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Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation

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13.ABSTRACT (Maximum 200 words)

The report presents a study of transit bus life cycle cost (LCC) analysis, and projected transit bus emissions and fuel economy for 2007 model year buses. It covers four bus types: diesel buses using ultra low sulfur diesel (ULSD), diesel buses using B20 biodiesel (20% biodiesel and 80% ULSD), compressed natural gases (CNG) buses, and hybrid diesel-electric buses.

LCC factors included capital costs (bus procurement, infrastructure, and emissions equipment) and operation costs (fuel, propulsion-related system maintenance, facility maintenance, and battery replacement) available from the literature. The report addresses how to estimate these costs, and presents these data in units of dollars per bus mile and dollar per bus seat mile.

Tailpipe emissions (particulate matter (PM), nitrogen oxides (NOx), non-methane hydrocarbon (NMHC), and greenhouse gas (GHG)) and fuel economy estimations were based on recent emissions and fuel economy studies, and adjusted with best engineering approach. GHG emissions were also computed on both a well-to-tank and tank-to-wheels emissions. The GHG reported were considered to be only carbon dioxides (CO_2) and methane. The emissions data are reported in units of grams per mile, and fuel economy data are in miles per gallon.

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Acronyms

AEO	Annual Energy Outlook
APTA	American Public Transportation Association
B20 Biodiesel	20% Biodiesel and 80% Fossil Diesel
CAFEE	Center for Alternative Fuels, Engines & Emissions
CBD	Central Business District
CNG	Compressed Natural Gas
CPI	Consumer Price Index
DGE	Diesel Gallon (Energy) Equivalent
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environment Protection Agency
FTA	Federal Transit Administration
GCRTA	Greater Cleveland Regional Transit Authority
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
KC Metro	King County Metro Transit
HC	Hydrocarbon
LACMTA	Los Angeles County Metropolitan Transportation Authority
LCC	Life Cycle Cost
MAN	Manhattan Cycle

MMBTU	One Million British Thermal Units
MY	Model Year
NiMH	Nickel-Metal Hydride
NMHC	Non-Methane Hydrocarbon
NOx	Nitrogen Oxides
NTD	National Transit Database
NYCT	New York City Transit
OCTA	Orange County Transit Authority
OEM	Original Equipment Manufacturer
PM	Particulate Matter
RTD	Regional Transportation District
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TTW	Tank-to-Wheels
ULSD	Ultra Low Sulfur Diesel
WMATA	Washington Metropolitan Area Transit Authority
WTT	Well-to-Tank
WTW	Well-to-Wheels
WVU	West Virginia University

Executive Summary

Changes in heavy-duty engine emissions standards for the US in 2007, the desire for energy efficiency, and pressure to use clean or renewable energy sources have all highlighted the competitive technology choices for future transit bus propulsion. West Virginia University's Center for Alternative Fuels, Engines, & Emissions (CAFEE) completed a comparative review of four major fuel propulsion technologies that are currently in use. Considered were diesel hybrid electric buses, conventional diesel buses fueled with ultra low sulfur diesel (ULSD) and B20 biodiesel (20% B100 Biodiesel and 80% ULSD), and natural gas transit buses, all of 40 foot length. The report presents estimates for 2007 transit bus operation cost and 2007 regulated and greenhouse gas emissions.

A bus 12-year life cycle cost (LCC) analysis for a fleet size of 100 buses was performed based on information available in the literature, manufacturers' specifications, and fuel economy data gathered by WVU. Only technology-dependent factors relevant to bus propulsion were considered; driver and management cost were excluded. Bus price, equipment and infrastructure cost (to support novel technology), fuel cost, propulsion-related systems maintenance, facility maintenance, and hybrid bus battery replacement were considered. Little information was found on brake life extension for hybrid technology, but it was determined to be a relatively small cost factor. Buses were assumed to operate at a national average speed of 12.72 mph, to travel for 37,009 miles per year, and to seat 40 passengers for the purposes of calculation.

Regulated and greenhouse gas (GHG) emissions for the four bus types for the 2007 model year were also estimated. Tailpipe regulated emissions included nitrogen oxides (NOx), particulate matter (PM), and non-methane hydrocarbons (NMHC), and the tailpipe GHG considered only carbon dioxides (CO_2) and methane. The tailpipe emissions estimations were based on recent WVU and NREL emissions studies, as well as engine certification data. GHG well-to-wheels emissions prediction was summed from well-to-tank emissions (based on the Argonne National Laboratory GREET model) and tank-to-wheels emissions (based on tailpipe emissions estimation under national operation condition).

This report will allow transit management to compare and understand the comparative environmental and cost performance of 2007 bus technologies that are already in revenue service, provided that the use reasonably reflects national average transit bus behavior. All costs were adjusted to current value (2007 dollars) and were computed on a per mile, per passenger mile, and lifetime basis.

Introduction

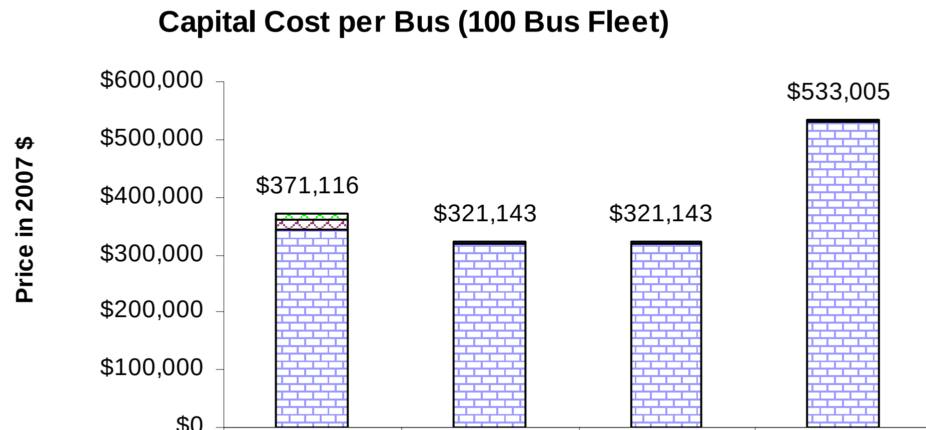
WVU's CAFEE has produced a set of LCC charts that compares CNG, hybrid diesel electric, ULSD and B20 biodiesel (20% biodiesel and 80% ULSD) fuel bus technologies. WVU is separately engaged in development of a comprehensive LCC report and model that addresses bus costs for 2007 and later model year buses for the TRB (Transportation Research Board) under program TCRP (Transit Cooperative Research Program) C-15. The C-15 final report will be available later in 2007, and the present report does not employ data that are specific to C-15. The present report has employed published cost and performance data, and emissions measurement data from WVU's heavy-duty vehicle database. The predictive tasks were made difficult, because this report is aimed at 2007 technology, and because the year 2007 is a breakpoint in diesel bus cost, configuration and emission performance as a result of the new US Environment Protection Agency (EPA) standards for heavy-duty engines. At the time of analysis, virtually no data were yet available on the performance of 2007 model year buses.

Assumptions for Bus Life Cycle Cost

1. The interested agency has previously operated diesel buses. This assumption impacts the capital cost of adopting new technologies.
2. The agency has purchased 100 new transit buses in the year 2007, and the bus useful life is 12 years. June 2007 is assumed to be the start date for the model.
3. The buses are all 40-ft, low floor designs, without elaborate equipment specifications.
4. The buses are operated at average national conditions.
5. When B20 biodiesel is used, the whole depot is converted, and additional, separate, fuel tanks are not required.
6. Driver and mechanic training costs are not considered, but mechanic time is considered in maintenance costs.
7. Driver operational costs are not considered.
8. Benefits such as emissions credits, fuel tax credit or subsidies for having alternative technology vehicles are not considered.
9. Federal, state, and local share of bus procurement price is not considered. In the case where only 80% federal subsidy was considered, the four bus types LCC were compared in a chart shown in the appendix.
10. The maintenance costs are constant (in 2007 dollar terms) for the 12 year life, and all data are presented as 2007 dollars.

Capital Costs

Figure 1 shows the capital costs of buses employing different fuel types and bus technologies. It includes costs for vehicle procurement, refueling station (CNG bus only), depot modification, and emissions reduction equipment (diesel bus only). The itemized costs are discussed below.



	CNG	ULSD	B20	Diesel Hybrid
Total	$371,116	$321,143	$321,143	$533,005
Emissions Equipment	$0	$1,434	$1,434	$0
Depot Modification	$8,750	$0	$0	$1,400
Refueling Station	$20,000	$0	$0	$0
Vehicle Cost	$342,366	$319,709	$319,709	$531,605

Figure 1 Capital costs per bus

Bus Procurement Costs

All bus procurement costs are the average prices calculated from the *2006 Transit Vehicle Database* published by the American Public Transportation Association (APTA) [1]. The database includes information on buses delivered by January 1, 2006, buses in the delivery process, and the buses on order up to 2011 [1]. The bus prices use only the data from CNG, diesel, and diesel hybrid buses, which are 40-ft low floor and are newer than 2004. The prices of a biodiesel bus and an ULSD bus are assumed to be the same as the reported price of a diesel bus. No costs were adjusted for inflation in preparing Figure 1. The bus purchase prices cannot be extended significantly into the future, because changing production numbers and changing technology (driven by regulation and innovation) will alter future costs. In many cases in the USA, bus procurements are subsidized with federal funds. In this case the values in Figure 1 will be reduced. The effect of subsidy is considered later in this report in the total LCC plot.

Infrastructure Costs

Infrastructure costs for CNG bus technology include two costs: for depot modification and for the refueling station. The available data have very wide ranges on both costs: depot modification costs were found to be $500,000 - $15,000,000 and refueling station costs were found to be $320,000 to $7,400,000 [2 - 12]. Instead of using averaged values (to avoid outliers), the median values were chosen. The median value of depot modification cost ($875,000) is the average value of Greater Cleveland Regional Transit Authority (GCRTA) ($750,000) and Los Angeles County Metropolitan Transportation Authority (LACMTA) ($1,000,000) reported by Cannon and Sun (2000) [6]. The median value of refueling station cost ($2,000,000) is close to costs reported by Motta et al. (1996) [2], Grace (2006) [11], and Lyons et al. (2000) [13]. These data were not adjusted for inflation, and the costs were spread on a “per bus” basis over the 100 buses purchased.

Infrastructure costs for diesel hybrid buses are the capital costs of the chargers that may be needed for certain battery technologies [12]. Other infrastructure costs for diesel hybrid buses have not been found in the public literature.

Infrastructure costs for ULSD and B20 biodiesel buses are considered zero, because a diesel infrastructure is already baseline. Diesel (USLD and B20) and diesel hybrid buses suffer a disadvantage relative to CNG buses in that they have particulate matter (PM) exhaust filtration.

These filters may require occasional cleaning, but the cost of a PM filter cleaning system, spread over 100 buses, is small.

Emissions Equipment Costs

Emissions equipment costs ($1,434) only involve an adjustment to the cost of diesel buses (ULSD and B20), since CNG buses meet the 2007 emissions standards without exhaust filtration. It was assumed that the prices for all diesel hybrid buses included aftertreatment (PM exhaust filtration) as an Original Equipment Manufacturer (OEM) installation. The sum of $1,434 was an adjusted price for diesel bus, as explained below. The typical cost to add a PM exhaust filter to a bus was estimated to be $6,367, which is an averaged value of the available public data [13]. An adjustment formula was employed for the cost information for the diesel (ULSD and B20) buses.

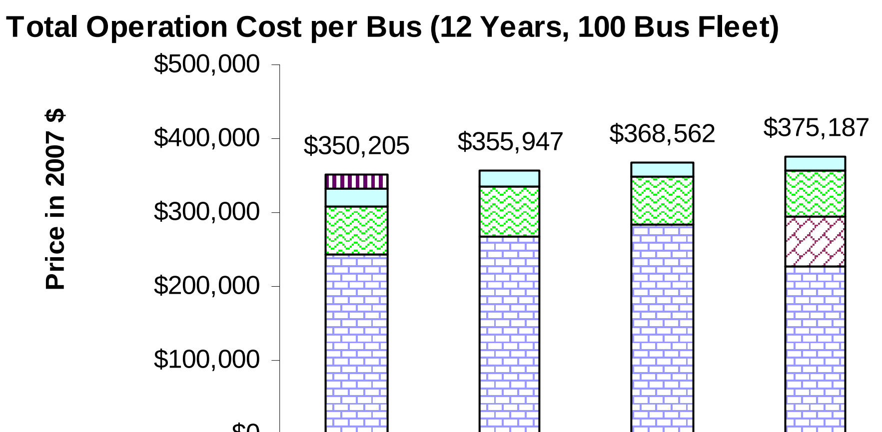
Upward cost adjustment per diesel bus =

$6,367 x (1/2 of the number of 2004 – 2006 diesel buses) / (the number of all diesel buses)

where the term "buses" in this formula refers to the bus deliveries and orders used in calculating the purchase price. It was assumed in developing this formula that half of the buses delivered in the 2004 to 2006 period were already equipped with PM filtration, and all that all 2007 and later model year (MY) buses were so equipped. The price was adjusted to account for the fraction of buses that would need to have cost adjusted to meet 2007 standards, to make the pricing structure equitable when including some pre-2007 buses in the pricing mix.

Operation Costs

The following chart shows bus operation costs (presented in 2007 dollars) including compression electricity (CNG only), facility maintenance, propulsion-related system maintenance, battery replacement (Hybrid only), and fuel consumption. Data were not available for all technologies at one site, making the task difficult. Data were gathered from various sites. Warranty was not considered.



	CNG	ULSD	B20	Diesel Hybrid
Total	$350,205	$355,947	$368,562	$375,187
Compression Electricity	$19,003	$0	$0	$0
Facility Maintenance	$24,433	$20,723	$21,039	$17,470
Propulsion-related System Maintenance	$62,588	$66,394	$62,706	$63,589
Battery Replacement	$0	$0	$0	$67,500
Fuel Costs	$244,181	$268,830	$284,818	$226,629

Figure 2 Total operation costs per bus

Fuel Costs

Fuel costs were calculated from the product of national annual average mileage, estimated fuel economy, and predicted fuel price. All prices were in 2007 dollars, and CNG price data were all converted to the base of diesel gallon (energy) equivalent (DGE). One DGE of CNG was equivalent to about 126 cubic feet of CNG.

National annual average bus mileage traveled was determined from the *2004 and 2005 National Transit Profile* in Federal Transit Administration's (FTA) National Transit Database (NTD) [14, 15]. The annual mileage was calculated by dividing annual bus revenue miles by the total number of buses operated in maximum service. The value (37,009 miles) was the result of averaging the 2004 and 2005 mileage. This mileage was not altered for future years beyond 2007. It was rather assumed that increased revenue miles would be met by operating an increased number of buses.

Fuel economy was predicted based on national average speed. A bus fuel economy – average speed model was created from late model bus emissions and fuel consumption studies undertaken by WVU's CAFEE. WVU has tested late model year CNG, diesel, and diesel hybrid buses on a range of bus chassis test cycles. Parabolic trend lines were created using a best fit for fuel economy as a function of average speed of all test cycles. By applying a national average speed (12.72 mph), the fuel economy of diesel, diesel hybrid, and CNG buses was obtained. It is important to note that the fuel economy differences between CNG, diesel and diesel hybrid buses will change on both a geometric or arithmetic basis as the duty cycle (and hence the average speed of operation) varies. For example, hybrid buses are known to offer a higher percent advantage in fuel economy at lower speeds. The national average speed was calculated from the 2004 and 2005 FTA NTD database [14, 15]. The speed was acquired by dividing the annual bus revenue miles by annual bus revenue hours for each year and then averaging the two values. B20 Biodiesel bus fuel economy was estimated as 98.5% of the diesel bus economy when actual biodiesel gallons were used. The reason is that US DOE Energy Efficiency and Renewable Energy (EERE) analysts indicate in the *Clean Cities Fact Sheet* that biodiesel fuel economy is 1% to 2% lower than for diesel [16]. NREL's bus evaluation at the Regional Transportation District (RTD) fleet showed that in fuel economy the biodiesel buses are 1.1% lower than the diesel buses (one outlier bus removed), and it also reported about 2% lower in laboratory tests [17]. The cause is that biodiesel has less energy content than diesel as a result of the oxygen content in the biodiesel. It is believed that ULSD, as a result of increased saturation, may have less energy content per gallon than 2006 "500 ppm" diesel, and this may close the gap between USLD and B20 fuel economy, but no adjustment was made for ULSD.

The values found for transit bus fuel consumption from the chassis dynamometer testing were more generous than values typically reported by bus operators. This is because fuel may be used for on-board climate control. Most buses in the nation have air conditioning, but it is used only seasonally. Some buses in cold climates also have fuel-fired heaters. The fuel economy is also decreased by idling activities that are not reflected in the average speed of in-use operation. For this analysis, fuel economy was decreased across the board by 10% to account for this additional consumption. Although it may be argued that hybrid buses should have a greater percentage penalty because the hotel loads are likely to consume a set quantity of fuel, these buses also often have downsized engines, which reduces idling fuel consumed. The non-linear impact of air conditioning and auxiliary loads on throttled natural gas engines was impossible to predict accurately in the present analysis, and so a percentage was employed for all technologies.

Figure 3 shows the estimated fuel economy for the four types of buses. Figure 4 shows chassis dynamometer fuel economy data available to WVU, and they did not include the 10% adjustment. In Figure 4 the B20 bus fuel economy was adjusted by the 1.5% value. Figure 4 shows that the hybrid buses enjoy a higher percentage advantage over diesel buses on the Central Business District (CBD) (26%) and the Manhattan (MAN) cycle (37%) than on the 12.72 mph projection. Figure 3 shows that the diesel hybrid bus fuel economy for the 12.72 mph projection is 19% better than the diesel bus fuel economy. The Orange County Transit Authority (OCTA) cycle has a similar average speed (12.3 mph) to the national average speed and shows an improvement (see Figure 4) of 18%. A recent summary [18] presented hybrid bus fuel economy advantages of 20% to 40% over a spectrum of sites. Data are available [19] for operation of 60-ft diesel hybrid and diesel buses, with different hybrid and diesel operation (average speed 12.9 mph for diesel, 12.2 mph for hybrid) in King County, WA, and show a 22% advantage. The 19% value for 12.72 mph operation is therefore reasonably supported by other data.

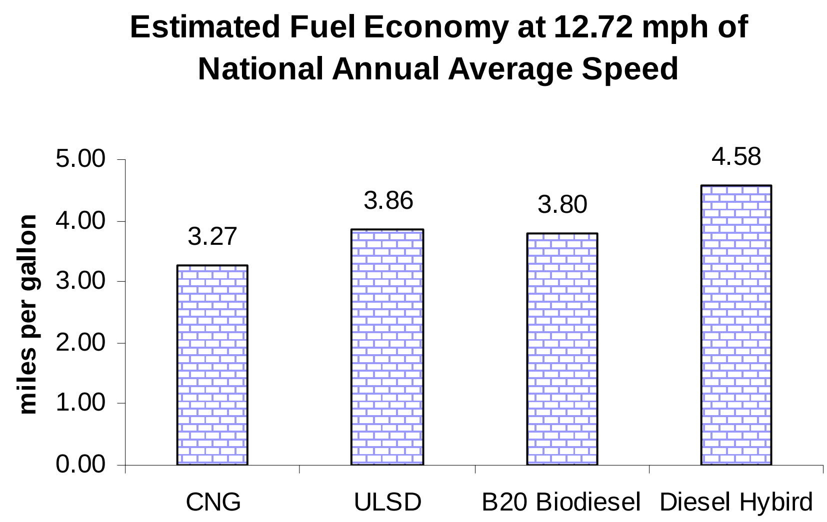
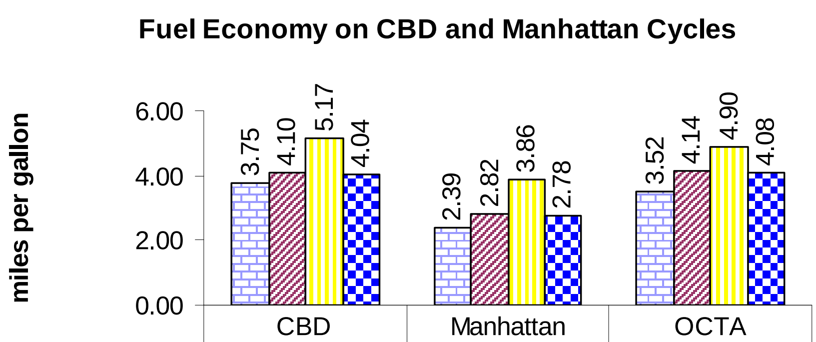


Figure 3 Estimated fuel economy (CNG bus is on the DGE base), adjusted by 10% for idling and hotel loads)



	CBD	Manhattan	OCTA
CNG	3.75	2.39	3.52
ULSD	4.10	2.82	4.14
Diesel Hybrid	5.17	3.86	4.90
B20 Biodiesel	4.04	2.78	4.08

Figure 4 Fuel economy on CBD, Manhattan, and OCTA cycles (CNG bus is on the DGE base), not adjusted by 10%.

Fuel (CNG and diesel) prices were adopted from the price forecast from the *2007 Annual Energy Outlook* (AEO) by the Energy Information Administration (EIA) [20]. AEO predicts the fuel price in 2005 dollars up to the year 2030. The researchers used the fuel price (for transportation) from 2007 to 2019, and converted the 2005 dollars into 2007 dollars by using the 2005 rate of inflation (3.4%) and 2006 rate of inflation (3.2%) from the Consumer Price Index (CPI) provided by the Bureau of Labor Statistics [21]. The price of fuel in 2007 dollars is predicted to drop substantially over the next 12 years according to the AEO forecast.

The B20 price was projected in the following way. The 2006 year B100 price was taken as the base, and this was an averaged B100 price from available *Clean Cities Alternative Fuel Price Reports* (quarterly from September 2005 to October 2006) [22]. The fossil diesel price (2006) was from the AEO. Both prices were converted to 2007 dollars. Then, the B20 biodiesel price ($3.03) was calculated by adding 20% of the B100 biodiesel price and 80% of the fossil diesel price. The price was 4.3% higher than the fossil diesel price. No literature has been found on the forecast of the B100 biodiesel price. It was assumed that the B20 biodiesel price would remain in the same ratio to the fossil diesel price during the 12 year period.

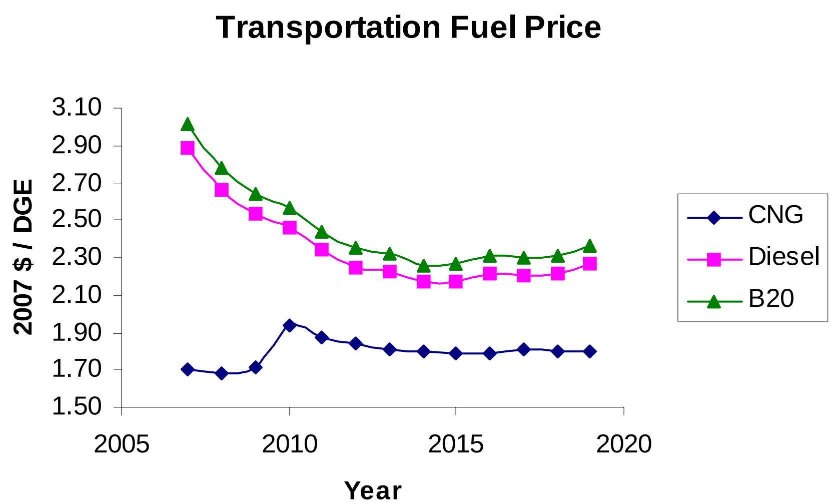
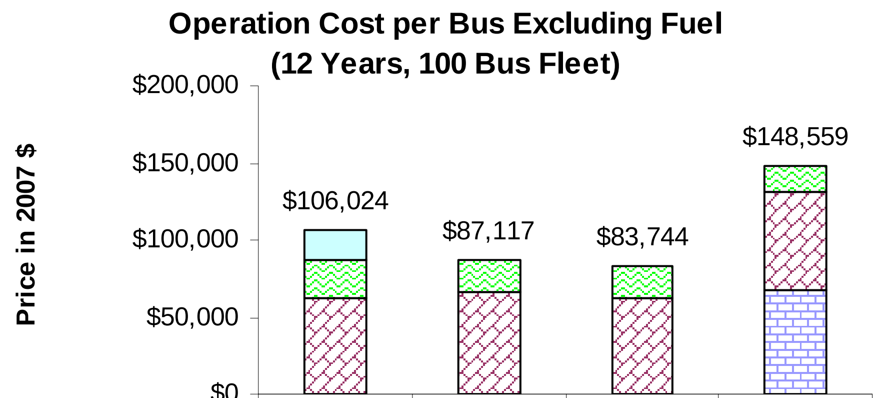


Figure 5 EIA diesel and CNG price prediction and adjusted B20 price (2007 –2019)

Figure 6 shows all operation costs excluding the fuel costs. These data include the costs for compression electricity (CNG only), facility maintenance, propulsion-related system maintenance, and battery replacement (hybrid only). The itemized costs are discussed below.



	CNG	ULSD	B20	Diesel Hybrid
Total	$106,024	$87,117	$83,744	$148,559
Compression Electricity	$19,003	$0	$0	$0
Facility Maintenance	$24,433	$20,723	$21,039	$17,470
Propulsion-related System Maintenance	$62,588	$66,394	$62,706	$63,589
Battery Replacement	$0	$0	$0	$67,500

Figure 6 Operation costs excluding fuel cost

Propulsion-Related Systems Maintenance Costs

The researchers did not include early historical bus evaluation studies in considering vehicle maintenance costs. National Renewable Energy Laboratory (NREL) bus evaluation studies provided the maintenance costs from four sites: Washington Metropolitan Area Transit Authority (WMATA) [5], New York City Transit (NYCT) [12], King County Metro Transit (KC Metro) in Seattle, Washington [19], and Regional Transportation District (RTD) in Boulder, Colorado [17]. It was difficult to estimate the costs on an equitable basis, because no data were available for a single site with all late model year technologies.

The available data showed that NYCT has much higher “per mile” propulsion-related system maintenance costs (nearly double the costs of the other sites). This is mainly because its slow speed operation causes New York buses to operate for more hours per mile of service. NYCT data were not used in propulsion-related system maintenance cost estimation because their operating speed was far below the national average. The WVU researchers did evaluate the use of “per hour” and “per gallon” propulsion related maintenance costs, but found these did not establish site to site equivalence.

Diesel bus maintenance cost (0.150 $/mile) is the result of averaging the KC Metro [19] and WMATA studies [5]. The cost was used as the baseline to estimate the costs for the other three technologies. No adjustment was made for the fact that the KC metro buses were 60-ft articulated units. B20 biodiesel maintenance cost (0.141 $/mile) was lowered from the baseline diesel by 5.5% based on data from the RTD study, although there is no fundamental argument on why the diesel and B20 maintenance costs should differ. CNG maintenance cost (0.141 $/mile) was adjusted to be lower than the diesel baseline by 5.7% from the WMATA study data [5]. Hybrid maintenance cost (0.143 $/mile) was adjusted to be lower than the diesel baseline by 4.2% from the KC Metro study data [19]. Data show that propulsion-related maintenance cost represents between one fourth and one third of the total maintenance cost, and that there is little difference in maintenance cost between bus technologies.

Facility Maintenance Costs

No consistent basis was available for predicting facility maintenance costs. Two recent studies were used to obtain and estimate the costs of facility maintenance: the NREL CNG bus evaluation projects at WMATA and NYCT [5, 12]. The WMATA study provided a compression electricity cost ($0.14/DGE) for the CNG fuel station ($300,000 per year, and CNG usage was

182,000 DGE per month). The NYCT study provided the cost ($0.32/DGE) of the compression and maintenance for CNG station. The researchers assumed that the station maintenance costs were equivalent for the CNG and diesel buses ($0.32/DGE minus $0.14/DGE). The electricity for compression was assumed to be the only additional cost for CNG station noting the lack of available data.

In this way, the CNG facility maintenance cost ($0.18/DGE) and compression electricity ($0.14/DGE) cost were calculated from the annual CNG consumption (in DGE), which was obtained by dividing the national annual average mileage by the estimated CNG fuel economy. The same approach was applied to diesel, diesel hybrid, and B20 biodiesel buses. There is no need to convert B20 biodiesel bus fuel economy into the DGE base, because the energy content did not substantially affect the station maintenance. The result of the variation on facility maintenance costs reflected the fuel economy difference of the four bus types.

Battery Replacement Costs

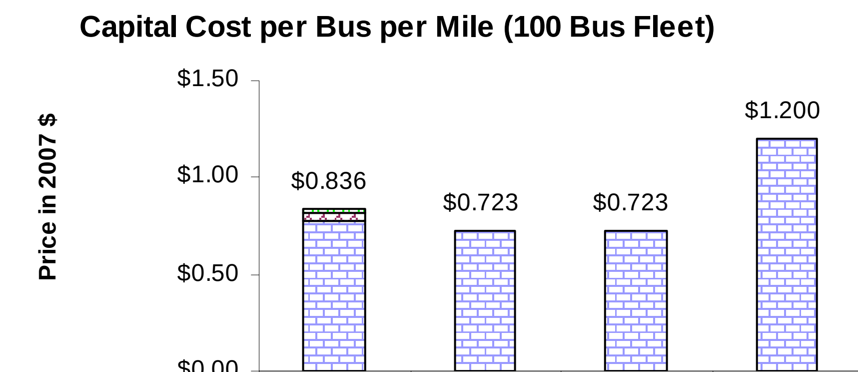
The FTA electric drive study provided information that battery packs of lead acid batteries have a life of 3 years [23]. Packs of nickel-metal hydride (NiMH) batteries have a life of 5 to 7 years [23]. The replacement cost of one pack is $25,000 for lead acid batteries and $35,000 - $45,000 for NiMH batteries [23]. It is difficult to project how battery technology will improve and how sales volume will reduce battery replacement cost in the future.

The researchers assumed that, for lead-acid battery packs, all buses would need three replacements at the price of $25,000 during 12 years life. On the other hand, for NiMH batteries packs, 50% of buses would need two replacements and 50% of buses would need one replacement at the price of $40,000. As a result, the lead acid battery pack cost for 12 years was

$25,000 multiplied by 3. For the NiMH battery pack, the cost was $40,000 multiplied by (0.5 x 2 + 0.5 x1). The battery replacement cost ($67,500) was the average of the two projected costs.

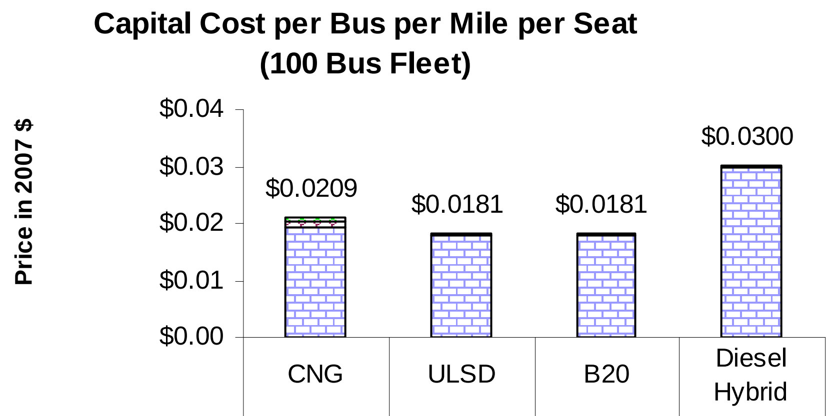
Per Bus Mile, Per Seat Mile Costs

Additional charts were created for capital and operation costs per bus per mile and per bus per mile per seat. The annual mileage used the national annual average mileage (37,009 miles). The passenger seat information was from the APTA *2006 Transit Vehicle Database* [1]. It was found that CNG buses had an average of 40 seats, and 39 seats were found for all the other three types. For calculation purpose all 40-ft buses were assumed to have 40 passenger seating capability.



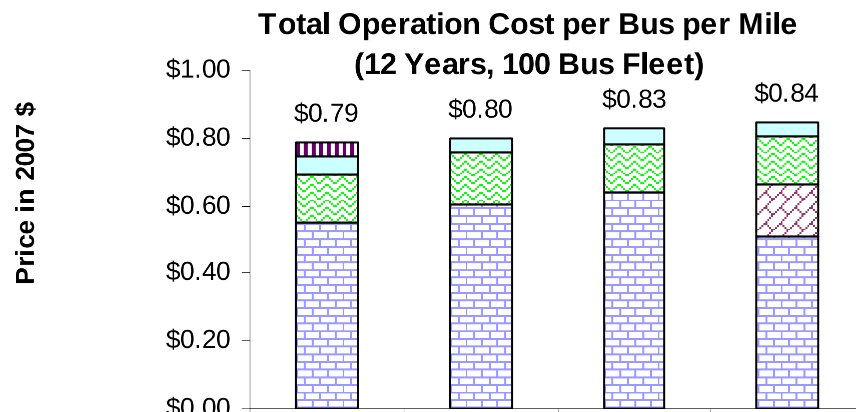
	CNG	ULSD	B20	Diesel Hybrid
Total	$0.836	$0.723	$0.723	$1.200
Emissions Equipment	$0.000	$0.003	$0.003	$0.000
Depot Modification	$0.020	$0.000	$0.000	$0.003
Refueling Station	$0.045	$0.000	$0.000	$0.000
Vehicle Cost	$0.771	$0.720	$0.720	$1.197

Figure 7 Capital costs per bus per mile (annual mileage: 37,009 miles)



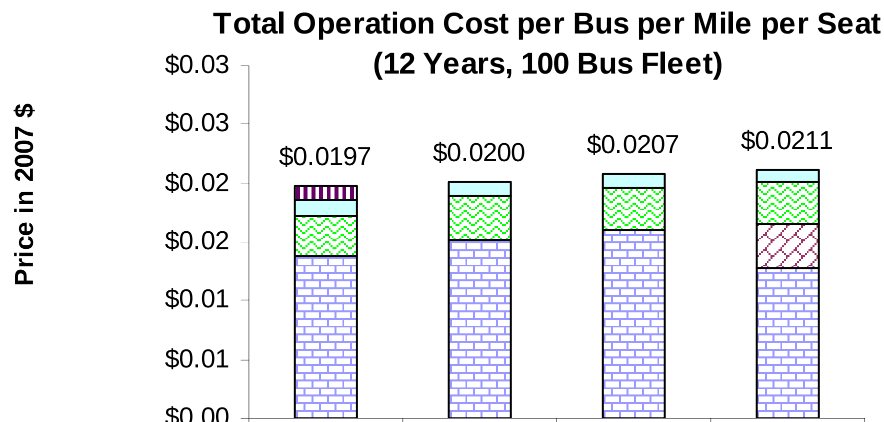
	CNG	ULSD	B20	Diesel Hybrid
Total	$0.0209	$0.0181	$0.0181	$0.0300
Emissions Equipment	$0.0000	$0.0001	$0.0001	$0.0000
Depot Modification	$0.0005	$0.0000	$0.0000	$0.0001
Refueling Station	$0.0011	$0.0000	$0.0000	$0.0000
Vehicle Cost	$0.0193	$0.0180	$0.0180	$0.0299

Figure 8 Capital costs per bus per mile per seat



	CNG	ULSD	B20	Diesel Hybrid
Total	$0.79	$0.80	$0.83	$0.84
Compression Electricity	$0.04	$0.00	$0.00	$0.00
Facility Maintenance	$0.06	$0.05	$0.05	$0.04
Propulsion-related System Maintenance	$0.14	$0.15	$0.14	$0.14
Battery Replacement	$0.00	$0.00	$0.00	$0.15
Fuel Costs	$0.55	$0.61	$0.64	$0.51

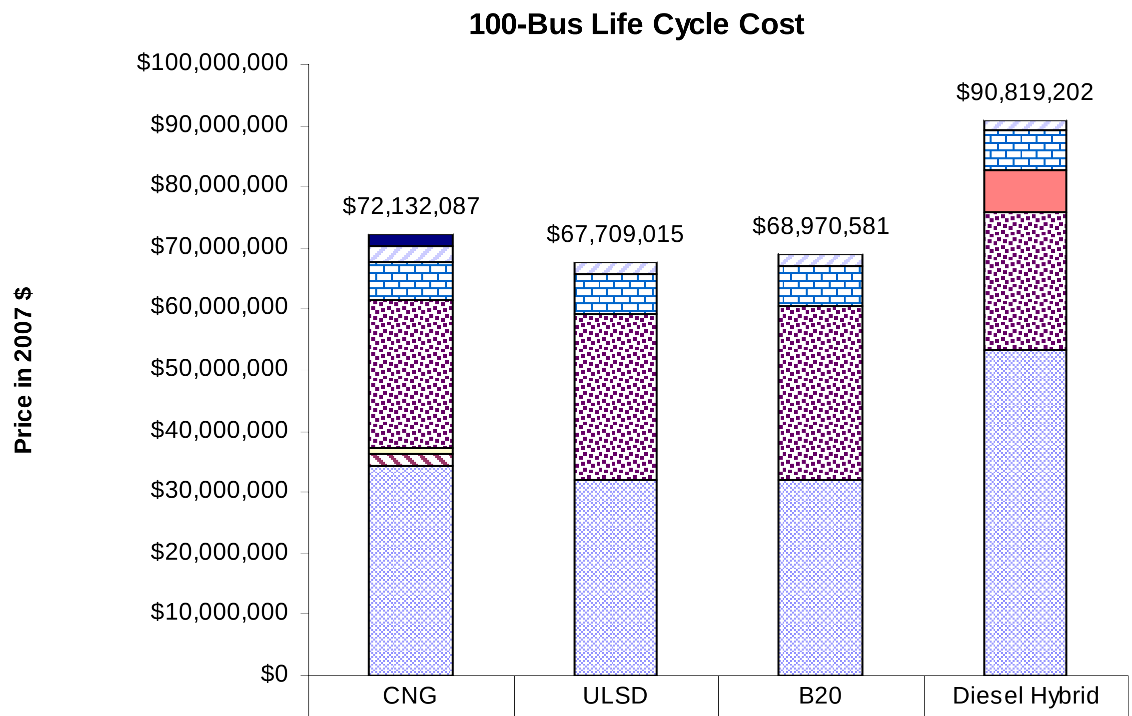
Figure 9 Operation costs per bus per mile (annual mileage: 37,009 miles)



	CNG	ULSD	B20	Diesel Hybrid
Total	$0.0197	$0.0200	$0.0207	$0.0211
Compression Electricity	$0.0011	$0.0000	$0.0000	$0.0000
Facility Maintenance	$0.0014	$0.0012	$0.0012	$0.0010
Propulsion-related System Maintenance	$0.0035	$0.0037	$0.0035	$0.0036
Battery Replacement	$0.0000	$0.0000	$0.0000	$0.0038
Fuel Costs	$0.0137	$0.0151	$0.0160	$0.0128

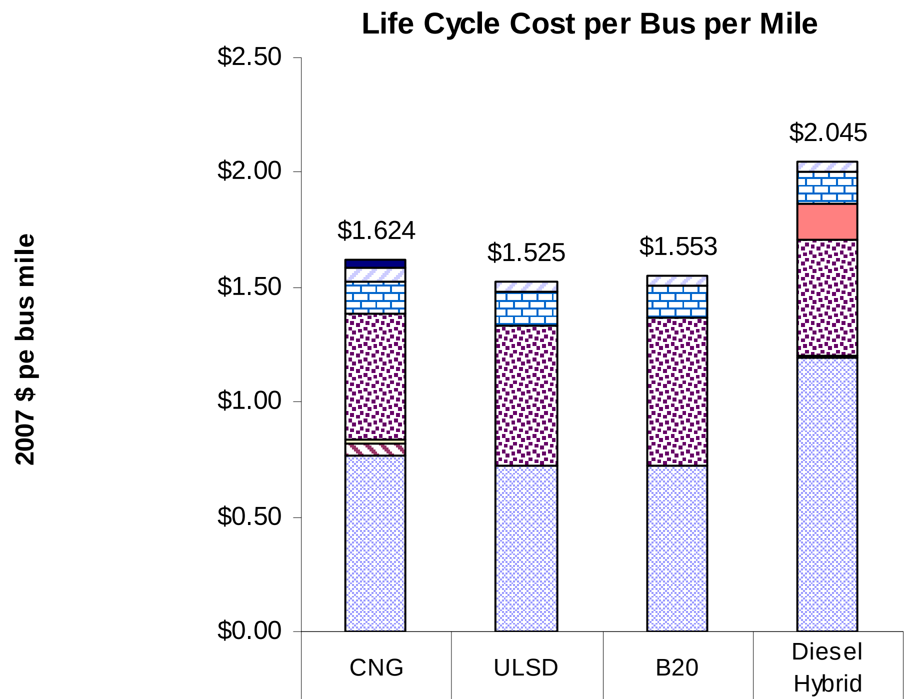
Figure 10 Operation costs per bus per mile per seat

Summary Charts



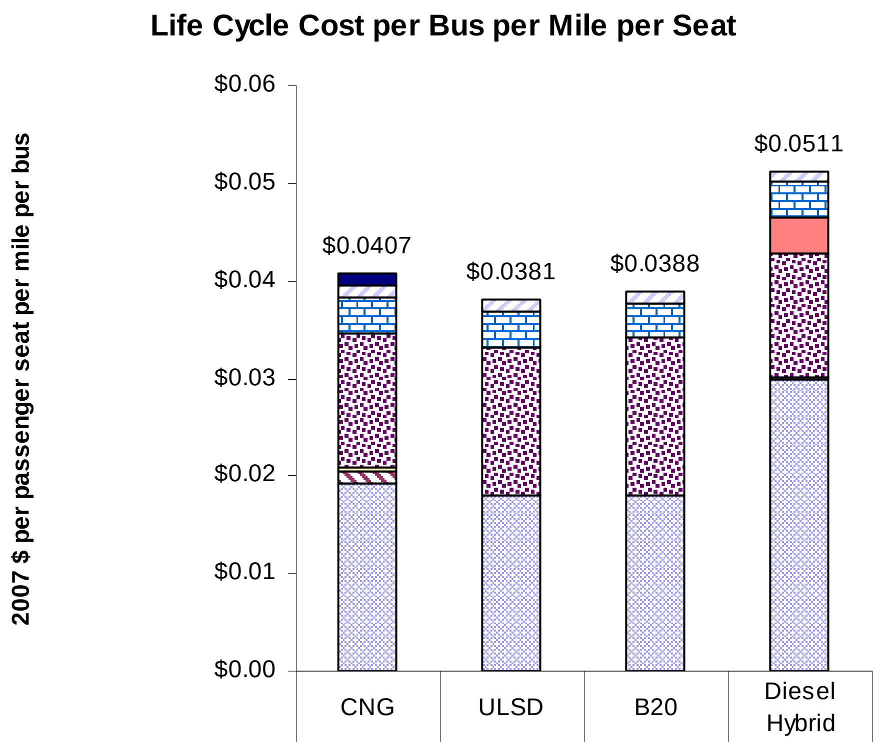
	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$72,132,087	$67,709,015	$68,970,581	$90,819,202
Compression Electricity	$1,900,323	$0	$0	$0
Facility Maintenance	$2,443,272	$2,072,295	$2,103,853	$1,746,986
Propulsion-related System Maintenance	$6,258,817	$6,639,421	$6,270,564	$6,358,882
Battery Replacement	$0	$0	$0	$6,750,000
Fuel Costs	$24,418,105	$26,882,953	$28,481,818	$22,662,869
Emissions Equipment	$0	$143,409	$143,409	$0
Depot Modification	$875,000	$0	$0	$140,000
Refueling Station	$2,000,000	$0	$0	$0
Vehicle Cost	$34,236,570	$31,970,937	$31,970,937	$53,160,465

Figure 11 Total life cycle cost for a 100 bus fleet for 12 years without procurement subsidy. When an 80% bus procurement subsidy is considered, the four technologies yield similar total LCC values, as shown in the Appendix (Figure A1).



	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$1.624	$1.525	$1.553	$2.045
Compression Electricity	$0.043	$0.000	$0.000	$0.000
Facility Maintenance	$0.055	$0.047	$0.047	$0.039
Propulsion-related System Maintenance	$0.141	$0.150	$0.141	$0.143
Battery Replacement	$0.000	$0.000	$0.000	$0.152
Fuel Costs	$0.550	$0.605	$0.641	$0.510
Emissions Equipment	$0.000	$0.003	$0.003	$0.000
Depot Modification	$0.020	$0.000	$0.000	$0.003
Refueling Station	$0.045	$0.000	$0.000	$0.000
Vehicle Cost	$0.771	$0.720	$0.720	$1.197

Figure 12 Life cycle cost per bus per mile for a 100 bus fleet for 12 years



	CNG	ULSD	B20	Diesel Hybrid
Total: CC+OC	$0.0407	$0.0381	$0.0388	$0.0511
Compression Electricity	$0.0011	$0.0000	$0.0000	$0.0000
Facility Maintenance	$0.0014	$0.0012	$0.0012	$0.0010
Propulsion-related System Maintenance	$0.0035	$0.0037	$0.0035	$0.0036
Battery Replacement	$0.0000	$0.0000	$0.0000	$0.0038
Fuel Costs	$0.0138	$0.0151	$0.0160	$0.0128
Emissions Equipment	$0.0000	$0.0001	$0.0001	$0.0000
Depot Modification	$0.0005	$0.0000	$0.0000	$0.0001
Refueling Station	$0.0011	$0.0000	$0.0000	$0.0000
Vehicle Cost	$0.0193	$0.0180	$0.0180	$0.0299

Figure 13 Life cycle cost per passenger seat per bus per mile for a 100 bus fleet for 12 years

Emissions Estimation

The PM, Nitrogen Oxides (NOx), and Non-Methane Hydrocarbon (NMHC) emissions of diesel, diesel hybrid, and CNG buses were estimated primarily from recent emissions and fuel consumption studies undertaken by WVU, from certification levels, and from ratios of certification levels. Since no 2007 field data were available, it was necessary to adjust some emissions for model year using certification standards. The B20 biodiesel PM, NOx, and NMHC emissions were predicted based on adjustment of diesel data using the averaged percent changes from recent WVU data and a recent biodiesel emissions study made by McCormick (2006) [24]. The actual difference between B20 and diesel NOx emissions depends on the specific composition of the diesel and biodiesel, and may vary substantially as shown in data collected by the NREL [25]. B20 biodiesel was therefore assumed to increase NOx emissions by 3.3% and decrease PM and hydrocarbon (HC) emissions by 20% and 15% respectively. The three values were used to adjust the MY 2007 bus NOx, PM, and NMHC emissions results for B20 versus diesel. No literature has been found on how the PM trap and the advanced engine technology of 2007 buses affect the B20 biodiesel PM, NOx, and NMHC reduction, and diesel trends were used in these cases.

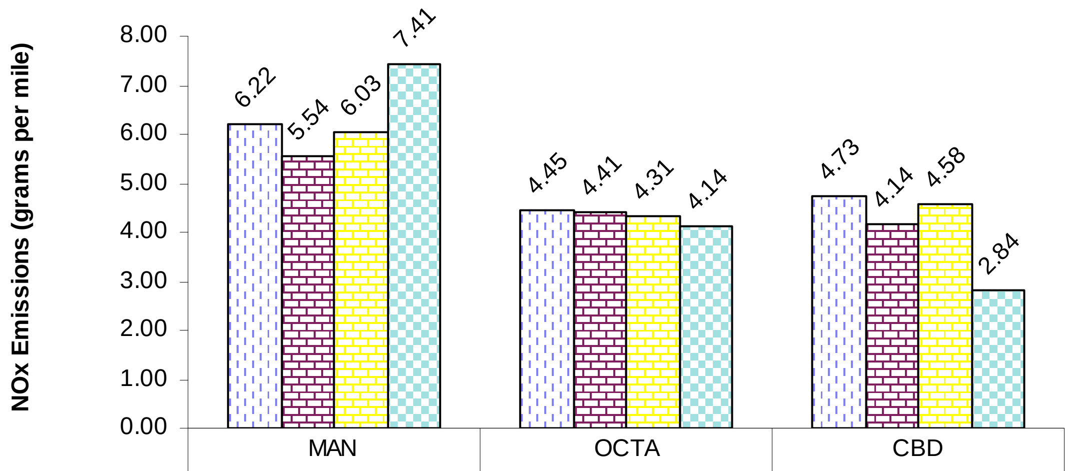
NOx: The diesel and diesel hybrid bus NOx emissions were estimated to have a reduction ratio corresponding to the ratio of the 2007 average NOx emissions standard (1.2 g/bhp-hr) to the 2004-2006 standard (2.4 g/bhp-hr, which was actually implemented in October 2002 for most diesel engine manufacturers). As a result, diesel and diesel hybrid bus NOx emissions were considered to be recent (model year 2004-2006) emissions field data multiplied by a factor of 0.5, where the 0.5 factor was obtained by dividing the 2004-2006 standard into the 2007 standard [1.2 (g/bhp-hr) / 2.4 (g/bhp-hr)]. Since CNG bus engines meeting the 2010 emissions standard of

0.2 g/bhp-hr NOx (through using stoichiometric burn) may be available in the middle of 2007, and since market penetration of these new engines is likely to be high, the CNG bus NOx emissions were adjusted by using the CNG bus recent data multiplied by {(1.2/2.4)+(0.2/2.4)}/2. It was assumed in posing this formula that half of the 2007 CNG buses would be powered by the stoichiometric 0.2 g/bhp-hr engines and half by 1.2g/bhp-hr engines. The authors concede that the delay time between date of engine manufacture and date of bus commissioning may alter this ratio for the 2007 calendar year. B20 bus NOx emissions were obtained by increasing the diesel NOx emissions by 3.3%.

PM: Diesel hybrid (PM trap equipped) and CNG bus PM emissions were predicted using the latest WVU field data available from DOE and DOT studies. From 2007 onward all conventional diesel buses were assumed to be equipped with PM traps, but the latest WVU data were for 2006 diesel buses without traps. Therefore the diesel bus PM emissions were projected in the same way that NOx was predicted, by employing ratios of standards. Conventional drive diesel bus 2007 PM emissions were taken to be the emissions of late model year diesel buses (not PM trap equipped) multiplied by the ratio of 2004-2006 to 2007 PM standards, namely 0.01(g/bhp-hr)/0.07(g/bhp-hr). Some PM traps may be more efficient than is implied by the sevenfold reduction, but the actual reduction will vary by design and operation conditions. B20 PM emissions were obtained by decreasing the diesel PM emissions by 20%, although data for B20 reduction were for non-trap vehicles. All of the post-2007 PM emissions data are low relative to legacy diesel PM data.

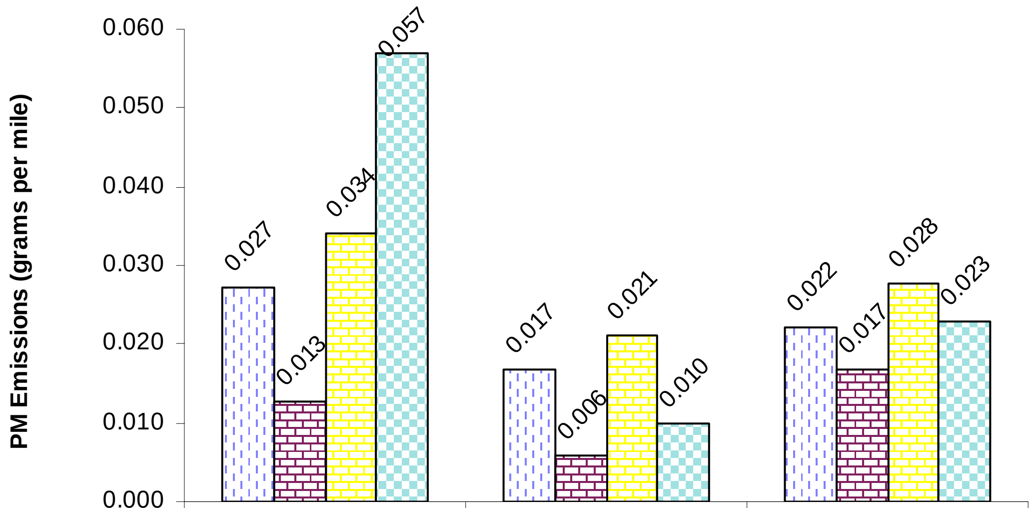
NMHC: Diesel exhaust contains very low levels of methane, and so for diesel, B20 biodiesel and diesel-hybrid buses, the NMHC were equated with the total HC in the exhaust. The data for the hybrid buses were available directly from field data, but the field data for conventional buses were from 2006 model year buses that were not trap equipped. For the case of HC, the standards do not give adequate guidance for adjustment for trap oxidation. Data were available from a DOE/WVU study of a 2002 model year retrofitted diesel bus equipped with EGR and a trap, and this was used as an estimate of 2007 model year HC. B20 bus NMHC emissions were obtained by decreasing the diesel NMHC emissions by 15%. CNG bus HC emissions consist primarily of methane, and the quantity of NMHC will depend on not only the duty cycle and engine technology, but also the fuel composition. If domestic LNG is used as the primary fuel source, NMHC are lower than when pipeline CNG is used, because domestic LNG tends to be high in methane. If an oxidation catalyst is used on the natural gas bus exhaust, NMHC are usually oxidized more readily than methane. Methane/NMHC split ratio data (95% methane to 5% NMHC) were taken from available recent model year bus emissions testing on the WMATA cycle (8.32 mph average cycle speed), and this ratio was applied to the HC value for the CNG buses to yield a NMHC value [26].

Figure 14, Figure 15, Figure 16 and show the predicted 2007 NOx, PM, and NMHC emissions from the four bus types on MAN, OCTA, and CBD cycles. It should be noted that the PM levels for all four 2007 technologies are lower by more than an order of magnitude than those from legacy diesel buses currently in service. From a research perspective, PM levels are now so low that accurate mass characterization has become challenging,



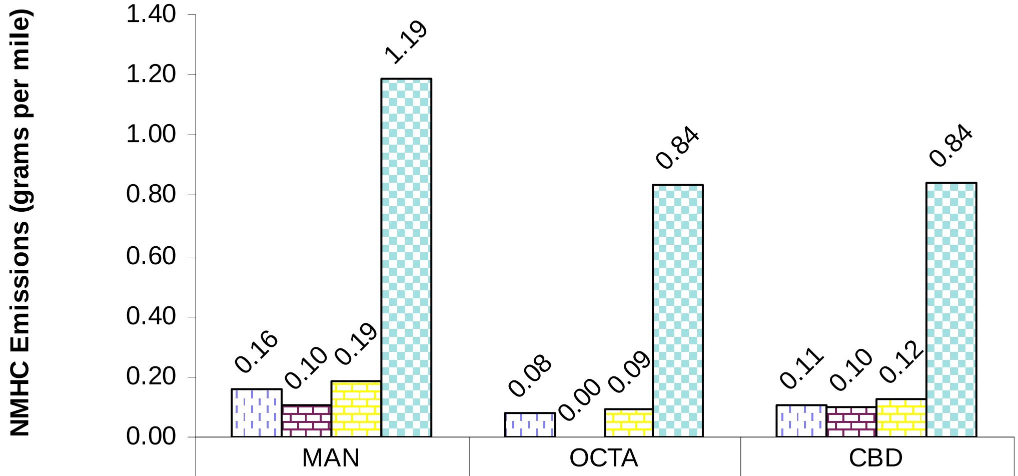
	MAN	OCTA	CBD
B20 Biodiesel	6.22	4.45	4.73
Diesel Hybrid	5.54	4.41	4.14
Diesel	6.03	4.31	4.58
CNG	7.41	4.14	2.84

Figure 14 2007 NOx emissions prediction



	MAN	OCTA	CBD
B20 Biodiesel	0.027	0.017	0.022
Diesel Hybrid	0.013	0.006	0.017
Diesel	0.034	0.021	0.028
CNG	0.057	0.010	0.023

Figure 15 2007 PM emissions prediction: note that all values are low in comparison to legacy bus fleet PM emissions.

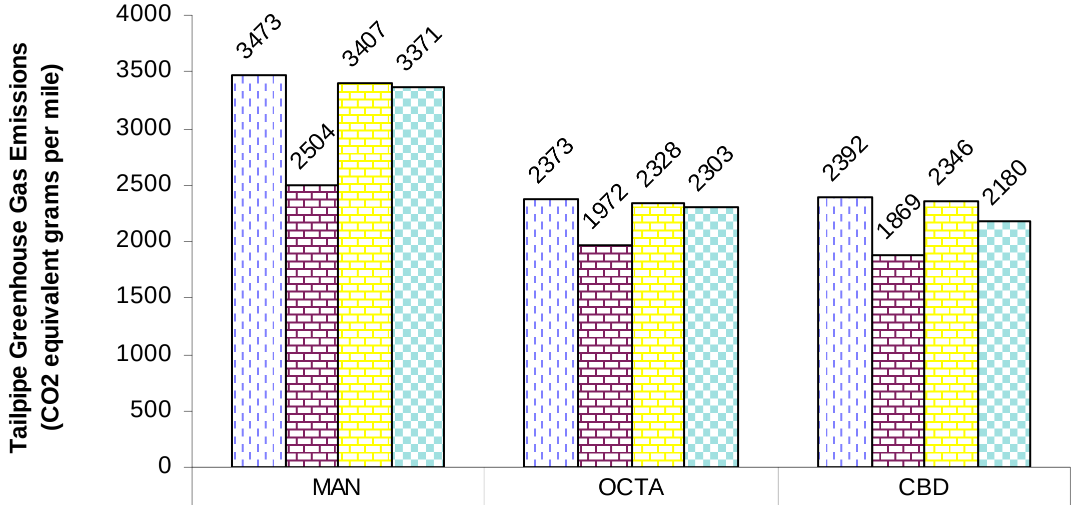


	MAN	OCTA	CBD
B20 Biodiesel	0.16	0.08	0.11
Diesel Hybrid	0.10	0.00	0.10
Diesel	0.19	0.09	0.12
CNG	1.19	0.84	0.84

Figure 16 2007 NMHC emissions prediction

Tailpipe Greenhouse Gas Emissions

Greenhouse gases (GHG) emitted by the tailpipe were considered to be only CO_2 and methane. The EIA have concluded that methane is 23 times more effective as a greenhouse gas than CO_2 [27]. Diesel and diesel-hybrid buses were assumed to emit no significant methane relative to CO_2 output, and the methane quantity used in the CNG bus computation was derived from the same methane/NMHC split used in the computation for Figure 16. By averaging McCormick's latest B20 emissions study [24] and the WVU study, B20 biodiesel buses were found to emit 2% higher CO_2 at tailpipe than the diesel buses. Thus 2% value is related to the fuel energy content and relative carbon to oxygen ratio. Figure 17 shows the greenhouse gas data as CO_2 equivalence.

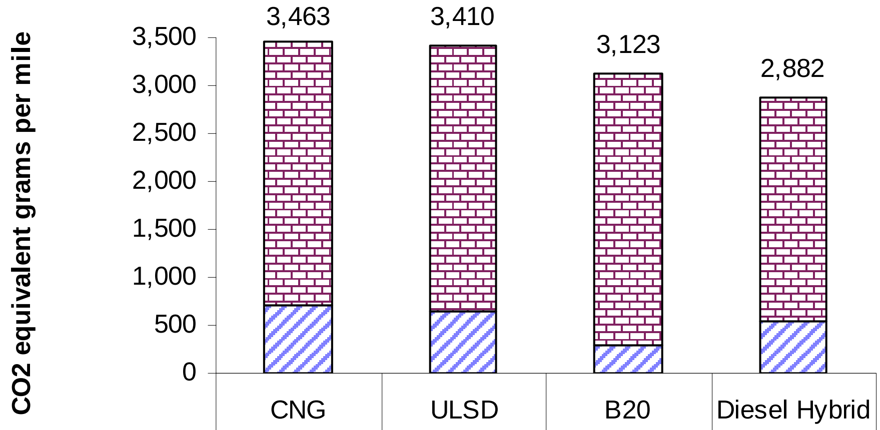


	MAN	OCTA	CBD
B20 Biodiesel	3473	2373	2392
Diesel Hybrid	2504	1972	1869
Diesel	3407	2328	2346
CNG	3371	2303	2180

Figure 17 2007 Tailpipe greenhouse gas emissions prediction

Well-to-Wheels Greenhouse Gas Emissions

Well-to-wheels (WTW) GHG emissions included emissions termed well-to-tank (WTT) and tank-to-wheels (TTW). Figure 18 presents the average WTW emissions (CO_2 equivalent grams per mile) for four bus types during 12 years of bus life. A year-by-year estimation is shown in Figure 20 at the end of this section.



	CNG	ULSD	B20	Diesel Hybrid
Well to Wheels	3,463	3,410	3,123	2,882
Tank to Wheels	2,753	2,774	2,828	2,346
Well to Tank	711	636	295	536

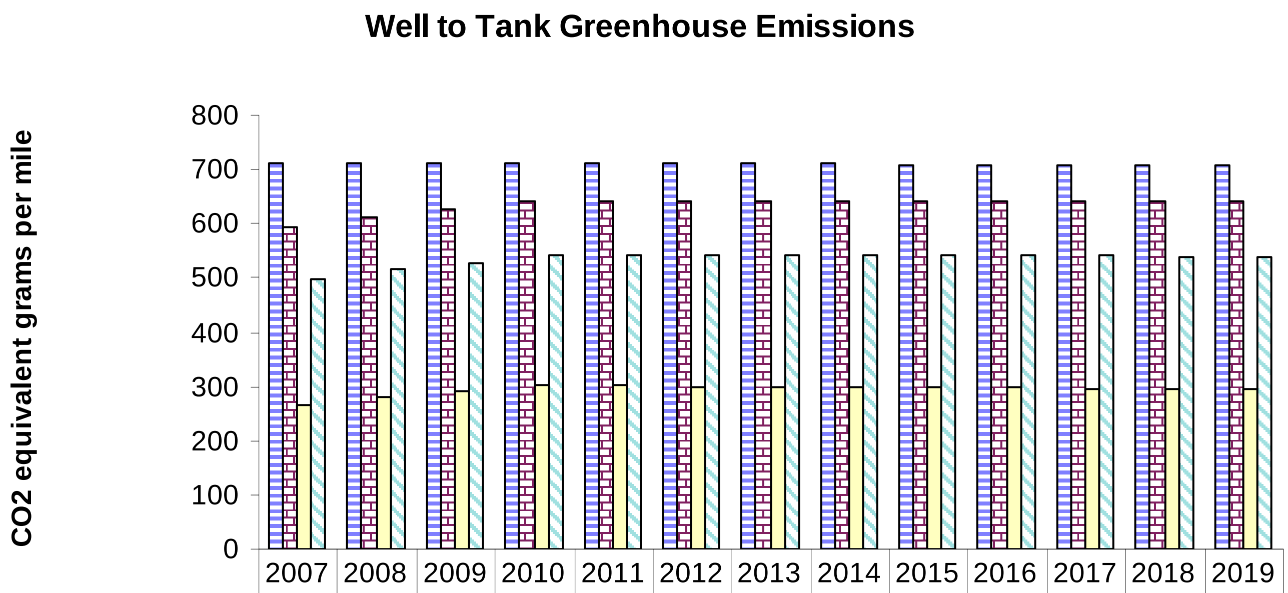
Figure 18 Average well-to-wheels GHG emissions prediction per year

WTT GHG emission prediction from 2007 to 2019 was from the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model of Argonne National Laboratory. The model is available at Argonne's website [28]. The WTT GHG emissions estimation used the GREET default setting on fuel production simulation methodologies and pathways. The only adjustment was that the ULSD market share (as opposed to Low Sulfur Diesel) was changed to 100% during the period (GREET uses 40% in 2007, 60% in 2008, and 80% in 2010). The GREET GHG emissions data were available in grams per MMBTU. The data were converted into grams per gallon by using the fuel properties supplied by the GREET model. In the model, the ULSD heating value is 129,488 BTU/gallon, and B100 biodiesel has 119,550 BTU/gallon. Therefore, the B20 biodiesel heating value is 127,500 BTU/gallon (a sum of 20% biodiesel and 80% ULSD heating value). The unit was converted from grams per gallon to grams per mile by using the fuel economy, estimated in the operation cost section. Figure 19 shows the WTT GHG emissions estimation from 2007 to 2019.

TTW GHG emissions estimation was based on GHG emissions on the OCTA cycle, presented in the previous section, with adjustment. The GHG emissions were assumed proportional to the fuel consumption. By calculating the ratio of the predicted fuel economy and OCTA fuel economy, TTW GHG emissions were from the OCTA results divided by the ratio. Then results were multiplied by 1/0.9 to reflect the 10% correction for idle and hotel load. Table 1 shows the data used in the calculation.

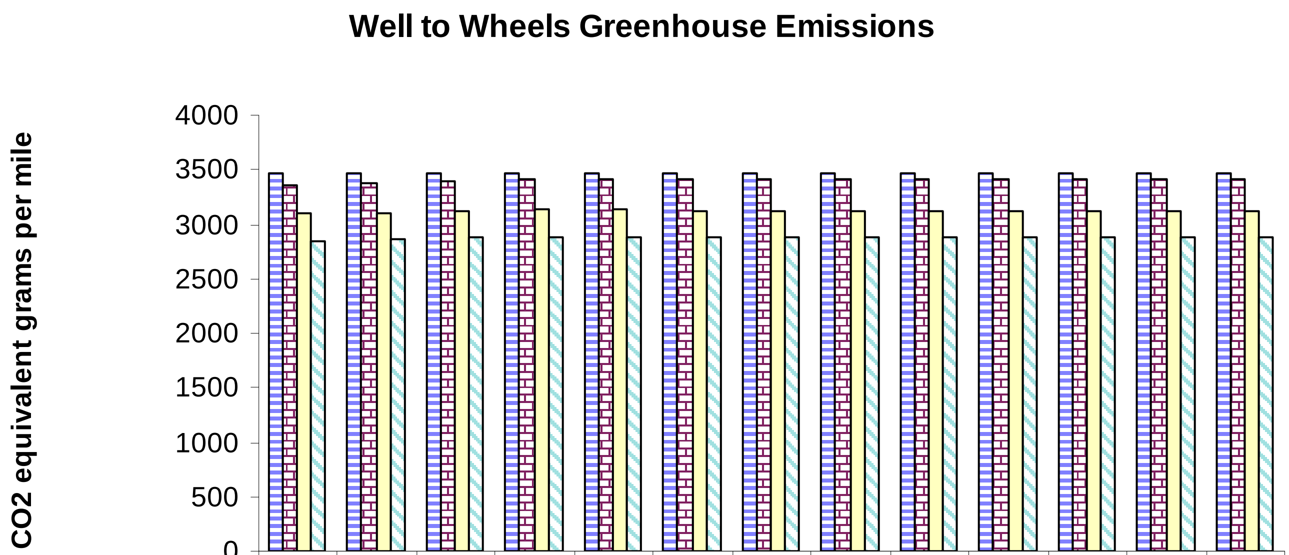
Table 1 TTW GHG emissions calculation table

	CNG	ULSD	B20 Biodiesel	Diesel Hybrid
OCTA Fuel Economy (mpg)	3.52	4.14	4.08	4.90
Predicted Fuel Economy (mpg)	3.27	3.86	3.80	4.58
OCTA GHG Emissions (grams/mile)	2,303	2,328	2,373	1,972
TTW GHG Emissions (grams/mile)	2,478	2,497	2,545	2,112
TTW Corrected by (1/0.9) for Idle & Hotel Load	2753	2774	2828	2346



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CNG	713	713	713	712	712	711	711	710	709	709	709	708	708
ULSD	592	610	627	642	642	642	642	642	641	641	641	640	640
B20	265	279	291	301	301	300	299	298	297	297	296	296	295
Diesel Hybrid	499	515	529	541	541	541	541	541	541	540	540	540	539

Figure 19 Well-to-tank GHG emissions 2007 – 2019 prediction using GREET model



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CNG	3466	3466	3465	3465	3465	3464	3464	3463	3462	3462	3461	3461	3460
ULSD	3366	3384	3401	3416	3416	3416	3416	3416	3416	3415	3415	3414	3414
B20	3094	3107	3119	3130	3129	3128	3127	3126	3126	3125	3125	3124	3124
Diesel Hybrid	2846	2861	2875	2888	2888	2888	2887	2887	2887	2887	2886	2886	2886

Figure 20 Well–to-wheels GHG emissions 2007 – 2019 prediction

Conclusions

The LCC analysis for a 100-bus fleet revealed that present day hybrid technology had a higher capital cost than diesel technology, without considering any hybrid incentives. The capital cost was slightly higher for CNG buses than for diesel buses. However, operation cost analysis was similar for the four bus types. CNG operation cost was the lowest, partly because the forecast CNG price more than compensated for CNG bus throttled engine fuel economy and additional cost of compression electricity. Although hybrid buses offered the best fuel economy, this was offset by the battery replacement cost. Generally, the LCC summary chart showed that diesel buses are still the most economic technology, and diesel buses fueled by B20 biodiesel were only slightly higher in overall cost due to the added expense of the fuel. In the case where only 20% of the bus procurement cost was considered, as a result of subsidies, the four bus types had a sufficiently similar life cycle cost (see a comparative chart shown in the appendix) that changes in fuel cost and battery technology could affect their relative positions in the scale of cost, and the four technologies were competitive on a cost basis. Hybrid buses operating on B20 were not separately evaluated, but would have similar cost to hybrid buses operating on ULSD.

Hybrid buses were attractive in offering emissions advantages. The estimation showed that hybrid buses offered lower tailpipe PM, NMHC, and GHG than the diesel and CNG buses on the CBD, MAN, and OCTA cycles. Hybrid buses were also estimated to have better NOx emissions on the MAN cycle (a low-speed transient operation). CNG buses were estimated to have the best NOx emissions for the CBD and OCTA cycles, because the stoichiometric CNG engine technology emerging in 2007 will have substantially lower NOx emissions than the prior lean-burn technology. Recent studies showed that B20 biodiesel buses emitted lower tailpipe PM and NMHC than the ULSD fueled conventional buses. However, slightly higher tailpipe NOx and CO_2 emissions were emitted by B20 buses than from the ULSD diesel. From a global perspective, the hybrid bus performed best on well to wheels GHG emissions under national average operating conditions (average speed 12.72 mph). By benefiting from low well-to-tank GHG emissions (which include plant uptake of CO_2), B20 diesel buses were the second best bus technology for well to wheels GHG emissions.

Most conclusions in this report were based on buses operating at national average speed. When considering or selecting bus technologies, it is important to recognize that fuel economy and emissions depended strongly on bus route and bus operation conditions. The nature of bus activity influences the performance of hybrid drive systems, throttled engines, and diesel engines in different ways and relative differences between technologies will change with parameters such as average speed of operation and terrain (grade) of the route.

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Appendix: LCC Comparative Chart accounting for an 80% Subsidy on Bus Cost

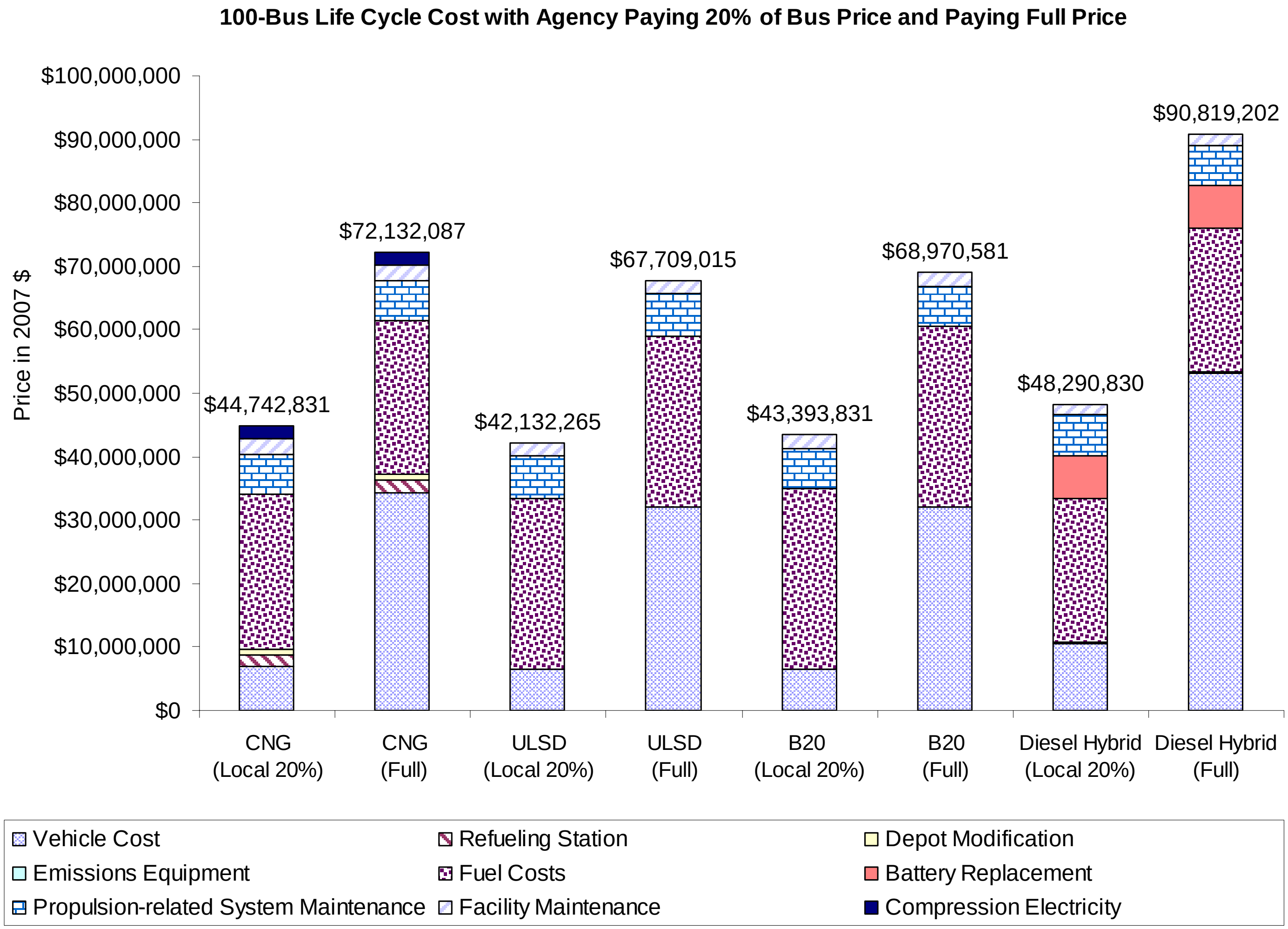

Figure A1 A comparative chart for 100-Bus life cycle cost for 12 years (Agency pays 20% and 100% (full) of bus price.).