Feasibility of Electric Bus Operations for Austin Capital Metropolitan Transportation Authority

THOMAS FOWLER AND MARK EURITT

An increase in air pollution and dependence on foreign oil in the United States has led to a growing interest in alternative fuel vehicles (AFVs). The transportation sector's significant contribution to these problems has prompted federal and state regulations that now require large public fleets to convert to AFVs. In the transit industry, a variety of AFVs are available that meet federal and state requirements. The results of a study that focused on buses powered by electricity, one such alternative fuel, are presented; Austin's Capital Metropolitan Transportation Authority (Capital Metro) was used as a case study in attempts to determine the technical and economic feasibility of electric bus operations. The results of the research indicate that electric buses are feasible on Capital Metro's low-mileage circulator routes in the central business district.

Increasing air pollution and dependence on foreign oil in the United States have led to a growing interest in alternative fuel vehicles (AFVs). The transportation sector's significant contribution to these problems has prompted federal and state regulations that now require large public fleets to convert to AFVs. In the transit industry, a variety of AFVs are available that meet federal and state requirements, including compressed natural gas (CNG), liquefied natural gas (LNG), propane, and battery-powered electric. Each type of alternative-fueled bus is considered a low-emission vehicle, but only electric buses offer the advantage of zero tailpipe emissions and fuel flexibility. Unfortunately, there are technical and economic disadvantages of electric bus operations. Electric buses have a limited range, require several hours to recharge their batteries, and have a substantially higher capital cost than other types of alternative-fueled buses. Before electric buses can be considered as a feasible AFV, the technical capabilities and costs of electric buses must be determined.

This paper includes an overview of the current state of electric bus availability, performance, and use; a methodology for selecting bus routes appropriate for electric bus operation in Austin, Tex.; and a discussion on the costs and benefits of electric bus operations compared to Austin Capital Metro's diesel and CNG bus operations. This paper is a summary of a study performed by The University of Texas Center for Transportation Research for the Southwest University Transportation Center, funded by Texas Oil Overcharge funds.

T. Fowler, Parsons Brinckerhoff, 301 North Charles Street, Baltimore, Md. 21201. M. Euritt, Center for Transportation Research, 3208 Red River, Suite 200, University of Texas at Austin, Austin, Tex. 78705.

ELECTRIC BUS AVAILABILITY, PERFORMANCE, AND USE

Availability

Specialty Vehicle Manufacturing Corporation, located in Downey, Calif., is the largest manufacturer of dedicated electric buses. The Chattanooga Area Regional Transportation Authority (CARTA); the City of Monterey, Calif.; and the Georgia Power Corporation are all operating 22-ft (6.7-m), 22-passenger electric buses manufactured by this company. In addition to the 22-ft (6.7-m) bus, Specialty Vehicle Manufacturing Corporation offers a 22-ft (6.7-m), 21-passenger trolley; a 22-ft (6.7-m), 22-passenger shuttle; a 29-ft (8.8-m), 28-passenger bus; and a 31-ft (9.4-meter), 28-passenger bus.

Advanced Vehicle Systems, Inc. was formed in Chattanooga, Tennessee, as a sister company of Specialty Vehicle Manufacturing Corporation to meet the growing electric bus demand of CARTA for electric buses. In 1993 CARTA operated four 22-ft (6.7-m) Advanced Vehicle Systems buses. Advanced Vehicle Systems offers the same vehicle models as Specialty Vehicle Manufacturing Corporation and is designated as the eastern United States supplier of Specialty Vehicle Manufacturing Corporation's line of electric buses.

Marketing of the vehicles produced by both Specialty Vehicle Manufacturing Corporation and Advanced Vehicle Systems is provided by the Electric Vehicle Marketing Corporation, based in Palm Desert, Calif.

Bus Manufacturing U.S.A., Inc., located in Goleta, Calif., built eight 22-ft (6.7-m) open-air shuttles for the Santa Barbara Metropolitan Transit District (MTD). The shuttle accommodates 22 seated passengers and 7 standing passengers.

Nordskog Industries, Inc., of Redlands, Calif., built three electric shuttles for the Sacramento Municipal Utility District (SMUD). Nordskog Industries has been building electric vehicles for applications in airports and industry for more than 40 years. The company is currently producing a 14-passenger and a 20-passenger electric shuttle.

APS Systems (Oxnard, Calif.), Futura Propulsion Systems (Mission Viejo, Calif.), and NEVCOR (Stanford, Calif.) are each developing electric buses, but in 1993 they had not produced an electric bus that was in service.

Performance Characteristics

Table 1 identifies cost, performance, and specifications of several models of battery-powered electric transit vehicles manufactured by

TABLE 1 Electric Bus Cost, Performance, and Specifications

Performance Measure	Advanced Vehicle Systems Inc./ Specialty Vehicle Manufacturing Corporation		
	Trolley (3122T)	22' (6.7-m) Bus (3122B)	31' (49.9-m) Bus (5131)
Base Price	$140,000	$140,000	$215,000
Maximum Speed (mph) / (km/hr)	30 / 48.3	35 / 56.3	45 / 72.4
Range per charge	75-100 / 121-161	75-100 / 121-161	50-75 / 80-121
Length (ft/m)	22 / 6.7	22 / 6.7	31 / 49.9
Height (in/cm)	103 / 261.6	99 / 261.5	94 / 238.8
Width (in/cm)	81 / 205.7	92 / 233.7	96 / 243.8
Seating Capacity (passengers)	21	22	25
Gross Vehicle Weight (lbs/kg)	12000 / 5443	16000 / 7258	19200 / 8709
Regenerative Braking	Yes	Yes	Yes
Battery Type	Lead Acid	Lead Acid	Lead Acid

Sources: Electric Vehicle Marketing Corporation, 1992; Electric Transit Vehicle Institute, 1993.

Advanced Vehicle Systems, Inc. and Specialty Vehicle Manufacturing Corporation.

The base price of an electric bus is high relative to that of a diesel-powered bus. For example, the purchase price of the 30-ft (9.1-m), 29-passenger Gillig Phantom bus operated by the Capital Metropolitan Transportation Authority (Capital Metro) is $174,000. The purchase price of the 31-ft (9.4-m), 25-passenger Advanced Vehicle Systems battery-powered electric bus operated by CARTA is $215,000—$41,000 higher than the cost of the comparable diesel-powered bus.

Maximum speed of each bus, while low relative to that of internal combustion engine buses, should be adequate for most shuttle routes and bus routes located in downtown areas. The range per charge for the buses limits daily operation to approximately 10 hr depending on the type of route on which the bus is operated. The experience of agencies operating the 22-ft (6.7-m) bus manufactured by Advanced Vehicle Systems, Inc. and Specialty Vehicle Manufacturing Corporation reveals an actual range of 65 to 75 mi (104.6 to 120.7 km) per charge.

The use of regenerative braking on these buses extends their operating range. The Santa Barbara MTD estimated that the use of regenerative braking provides an extra 1.5 hr of service per charge for its shuttles (*1*).

Agencies Operating Electric Buses

CARTA and the Santa Barbara MTD both have been operating electric buses for several years and provided extensive information about the performance and operating costs of electric buses. The experiences of these two areas have been discussed to a limited extent by Gleason (*1*) and Dugan (*2*).

Chattanooga Area Regional Transportation Authority

The Chattanooga experience with battery-powered electric buses began with the revitalization of the city's central downtown area. CARTA opted for a shuttle circulator system to provide transportation to visitors of the 2-mi (3.2-km), four- to six-block-wide revitalized central downtown area. A unique and innovative shuttle to match the downtown area was desired. Given the city's recent commitment to environmental issues, an environmentally friendly shuttle was also desired. Electric buses fit the role of a unique, innovative, and environmentally friendly vehicle, and they were chosen to operate on the downtown shuttle route.

CARTA operated two Specialty Vehicle Manufacturing Corporation and four Advanced Vehicle Systems, Inc. battery-powered electric buses on its downtown shuttle route in 1993. Eight additional buses were ordered from Advanced Vehicle Systems, Inc. in 1993 including one 31-ft (9.4-m), 28-passenger electric bus. Funding has been approved for the purchase of 10 more electric buses in 1994, which will bring CARTA's total electric bus fleet to 24 buses. Initial costs of the Specialty Vehicle Manufacturing Corporation buses were approximately $140,000 per bus. The 31-ft (9.4-m) bus to be manufactured by Advanced Vehicle Systems, Inc. has a purchase price of $215,000. Fuel costs for the electric buses have been in the range of 4.5 to 5.7 cents/mi (2.8 to 3.5 cents/km) and maintenance costs have been estimated at 35 cents/mi (21.8 cents/km). For a comparable diesel bus, fuel costs are about 18 cents/mi (11.2 cents/km) and maintenance costs are about 70 cents/mi (43.5 cents/km). The electric buses have had a range of approximately 65 mi (104.6 km) and are operated 7 to 8 hr on their shuttle route.

Santa Barbara Metropolitan Transit District

Like CARTA, MTD procured a fleet of electric shuttles to operate on a downtown route. The downtown-waterfront shuttle serves Santa Barbara's commercial district and waterfront.

The first electric shuttle bus, manufactured by Bus Manufacturing, U.S.A., Inc., began operation in January 1991. Manufacturing of additional buses was subcontracted to Specialty Vehicle Manufacturing Corporation. In 1993 MTD operated eight 22-ft (6.7-m) electric shuttle buses on its downtown-waterfront shuttle route. The shuttles are scheduled for at least 10 hr of service per day, and some have operated for as long as 12 hr in a single day. Their range has been approximately 85 mi (136.8 km) on a single charge. Recharging occurs overnight to take advantage of off-peak electric utility rates. Fuel costs for the MTD electric shuttle buses are estimated at 2.9 cents/mi (1.8 cents/km), while fuels costs for the diesel buses operated in Santa Barbara are estimated at 16 cents/mi (9.9 cents/km). The range of the electric shuttle buses was found to be highly sensitive to the operating characteristics of the bus drivers. Slow rates of accelerations and thoughtful deceleration that make the best use of regenerative braking systems can increase the range of the electric shuttle buses.

MTD has expressed great satisfaction with its electric shuttle buses. Between 1991, when electric shuttle buses first began replacing diesel buses, and 1992, ridership on the route had increased 800 percent to nearly 1 million passengers per year (*1*). MTD attributed much of this increase to the use of electric buses and has had many requests to introduce or extend the electric shuttle bus service to other parts of the city. MTD has yet to compile the data collected from these experiences into a comprehensive study of the feasibility of electric bus operations, describing the decision to introduce electric buses into service partially as a "leap of faith."

APPLICATIONS FOR ELECTRIC BUSES

Capital Metro Route Services

Capital Metro currently provides service throughout a 471-mi^2 (1,219.9-km^2) area that encompasses the cities of Austin, Cedar Park, Leander, Lago Vista, Jonestown, Pflugerville, Manor, San Leanna; the unincorporated area of Precinct 2 in Travis County; and the Anderson Mill area in Williamson County.

Capital Metro offers a variety of route services to the public, including metro routes, flyer routes, 'Dillo routes, express/park and ride routes, and the University of Texas shuttle routes.

Capital Metro offers 40 metro routes, which provide local service throughout the Austin area. Most metro routes run north-south and pass through the downtown area, although several cross-town and feeder routes do exist. Service on all routes begins by 6:30 a.m. on weekdays and continues as late as midnight. Weekend service is also provided on most routes. The one-way fare for adults is 50 cents.

Flyer routes combine local service within various neighborhoods with express service to downtown Austin. There are currently seven flyer routes, which are operated only on weekdays during morning and late afternoon periods. A one-way adult fare of 50 cents is charged.

Four express/park-and-ride routes provide express service from free park-and-ride lots to downtown Austin. The IRS/VA Express, North East Express, and Pflugerville Express routes are operated only on weekdays during morning and late afternoon periods. The Leander Express is operated continuously throughout the day on weekdays and Saturdays. A one-way fare of $1.00 is charged for adults.

'Dillo service is provided on three routes and acts as a circulator service in downtown Austin, the Capitol Complex, the University of Texas campus, and the Austin Convention Center. 'Dillo buses operate using diesel engines but resemble older versions of electric trolleys. The Convention Center/UT 'Dillo offers service during weekdays and Saturdays, while the Congress Capitol 'Dillo and the ACC/Lavaca 'Dillo offer service on weekdays only. 'Dillo service is free, and a free park-and-ride lot located near Palmer Auditorium is serviced by each of the 'Dillo routes.

Twelve shuttle routes provide service to the University of Texas campus when classes are in session. Shuttle routes operate full weekday schedules and most provide limited service on Sundays. Students pay a fee each semester for unlimited use of the shuttle buses, as well as metro route buses, during the semester. The adult one-way fare for nonstudents is 50 cents.

Criteria for Route Selection

The selection of Capital Metro routes most feasible for the implementation of electric buses is based primarily on route service area and route characteristics.

Route Service Area

One of the most important considerations for route selection is that of the area serviced. In order to maximize the benefits of zero tailpipe emissions, electric buses should be operated in densely developed areas such as central business districts (CBDs). This allows transit agencies to operate buses in urban areas (where air pollution is generally a problem) without adversely affecting air quality.

Routes that place buses in highly visible areas should also be considered. The absence of exhaust fumes and the quiet operation of an electric bus distinguishes it from a standard transit bus. Most people realize the importance of clean air and will appreciate the efforts of a transit company to reduce air pollution within a city.

The decisions to use electric buses on routes in Santa Barbara and Chattanooga were partly because of the clean image of electric vehicles. Both Santa Barbara and Chattanooga operate their electric buses in dense areas of the city popular with local residents and tourists. The Santa Barbara and Chattanooga transit agencies found that the public appreciated their efforts to improve air quality, and the novelty of an electric bus increased ridership along the routes serviced by the electric buses.

Route Characteristics

Several route characteristics also influence the feasibility of electric bus implementation. These characteristics include

1. Maximum speed required along the route;
2. Number of stops along the route;
3. Service hours for the route;
4. Terrain along the route; and
5. Ridership on the route.

The highest operating speed of an electric bus is approximately 40 mph (64.4 km/hr). This relatively low maximum speed does not allow operation of an electric bus on a freeway, but it is generally adequate for operation in downtown urban areas and has not presented a problem in either Chattanooga or Santa Barbara. A careful evaluation of any route, on which an electric bus will be operated should be performed to determine if the maximum speed of the bus is adequate.

The number of stops along the route contribute to the effectiveness of a battery-powered electric bus compared to a diesel-powered or CNG-powered bus. During each stop for boarding and deboarding passengers, internal combustion engine buses emit pollutants and use energy while idling. The use of an electric bus on routes with frequent stops eliminates pollutants resulting from periods of idling. Overall energy consumption is also reduced because the electric bus consumes no energy when stopping for passengers for traffic control signals, or for road congestion.

The maximum range of 70 to 75 mi (112.6 to 120.7 km) per charge limits the daily operation time of the bus. A bus that operates with an average speed of 10 mph (16.1 km/hr) will be limited to approximately 7 to 7.5 h of service per day, depending on the driving characteristics of the driver and the terrain on which the bus is operated. Quick accelerations and steep grades will reduce the range, while gentle accelerations, level terrain, and thoughtful use of the regenerative braking systems will increase the range.

Finally, ridership on the route must be considered to ensure that an electric bus, which seats less than half the passengers of a standard full-size, diesel-powered bus, can accommodate demand.

Recommended Routes

An evaluation of all metro routes, flyer routes, express routes, 'Dillo routes, and UT shuttle routes was made to determine which routes are most feasible for implementation of electric buses.

Infeasible Routes

An initial evaluation of all routes serviced by Capital Metro was made to determine which routes were not feasible for electric bus use. Routes were eliminated from consideration based on two criteria: (*a*) maximum speed required on the route and (*b*) area serviced by the route.

Routes that required buses to operate on freeways were eliminated from consideration because of electric bus speed limitations, as well as routes outside the CBD.

A route matrix was developed to indicate which routes operated on freeways and which routes operated outside the CBD. The matrix also indicates which routes are served exclusively by large transit buses (buses at least 30 ft [9.1 m] long). Routes that are served by smaller buses under 30 ft (9.1 m) are preferred because electric buses, most of which are also under 30 ft (9.1 m), would be adequate to accommodate ridership on those routes. However, service of a route by smaller bus is not a requirement for implementation of an electric bus. Headways can be shortened so that smaller buses can service routes where large buses currently operate. Also, ridership on a particular route may be low enough that smaller buses can accommodate demand.

The route matrix was applied to each type of route service offered by Capital Metro. A majority of metro routes operate primarily outside the CBD, providing service from less dense urban and suburban areas to the CBD. Because of their operation outside the CBD, all metro routes were eliminated from consideration.

All express/park and ride routes and most flyer routes were eliminated because of their routing onto freeways. Those flyer routes not operating on freeways require buses to travel fairly long distances without stopping for passengers and to operate outside the CBD. These flyer routes were also eliminated from consideration.

Finally, most UT shuttle routes operate outside the CBD, and several operate on freeways. UT shuttle routes meeting either of these criteria were eliminated from consideration.

Selected Routes

Based on the initial evaluation criteria, three 'Dillo routes and two UT shuttle routes were selected for possible implementation of electric buses. 'Dillo routes include the Convention Center/UT 'Dillo, Congress Capitol 'Dillo, and ACC/Lavaca 'Dillo; UT shuttle routes include the Forty Acres and West Campus routes. These routes were selected initially because of their continuous service in high-density areas, which provides exposure for the electric buses and maximizes the zero tailpipe emissions benefits.

The three 'Dillo routes and two UT shuttle routes are all located in areas that make electric bus utilization a feasible alternative. Selection of the best fit route was based on three additional criteria:

1. Number of bus stops per mile (km) along the route;
2. Average speed of the bus on the route; and
3. Daily ridership.

The number of bus stops/mi. (km) indicates the frequency of stops the buses make during service of the route. As explained previously, the greater the frequency of stops, the more beneficial electric buses are relative to ICE buses. The Congress Capitol 'Dillo had the greatest number of bus stops per mile with 24 stops on a route of 3.9 mi (6.3 km), equivalent to 6.2 stops per mile (3.9 stops per kilometer).

Low average speeds on routes allow electric buses to service the route for a longer period of time throughout the day, which is crucial because of the current range limitations of electric buses. The Congress Capitol 'Dillo also had the lowest average speed of any selected route, completing a 3.9-mi (6.3-km) route in 32 min, which averages to a speed of 7.3 mph (11.7 km/hr).

Finally, weekday ridership surveys were obtained from Capital Metro to ensure that the smaller electric vehicles had the capacity to handle ridership demand on selected routes. In the case of replacement of 'Dillo service with electric buses, ridership is not a major consideration because the electric buses seat approximately the same number of riders as the 'Dillo buses. Based on the ridership data for the 'Dillo routes, currently manufactured electric buses with seating capacities of 22 passengers are adequate to accommodate ridership demand on the 'Dillo routes. However, the high weekday ridership of the Forty Acres and West Campus UT shuttle routes may prove troublesome for the smaller electric buses. In all probability, current headways of buses on these routes during peak demand times would need to be reduced by using additional buses to meet ridership demand.

Final Route Recommendations

Of the four selected routes, the Congress Capitol 'Dillo route offers the most feasible route for electric buses. The operation of this route in a high-density urban area takes full advantage of the benefits of a zero-emission vehicle. Operation of the Congress Capitol 'Dillo along Congress Avenue from Town Lake to the Capitol will provide much exposure for the electric buses to both Austin residents and out-of-town tourists. The high frequency of bus stops along the route and low average speed will help minimize the negative effects of the 70- to 75-mi (112.6 to 120.7 km) range. The current average operating speed of the Congress Capitol 'Dillo of 7.5 mph (12.1 km/hr) allows electric buses to operate continuously for approximately 10 h before requiring a recharge.

COSTS AND BENEFITS OF ELECTRIC BUSES

Capital Costs

The costs of several models of diesel, natural gas, and electric buses are included in Table 2. Costs for the diesel and natural gas buses represent the total cost of each bus, including such features as wheelchair lifts and air conditioning. Electric bus costs represent the total bus cost and include the cost of a separate battery charger unit.

The Capital Metro buses presented in Table 2 represent all bus types purchased in the last 5 years. The two models of CARTA's electric buses currently in operation are not equipped with air conditioning or heating units from the manufacturer. CARTA has installed propane-fueled heaters on several buses but has not equipped any buses with air conditioning. The MTD electric bus is an open-air shuttle. These open-air shuttles have an overhead roof but do not include doors or passenger windows.

In addition to the cost per bus, Table 2 also gives the cost per passenger seat for each bus. This was calculated by dividing the cost of the bus by the seating capacity to determine the cost of a bus to provide service to one passenger. The least expensive units based on cost per passenger seat are the diesel-fueled Gillig Phantoms. MTD's open-air electric shuttle also had a low cost relative to the other buses, but it is not suited for service in cold or inclement weather. The TMC RTS CNG buses represented the mid-price range based on cost per seat. CARTA's electric buses and the CNG-fueled trolley were on the high side of the cost per passenger seat estimates.

Fuel Costs

The fuel costs per mile of the electric buses are well below those of diesel and CNG buses, 12.4 cents/mi (20 cents/km) and 8.1 cents/mi. (13 cents/km), respectively. CARTA's electric buses consume 1.5 to 1.9 kWh/mi (0.93 to 1.2 kWh/km) of travel, and, unlike diesel and CNG buses, which idle and continue to consume fuel when stopped, electric buses do not consume any electricity when stopped. CARTA's estimate of 4.5 to 5.7 cents/mi (2.8 to 3.5 cents/km) is below the fuel costs of the diesel and CNG buses, even when measured by passenger seat per mile. MTD's estimate of 7 cents/mi (4.4 cents/km) is also below the fuel costs of diesel and CNG buses. When measured based on fuel costs per passenger seat per mile, fuel costs of the MTD electric shuttle are equivalent to the fuel costs for CNG buses and below the fuel costs for diesel buses.

Maintenance Costs

Maintenance costs for Capital Metro's diesel and CNG buses are estimated at 30.8 cents/m (49.6 cents/km). Maintenance costs for CARTA's 22-ft (6.7-m) electric buses, 28.9 cents/mi (46.4 cents/km), also include the cost for battery replacement. It is estimated that battery life is consumed at 1,500 recharge cycles (*1*). CARTA's buses have experienced only approximately 500 cycles at this time, and CARTA expects to pay $12,000 per battery pack for replacement (*1*).

Specific maintenance data were not available from MTD, but MTD's initial estimates for battery cycle life and replacement costs matched those of CARTA.

Total maintenance costs, including battery replacement costs, are lower for electric buses compared to diesel and CNG buses. However, if compared on a cost per passenger seat basis, the maintenance costs of the electric buses are actually higher than those of diesel and CNG buses.

The reduced maintenance costs of electric buses (due to their lack of transmissions, cooling systems, and tune-ups) are partially offset by the costs for battery maintenance and replacement. Maintenance costs will remain comparable if a larger electric bus is compared

TABLE 2 Capital Costs of Buses

Transit Agency	Bus	Fuel Type	Length	Seating Capacity	Cost	Cost per Passenger Seat
Capital Metro	1993 TMC RTS[a]	CNG	40' (12.2 m)	41	$247,000	$6,024
Capital Metro	1993 Chance Trolley ('Dillo)	CNG	28.8' (8.8 m)	28	$209,000[b]	$7,464
Capital Metro	1989 Gillig Phantom	Diesel	35' (10.7 m)	39	$187,000	$4,795
Capital Metro	1989 Gillig Phantom	Diesel	30' (9.1 m)	29	$174,000	$6,000
CARTA	1994 Advanced Vehicle Systems 31' Bus	Electric	31' (9.4 m)	25	$220,000[c]	$8,800
CARTA	1993 Advanced Vehicle Systems 22' Bus	Electric	22' (6.7 m)	22	$145,000[c]	$6,591
MTD	1992 Bus Manufacturing U.S.A, Inc. 22' Open Air Shuttle	Electric	22' (6.7 m)	22	$125,000[c]	$5,682

[a]Capital Metro currently operates 30 of these buses.
[b]This is an experimental leased vehicle.
[c]Includes $5,000 cost of battery charger.

with a diesel and a CNG bus because bus size does not have a significant impact on maintenance costs. (It would, however, increase the fuel costs because of the larger battery pack required for bigger buses.) Unfortunately, CARTA did not have estimates on maintenance costs for its 31-ft (9.4-m), 25-passenger bus, which only recently began route service. The maintenance costs for this bus should be similar to the maintenance costs for the 22-ft (6.7-m), 22-passenger electric bus. If this is true, maintenance costs per passenger seat on the 31-ft (9.4-m) electric bus would be 1.9 cents/mi (1.2 cents/km), still higher than the diesel and CNG costs per passenger seat but lower than the maintenance costs per passenger seat for the 22-ft (6.7 m) electric bus.

Emissions

The primary benefit of electric buses is zero tailpipe emissions. There are, however, emissions associated with electricity generation that must be accounted for, but total fuel-cycle emissions of electric buses are still less than those of diesel and natural gas buses. A pollutant cost index is developed in this section to determine the damage cost of individual pollutants. These pollutant costs are then applied to the emissions levels of each bus to estimate the pollutant damage costs for operating each bus.

Pollutant Costs

There are several methods that can be used to measure the social costs of pollutants (*3*). The damage cost method evaluates damage in the form of medical injuries, death, lost earnings, and physical damage to property and agriculture. External social costs reflect the actual expenditures used to compensate for these damages. The revealed preference method measures how much people would be willing to pay to avoid a particular externality. Real estate property values are often used as a measure of the price a person will pay to avoid an externality such as noise or air pollution. Finally, the optimal control costs method measures the cost of reducing an externality to some limit that is considered optimal. For example, if the Environmental Protection Agency (EPA) ambient air standards are considered optimal, the social costs of a particular pollutant are then the cost to reduce the level of that pollutant to the EPA standards.

A literature review revealed four studies that attempt to estimate pollutant costs on a cost per unit weight basis: Small (*4*), Haugaard (*5*), Massachusetts Department of Public Utilities (*6*), and Ottinger et al. (*7*). All of the studies use the damage cost method for estimating pollutant costs. Table 3 presents pollutant cost estimates for each of the studies in 1993 dollars. While it would be valuable to discuss these studies in greater detail, such a discussion is beyond the scope of this paper.

Total Fuel-Cycle Emission

Total fuel-cycle emissions are determined for the CNG, diesel, and electric buses. Total fuel-cycle emissions include emissions due to feedstock extraction, feedstock transportation, conversion of feedstock into end use fuel or electricity, transportation of end-use fuel, and tailpipe emissions of vehicles. Estimates for total fuel-cycle emissions are given in Table 4. Emissions for the CNG and diesel buses are divided into two categories, fuel-cycle and tailpipe emissions. Fuel-cycle emissions are defined in this paper as all emissions associated with the total fuel-cycle other than tailpipe emissions.

Emissions from the operation of CNG buses are estimated for fuel-cycle emissions, which include emissions from extraction, transportation, and compression of the fuel, as well as emissions from the tailpipe. Values given in Table 4 for fuel-cycle emissions are based on a study by Darrow (*8*) prepared for the Gas Research Institute. The study uses a small van as a base vehicle for calculations of grams per mile equivalent emissions. The estimates for CNG bus emissions in Table 4 are adjusted to reflect the lower fuel efficiency, and therefore higher emissions, of the CNG buses.

Tailpipe emissions for the CNG buses are based on the engine manufacturer's estimates of tailpipe emissions in grams per brake horsepower hour. Using a conversion factor determined by Kitchen and Damico (*9*), grams per brake horsepower hour are converted to grams per mile for a vehicle operating in the CBD driving cycle. The CBD driving cycle attempts to simulate driving in a dense urban environment with the vehicle operating at an average speed of 12.4 mph (19.9 km/hr).

Diesel bus fuel cycle emissions are based on Darrow's (*8*) emission estimates for a gasoline-powered vehicle. (Darrow did not include a diesel-powered vehicle in his study.) Estimates for diesel bus emissions are adjusted to reflect the lower fuel economy of the diesel buses compared to the gasoline van used in Darrow's study.

Tailpipe emissions for the diesel buses are based on Kitchen and Damico's (*9*) study. In their study, emissions per mile are determined for a diesel bus operating with an engine comparable to those in Capital Metro's diesel buses. The emissions are estimated using the CBD driving cycle.

Electric vehicle emissions are based on emissions associated with feedstock extraction and electricity generation. There are zero tailpipe emissions associated with electric buses.

Feedstock extraction emissions include emissions from mining and drilling, and emissions from the transport of feedstock fuel. Darrow's study (*8*) estimates the emissions in grams per mile based on an electric van with an electricity consumption rate of 0.48 kWh/mi (0.30 kWh/km). Darrow's estimates of emissions on a per mile basis were increased for use in the study on which this paper is based to appropriately reflect the greater electricity consumption of the electric buses.

TABLE 3 Pollutant Costs (cents/g, January 1993 dollars)

Study	CO	HC	NO_x	SO_x	Part.
Small	0.0019	0.0294	0.097	0.120	0.057
Haugaard	0.0029	0.0384	0.122	0.155	0.142
Ottinger	*	*	0.180	0.448	0.262
Massachusetts Department of Public Utilities	0.096	*	0.822	0.189	0.506

*Values not given

TABLE 4 Bus Emissions [g/mi(g/km)]

Bus	CO	HC	NO_x	SO_x	Part.
Capital Metro CNG[a]					
Fuel Cycle	0.40 (0.25)	0.62 (0.39)	3.26 (2.03)	1.96 (1.22)	0.04 (0.02)
Tailpipe	3.38 (2.10)	1.25 (0.78)	10.68 (6.64)	*	0.13 (0.08)
Total	**3.78 (2.35)**	**1.87 (1.16)**	**13.94 (8.66)**	**1.96 (1.22)**	**0.17 (0.11)**
Capital Metro					
Diesel[a]	0.50 (0.31)	1.58 (0.98)	1.41 (0.88)	0.27 (0.17)	0.08 (0.05)
Fuel Cycle	26.8 (16.66)	1.4 (0.87)	27.6 (17.15)	*	3.1 (1.93)
Tailpipe	**27.30**	**2.98 (1.85)**	**29.01**	**0.27 (0.17)**	**3.18 (1.98)**
Total	**(16.97)**		**(18.03)**		
CARTA 22' Electric Bus[b]					
Feedstock Extraction	0.06 (0.04)	0.08 (0.05)	0.23 (0.14)	0.03 (0.02)	0.01 (0.006)
Power Plant	0.12 (0.07)	0.04 (0.02)	4.38 (2.72)	7.87 (4.89)	0.01 (0.006)
Tailpipe	0.0	0.0	0.0	0.0	0.0
Total	**0.18 (0.11)**	**0.12 (0.07)**	**4.61 (2.87)**	**7.90 (4.91)**	**0.02 (0.012)**
MTD 22' Electric Bus[c]					
Feedstock Extraction	0.04 (0.02)	0.06 (0.04)	0.16 (0.10)	0.02 (0.01)	0.01 (0.006)
Power Plant	0.07 (0.04)	0.02 (0.01)	2.77 (1.72)	5.56 (3.46)	0.01 (0.006)
Tailpipe	0.0	0.0	0.0	0.0	0.0
Total	**0.11 (0.07)**	**0.08 (0.05)**	**2.93 (1.82)**	**5.58 (3.47)**	**0.02 (0.012)**

*Values not given

[a]Based on Cummins L10 Engine (Kitchen and Damico, 1992).
[b]Electric bus energy consumption estimated to be 1.9 kWh/mile (1.18 kWh/km) (Hartman, 1993), emissions data based on data from SCEVC (1992) and Hamilton (1992).
[c]Electric bus energy consumption estimated to be 1.2 kWh/mile (0.75 kWh/km) (Gleason, 1992), emissions data based on data from SCEVC (1992) and Hamilton (1992).

Electricity generation emissions vary depending on the fuel used to produce electricity. Based on an analysis of power generation in Austin, it is assumed that half of the electricity is produced from natural gas plants and that half is produced from coal plants. Estimates of emissions from these power plants are used to determine the emissions per mile of electric buses because of electricity generation.

Damage Costs Due to Emissions

Based on the information in Table 3, pollutant damage values used in this analysis are 0.0024 cents/g for carbon monoxide, 0.0339 cents/g for hydrocarbons, 0.133 cents/g for nitrogen oxides, 0.155 cents/g for sulfur oxides, and 0.154 cents/g for particulates. Using these values and the information given in Table 4, the damage costs of pollutants are calculated per distance of operation of the buses. These damage costs are based only on emissions from the tailpipe of the vehicles and from the generation of electricity.

Analysis

FTA requires that 35- to 40-ft (10.7- to 12.2-m) buses purchased with their assistance operate a minimum of 500,000 mi (804 500 km) or 12 years. Smaller buses have shorter FTA life-span requirements; however, for the purpose of this analysis, it is assumed that all buses analyzed are operated for 500,000 mi, at which time they are retired and retain no value.

Refueling infrastructure and operating costs are not considered, although it is important that these costs can have a significant effect on the cost of bus operations. Construction costs for Capital Metro's CNG refueling station were approximately $2.7 million, and operating costs for the station are approximately 10 cents/gal equivalent of fuel distributed.

Total costs are recalculated for Capital Metro's 40-ft (12.2-m) TMC RTS CNG bus, 35-ft (10.7-m), diesel-power Gillig Phantoms; and 30-ft (10.7-m) diesel-power Gillig Phantoms; CARTA's 31-ft (9.4-m) and 22-ft (6.7-m) electric buses; and MTD's 22-ft (6.7-m), open-air shuttle. The purchase costs of the buses are added to the fuel costs, maintenance costs, and air pollution costs of operating each bus for 500,000 mi (804 500 km). (Capital Metro's 1993 Chance Trolley is not included in either scenario because an actual purchase price is unknown and maintenance costs for the trolley are not available.)

Table 5 presents the results. The total cost is lowest for the three electric bus models. Over a lifetime of 500,000 mi (804 500 km), electric buses generate an average fuel cost savings of $71,333 compared with diesel buses and $36,333 compared with CNG buses. Maintenance cost savings for the electric buses compared to diesel and CNG buses are approximately $16,000. Pollution costs are lowest for the electric buses, averaging $8,267 over 500,000 mi. Pollution costs are highest for the diesel buses at $22,800 and moderate for the CNG bus, at $11,300.

On a cost-per-passenger-seat basis, electric buses compare less favorably with diesel and CNG buses. The 40-ft (12.2-m) CNG bus and the 35-ft (10.7-m) diesel bus have the lowest cost per passenger seat. Cost per passenger seat for the electric buses is compara-

TABLE 5 Total Social Costs of Buses, 500,000-mi Vehicle Life

Bus	Purchase Cost	Fuel Cost per mile (km)	Maintenance Cost per mile (km)	Pollutant Damage Costs per mile (km)	Total Cost[g]	Cost per Passenger Seat[g]
40' (12.2 m) CNG	\$247,000	13¢[a] (8.1¢)	49.6¢[e] (30.8¢)	2.26¢ (1.40¢)	\$571,300	\$13,934
35' (10.7 m) Diesel	\$187,000	20¢[b] (12.4¢)	49.6¢[e] (30.8¢)	4.56¢ (2.83¢)	\$557,800	\$14,303
30' (9.1 m) Diesel	\$174,000	20¢[b] (12.4¢)	49.6¢[e] (30.8¢)	4.56¢ (2.83¢)	\$544,800	\$18,786
31' (9.4 m) Electric Bus	\$220,000	5.1¢[c] (3.2¢)	46.4¢[f] (28.9¢)	1.85¢ (1.15¢)	\$486,750	\$19,470
22' (6.7 m) Electric Bus	\$145,000	5.1¢[c] (3.2¢)	46.4¢[f] (28.9¢)	1.85¢ (1.15¢)	\$411,750	\$18,716
22' (6.7 m) Electric Shuttle	\$125,000	7¢[d] (4.4¢)	46.4¢[f] (28.9¢)	1.26¢ (0.78¢)	\$398,300	\$18,105

[a]Based on average Capital Metro CNG fleet fuel costs.
[b]Based on average Capital Metro diesel fleet fuel costs.
[c]Average value of CARTA's high and low end fuel costs estimate.
[d]MTD estimate.
[e]Maintenance costs are based on Capital Metro's 1994 fleet maintenance budget.
[f]Maintenance costs are based on CARTA's 22-foot (6.7- m) and are assumed to be the same for the Advanced Vehicle Systems 31-foot (9.4-m) bus and the Bus Manufacturing, U.S.A. Inc. 22-foot (6.7-m) shuttle.

ble to those for the CNG trolley (not shown in Table 5) and the 30-ft (9.1-m) diesel bus.

On routes where peak ridership is often less than seating capacity, larger diesel and CNG buses can be replaced with electric buses. In these cases, electric buses offer a cost savings, based on purchase, maintenance, fuel costs, and air pollution compared to diesel and CNG buses.

Finally, the analysis does not include a study of fueling infrastructure. Including the CNG station development and operating costs, estimated to be about \$0.30/gal equivalent by the Department of Energy, increases the total cost of the CNG bus to \$620,628, or \$15,137 per passenger seat.

CONCLUSIONS

Technical feasibility can be measured through objective criteria such as range, maximum speed, and size of an electric bus. Determining economic feasibility is a great deal more difficult. Valuing the monetary benefit from emissions reductions is inaccurate, as displayed by the disparity in results of the pollutant costs studies discussed previously. Several economic factors that contribute to the feasibility of electric bus operations were not considered in the study. Benefits of a reduction in dependence on foreign oil resulting from the use of electric vehicles, energy conservation, and decreases in noise pollution are all valuable attributes of battery-powered electric buses to which it is extremely difficult to accurately assign monetary values.

Based on the review of the current state of electric bus availability, performance, and use, electric buses are technically feasible for operation in transit services. Electric buses provide adequate range, speed, and size to service a variety of routes. Transit officials must be fully aware of the limitations of the buses, however, and be sure to select routes suitable for electric bus operations. One such decision process for route selection is presented in this paper.

Operation of electric buses can be economically feasible if their smaller passenger seating capacity is adequate to serve present demand. The fuel and maintenance costs of electric buses are below those of diesel and natural gas buses, and over their expected service life, the fuel and maintenance savings can make electric buses an attractive alternative fuel option.

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