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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Route "7" map (28.6 km RT)

Routes and duty cycles





Route "L" map (29.2 km RT)	Route stat	istics			
Arva	_	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		London route "L"	29.2	~ 70	
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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...



E-bus energy consumption and SOC

calculations

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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



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Key variables affecting the energy consumption

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

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Ebus energy consumption and charging power calculatio	ns	State o Proterr	of Charge ra (660 k	: (SOC Wh)	C): Ro	oute "Z	7" (28	8.6 kn	n RT)		
Llood in house Metleh and Duthen code				S	South to We	est		v	Vest to Sou	ıth	
 Used in-house Matiab and Python code Physical characteristics of fully electric 60ft New Flyer (2019) and a 60 ft Proterra (2020) 				kWh	Total	SOC at route end		kWh	Total	SOC at route end	
 Accounted for variation in topography Regenerative braking power split: 35% 				per km	kwn used	5 % buffer	10% buffer	per km	kwn used	5 % buffer	10 % buffer
 Constant accessory draw Heavy duty cycle: 26,000 W Modium duty cycle: 13,000 W 			Light duty	0.6	8.62	93.6%	88.6%	0.57	8.24	93.7%	88.7%
 Light duty cycle: 0 W 			Medium duty	1.79	25.67	90.9%	85.9%	1.79	25.78	90.9%	85.9%
• Maximum passenger number : 160 (\sim 60 seats and \sim 60 standees)			Heavy duty	3.3	47.44	87.4%	82.4%	3.26	46.93	87.5%	82.5%
			Note: Ideal batt	tery initial	SOC = 100)%, 5 % buf	fer initial	SOC = 95%	5, 10 % buf	fer initial S	SOC = 90 %
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State of Charge (SOC): Route "7" (28.6 km RT) New Flyer (640 kWh)

	S	outh to We	st		N	lest to Sou	th	
	kWh	SOC at rout end Total		t route nd	kWh	Total	SOC a er	t route nd
	per km	kWh used	5 % buffer	10% buffer	per km	kWh used	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 bat	tery initial	SOC = 100	%, 5 % buf	fer initial s	SOC = 95%	, 10 % buf	fer initial S	OC = 90 9

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

	East t	o North dir	ection		North to Easts direction					
kWh		Total	SOC a er	t route nd	kWh	Total	SOC a er	t route nd		
	per km	used	5 % buffer	10% buffer	per km	kWh used	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 %





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

	East 1 kWh	to North dir Total	ection SOC a er	t route nd	kWh Total per km used	to Easts di Total	rection SOC a er	t route nd
	per km	used	5 % buffer	10% buffer	per km	used	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%
	tonyinitial	SOC - 100	% 5 % hu	ffer initial	SOC = 95%	6 10 % hut	fer initial 9	$SOC = 90^{\circ}$

Charging infrastructure simulation

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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

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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%.

Energy from the grid (kWh) 583.1	Number of runs (roundtrips) without charging	Overnight/at- garage charging time (hours)	Energy from the grid (kWh)
583.1	31	4.2	568.0
	•	4.2	550.0
577.4	10	4.2	569.2
558.6	5	4.1	552.9
	558.6	558.6 5	558.6 5 4.1

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

Notes:		Ea	st to Nort	h direction		North to East direction				
Ideal charging: the energy from the grid goes straight to the		ldeal cha 100 %	rging %	Typical ef 86	ficiency %	ldeal cha 100	arging %	Typical e 86	fficiency %	
battery Typical efficiency: 86% of the energy from		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)	
the grid goes to the battery (91% charger efficiency 95 % battery	Light duty	0.86	8.63	1.0	7.48	0.82	8.25	0.95	7.16	
efficiency).	Medium duty	2.57	25.69	2.97	22.29	2.58	25.8	2.98	22.39	
Range of operation: SOC 10%-90%	Heavy duty	4.74	47.42	5.49	41.14	4.69	46.88	5.42	40.67	

Fast charging





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

Notes:		Ea	st to North	direction		North to East direction					
Ideal charging: the energy from the grid goes straight to the	leal charging: the nergy from the grid bes straight to the		nging %	Typical e 86	fficiency %	ldeal cha 100	arging %	Typical e 86	fficiency %		
battery Typical efficiency: 86% of the energy from		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)		
the grid goes to the battery (91% charger	Light duty	0.84	8.4	0.97	7.29	0.8	8.04	0.93	6.97		
efficiency).	Medium duty	2.53	25.31	2.93	21.96	2.55	25.49	2.95	22.12		
Range of operation: SOC 10%-90%	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:		Ea	st to Nortl	h direction		North to East direction				
Ideal charging: the energy from the grid goes straight to the batton		Ideal charging 100 %		Typical efficiency 86 %		ldeal charging 100 %		Typical efficiency 86 %		
Typical efficiency: 86% of the energy from the grid goes to the		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)	
battery (91% charger efficiency, 95 % battery	Light duty	0.78	7.8	0.9	6.77	0.91	9.15	1.06	7.94	
management system efficiency).	Medium duty	2.56	25.58	2.96	22.19	2.64	26.44	3.06	22.94	
Range of operation: SOC 10%-90%	Heavy duty	4.96	49.61	5.74	43.04	5.09	50.92	5.89	44.17	

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

Notes:		East to North direction				North to East direction				
Ideal charging: the energy from the grid goes straight to the battery		Ideal cha 100	arging %	Typical e 86	fficiency %	ldeal cha 100	arging %	Typical e 86	fficiency %	
Typical efficiency: 86% of the energy from the grid goes to the		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)	
battery (91% charger efficiency, 95 % battery	Light duty	0.76	7.6	0.88	6.59	0.89	8.91	1.03	7.73	
management system efficiency).	Medium duty	2.52	25.22	2.92	21.88	2.61	26.07	3.02	22.62	
SOC 10%-90%	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	Fuel parameters
Vehicle curb weight	19,409	kg	LHV of low sulfur of
Mean passenger weight	75	kg	Diesel density
Maximum passengers	128	-	CO. content of fue
Engine maximum power	246	kW	
Drivetrain efficiency	95	%	*Note: emission factor
Rolling coefficient	Provided by OEM	-	of diesel in heavy-du

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
ote: emission factors for mob diesel in heavy-duty vehicles,	ile fuel co see [2]	mbustion

 [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

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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

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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)			Sample ro schedule	ute "7" wo	eekday	Total # round trips/day: Weekday: 108, Saturday: 108, Sunday: 96		
				West to South		South to West		
Rapid Transit Operating Schedule Information The "7" Corridor will operate on a 10-minute frequency during the following periods			Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)
Monday – Saturday from 6am to midnight (18 hou	rs of operation)		6:00	6:35	5	6:00	6:35	5
Sunday & Stat Holidays from 7am to 11pm (16 hours of operation)			6:10	6:45	min 5	6:10	6:45	5
			6:20	6:55 - 1	390	6:20	6:55	5
Monday – Saturday from 6am to midnight (18 hou		6:30	eBHSsenc	5 5	6:30	7:05	5	
Sunday & Stat Holidays from 7am to 11pm (16 hours of operation)			6:40	freque.	5	6:40	7:15	5
			6:50	7:25	5	6:50	7:25	5
Stop at the ter	minal station: 5 min		7:00	7:35	5	7:00	7:35	5
			7:10	7:45	5	7:10	7:45	5
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Sample route "L" weekday	Total # round trips/day: Weekday: 216,		Required n	umber of bu	ises if slow (harging	is used: Ro	outes "7" & "I
schedule	Saturday: 216, Sunday: 192							
West to South	South to West		Minimum require	ed for the schedule	, 1			
Wonderland & White Oaks STOP time (min)	White Oaks Wonderland & STOP time (min)		to i diese		NI	umber of 60ft ro	quired to fully aloo	trify the route
Oxford (arrive)	(starts) Oxford						iquired to fully elec	the route

Sample ro	ute "L" we	екаау	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		6:10	6:45	5	
	5m	IIII Feo. SA				
6:40	eBus Pency	5 enci	6:40	7:15	5	
6:45	freq.20	5	6:45	7:20	5	
6:50	7:25	5	6:50	7:25	5	









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

		Number of 60ft required to	fully electrify the route
Route 7 – less		Proterra	New Flyer
frequent	Light duty	8 [vs. 8]	8
	Medium duty	8	8
	Heavy duty	12	12
inimum required for the s	chedule, 1		
inimum required for the so to 1 diesel replaceme	chedule, 1	Number of 60ft required to	o fully electrify the route
inimum required for the set to 1 diesel replacement	chedule, 1	Number of 60ft required to Proterra	o fully electrify the route New Flyer
inimum required for the second to 1 diesel replacement Route L – more frequent	chedule, 1 ent Light duty	Number of 60ft required to Proterra 16 [vs. 16]	o fully electrify the route New Flyer 16
inimum required for the se to 1 diesel replaceme Route L – more frequent	Light duty Medium duty	Number of 60ft required to Proterra 16 [vs. 16] 16	o fully electrify the route New Flyer 16 16

Slow charging

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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.

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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	a (660 k\	Nh)	Charging costs:	Route "7" (28.6 km RT)) New Fly	yer (640 l	kWh)
Notes:		Light	Medium	Heavy	Notes:		Light	Medium	Heavy
	Yearly MWh estimated	727	2,220	4,072		Yearly MWh estimated	708	2,189	4,030
Rates: General Service,	Electricity cost (CAD \$)	\$ 68,098	\$ 207,808	\$ 381,163	Rates: General Service,	Electricity cost (CAD \$)	\$ 66,321	\$204,981	\$377,286
Greater Than 50 kW with	Delivery cost (CAD \$)	\$ 96,005	\$ 132,007	\$ 240,012	Greater Than 50 kW with	Delivery cost (CAD \$)	\$ 96,005	\$132,007	\$240,012
no interval meter rates Assumed 1 slow charger	Regulatory cost (CAD \$)	\$ 7,933	\$ 24,203	\$ 44,391	no interval meter rates	Regulatory cost (CAD \$)	\$ 7,726	\$ 23,874	\$ 43,939
Assumed 1 slow charger	Total charging cost for a year (CAD \$)	\$ 172,036	\$ 364,017	\$ 665,566	Assumed 1 slow charger	Total charging cost for a year (CAD \$)	\$170,052	\$360,861	\$661,237
Assumed 1 slow charger per bus Total cost per route	Diesel cost for a year (CAD \$)	\$ 235,268	\$ 431,601	\$ 688,558	per bus	Diesel cost for a year (CAD \$)	\$235,268	\$431,601	\$688,558
Total cost per route	Benefits (CAD \$)	\$ 63,232	\$ 67,583	\$ 22,992	Total cost per route	Benefits (CAD \$)	\$ 65,216	\$ 70,740	\$ 27,321
(inclusive of all buses)	Carbon price electricity (CAD \$) with $50/TCO2e$	\$ 1,601	\$ 4,884	\$ 8,959	(inclusive of all buses)	Carbon price electricity (CAD \$) with \$50/TCO2e	\$ 1,559	\$ 4,818	Heavy 4,030 \$377,286 \$240,012 \$43,939 \$661,237 \$688,558 \$27,321 3 \$ 8,868 \$ 37,833 \$ 56,286 10 years
	Carbon price diesel (CAD \$) with \$50/TCO2e	\$ 12,927	\$ 23,714	\$ 37,833		Carbon price diesel (CAD \$) with \$50/TCO2e	\$ 12,927	Medium Heavy 2,189 4,030 1 \$204,981 \$377,286 5 \$132,007 \$240,012 6 \$23,874 \$43,936 2 \$360,861 \$661,237 8 \$431,601 \$688,556 6 \$70,740 \$27,32* 9 \$4,818 \$8,866 27 \$23,714 \$37,83 84 \$89,636 \$56,28 price over the last 10 years \$400,200	\$ 37,833
	Benefits with Carbon price (CAD \$)	\$ 74,558	\$ 86,413	\$ 51,866		Benefits with Carbon price (CAD \$)	\$ 76,584	\$ 89,636	\$ 56,286
	* at \$0.9116/L based on London Transit's a	verage fuel price	over the last 10	years	* 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	a (660 kV	Vh)
Notes:		Light	Medium	Heavy
	Yearly MWh estimated	1,461	4,485	8,677
Rates: General Service,	Electricity cost (CAD \$)	\$136,761	\$419,816	\$ 812,248
Greater Than 50 kW with	Delivery cost (CAD \$)	\$192,010	\$264,013	\$ 504,025
no interval meter rates	Regulatory cost (CAD \$)	\$ 15,929	Medium Heavy 4,485 8,677 i1 \$419,816 \$ 812,248 0 \$264,013 \$ 504,025 :9 \$ 48,892 \$ 94,592 :0 \$732,722 \$1,410,865 :6 \$861,731 \$1,440,685 :6 \$ 9,867 \$ 19,097 :23 \$ 47,348 \$ 79,155	\$ 94,592
Assumed 1 slow charger	Total charging cost for a year (CAD \$)	\$344,700	\$732,722	\$1,410,865
per bus	Diesel cost for a year (CAD \$)	\$475,436	\$861,731	Heavy edium Heavy ,485 8,677 19,816 \$ 812,248 64,013 \$ 504,025 48,892 \$ 94,592 32,722 \$1,410,865 61,731 \$1,440,685 29,009 \$ 29,820 9,867 \$ 19,091 47,348 \$ 79,159 66,490 \$ 89,887
Total cost per route	Benefits (CAD \$)	\$ 130,736	\$ 129,009	\$ 29,820
(inclusive of all buses)	Carbon price electricity (CAD \$) with \$50/TCO2e	\$ 3,214	\$ 9,867	Medium Heavy 4,485 8,677 \$419,816 \$ 812,248 \$264,013 \$ 504,025 \$48,892 \$ 94,592 \$732,722 \$1,410,865 \$861,731 \$1,440,685 \$ 9,867 \$ 19,091 \$ 47,348 \$ 79,159
	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:		Light	Medium	Heavy
lleed leeder lleder	Yearly MWh estimated	1,423	4,421	8,588
Rates: General Service.	Electricity cost (CAD \$)	\$133,207	\$413,839	\$ 803,928
Greater Than 50 kW with	Delivery cost (CAD \$)	\$192,010	\$264,013	\$ 504,025
no interval meter rates	Regulatory cost (CAD \$)	\$ 15,515	\$ 48,196	\$ 93,623
Assumed 1 slow charger	Total charging cost for a year (CAD \$)	\$340,732	\$726,048	\$1,401,576
per bus	Diesel cost for a year (CAD \$)	\$475,436	\$861,731	\$1,440,685
Total cost per route	Benefits (CAD \$)	\$ 134,704	\$ 135,683	\$ 39,109
(inclusive of all buses)	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



	Charging costs	: Route ``7″ (28.6 km RT)) Proterr	a (660 k\	Nh)
	Note:		Light	Medium	Heavy
	Used London Hydro Rates: Year	Yearly MWh estimated	761	2,321	3,900
	General Service, Greater	Electricity cost (CAD \$)	\$ 88,882	\$271,178	\$455,661
	interval meter rates	Regulatory cost (CAD \$)	\$ 8,295	\$ 25,302	\$ 42,513
Eact charging		Delivery cost (CAD \$)	\$ 14,572	\$ 35,880	\$ 57,541
rast charging	Diesel at \$0.9116/L based on London Transit's	Total charging cost for a year (CAD \$)	\$111,749	\$332,360	\$555,715
	average fuel price over the	Diesel cost for a year (CAD \$)	\$235,268	\$431,601	\$688,558
	last 10 years	Benefits (CAD \$)	\$123,519	\$ 99,241	\$132,843
	Total cost per route	Carbon price electricity (CAD \$) with \$50/TCO2e	\$ 1,674	\$ 5,106	\$ 8,580
	(inclusive of all buses)	Carbon price diesel (CAD \$) with \$50/TCO2e	\$ 33,938	\$ 62,259	\$ 99,326
		Benefits with Carbon price (CAD \$)	\$ 155,782	\$ 156,394	\$ 223,588
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Charging costs – Route "7" (28.6 km RT) New Flyer (640 kWh)

Note:		Light	Medium	Heavy
Used London Hydro	Yearly MWh estimated	741	2,289	3,900
Rates: General Service,	Electricity cost (CAD \$)	\$ 86,562	\$267,485	\$455,661
Greater Than 50 KW with	Regulatory cost (CAD \$)	\$ 8,079	\$ 24,958	\$ 42,513
no interval meter rates	Delivery cost (CAD \$)	\$ 14,287	\$ 35,495	\$ 57,541
Diesel at \$0.9116/L	Total charging cost for a year (CAD \$)	\$108,927	\$327,937	\$555,715
based on London Transit's	Diesel cost for a year (CAD \$)	\$235,268	\$431,601	\$688,558
the last 10 years	Benefits (CAD \$)	\$126,341	\$103,664	\$132,843
Total cost per route	Carbon price electricity (CAD \$) with \$50/TCO2e	\$ 1,630	\$ 5,036	\$ 8,580
(inclusive of all buses)	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)







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lote:		Light	Medium	Heavy	Note:		Light	Medium	Heavy
Used London Hydro	Yearly MWh estimated	1,515	4,652	7,737	Used London Hydro	Yearly MWh estimated	1,476	4,585	7,737
Rates: General Service,	Electricity cost (CAD \$)	\$177,208	\$544,009	\$ 904,952	Rates: General Service,	Electricity cost (CAD \$)	\$172,602	\$536,263	\$ 904,9
Diesel at \$0.9116/L	Regulatory cost (CAD \$)	\$ 16,520	\$ 50,704	\$ 84,343	Greater Than 50 KW with no interval meter rates	Regulatory cost (CAD \$)	\$ 16,090	\$ 49,983	\$ 84,3
	Delivery cost (CAD \$)	\$ 20,892	\$ 53,077	\$ 84,377		Delivery cost (CAD \$)	\$ 20,445	\$ 52,369	\$ 84,3
	Total charging cost for a year (CAD \$)	\$214,620	\$647,790	\$1,073,671	Diesel at \$0.9116/L based on London Transit's	Total charging cost for a year (CAD \$)	\$209,138	\$638,614	\$1,073,6
verage fuel price over	Diesel cost for a year (CAD \$)	\$475,436	\$861,731	\$1,440,685	average fuel price over	Diesel cost for a year (CAD \$)	\$475,436	\$861,731	\$1,440,6
he last 10 years	Benefits (CAD \$)	\$260,816	\$213,941	\$ 367,014	the last 10 years	Benefits (CAD \$)	\$266,298	\$223,117	\$ 367,0
otal cost per route	Carbon price electricity (CAD \$) with	\$ 3,333	\$ 10,234	\$ 17,021	Total cost per route	Carbon price electricity (CAD \$) with \$50/TCO2e	\$ 3,247	\$ 10,087	\$ 17,0
inclusive of all buses)	Carbon price diesel (CAD \$) with \$50/TCO2e	\$ 68,583	\$124,306	\$ 207,821	(inclusive of all buses)	Carbon price diesel (CAD \$) with \$50/TCO2e	\$ 68,583	\$124,306	\$ 207,8
	Benefits with Carbon price (CAD \$)	\$326,066	\$328,013	\$ 557,814		Benefits with Carbon price (CAD \$)	\$331,634	\$337,336	\$ 557,8

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





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

Iotal electricity production (2015): 159.7 TWh
Total emission (2015): 7.1 MT CO2e

The emission is calculated as 0.044 Tonne CO2e/MWh



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
CO2e from electricity (Tonne)	33	102	172
CO2e from diesel (Tonne)*	679	1245	1987
CO2e 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 CO2e/L

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

Fast charging

	Light	Medium	Heavy
Yearly electricity estimated (MWh)	741	2,289	3,900
Yearly diesel use (L)	258,082	473,454	755,329
CO2e from electricity (Tonne)	33	101	172
CO2e from diesel (Tonne)*	679	1245	1987
CO2e 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 CO2e/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
CO2e from electricity (Tonne)	67	205	340
CO2e from diesel (Tonne)*	1372	2486	4156
CO2e 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 CO2e/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"



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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)





	West to South			South to West	:			West to South			South to Wes	t
Wonderland & Oxford (starts)	White Oaks (arrive)	STOP time (min)	White Oaks (starts)	Wonderland & Oxford (arrive)	STOP time (min)	W	/onderland & 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		6:00	6:35	5	6:00	6:35	5
6:10	6:45	nin	6:10	6:45	5		6:05	6:40	5	6:05	6:40	5
6:20	B:55 10	954	6:20	6:55	5		6:10	6:45	COS	6:10	6:45	5
6:30 🧧	BUSTONCY	5 ncv	6:30	7:05	5			n-5min	Teo. A			
6:40	freque:15	5	6:40	7:15	5		6:40	SUS DI 15V	She She	6:40	7:15	5
6:50	7:25	5	6:50	7:25	5		6:45	requerter 7:20	5	6:45	7:20	5
7:00	7:35	5	7:00	7:35	5		6:50	7:25	5	6:50	7:25	5
7:10	7:45	5	7:10	7:45	5				-			-

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

	S	outh to W	est		West to South				
	kWh Tota	SOC at route Total end kWh		kWh	Total kWb	SOC a er	t route nd		
	km	used	5 % buffer	10% buffer	km	used	5 % buffer	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)

	S	outh to We	est		V	lest to Sou	outh		
	kWh per	Total kWh	SOC a er	t route nd	kWh per	Total kWh	SOC a er	t route nd	
	km	used	5 % buffer	10% buffer	km	used	5 % buffer	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 %







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 Typical efficiency Worst case Ideal charging Typical efficiency Worst case 100 % efficiency 100 % 86 % efficiency 86 % 71% 71% Charging Energy Chargin Energy Chargin Energy Endpoint Energy Chargin Energy Chargin Energy Recall: 40 fts from charging time (min) from from from from from a time a time a time a time the grid the grid (min) the grid time (min) the grid (min) the grid (min) the grid (min) (kWh) (kWh) (kWh) (kWh) (kWh) (kWh) Charging infrastructure simulation Light duty 0.77 5.79 6.7 1.09 0.73 5.45 0.84 6.31 1.02 7.68 0.89 8.16 Medium 1.91 14.31 2.21 16.55 2.69 20.15 1.91 14.32 2.21 16.56 2.69 20.16 duty Heavy duty 23.07 3.08 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 CUTRIC

charger

Light duty

Medium

Heavy duty

efficiency)

duty

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East to North direction

Chargin

g time

(min)

0.8

2.15

3.73

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

Typical efficiency

86 %

Energy

from

the grid

(kWh)

5.98

16.15

28.0

Ideal charging

100 %

Energy

from

the arid

(kWh)

5.17

13.96

24.21

Charging

time (min)

0.69

1.86

3.23

CUTRI

Worst case

efficiency

71%

Energy

from

the arid

(kWh)

8.6

20.85

34.88

Chargin

g time

(min)

1.15

2.78

4.65

North to East direction

Chargin

g time

(min)

0.94

2.28

3.82

Ideal charging

100 %

Energy

from

the arid

(kWh)

6.11

14.8

24.76

Endpoint

charging

time (min)

0.81

1.97

3.3

Typical efficiency

86 %

Energy

from

the grid

(kWh)

7.06

17.13

28.64

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

		So	uth to Wes	t direction			West to South direction					
	Ideal charging 100 %		Typical efficiency 86 %		Worst case efficiency 71%		Ideal charging 100 %		Typical efficiency 86 %		Wors effic 71	t case iency I%
	Charging time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Chargin g 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



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

Worst case

efficiency

71%

Energy

from

the arid

(kWh)

7.28

19.66

34.1

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

Chargin

g time

(min)

0.97

2.62

4.55



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

		Ea	st to North	direction			North to East direction					
	ldeal cha 100	arging %	Typical e 86	fficiency %	Wors effici 71	t case iency I%	Ideal cha 100	arging %	Typical e 86	efficiency %	Wors effici 71	t case ency %
	Charging time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Endpoint charging time (min)	Energy from the grid (kWh)	Chargin g time (min)	Energy from the grid (kWh)	Chargin g 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

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

		Light	Medium	Heavy
	Yearly MWh estimated	507	1,290	2,077
Note:	Electricity cost (CAD \$)	\$59,258	\$150,692	\$242,669
	Regulatory cost (CAD \$)	\$5,531	\$14,062	\$22,642
Used London Hydro Rates:	Delivery cost (CAD \$)	\$11,058	\$21,625	\$32,477
Than 50 KW with no	Total charging cost for a year (CAD \$)	\$75,848	\$186,378	\$297,789
interval meter rates	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

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

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

		Light	Medium	Heavy
	Yearly MWh estimated	535	1,334	2,130
	Electricity cost (CAD \$)	\$62,475	\$155,913	\$248,837
Note:	Regulatory cost (CAD \$)	\$5,832	\$14,549	\$23,218
Used London Hydro Rates:	Delivery cost (CAD \$)	\$11,468	\$22,271	\$33,210
General Service, Greater Than 50 KW with no	Total charging cost for a year (CAD \$)	\$79,775	\$192,732	\$305,264
interval meter rates	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





		Light	Medium	Heavy			Light	Medium	
Note:	Yearly MWh estimated	1,009	2,571	4,379	Note: Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates	Yearly MWh estimated	1,065	2,656	
	Electricity cost (CAD \$)	\$117,964	\$300,735	\$512,190		Electricity cost (CAD \$)	\$124,558	\$310,679	
	Regulatory cost (CAD \$)	\$10,998	\$28,032	\$47,739		Regulatory cost (CAD \$)	\$11,613	\$28,959	
Used London Hydro Rates: General Service, Greater Than 50 KW with no interval meter rates	Delivery cost (CAD \$)	\$15,230	\$31,416	\$49,948		Delivery cost (CAD \$)	\$15,882	\$32,310	
	Total charging cost for a year (CAD \$)	\$144,192	\$360,182	\$609,876		Total charging cost for a year (CAD \$)	\$152,053	\$371,947	
	Diesel cost for a year (CAD \$)*	\$459,686	\$773,446	\$1,199,593		Diesel cost for a year (CAD \$)*	\$459,686	\$773,446	
	Diesel cost for a year with cap & trade (\$CAD)	\$483,557	\$813,611	\$1,261,889		Diesel cost for a year with cap & trade (\$CAD)	\$483,557	\$813,611	
	Benefits (CAD \$)	\$315,494	\$413,264	\$589,717		Benefits (CAD \$)	\$307,633	\$401,499	
	Benefits (CAD \$) if cap & trade	\$339,365	\$453,429	\$652,013		Benefits (CAD \$) if cap & trade	\$331,504	\$441,664	
	* 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					* at \$0.9116/L based on London Transit ** with a current carbon price of \$18/T	's average fuel p CO2e	rice over the last	t 10

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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)



