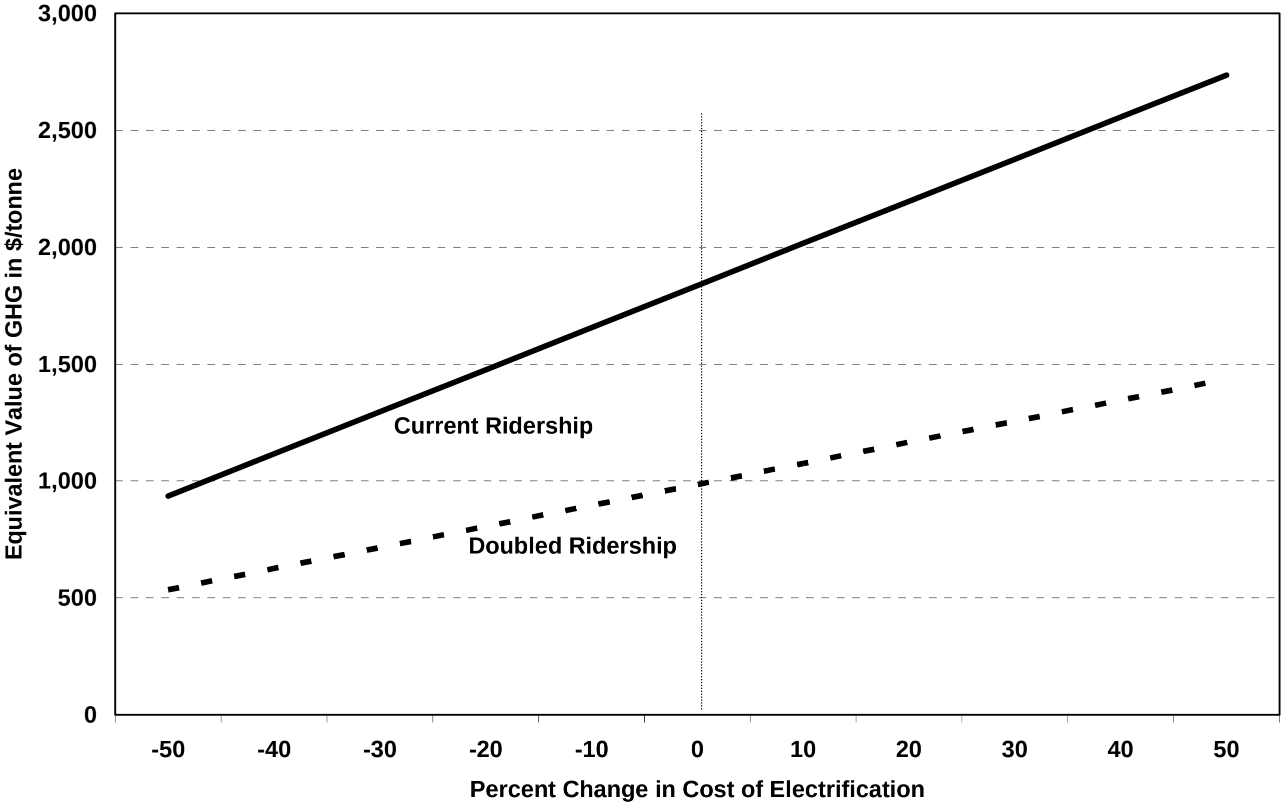


Figure 5.5– Implied Value of GHG Emissions for Variation in Electrification Estimates and Ridership Compared to Diesel Bus service



6. Conclusions

Recognizing the intrinsic appeal of any form of electrified transit relative to diesel buses and such variants as hybrid buses from the standpoint of GHG emissions, the main conclusions of this initial evaluation of electric trolley buses are as follows.

First, trolley buses consume less energy and produce lower emissions than either diesel or hybrid buses. They are also more attractive from the standpoint of air quality, noise, acceleration (notably in heavy traffic), and opportunities provided by central power generation to negotiate steeper grades.

Second, overall, the unit costs of service delivery are much higher than for either diesel or hybrid buses. Even if diesel fuel costs were to double, the incremental cost estimates of converting the sample network to trolley bus operation still remain very high.

Third, the main cost disadvantages of trolley buses derive from the electrification. In fact, the annual cost of electrification accounts for more than two-thirds of the total cost differential when compared to diesel bus operation.

Fourth, trolley buses offer less flexibility to both alter and extend routes to serve entirely new areas.

Fifth, the implied value per tonne of GHG emissions ($1,840) achieved through the operation of trolley buses is considerably higher than values currently assumed for GHG reductions (about $40 per tonne). Even a doubling of service on a similar network with the same total length of electrification still results in an implied value per tonne of about $985.

Sixth, for the large differences in capital investment, the high implied cost per tonne for reducing GHG emissions raises an issue of the relative efficiency of reducing GHG emissions from transit by other means. Theses include:

- better performing hybrid buses,
- improvements in the cost effectiveness of fuel cell buses,
- development, within the foreseeable future, of all electric buses, possibly as a by product of initiatives driven by restructuring of the automotive industry with respect to electric automobiles, and
- expansion of bus services to new markets.

Finally, the high cost of trolley bus service derives primarily from the fact that, in Toronto, entirely new infrastructure is required for electrification as opposed to a situation (as in Vancouver) in which there is an existing electrification network in need of refurbishment. In this situation, although it is difficult to justify the large capital investment in electrification required for new trolley bus service from the standpoint of the TTC's finances alone, such investment may be considered by City Council as a separate initiative for achieving its GHG emissions reduction goals.