Techno-economic modelling of an electric bus demonstration project in London Ontario Fast Transit Route "7" & "L"

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Outline

- Routes and duty cycles
- E-bus energy consumption and SOC calculations
- Charging infrastructure simulation
- Comparative simulation of diesel bus fuel consumption
- Electricity costs estimations, simulation results and emissions calculation for each route
- GHG emission savings

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Routes and duty cycles

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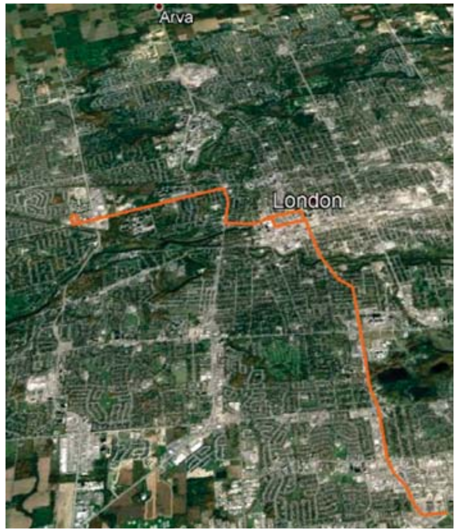
Route "7" map (28.6 km RT)



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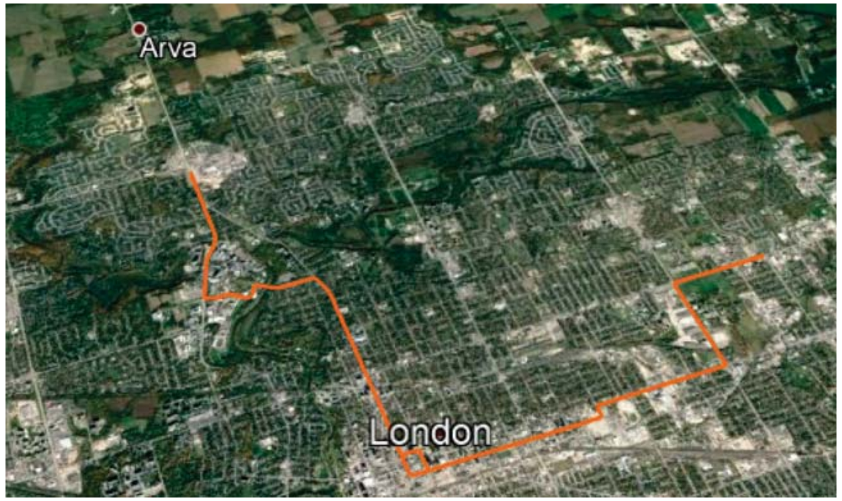
Route “L” map (29.2 km RT)



Route statistics

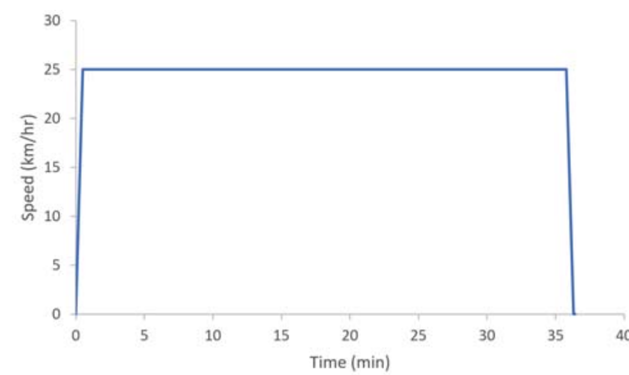
Name of route	Length of the route round trip (km)	Estimated time to complete the route round trip (min)
London route “7”	28.6	~ 70
London route “L”	29.2	~ 70

Model the route elevation profile & topography

- Used Google Earth to define the path (.kml files)
- Calculated the distances between the nodes
- Used a DEM (Digital Elevation Model) database to obtain the raw data for elevations
- Used filtration/smoothing to obtain realistic road grades (multiple steps of Savittzky-Golay filter)

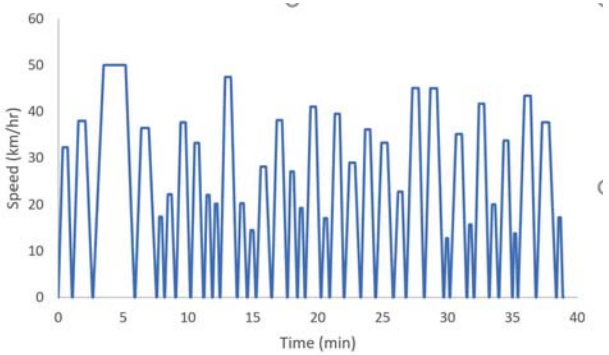
Route L (29.2 km RT) - Duty cycles development

- **Light duty cycle (1 driver, no auxiliary load)**
  - Constant velocity, no stop



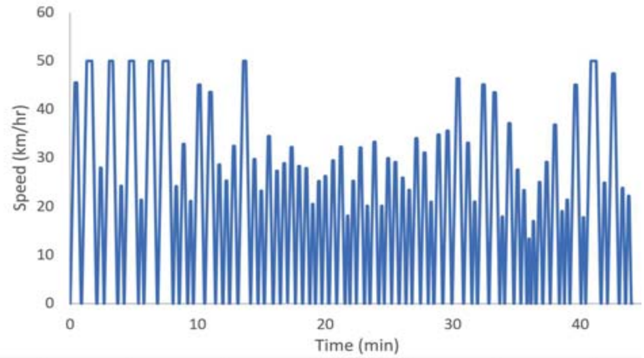
Route L (29.2 km RT) - Duty cycles development

- **Medium duty cycle (half full passenger load, half auxiliary load)**
  - Stop for all bus stops
  - Additional stops at 50 % of other stops: randomly selected from all the traffic lights, passenger walks etc…



Route L (29.2 km RT) - Duty cycles development

- **Heavy duty cycle (full passenger load, full auxiliary load)**
  - Stop for all bus stops, traffic lights, stop signs and additional stopping for pedestrians



E-bus energy consumption and SOC calculations

Key variables affecting the energy consumption

- Weight of the vehicle: a 60 ft is roughly 30 ~ 40 % heavier than a 40 ft
- Auxiliary load
- Tire rolling coefficient
- Regenerative braking usage
- Gear ratio

Ebus energy consumption and charging power calculations

- Used in-house Matlab and Python code
- Physical characteristics of fully electric 60ft New Flyer (2019) and a 60 ft Proterra (2020)
- Accounted for variation in topography
- Regenerative braking power split: 35%
- Constant accessory draw
  - Heavy duty cycle: 26,000 W
  - Medium duty cycle: 13,000 W
  - Light duty cycle: 0 W

- Maximum passenger number : 160 (~ 60 seats and ~ 60 standees)

State of Charge (SOC): Route "7" (28.6 km RT) Proterra (660 kWh)

	South to West				West to South			
	kWh per km	Total kWh used	SOC at route end		kWh per km	Total kWh used	SOC at route end	
			5 % buffer	10% buffer			5 % buffer	10 % buffer
Light duty	0.6	8.62	93.6%	88.6%	0.57	8.24	93.7%	88.7%
Medium duty	1.79	25.67	90.9%	85.9%	1.79	25.78	90.9%	85.9%
Heavy duty	3.3	47.44	87.4%	82.4%	3.26	46.93	87.5%	82.5%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

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State of Charge (SOC): Route "7" (28.6 km RT) New Flyer (640 kWh)

	South to West				West to South			
	kWh per km	Total kWh used	SOC at route end		kWh per km	Total kWh used	SOC at route end	
			5 % buffer	10% buffer			5 % buffer	10 % buffer
Light duty	0.58	8.39	93.6%	88.6%	0.56	8.03	93.7%	88.7%
Medium duty	1.76	25.28	90.8%	85.8%	1.77	25.47	90.8%	85.8%
Heavy duty	3.28	47.17	87.2%	82.2%	3.22	46.24	87.4%	82.4%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

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State of Charge (SOC): Route "L" (29.2 km RT) Proterra (660 kWh)

	East to North direction				North to Easts direction			
	kWh per km	Total kWh used	SOC at route end		kWh per km	Total kWh used	SOC at route end	
			5 % buffer	10% buffer			5 % buffer	10 % buffer
Light duty	0.53	7.79	93.8%	88.8%	0.63	9.14	93.5%	88.5%
Medium duty	1.75	25.55	90.9%	85.9%	1.81	26.42	90.8%	85.8%
Heavy duty	3.4	49.64	87.1%	82.1%	3.49	50.91	86.9%	81.9%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

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State of Charge (SOC): Route "L" (29.2 km RT) New Flyer (640 kWh)

	East to North direction				North to Easts direction			
	kWh per km	Total kWh used	SOC at route end		kWh per km	Total kWh used	SOC at route end	
			5 % buffer	10% buffer			5 % buffer	10 % buffer
Light duty	0.52	7.59	93.8%	88.8%	0.61	8.9	93.5%	88.5%
Medium duty	1.73	25.19	90.9%	85.9%	1.78	26.04	90.7%	85.7%
Heavy duty	3.35	48.91	87.0%	82.0%	3.47	50.61	86.7%	81.7%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

Charging infrastructure simulation

State of the art of the technology

- Today, the technology requires slow charging (~150 kW) and can have partial fast charging.
- By 2020 however, the technology will accommodate fast charging (450 – 600 kW) solutions at least partially (e.g if the SOC is within a certain range).

We modeled both solutions.

Slow charging (150kW)

Electricity demand: Route “7” (28.6 km RT)

- Battery buffer of 10%. SOC cannot be below 10%.
- Slow charge at garage. 150 kW, 90% efficient, final SOC 90%.

	Proterra			New Flyer		
	Number of runs (roundtrips) without charging	Overnight charging time (hours)	Energy from the grid (kWh)	Number of runs (roundtrips) without charging	Overnight charging time (hours)	Energy from the grid (kWh)
Light duty	31	4.3	580.7	31	4.2	565.6
Medium duty	10	4.2	571.7	10	4.2	563.9
Heavy duty	6	4.7	629.1	5	3.8	518.9

Electricity demand: Route “L” (29.2 km RT)

- Battery buffer of 10%. SOC cannot be below 10%.
- Slow charge at garage. 150 kW, 90% efficient, final SOC 90%.

	Proterra			New Flyer		
	Number of runs (roundtrips) without charging	Overnight/at-garage charging time (hours)	Energy from the grid (kWh)	Number of runs (roundtrips) without charging	Overnight/at-garage charging time (hours)	Energy from the grid (kWh)
Light duty	31	4.3	583.1	31	4.2	568.0
Medium duty	10	4.3	577.4	10	4.2	569.2
Heavy duty	5	4.1	558.6	5	4.1	552.9

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Fast charging

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Electricity demand: Route “7” (28.6 km RT) Proterra (660 kWh) 600 kW charger

Notes:

Ideal charging: the energy from the grid goes straight to the battery

Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency).

Range of operation: SOC 10%-90%

	East to North direction				North to East direction			
	Ideal charging 100 %		Typical efficiency 86 %		Ideal charging 100 %		Typical efficiency 86 %	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.86	8.63	1.0	7.48	0.82	8.25	0.95	7.16
Medium duty	2.57	25.69	2.97	22.29	2.58	25.8	2.98	22.39
Heavy duty	4.74	47.42	5.49	41.14	4.69	46.88	5.42	40.67

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Electricity demand: Route "7" (28.6 km RT) New Flyer (640 kWh) 600 kW charger

Notes:

Ideal charging: the energy from the grid goes straight to the battery

Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency).

Range of operation: SOC 10%-90%

	East to North direction				North to East direction			
	Ideal charging 100 %		Typical efficiency 86 %		Ideal charging 100 %		Typical efficiency 86 %	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.84	8.4	**0.97**	7.29	0.8	8.04	**0.93**	6.97
Medium duty	2.53	25.31	**2.93**	21.96	2.55	25.49	**2.95**	22.12
Heavy duty	4.72	47.21	**5.46**	40.96	4.62	46.22	**5.35**	40.1

Electricity demand: Route "L" (29.2 km RT) Proterra (660 kWh) 600 kW charger

Notes:

Ideal charging: the energy from the grid goes straight to the battery

Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency).

Range of operation: SOC 10%-90%

	East to North direction				North to East direction			
	Ideal charging 100 %		Typical efficiency 86 %		Ideal charging 100 %		Typical efficiency 86 %	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.78	7.8	**0.9**	6.77	0.91	9.15	**1.06**	7.94
Medium duty	2.56	25.58	**2.96**	22.19	2.64	26.44	**3.06**	22.94
Heavy duty	4.96	49.61	**5.74**	43.04	5.09	50.92	**5.89**	44.17

Electricity demand: Route "L" (29.2 km RT) New Flyer (640 kWh) 600 kW charger

Notes:

Ideal charging: the energy from the grid goes straight to the battery

Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency).

Range of operation: SOC 10%-90%

	East to North direction				North to East direction			
	Ideal charging 100 %		Typical efficiency 86 %		Ideal charging 100 %		Typical efficiency 86 %	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.76	7.6	**0.88**	6.59	0.89	8.91	**1.03**	7.73
Medium duty	2.52	25.22	**2.92**	21.88	2.61	26.07	**3.02**	22.62
Heavy duty	4.89	48.9	**5.66**	42.42	5.07	50.67	**5.86**	43.96

Comparative simulation of diesel bus fuel consumption

Fuel consumption simulation: New Flyer 2013 XD60s

- Used Python code developed in-house, based on work from [1]

Vehicle parameters	Value	Unit
Vehicle curb weight	19,409	kg
Mean passenger weight	75	kg
Maximum passengers	128	-
Engine maximum power	246	kW
Drivetrain efficiency	95	%
Rolling coefficient	Provided by OEM	-

Fuel parameters	Value	Unit
LHV of low sulfur diesel	42.6	MJ/kg
Diesel density	850	kg/m^3
CO_2 content of fuel *	2.630	kg CO_{2e}/L fuel

*Note: emission factors for mobile fuel combustion of diesel in heavy-duty vehicles, see [2]

[1] W. Edwardes and H. Rakha "Modeling Diesel and Hybrid Bus Fuel Consumption with Virginia Tech Comprehensive Power-Based Fuel Consumption: Model Enhancements and Calibration Issues Model". Transportation Research Record: Journal of the Transportation Research Board, No. 2533
[2] BC Ministry of Environment "2016/17 B.C. Best practices Methodology for quantifying greenhouse gas emissions" Victoria, May 2016

Fuel consumption: Route "7" (28.6 km RT)

Runs (round trips) per week to compare with e-buses based on the schedule: 744

	Light-Duty	Medium-Duty	Heavy-Duty
Fuel used per run (round trip) per bus (L)	6.6	12.2	19.4
Fuel efficiency of diesel equivalent (L/100km)	**23.1**	**42.4**	**67.7**
Emitted CO2e per year (kg)	678,756	1,245,184	1,986,515
Cost of diesel per year @$0.9116/L ($) *	**$235,268**	**$431,601**	**$ 688,558**

* Note: $0.9116/L based on London Transit's average fuel price over the last 10 years

Fuel consumption: Route "L" (29.2 km RT)

Runs (round trips) per week to compare with e-buses based on the schedule: 1488

	Light-Duty	Medium-Duty	Heavy-Duty
Fuel used per run (round trip) per bus (L)	6.7	12.2	20.3
Fuel efficiency of diesel equivalent (L/100km)	**23**	**41.7**	**69.7**
Emitted CO2e per year (kg)	1,371,652	2,486,126	4,156,430
Cost of diesel per year @$0.9116/L ($) *	**$475,436**	**$861,731**	**$1,440,685**

* Note: $0.9116/L based on London Transit's average fuel price over the last 10 years

Electricity costs estimations, emission reduction and simulation results for each route

Assumptions on the schedule (revised)

Rapid Transit Operating Schedule Information

The "7" Corridor will operate on a 10-minute frequency during the following periods
Monday – Saturday from 6am to midnight **(18 hours of operation)**
Sunday & Stat Holidays from 7am to 11pm **(16 hours of operation)**

The "L" Corridor will operate on a 5-minute frequency during the following periods
Monday – Saturday from 6am to midnight **(18 hours of operation)**
Sunday & Stat Holidays from 7am to 11pm **(16 hours of operation)**

Stop at the terminal station: 5 min

Sample route "7" weekday schedule

Total # round trips/day: Weekday: 108, Saturday: 108, Sunday: 96

West to South			South to West		
Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)
6:00	6:35	5	6:00	6:35	5
6:10	6:45	5	6:10	6:45	5
6:20	6:55	5	6:20	6:55	5
6:30	7:05	5	6:30	7:05	5
6:40	7:15	5	6:40	7:15	5
6:50	7:25	5	6:50	7:25	5
7:00	7:35	5	7:00	7:35	5
7:10	7:45	5	7:10	7:45	5
	….			…	

eBus A – 10 min frequency
eBus B – 10 min frequency

Sample route "L" weekday schedule

Total # round trips/day: Weekday: 216, Saturday: 216, Sunday: 192

West to South			South to West		
Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)
6:00	6:35	5	6:00	6:35	5
6:05	6:40	5	6:05	6:40	5
6:10	6:45	5	6:10	6:45	5
	---			…	
6:40	7:15	5	6:40	7:15	5
6:45	7:20	5	6:45	7:20	5
6:50	7:25	5	6:50	7:25	5
	….			…	

eBus A – 5 min frequency
eBus B – 5min frequency

Required number of buses if **slow charging** is used: Routes "7" & "L"

Minimum required for the schedule, 1 to 1 diesel replacement

Route 7 – less frequent

Number of 60ft required to fully electrify the route		
	Proterra	New Flyer
Light duty	8 [vs. 8]	8
Medium duty	11	11
Heavy duty	20	20

Minimum required for the schedule, 1 to 1 diesel replacement

Route L – more frequent

Number of 60ft required to fully electrify the route		
	Proterra	New Flyer
Light duty	16 [vs. 16]	16
Medium duty	22	22
Heavy duty	42	42

Required number of buses if **fast charging (600 kW)** is used: Routes "7" & "L"

Minimum required for the schedule, 1 to 1 diesel replacement

Route 7 – less frequent

Number of 60ft required to fully electrify the route	Proterra	New Flyer
Light duty	8 [vs. 8]	8
Medium duty	8	8
Heavy duty	12	12

Minimum required for the schedule, 1 to 1 diesel replacement

Route L – more frequent

Number of 60ft required to fully electrify the route	Proterra	New Flyer
Light duty	16 [vs. 16]	16
Medium duty	16	16
Heavy duty	27	27

Fully electrifying the route is possible with rapid chargers is possible

- Note, routes will not operate continuously on a heavy duty cycle mode.
- Four chargers are required, one at each North, East, West and South terminal
- **Route "7"**
  - Two buses charge in a 15min interval (used for demand charges calculations)
- **Route "L"**
  - Three buses charge in a 15min interval (used for demand charges calculations)
- There is a possibility to refine the model to include longer stops and charging at the Central Transit Hub if this is a preferred strategy to utilize fewer e-buses in total.

Slow charging

Overnight charging costs

- Assumed a constant overnight electricity cost of $0.0936 /kWh (average 2016 night market price and added global adjustment rate that changes monthly)
- Remaining electricity price is calculated as per previous modelling, expecting the charging power is 150kW

Charging costs: Route "7" (28.6 km RT) Proterra (660 kWh)

Notes:

Used London Hydro Rates: General Service, Greater Than 50 kW with no interval meter rates

Assumed 1 slow charger per bus

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	727	2,220	4,072
Electricity cost (CAD $)	$ 68,098	$ 207,808	$ 381,163
Delivery cost (CAD $)	$ 96,005	$ 132,007	$ 240,012
Regulatory cost (CAD $)	$ 7,933	$ 24,203	$ 44,391
Total charging cost for a year (CAD $)	**$ 172,036**	**$ 364,017**	**$ 665,566**
Diesel cost for a year (CAD $)	$ 235,268	$ 431,601	$ 688,558
Benefits (CAD $)	**$ 63,232**	**$ 67,583**	**$ 22,992**
Carbon price electricity (CAD $) with $50/TCO2e	$ 1,601	$ 4,884	$ 8,959
Carbon price diesel (CAD $) with $50/TCO2e	$ 12,927	$ 23,714	$ 37,833
Benefits with Carbon price (CAD $)	**$ 74,558**	**$ 86,413**	**$ 51,866**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years

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Charging costs: Route "7" (28.6 km RT) New Flyer (640 kWh)

Notes:

Used London Hydro Rates: General Service, Greater Than 50 kW with no interval meter rates

Assumed 1 slow charger per bus

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	708	2,189	4,030
Electricity cost (CAD $)	$ 66,321	$204,981	$377,286
Delivery cost (CAD $)	$ 96,005	$132,007	$240,012
Regulatory cost (CAD $)	$ 7,726	$ 23,874	$ 43,939
Total charging cost for a year (CAD $)	**$170,052**	**$360,861**	**$661,237**
Diesel cost for a year (CAD $)	$235,268	$431,601	$688,558
Benefits (CAD $)	**$ 65,216**	**$ 70,740**	**$ 27,321**
Carbon price electricity (CAD $) with $50/TCO2e	$ 1,559	$ 4,818	$ 8,868
Carbon price diesel (CAD $) with $50/TCO2e	$ 12,927	$ 23,714	$ 37,833
Benefits with Carbon price (CAD $)	**$ 76,584**	**$ 89,636**	**$ 56,286**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years

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Charging costs: Route "L" (29.2 km RT) Proterra (660 kWh)

Notes:

Used London Hydro Rates: General Service, Greater Than 50 kW with no interval meter rates

Assumed 1 slow charger per bus

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	1,461	4,485	8,677
Electricity cost (CAD $)	$136,761	$419,816	$ 812,248
Delivery cost (CAD $)	$192,010	$264,013	$ 504,025
Regulatory cost (CAD $)	$ 15,929	$ 48,892	$ 94,592
Total charging cost for a year (CAD $)	**$344,700**	**$732,722**	**$1,410,865**
Diesel cost for a year (CAD $)	$475,436	$861,731	$1,440,685
Benefits (CAD $)	**$ 130,736**	**$ 129,009**	**$ 29,820**
Carbon price electricity (CAD $) with $50/TCO2e	$ 3,214	$ 9,867	$ 19,091
Carbon price diesel (CAD $) with $50/TCO2e	$ 26,123	$ 47,348	$ 79,159
Benefits with Carbon price (CAD $)	**$ 153,645**	**$ 166,490**	**$ 89,887**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years

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Charging costs: Route "L" (29.2 km RT) New Flyer (640 kWh)

Notes:

Used London Hydro Rates: General Service, Greater Than 50 kW with no interval meter rates

Assumed 1 slow charger per bus

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	1,423	4,421	8,588
Electricity cost (CAD $)	$133,207	$413,839	$ 803,928
Delivery cost (CAD $)	$192,010	$264,013	$ 504,025
Regulatory cost (CAD $)	$ 15,515	$ 48,196	$ 93,623
Total charging cost for a year (CAD $)	**$340,732**	**$726,048**	**$1,401,576**
Diesel cost for a year (CAD $)	$475,436	$861,731	$1,440,685
Benefits (CAD $)	**$ 134,704**	**$ 135,683**	**$ 39,109**
Carbon price electricity (CAD $) with $50/TCO2e	$ 3,131	$ 9,727	$ 18,896
Carbon price diesel (CAD $) with $50/TCO2e	$ 26,123	$ 47,348	$ 79,159
Benefits with Carbon price (CAD $)	**$ 157,696**	**$ 173,304**	**$ 99,372**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years

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Fast charging

Charging costs: Route "7" (28.6 km RT) Proterra (660 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

Diesel at $0.9116/L based on London Transit's average fuel price over the last 10 years

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	761	2,321	3,900
Electricity cost (CAD $)	$ 88,882	$271,178	$455,661
Regulatory cost (CAD $)	$ 8,295	$ 25,302	$ 42,513
Delivery cost (CAD $)	$ 14,572	$ 35,880	$ 57,541
Total charging cost for a year (CAD $)	**$111,749**	**$332,360**	**$555,715**
Diesel cost for a year (CAD $)	$235,268	$431,601	$688,558
Benefits (CAD $)	**$123,519**	**$ 99,241**	**$132,843**
Carbon price electricity (CAD $) with $50/TCO2e	$ 1,674	$ 5,106	$ 8,580
Carbon price diesel (CAD $) with $50/TCO2e	$ 33,938	$ 62,259	$ 99,326
Benefits with Carbon price (CAD $)	**$ 155,782**	**$ 156,394**	**$ 223,588**

Charging costs – Route "7" (28.6 km RT) New Flyer (640 kWh)

Note:

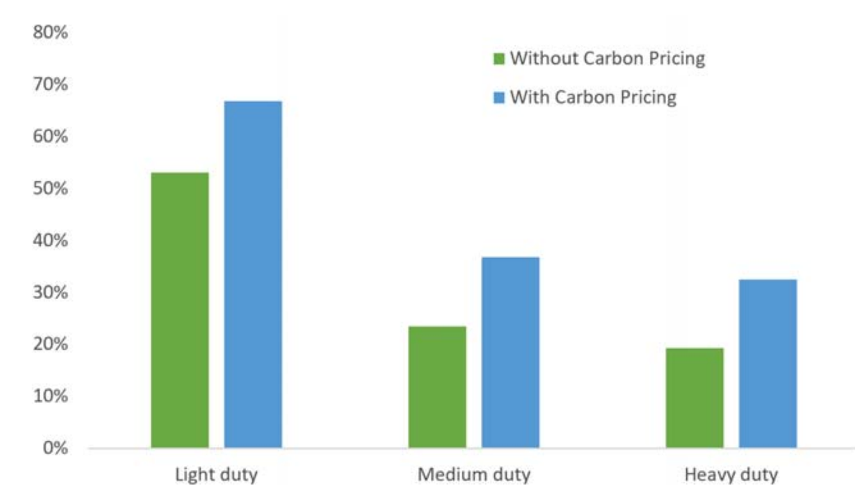
Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

Diesel at $0.9116/L based on London Transit's average fuel price over the last 10 years

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	741	2,289	3,900
Electricity cost (CAD $)	$ 86,562	$267,485	$455,661
Regulatory cost (CAD $)	$ 8,079	$ 24,958	$ 42,513
Delivery cost (CAD $)	$ 14,287	$ 35,495	$ 57,541
Total charging cost for a year (CAD $)	**$108,927**	**$327,937**	**$555,715**
Diesel cost for a year (CAD $)	$235,268	$431,601	$688,558
Benefits (CAD $)	**$126,341**	**$103,664**	**$132,843**
Carbon price electricity (CAD $) with $50/TCO2e	$ 1,630	$ 5,036	$ 8,580
Carbon price diesel (CAD $) with $50/TCO2e	$ 33,938	$ 62,259	$ 99,326
Benefits with Carbon price (CAD $)	**$ 158,648**	**$ 160,887**	**$ 223,588**

Average yearly benefits: Fast charging Route "7" (28.6 km RT)



Charging costs: Route "L" (29.2 km RT) Proterra (660 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

Diesel at $0.9116/L based on London Transit's average fuel price over the last 10 years

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	1,515	4,652	7,737
Electricity cost (CAD $)	$177,208	$544,009	$ 904,952
Regulatory cost (CAD $)	$ 16,520	$ 50,704	$ 84,343
Delivery cost (CAD $)	$ 20,892	$ 53,077	$ 84,377
Total charging cost for a year (CAD $)	**$214,620**	**$647,790**	**$1,073,671**
Diesel cost for a year (CAD $)	$475,436	$861,731	$1,440,685
Benefits (CAD $)	**$260,816**	**$213,941**	**$ 367,014**
Carbon price electricity (CAD $) with $50/TCO2e	$ 3,333	$ 10,234	$ 17,021
Carbon price diesel (CAD $) with $50/TCO2e	$ 68,583	$124,306	$ 207,821
Benefits with Carbon price (CAD $)	**$326,066**	**$328,013**	**$ 557,814**

CUTRIC CRITUC

Charging costs: Route "L" (29.2 km RT) New Flyer (640 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

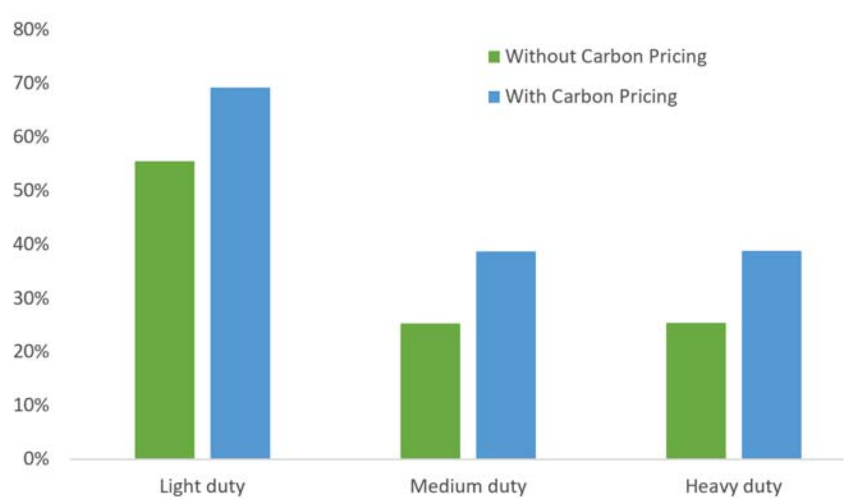
Diesel at $0.9116/L based on London Transit's average fuel price over the last 10 years

Total cost per route (inclusive of all buses)

	Light	Medium	Heavy
Yearly MWh estimated	1,476	4,585	7,737
Electricity cost (CAD $)	$172,602	$536,263	$ 904,952
Regulatory cost (CAD $)	$ 16,090	$ 49,983	$ 84,343
Delivery cost (CAD $)	$ 20,445	$ 52,369	$ 84,377
Total charging cost for a year (CAD $)	**$209,138**	**$638,614**	**$1,073,671**
Diesel cost for a year (CAD $)	$475,436	$861,731	$1,440,685
Benefits (CAD $)	**$266,298**	**$223,117**	**$ 367,014**
Carbon price electricity (CAD $) with $50/TCO2e	$ 3,247	$ 10,087	$ 17,021
Carbon price diesel (CAD $) with $50/TCO2e	$ 68,583	$124,306	$ 207,821
Benefits with Carbon price (CAD $)	**$331,634**	**$337,336**	**$ 557,814**

CUTRIC CRITUC

Average yearly benefits: Fast charging Route "L" (29.2 km RT)



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Ontario 2015 Grid Emissions [2]

	Solar / Wind / Bioenergy	Natural Gas	Nuclear	Coal	Waterpower
Electricity production (TWh)	14.2	15.9	92.3	0	37.3
Percentage of the grid use (%)	8.89	9.96	57.80	0.00	23.36

- Total electricity production (2015): 159.7 TWh
- Total emission (2015): 7.1 MT CO2e
- The emission is calculated as **0.044 Tonne CO2e/MWh**

CUTRIC CRITUC

Fast charging

Emissions reduction: Route "7" (28.6 km RT) Proterra (660 kWh)

	Light	Medium	Heavy
Yearly electricity estimated (MWh)	761	2,321	3,900
Yearly diesel use (L)	258,082	473,454	755,329
CO_2e from electricity (Tonne)	33	102	172
CO_2e from diesel (Tonne)*	679	1245	1987
CO_2e reduction for a year (Tonne)	**645**	**1143**	**1815**

* : Mobile emissions factor for mobile fuel combustion of diesel in heavy-duty vehicles is 2.63 kg CO_2e/L

Emissions reduction: Route "7" (28.6 km RT) New Flyer (640 kWh)

	Light	Medium	Heavy
Yearly electricity estimated (MWh)	741	2,289	3,900
Yearly diesel use (L)	258,082	473,454	755,329
CO_2e from electricity (Tonne)	33	101	172
CO_2e from diesel (Tonne)*	679	1245	1987
CO_2e reduction for a year (Tonne)	**646**	**1144**	**1815**

* : Mobile emissions factor for mobile fuel combustion of diesel in heavy-duty vehicles is 2.63 kg CO_2e/L

Emissions reduction: Route "L" (29.2 km RT) Proterra (660 kWh)

	Light	Medium	Heavy
Yearly electricity estimated (MWh)	1,515	4,652	7,737
Yearly diesel use (L)	521,541	945,295	1,580,392
CO_2e from electricity (Tonne)	67	205	340
CO_2e from diesel (Tonne)*	1372	2486	4156
CO_2e reduction for a year (Tonne)	**1305**	**2281**	**3816**

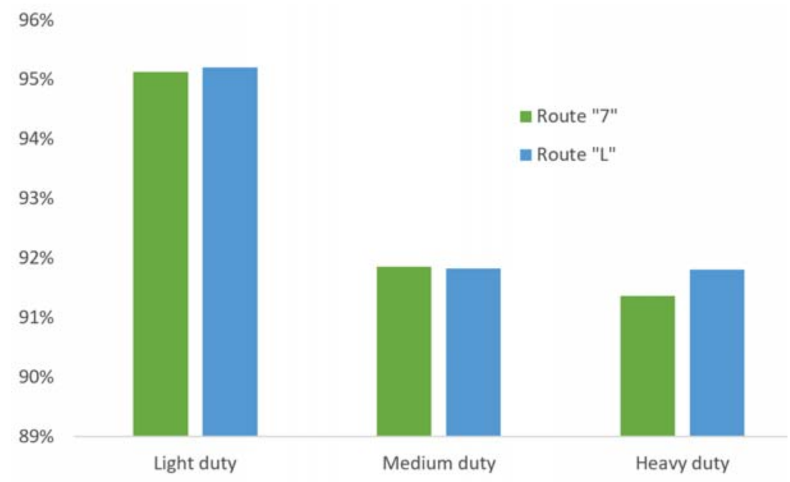
* : Mobile emissions factor for mobile fuel combustion of diesel in heavy-duty vehicles is 2.63 kg CO_2e/L

Emissions reduction: Route "L" (29.2 km RT) New Flyer (640 kWh)

	Light	Medium	Heavy
Yearly electricity estimated (MWh)	1,476	4,585	7,737
Yearly diesel use (L)	521,541	945,295	1,580,392
CO2e from electricity (Tonne)	65	202	340
CO2e from diesel (Tonne)*	1372	2486	4156
CO2e reduction for a year (Tonne)	**1307**	**2284**	**3816**

* : Mobile emissions factor for mobile fuel combustion of diesel in heavy-duty vehicles is 2.63 kg CO2e/L

Average yearly emission reductions: Route "7" and route "L"



Recall: 40 ft scenario

Electricity costs estimations, emission reduction and simulation results for each route

Assumptions on the schedule (revised)

Rapid Transit Operating Schedule Information

The "7" Corridor will operate on a 10 minute frequency during the following periods

Monday – Saturday from 6am to midnight **(18 hours of operation)**

Sunday & Stat Holidays from 7am to 11pm **(16 hours of operation)**

The "L" Corridor will operate on a 5 minute frequency during the following periods

Monday – Saturday from 6am to midnight **(18 hours of operation)**

Sunday & Stat Holidays from 7am to 11pm **(16 hours of operation)**

Stop at the terminal station: 5 min (maximum charging time is less than 4 min)

Sample route "7" weekday schedule

Total # round trips/day: Weekday: 108, Saturday: 108, Sunday: 96

West to South			South to West		
Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)
6:00	6:35	5	6:00	6:35	5
6:10	6:45	5	6:10	6:45	5
6:20	6:55	5	6:20	6:55	5
6:30	7:05	5	6:30	7:05	5
6:40	7:15	5	6:40	7:15	5
6:50	7:25	5	6:50	7:25	5
7:00	7:35	5	7:00	7:35	5
7:10	7:45	5	7:10	7:45	5
	....			...	

eBus A – 10 min frequency
eBus B – 10 min frequency

Sample route "L" weekday schedule

Total # round trips/day: Weekday: 216, Saturday: 216, Sunday: 192

West to South			South to West		
Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)
6:00	6:35	5	6:00	6:35	5
6:05	6:40	5	6:05	6:40	5
6:10	6:45	5	6:10	6:45	5
	...			...	
6:40	7:15	5	6:40	7:15	5
6:45	7:20	5	6:45	7:20	5
6:50	7:25	5	6:50	7:25	5
	....			...	

eBus A – 5 min frequency
eBus B – 5min frequency

State of Charge (SOC) - Route "7" (28.6 km RT) with Nova Bus (76 kWh)

	South to West				West to South			
	kWh per km	Total kWh used	SOC at route end: 5 % buffer	SOC at route end: 10% buffer	kWh per km	Total kWh used	SOC at route end: 5 % buffer	SOC at route end: 10 % buffer
Light duty	0.4	5.79	87.0%	82.0%	0.38	5.45	87.5%	82.5%
Medium duty	0.99	14.29	75.2%	70.2%	1.0	14.3	75.2%	70.2%
Heavy duty	1.6	23.04	63.1%	58.1%	1.6	23.0	63.1%	58.1%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

State of Charge (SOC) - Route "7" (28.6 km RT) with New Flyer (200 kWh)

	South to West				West to South			
	kWh per km	Total kWh used	SOC at route end: 5 % buffer	SOC at route end: 10% buffer	kWh per km	Total kWh used	SOC at route end: 5 % buffer	SOC at route end: 10 % buffer
Light duty	0.43	6.12	91.8%	86.8%	0.4	5.73	92.0%	87.0%
Medium duty	1.03	14.82	87.2%	82.2%	1.03	14.76	87.2%	82.2%
Heavy duty	1.64	23.63	82.6%	77.6%	1.64	23.58	82.6%	77.6%

Note: Ideal battery initial SOC = 100%, 5 % buffer initial SOC = 95%, 10 % buffer initial SOC = 90 %

Recall: 40 fts
Charging infrastructure simulation

Electricity demand – Route "7" (28.6 km RT) Nova Bus (76 kWh) 450 kW charger

	South to West direction						West to South direction					
	Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%		Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.77	5.79	**0.89**	6.7	1.09	8.16	0.73	5.45	**0.84**	6.31	1.02	7.68
Medium duty	1.91	14.31	**2.21**	16.55	2.69	20.15	1.91	14.32	**2.21**	16.56	2.69	20.16
Heavy duty	3.08	23.07	**3.56**	26.68	4.33	32.49	3.07	23.02	**3.55**	26.63	4.32	32.43

Note: Ideal charging: the energy from the grid goes straight to the battery
Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency)
Worst case efficiency: 71% of the energy from the grid goes to the battery

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Electricity demand – Route "7" (28.6 km RT) New Flyer (200 kWh) 450 kW charger

	South to West direction						West to South direction					
	Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%		Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.82	6.12	**0.94**	7.08	1.15	8.63	0.77	5.74	**0.89**	6.64	1.08	8.08
Medium duty	1.98	14.84	**2.29**	17.16	2.79	20.9	1.97	14.77	**2.28**	17.08	2.77	20.8
Heavy duty	3.15	23.65	**3.65**	27.36	4.44	33.31	3.15	23.61	**3.64**	27.31	4.43	33.25

Note: Ideal charging: the energy from the grid goes straight to the battery
Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency)
Worst case efficiency: 71% of the energy from the grid goes to the battery

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Electricity demand – Route "L" (29.2 km RT) Nova Bus (76 kWh) 450 kW charger

	East to North direction						North to East direction					
	Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%		Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.69	5.17	**0.8**	5.98	0.97	7.28	0.81	6.11	**0.94**	7.06	1.15	8.6
Medium duty	1.86	13.96	**2.15**	16.15	2.62	19.66	1.97	14.8	**2.28**	17.13	2.78	20.85
Heavy duty	3.23	24.21	**3.73**	28.0	4.55	34.1	3.3	24.76	**3.82**	28.64	4.65	34.88

Note: Ideal charging: the energy from the grid goes straight to the battery
Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency)
Worst case efficiency: 71% of the energy from the grid goes to the battery

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Electricity demand – Route "L" (29.2 km RT) New Flyer (200 kWh) 450 kW charger

	East to North direction						North to East direction					
	Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%		Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%	
	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)	Charging time (min)	Energy from the grid (kWh)
Light duty	0.73	5.46	**0.84**	6.31	1.03	7.69	0.86	6.46	**1.0**	7.47	1.21	9.09
Medium duty	1.92	14.43	**2.23**	16.69	2.71	20.32	2.04	15.28	**2.36**	17.68	2.87	21.53
Heavy duty	3.32	24.93	**3.85**	28.84	4.68	35.12	3.4	25.47	**3.93**	29.46	4.78	35.87

Note: Ideal charging: the energy from the grid goes straight to the battery
Typical efficiency: 86% of the energy from the grid goes to the battery (91% charger efficiency, 95 % battery management system efficiency)
Worst case efficiency: 71% of the energy from the grid goes to the battery

Fully electrifying the route is possible today with 40fts

- According to the developed schedule, **8 buses are required for route "7", 16 buses are required for route "L"**, therefore **24 electric buses** are needed
- Four chargers are required, at each North, East, West and South terminals
  - Route "7" : Two buses charge in a 15min interval (used for demand charges calculations)
  - Route "L": Three buses charge in a 15min interval (used for demand charges calculations)
- There is a possibility to refine the model to include longer stops and charging at the Central Transit Hub if this is a preferred strategy

Charging costs – Route "7" (28.6 km RT) Nova Bus (76 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

	Light	Medium	Heavy
Yearly MWh estimated	507	1,290	2,077
Electricity cost (CAD $)	$59,258	$150,692	$242,669
Regulatory cost (CAD $)	$5,531	$14,062	$22,642
Delivery cost (CAD $)	$11,058	$21,625	$32,477
Total charging cost for a year (CAD $)	**$75,848**	**$186,378**	**$297,789**
Diesel cost for a year (CAD $)*	$227,459	$386,218	$570,636
Diesel cost for a year with cap & trade ($CAD)	$239,271	$406,275	$600,270
Benefits (CAD $)	**$151,611**	**$199,840**	**$272,847**
Benefits (CAD $) if cap & trade	**$163,423**	**$219,897**	**$302,481**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years
** with a current carbon price of $18/TCO2e

Charging costs – Route "7" (28.6 km RT) New Flyer (200 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

	Light	Medium	Heavy
Yearly MWh estimated	535	1,334	2,130
Electricity cost (CAD $)	$62,475	$155,913	$248,837
Regulatory cost (CAD $)	$5,832	$14,549	$23,218
Delivery cost (CAD $)	$11,468	$22,271	$33,210
Total charging cost for a year (CAD $)	**$79,775**	**$192,732**	**$305,264**
Diesel cost for a year (CAD $)*	$227,459	$386,218	$570,636
Diesel cost for a year with cap & trade ($CAD)	$239,271	$406,275	$600,270
Benefits (CAD $)	**$147,684**	**$193,486**	**$265,372**
Benefits (CAD $) if cap & trade	**$159,496**	**$213,543**	**$295,006**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years
** with a current carbon price of $18/TCO2e

Charging costs – Route "L" (29.2 km RT) Nova Bus (76 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

	Light	Medium	Heavy
Yearly MWh estimated	1,009	2,571	4,379
Electricity cost (CAD $)	$117,964	$300,735	$512,190
Regulatory cost (CAD $)	$10,998	$28,032	$47,739
Delivery cost (CAD $)	$15,230	$31,416	$49,948
Total charging cost for a year (CAD $)	**$144,192**	**$360,182**	**$609,876**
Diesel cost for a year (CAD $)*	$459,686	$773,446	$1,199,593
Diesel cost for a year with cap & trade ($CAD)	$483,557	$813,611	$1,261,889
Benefits (CAD $)	**$315,494**	**$413,264**	**$589,717**
Benefits (CAD $) if cap & trade	**$339,365**	**$453,429**	**$652,013**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years
** with a current carbon price of $18/TCO2e

Charging costs – Route "L" (29.2 km RT) New Flyer (200 kWh)

Note:

Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates

	Light	Medium	Heavy
Yearly MWh estimated	1,065	2,656	4,507
Electricity cost (CAD $)	$124,558	$310,679	$527,054
Regulatory cost (CAD $)	$11,613	$28,959	$49,124
Delivery cost (CAD $)	$15,882	$32,310	$51,252
Total charging cost for a year (CAD $)	**$152,053**	**$371,947**	**$627,430**
Diesel cost for a year (CAD $)*	$459,686	$773,446	$1,199,593
Diesel cost for a year with cap & trade ($CAD)	$483,557	$813,611	$1,261,889
Benefits (CAD $)	**$307,633**	**$401,499**	**$572,163**
Benefits (CAD $) if cap & trade	**$331,504**	**$441,664**	**$634,459**

* at $0.9116/L based on London Transit's average fuel price over the last 10 years
** with a current carbon price of $18/TCO2e

Questions?

Additional Q & A

- **SOC buffer** :
  - Slow charging: operates between 10-90 % SOC (current state of the technology)
  - Fast charging: operates between 5-95% SOC (assume technology improvements and future development)
- 150kW charger is assuming "at garage"
  - Note: we do not model the energy consumption of the bus between the terminal station and the depot (dead heading)
- The costs shown in the tables are operating costs for the route (including every buses in the fleet), but not inclusive of maintenance savings (which is a separate economic model)