Life-Cycle Costing in Support of Strategic Transit Vehicle Technology Decision: Hamilton Street Railway Looks to the Future

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The approach, data, methods, and results of a detailed disaggregate life-cycle costing analysis of transit vehicle operation at the Hamilton Street Railway (HSR) in Hamilton, Ontario, are summarized. The life-cycle costing was performed in 1991 as part of an overall study of future technology, which included particulate-trap-equipped diesel, compressed natural gas, and electric trolleybuses. The study used the HSR's detailed maintenance, fuel, mileage, and other records to obtain base diesel lifetime costs. A combination of internal records and those from manufacturers and other operators were used to forecast lifetime costs of the new technologies. Pollution, noise, transit planning, and other such aspects included in the overall study are not discussed. This analysis indicates that an all-natural-gas fleet would be the least expensive to operate in the long term, with an all-diesel fleet second most economical.

The Hamilton Street Railway (HSR) provides transit services to the Region of Hamilton-Wentworth, Ontario. Located at the western end of Lake Ontario, this city of 440,000 people is approximately midway (by road) between Buffalo and Toronto. This transit company has retained its historical name, despite the discontinuation of streetcar service in the postwar years in favor of electric trolleybuses and, later, gasoline and diesel buses.

In the early 1990s, an aging electric trolleybus fleet and infrastructure forced the Region to decide whether to invest substantially in electric trolleybus service or to move to an all engine-driven fleet.

Coincidentally, HSR was assessing the viability of compressed natural gas (CNG) as a bus fuel by running a fleet of 10 converted diesel buses. This prototype work, begun in 1983, was among the first in North America; it led to HSR, the Toronto Transit Commission, and Mississauga Transit being the first to place a significant order for production for CNG buses (totalling 50 Orion V buses with Cummins engines and roof-mounted CNG tanks) (*1,2*).

The mandate of the Alternative Vehicle Technology Investigation was therefore to study the relative merits of electric trolleybuses, diesel, and CNG buses based on a variety of environmental, economic, and other criteria.

The investigation involved representatives from the HSR, the Ministry of Transportation of Ontario (MTO), and a variety of specialist consultants. A citizen representative was also selected to participate in the study process. MTO participation was both as technical advisors and as providers of subsidy. The MTO's policy of providing 75 percent funding for capital purchases and 19.5 percent funding for operating expenses was considered in the economic evaluation. A special 90 percent subsidy rate for electric vehicle purchases was, at that time, under review.

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STUDY APPROACH

HSR was interested in making a decision in 1991 that would serve it through the next 20 years. Rather than considering only what vehicles to purchase this year or next, the question was more fundamental: what kind of vehicle technology should HSR invest in over the long term? This type of decision involves many more considerations than simply a determination of what is most convenient or most cost-effective.

The following criteria were addressed in evaluating the transit options:

- Noise pollution;
- Vehicle emissions;
- Air quality impact;
- Vehicle operating costs;
- Infrastructure costs;
- Availability of vehicles, parts, and energy;
- Special staffing needs;
- Safety;
- Energy cost and availability; and
- Public acceptance.

To maintain the highest possible standards throughout the study, HSR engaged specialist consultants in the areas of public involvement, noise, emissions, air quality, energy pricing, transit planning, cost modelling, and engineering design, so that each of these criteria could be investigated by experts in that particular field.

The approach of the study began with the definition of eight viable strategies for providing transit service in the Hamilton area. In each case, the service level was the same as that currently provided. The eight options were

1. Status quo (except that diesel buses would be equipped with particulate traps.) The 1992 (base year) mix was 45 trolleys, 170 diesel buses, and 25 CNG buses.
2. Option 1, plus extend one trolley line to McMaster University.
3. Option 2, plus extend another trolley line up the "Hamilton Mountain" (actually a section of the Niagara Escarpment).
4. Replace all retiring vehicles with CNG.
5. Replace all retiring vehicles with "improved diesel."

6. Option 1, except CNG replaces all retiring diesel buses.
7. Option 2, except CNG replaces all retiring diesel buses.
8. Option 3, except CNG replaces all retiring diesel buses.

This paper concerns only the cost modeling portion of the study.

APPROACH TO VEHICLE LIFE-CYCLE COSTING

The costs of vehicle ownership are complex and are not readily comparable with one another. One vehicle may have a higher purchase price but may be more fuel-efficient than another. Maintenance costs may be quite different and may have a different pattern over the vehicle's lifetime.

Life-cycle costing seeks to reconcile the differences among alternative vehicle types without losing any of the distinctions. A life-cycle costing table lays out all the expenditures relating to each option in the year in which they occur. Discounting is then applied to the table so that costs relating to different years may be compared on an equal footing.

Any end effects are treated as a residual value at the end of the study period. For example, if one option involved the purchase of a number of expensive vehicles in the last year of the study, the ownership value remaining in those vehicles at the horizon year is considered as a credit to that option. The residual value is determined using straight line interpolation, consistent with the fact that the vehicles are valued at their worth as functioning equipment to provide transit service, rather than their resale value.

Costs to be examined in this exercise include only those that may be subject to variation among the alternative vehicles, specifically maintenance, capital, energy, and infrastructure. Other costs, such as drivers and administration, do not affect the outcome of the study and so were not included in the analysis.

This study used cross-sectional analysis to determine the maintenance costs associated with the vehicles under investigation. Cross-sectional analysis uses many vehicles of different ages to determine the cost profile throughout a vehicle's lifetime. This is particularly appropriate to the Hamilton analysis because there is little difference among the vehicles other than their age. Cross-sectional analysis has the added advantage of being unaffected by inflation or changes in maintenance procedures.

An alternate approach may have been to obtain a picture of maintenance expenditures throughout a vehicle's lifetime. However, it is virtually never the case that every dollar spent in maintaining a vehicle is recorded and categorized. Furthermore, such a dataset could not be completed until the vehicle was retired. Such an approach to obtaining vehicle maintenance histories is clearly not appropriate to this type of study.

The study relied on the Vehicle Maintenance System (VMS) data base installed at the HSR, which made it possible to obtain in electronic format a detailed history of expenditures on each individual vehicle in the fleet, including details of the maintenance activity to date. Data relating to the most recent 12 months were used in the study because they were believed to be most reliable.

The maintenance life-cycle cost model used disaggregated maintenance cost models for the standard diesel bus as a basis for the analysis. The 1 year of available maintenance cost information on the entire fleet provided sufficient data to calibrate a separate cross-sectional life-cycle cost model for labor and materials in each of 15 component subgroups. The subgroups used in the study are given in Table 1. Figure 1 illustrates 1 of the 15 such models developed for the base case.

The cost models were then applied to the three technologies that were the subject of the investigation. Whereas other studies have attempted to derive maintenance costs for new technologies by estimating the total cost variation from the base case, this study benefitted from the availability of 15 different submodels, clearly identifiable by the technical differences among the different vehicle types. Ten categories of maintenance did not vary at all among vehicle types, as indicated in Table 1.

The improved diesel differed from the base case (standard diesel) in only two categories: the particulate trap and the electrical system. Particulate trap maintenance and replacement costs were estimated after discussions with trap designers and test fleet operators. Several categories did not apply to electric trolleybuses at all but were easily adapted to CNG from the baseline diesel costs using technical knowledge combined with HSR experience with the prototype CNG buses.

TABLE 1 Component Groups Used in Maintenance Cost Analysis

	Component
Common to all vehicle types:	Preventative Maintenance Tires, Steering, Suspension Air Systems Brakes Farebox / Communications Service / Cleaning Auxiliary Electrical Systems Body Heating / Air Conditioning
Engine-driven vehicles only:	Transmission, Drive Lines Engine and Accessories Cooling System Fuel System
Trolleys only:	Trolley Lines Electric Motive Power System

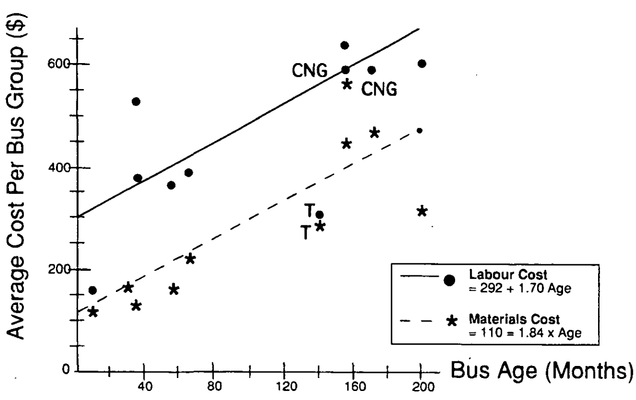

FIGURE 1 Tires and steering maintenance costs (example of derived component group cost relationship).

Unique electric trolleybus component costs were estimated from historical HSR costs for these items, using the experience of other North American trolley operators in determining the maintenance impacts to be expected with more modern equipment. Auxiliary power unit costs were estimated from technical data and limited HSR experience.

Miscellaneous garage costs were determined separately for the three vehicle types, ensuring that engine-related items such as batteries, antifreeze, and engine oil would not be assigned to trolleys. By breaking the costs of maintenance into small subcosts in this way, the total costs were easily assembled and defensible.

CAPITAL COSTS

Capital costs of CNG and diesel buses were obtained from recent HSR bids, which were nearly identical to the study buses in terms of options. The cost of the particulate trap was estimated and added to the diesel bus cost. Adjustments were made to account for inflation and taxes in the base year.

The purchase price of an electric trolleybus meeting the HSR requirements is not easily determined. Few trolleys had been purchased in North America in the previous 10 years, and few bus manufacturers were generally interested in producing them. The cost of an electric trolleybus was estimated using the results of an earlier study (by Cole, Sherman & Associates, Ltd, for the Hamilton Street Railway, unpublished work), as well as published bid prices from all trolley purchases in North America over the past 10 years; the result was verified using component costs.

Trolley purchase price depends heavily on bid quantity because the traction motors are not an "in-stock" item. The price used in this study depended on the assumption that another (larger) trolley user would place an order for new vehicles in the near future, and the HSR purchase could then be "piggy-backed" onto this order to obtain the benefit of a lower price. The estimated purchase prices of the three vehicle types to HSR in 1991 are presented in Table 2. Prices include all applicable taxes and are quoted in Canadian dollars; they all include air conditioning.

ENERGY COSTS

As is the case in many other studies of this nature, the cost of energy is the most significant, as well as the most subject to market fluctuations. For this reason, HSR engaged a specialist consultant in the field of energy pricing who produced high, low, and most likely estimates of energy prices for the three vehicle technologies for the entire study period.

Figure 2 illustrates the forecast energy prices, including all taxes, to the HSR. In reference to Figure 2, it should be noted that

1. All figures are expressed in Canadian dollars.
2. The cost of compressing CNG is included separately in the analysis, based on known compression energy and the electricity costs included in this paper.
3. The demand charge for electricity was estimated to grow at the same rate as the consumption charge shown included in this paper.

Comparisons among the prices are significantly different in Ontario from what is observed in many parts of the United States, in particular the low cost of natural gas in relation to that of diesel fuel. There are two main reasons for this. Natural gas is abundant in Canada and is supplied through a well established pipeline network. It is not subject to road taxes, because it is not in common use as a vehicle fuel. (This factor may change in the long term but is not expected to do so in the study timeframe.) Diesel fuel is, like gasoline, subjected to substantial taxation from both provincial and federal governments. Energy costs for trolleys included both consumption and demand charges for electricity. Demand charges were forecast to increase at the same rate as consumption charges during the study period.

The fuel (energy) efficiencies of the three vehicle technologies (summarized in Table 3) were determined from a combination of sources:

• Diesel bus fuel economy was derived from HSR fuel usage records, using detailed data to isolate the energy penalties associated with air conditioning (included on 1989 buses) and with the larger 6V92 engines (included since 1987). An additional 1 percent penalty was added to account for the particulate trap. The

TABLE 2 Summary of Vehicle Costs and Life Expectancies

Type	Cost	Life Expectancy
CNG:	$246,000	18 years
Diesel:	$243,000	18 years
Trolley:	$478,000	36 years, with a major refurbishment at about 18 years

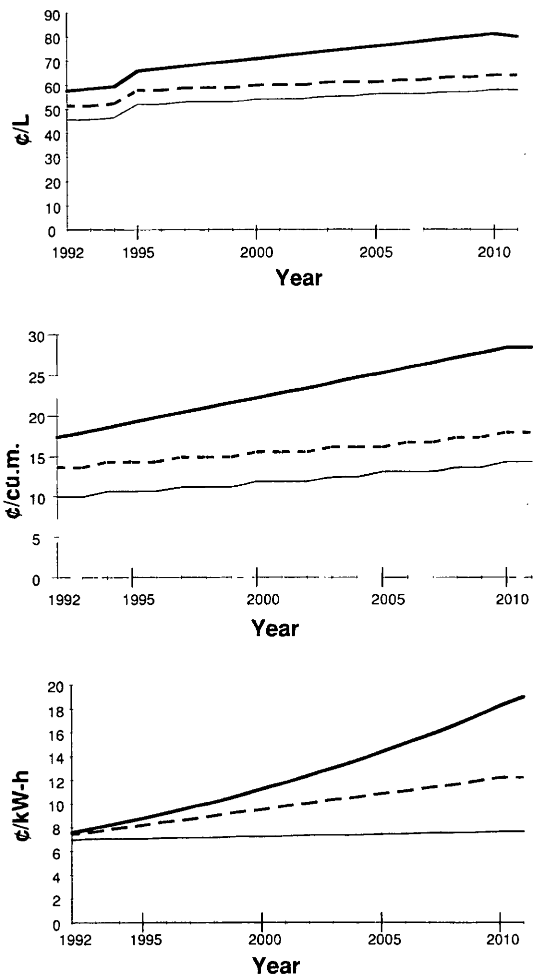

FIGURE 2 Diesel fuel cost projections (¢/L) (*top*); CNG cost projections (¢/m³) (*middle*); electricity cost projections (¢/kW-hr) (*bottom*).

resulting fuel economy was verified by comparison with published figures.

- CNG bus fuel economy was determined primarily from published figures, applying the deviations from "average" calculated for diesel buses to adjust the published figures to the HSR situation. The electricity required to compress the natural gas was taken from HSR records for its existing (prototype) CNG fleet. A premium for air conditioning was applied. Under Options 4, 6, 7, and 8, HSR's significantly increased CNG fleet would warrant the installation of a larger compression facility (see Infrastructure Costs). For these scenarios the compression energy was reduced because of the higher supply line pressure that would then be available.
- Trolley energy efficiency was estimated using HSR electricity charges for 1987 (the last year with uninterrupted trolley service on all routes). Both consumption and demand charges were divided by the number of fleet km to obtain an average. Adjustments were made to account for air conditioning and chopper controls (expected to be a feature of any new trolleys purchased after 1991). Energy efficiency determined in this way included distribution losses under actual HSR conditions and is not obscured by the existence of other power users, such as streetcars or subway trains, using the same distribution network.

INFRASTRUCTURE COSTS

Infrastructure costs were determined following a preliminary assessment of the infrastructure needs for each option and a preliminary design in each case. For the options that included electric trolleybuses, the existing infrastructure would need to be upgraded to allow the newer electric trolleybuses to operate because the older overhead does not provide clean enough power to operate the more sensitive new vehicles. In addition, some of the power supply lines would need to be buried to meet new city standards. Under Options 2, 3, 7, and 8, trolley extensions would be required, including an additional substation. Options 4, 6, 7, and 8 would require new natural gas compression facilities. Options 4 and 5 include the cost of demolishing old trolley lines.

The costs of these requirements were determined in some detail through a preliminary design that estimated numbers of poles, lengths of wire, and the degree to which other utilities would be affected. Construction/demolition costs were estimated, along with a suitable timetable for their implementation, as shown in Table 4. Preliminary design was also carried out on the natural gas compression facility, which is reflected in Scenario 4 Costs in Table 4.

UNDISCOUNTED COSTS (CASH FLOW)

To combine the costs of the different operating cost sources, overheads were determined that would bring the costs to a common denominator. Labor overhead included benefits, as well as direct supervision and clerical staff. Materials and capital costs were adjusted to include the cost of purchasing and stocking.

Figures 3 through 10 illustrate the costs in current dollars involved with operation of the fleet over the study period. Options

TABLE 3 Summary of Energy Usage for HSR Alternative Vehicles

Bus Type	Fuel Economy
Diesel Bus (with Particulate Trap)	71.3 L/100 km
CNG Bus	83.5 m^3/100 km plus compression energy @ • 35.6 kW-h/100 km. (Scenarios 1, 2, 3 and 5) • 22.4 kW-h/100 km. (Scenarios 4, 6, 7 and 8)
Electric trolleybus	308.5 kW-h/100 km plus 317 kW/trolley/year peak demand

TABLE 4 Infrastructure Capital Costs ($ millions)

Scenario	1	2	3	4	5
MAJOR COST GROUP					
1. Bus Maintenance Infrastructure					
1.1. Maintenance Facilities	0.050	0.100	0.100	5.400	0.050
2. Bus Route Infrastructure					
2.1 Sub-station Work	3.072	5.483	7.101	-	-
2.2 New Trolley Overhead	0.295	6.969	12.643	-	-
2.3 Existing Trolley O/H Upgrade(*)	9.552	9.848	9.848	-	-
2.4 Roadworks	0.266	1.148	2.305	-	-
2.5 Removal of O/H	-	-	-	1.909	1.909
Contingency/Engineering	2.647	4.710	6.399	1.461	0.391
TOTAL	15.882	28.258	38.396	8.770	2.350

* Scenarios 2 and 3 have a different feeder arrangement from Scenario 1 because of the new downtown sub-station required in Scenarios 2 and 3.

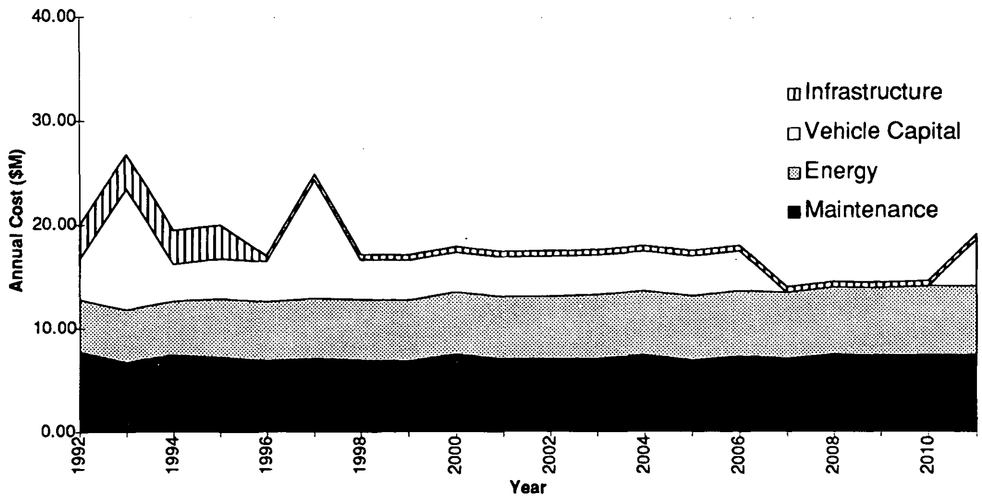

FIGURE 3 Summary of undiscounted costs for status quo scenario.

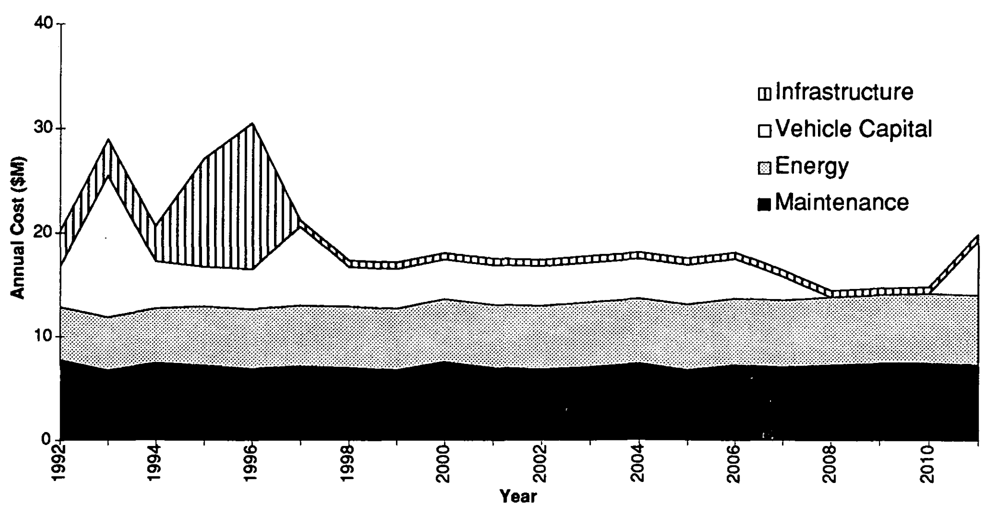

FIGURE 4 Summary of undiscounted costs for King Street Trolley extension scenario.

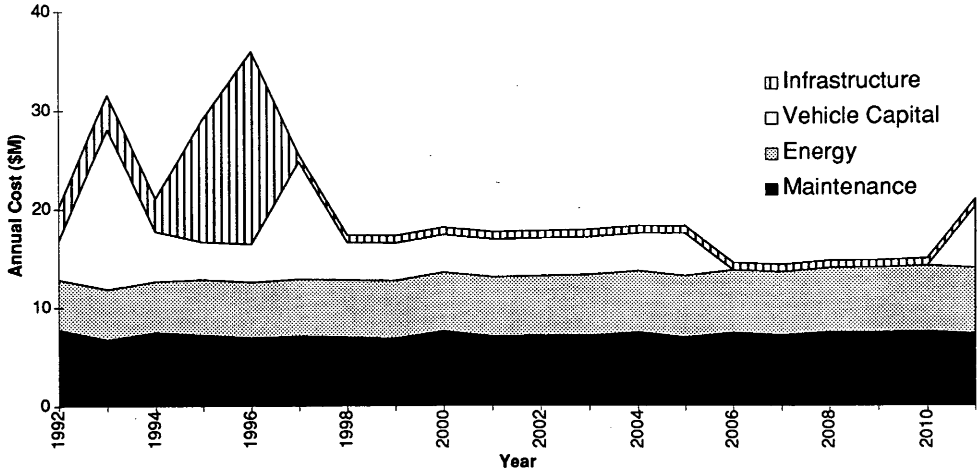

FIGURE 5 Summary of undiscounted costs for King Street and Mountain Trolley extension scenario.

1, 2, and 3 show increasing costs with the introduction of additional trolleys, due to the capital and infrastructure costs. Options 4 and 5 have very low infrastructure expenditures and relatively smooth expenditures on vehicle purchases throughout the study period. Option 4 is also notable for its lower energy costs. Options 6, 7, and 8 are less costly than the corresponding Options 1, 2, and 3 but are more costly than 4 and 5.

The costs were discounted at a rate of 6.8 percent (taken from actual HSR borrowing costs) and then were subjected to a sensitivity analysis that varied the costs in each category according to the uncertainty level associated with it. Figure 11 shows the ranges in total price for the eight options. The dollar amounts in Figure 11 represent the total amount of money HSR would need to put in the bank now to pay for the entire fleet for 20 years.

CONCLUSIONS AND RECOMMENDATIONS

As stated earlier, the life-cycle costing analysis outlined in this paper represents only a part of the study that was carried out for the HSR. For that reason, it would not be appropriate to draw

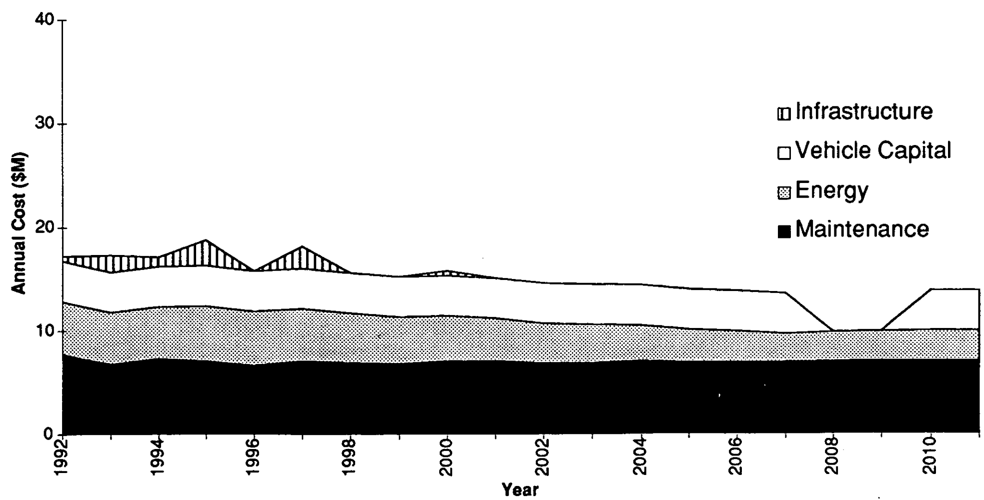

FIGURE 6 Summary of undiscounted costs for CNG bus scenario.

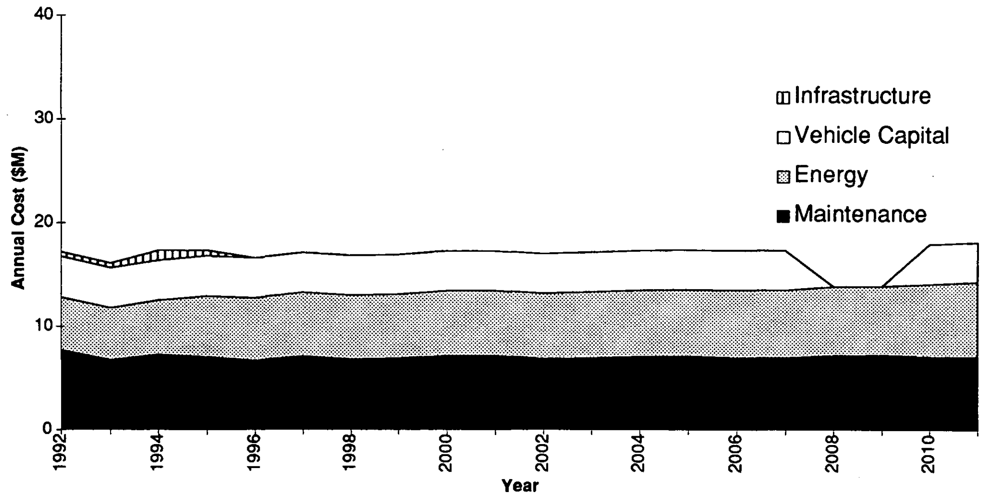

FIGURE 7 Summary of undiscounted costs for "improved diesel bus" scenario.

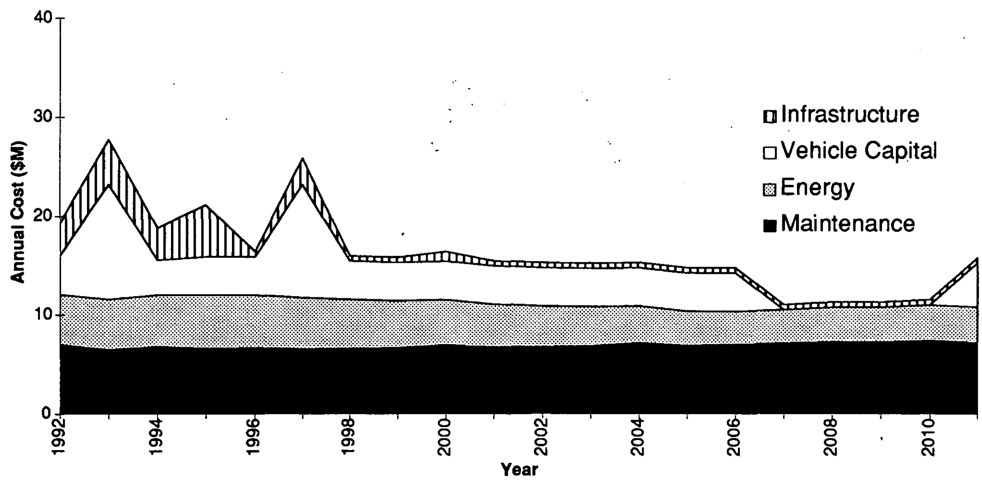

FIGURE 8 Summary of undiscounted costs for existing trolleys plus CNG buses scenario.

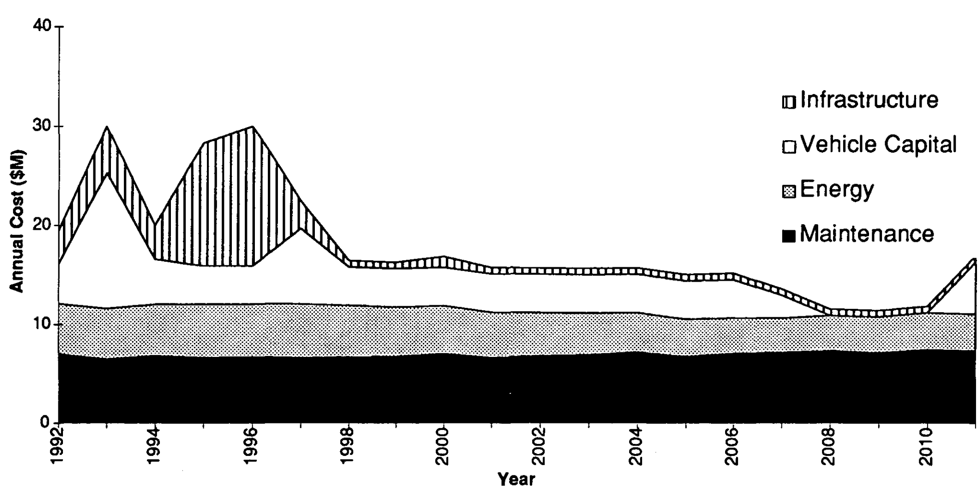

FIGURE 9 Summary of undiscounted costs for King Street Trolley Extension plus CNG buses scenario.

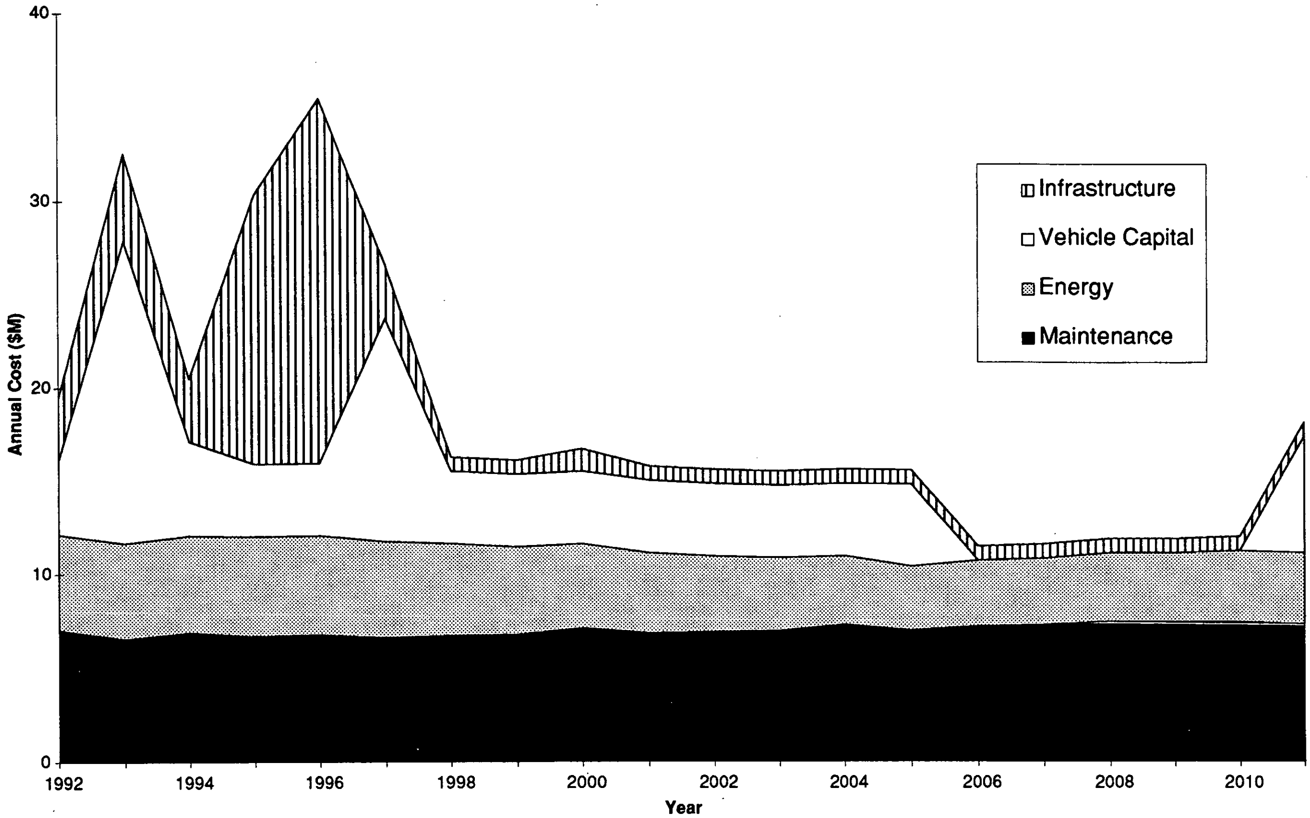

FIGURE 10 Summary of undiscounted costs for King Street and Mountain Trolley extension plus CNG buses scenario.

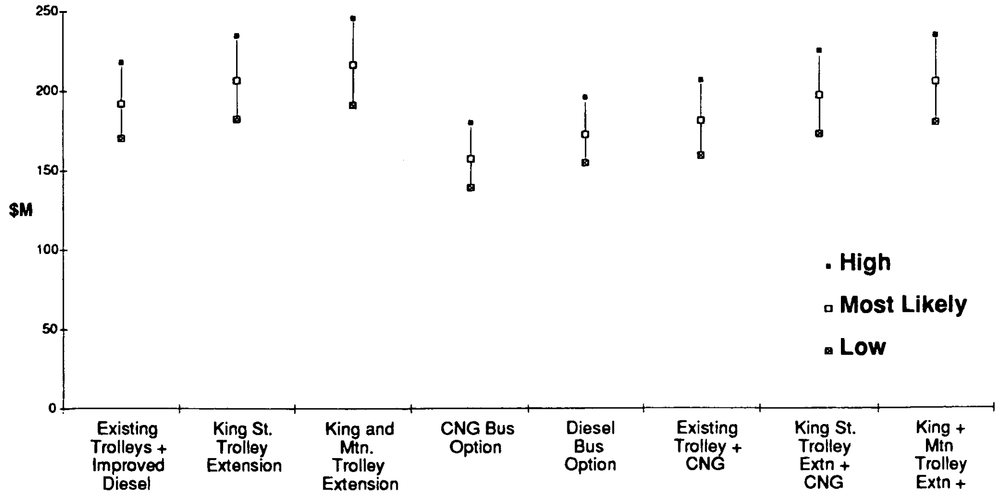

FIGURE 11 Summary of total cost sensitivities (at 6.8 percent discount rate).

a conclusion based solely on the outcome of this portion of the investigation.

If costs were the only consideration Option 4, featuring the CNG bus, would clearly be the choice for the HSR in view of its significantly lower forecast energy costs for the study period. As shown in Figure 6, the real cost of this option decreases with time, as more and more of the fleet is converted to the gaseous fuel. Option 5 is also reasonably priced, primarily because of its lower capital and infrastructure costs in comparison with options that feature the trolleys.

The study was subjected to expert review by a four-member panel. In addition, two series of public involvement sessions sought to acquire Hamiltonians' input into the direction of the study near its beginning and to give the opportunity for them to comment on its findings before a policy decision could be made.

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