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Electrification Opportunities in the Medium- and Heavy-Duty Vehicle Segment

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Summary

The medium- and heavy-duty (MD/HD) vehicle segment is a large emitter of greenhouse gas emissions. It will require drastic emissions reductions to realize a net-zero carbon future. Twelve short feasibility studies were conducted to evaluate the merits of battery electric or hydrogen fuel cell alternatives to conventional city buses, school buses, courier vehicles (step vans), refuse trucks, long-haul trucks and construction vehicles. These 'clean transportation alternatives' were evaluated on practicality, economics, and emission reduction in comparison to their conventional counterparts. Conclusions were drawn on which use cases would be best suited for accelerating the transformation of the MD/HD segment.

Keywords: medium-duty, heavy duty, electric vehicle, fuel cell vehicle, business model

1 Introduction

Medium- and heavy-duty (MD/HD) vehicles are used on-road to transport people and goods (buses, trucks) and off-road in for instance the construction, mining, agriculture and forestry sectors. Together, they cause over 40% of the total greenhouse gas (GHG) emissions of the transportation sector in Canada [1]. MD/HD vehicles mainly use diesel as their fuel, causing additional emissions of Criteria Air Contaminants (CACs) that impact health.

The government of Canada recently announced a new target for GHG emissions: By 2050, Canada should have net-zero carbon emissions [2]. This new target will require an almost total emission reduction of all sectors, including transportation.

The large majority of all electricity in Canada is generated from non-emitting sources. Electrification of transportation could therefore result in very significant GHG emission reductions, and could be a pathway towards the goal of net-zero carbon emission in 2050.

Over the last decade, the sales of electric passenger vehicles in Canada have increased to over 2.5% of all light-duty vehicle sales [3], and the fleet of electric passenger vehicles has grown to around 150,000 vehicles. However, the electrification of the MD/HD vehicle segment lags 5-10 years behind the developments in the passenger vehicle segment. There are currently a few hundred electrified MD/HD vehicles on the road (mainly electric buses), but the market entries of battery electric and hydrogen fuel cell variants of long haul truck are expected for the near future. While battery electric variants of passenger vehicles seem capable of providing the required operational characteristics for all or most passenger vehicles, there is a lack of knowledge on which clean technology (battery electric or hydrogen fuel cell) would be best suited for MD/HD vehicles. The MD/HD vehicle segment is very diverse with many different vehicle types and applications, which hinders a segment-wide approach to emission reduction. Instead, a more detailed evaluation of emission reduction options per use case is required.

2 Methodology

Twelve short, high-level feasibility studies were conducted to evaluate the practicality, economics and emission reduction potential of battery electric and hydrogen fuel cell alternatives to seven types of conventional diesel MD/HD vehicles. Details on the vehicles and the approximate size of their fleets are given in Table 1. Table 2 presents the specific clean transportation variants evaluated, and indicates the approximate stage of development for each use case.

Table 1: MD/HD vehicles evaluated and estimated fleet sizes in Canada

	Weight class	Fleet size
Courier vehicle	4-6	7,000 [4-6]
Refuse truck	8	14,000 [7]
Long-haul truck	8	200,000 [8]
School bus	7	50,000 [9-10]
City bus	8	30,000 [11]
Construction vehicles		
Small excavator	N/A	Unknown
Large excavator	N/A	Unknown

Table 2: Vehicle use cases and clean technologies evaluated, stage of development

	Battery electric	Stage of development	Hydrogen fuel cell	Stage of development
Courier vehicle	X	Pilot		
Refuse truck	X	Pilot	X	Prototype
Long-haul truck	X	Prototype	X	Prototype
School bus	X	Pilot		
City bus	X	Pilot/Commercial	X	Prototype
Small excavator	X	Prototype	X	Concept
Large excavator	X	Concept	X	Concept

A clean transportation alternative was deemed practical when the vehicle can be used in the same way as the conventional diesel variant with none or only minor adjustments to its operation. The assessment included both the driving and the recharging or refueling of the vehicle, to ensure it will be ready for its next working period.

The economic evaluation of the battery electric and hydrogen fuel cell vehicles focussed on determining the potential savings in annual operational costs (for fuel and maintenance) in comparison to conventional diesel variants. Unfortunately, it was impossible to expand this economic evaluation to include the calculation of a realistic payback time for these vehicles, because many vehicles are still at the stage of concept, prototype or first pilot. For these vehicles, either no information was available on their purchase price, or their price was very high due to low-volume production, not realistic for future large-scale deployment, nor suitable for comparison to the price of mas-produced diesel vehicles.

The prices for fuel and electricity used in the twelve feasibility studies are presented in Table 3. Different electricity prices were determined for vehicles using different power levels for their recharging. Given the goal to almost completely reduce GHG emissions, hydrogen was assumed to be produced through electrolysis using clean electricity. The price for hydrogen reflects the current cost level. A sensitivity study into the impact of future, lower hydrogen prices on the results for on-road MD/HD fuel cell vehicles is included at the end of this paper.

GHG emissions were evaluated using a value of 2.7 kg CO_2eq/L for diesel, an average electricity emission intensity for Canada of 0.15 kgCO_2eq/kWh, and an associated emissions of 7.9 kgCO_2eq/kg of hydrogen using this electricity.

Table 3: Fuel costs and electricity costs

Fuel costs ($/L)	1.20
Electricity costs (Level 2 – up to 20 kW, $/kWh)	0.10
Electricity costs (Level 3 – 50 kW, $/kWh)	0.35
Electricity costs (Level 3 – 300 kW, $/kWh)	0.50
Hydrogen ($/kg)	15

3 Results of Short Feasibility Studies

3.1 Perspective on the results

When bringing together scarce information on many different MD/HD use cases, and evaluating clean transportation alternatives that are in quite different stages of development, it is inevitable that the data set used will vary significantly in level of detail and will span the full range from real-world operational measurements to assumed performance values. The results of the twelve short feasibility studies should therefore be regarded as an indication of use cases that are more or less favourable for electrification, rather than a fully consistent set of precise numerical results.

3.2 Buses

City buses are at the forefront of MD/HD electrification, with pilot projects underway or planned in many Canadian cities [12]. Various recharging methods for electric city buses (overnight, end-of-route, mid-route) are being investigated. Electric buses seem close to being able to fulfil the same driving demands as most diesel buses, as several transit authorities have announced plans to stop buying diesel buses by the middle of this decade [13-18].

In this study, an electric city bus with an annual driving distance close to the reported average of 60,000 km [19] and with overnight recharging at 50 kW was evaluated. The electric city bus needed 1.2 kWh/km driven [13, 20], compared to 78L/100km for a diesel city bus [21]. Maintenance costs of electric buses were 40% lower than those of diesel buses [20].

Hydrogen fuel cell buses were assumed to consume 10 kg of hydrogen per 100 km [22-23] and to have the same maintenance costs as battery electric buses.

School buses generally drive about 100 km/day [9, 24], much less than city buses, and are parked for much longer periods overnight. This will allow electric school buses to use low-cost Level 2 recharging, instead of the more expense fast charging needed by city buses. Similar to electric city buses, electric school buses were assumed to need 40% less maintenance than diesel school buses.

The results of the economic evaluation (see Table 4) indicate that battery electric city buses and school buses can provide significant reductions in annual operating costs, benefiting from large savings on both fuel costs and maintenance costs. These outcomes seems promising to potentially enabling lower total cost of ownership values in the future.

Hydrogen fuel cell city buses do not create operational cost savings at the current price of hydrogen.

Both battery electric buses and hydrogen fuel cell buses drastically reduce emissions compared to diesel buses.

Table 4: Annual results for diesel, battery electric and hydrogen fuel cell buses

	Diesel school bus	Electric school bus	Diesel city bus	Electric city bus	H2 fuel cell city bus
Distance driven (km)	18,000	18,000	60,000	60,000	60,000
Fuel consumption (L/100 km)	34		78		
Fuel consumption (L)	6,120		46,800		
Electricity cons. (kWh/km)		0.88		1.2	
Electricity consumption (kWh)		15,840		72,000	
H2 consumption (kg/100 km)					10
H2 consumption (kg)					6,000
Fuel price ($/L, $/kWh, $/kg)	1.20	0.10	1.20	0.35	15
Fuel costs ($)	7,344	1,584	56,160	25,200	90,000
Maintenance costs ($)	12,780	9,000	50,000	30,000	30,000
Operational costs ($)	20,124	10,584	106,160	55,200	120,000
Cost saving ($)		9,540		50,960	-13,840
Cost savings (%)		47%		48%	-13%
GHG emissions (tonnes CO_2eq)	16.5	2.4	126.4	10.8	47.4
Em. Reduction (tonnes CO_2eq)		14.1		115.6	79.0
Em. Reduction (%)		86%		91%	62%

3.3 Trucks

There is great momentum in the development of electrified trucks, with for instance Tesla [25] and Nikola [26] being close to delivering commercial products in the long-haul category. Several large courier companies are experimenting with electrified step vans [27-32], and pilots are being conducted with electrified refuse trucks [33-35]. With very limited on-road results available, it was not possible to do a detailed evaluation of the practicality of these clean transportation use cases. Instead, a high-level assessment was made.

Courier vehicles (step vans) generally have fixed routes and predictable operating schedules with return-to-base operation. Their average daily distance of close to 100 km [24] and long overnight parking period make low-cost Level 2 recharging possible. Maintenance costs of electric step vans were estimated to be 60% of those of similar diesel vehicles [36-37]. Vehicle performance numbers for diesel and electric variants were taken from [38] and [39], respectively.

Refuse trucks collecting garbage in urban areas drive 50-200 km/day [35, 40], with up to 1,000 stops [41]. This mode of operation results in a low vehicle efficiency (83L/100 km) [21], and significant maintenance costs. Electrified refuse trucks have the potential for improved vehicle performance and reduced maintenance costs through the application of regenerative braking. Performance values for the electric refuse truck were based on [35], while performance characteristics for hydrogen fuel cell refuse trucks were not available and were estimated based upon the ratio between performance values for other vehicle types.

Diesel long haul trucks on average consume 39 L/100 km [21] and drive 150,000 km/year [42-43]. Performance data for battery electric and hydrogen fuel cell long haul trucks were scarce and had to be estimated, taking into account that new offerings reflect 'best in class' performance values, which are not directly comparable to the 'average' performance value available for conventional diesel trucks. Electrified long haul truck are expected to have only half of the maintenance costs of diesel truck [43]. Although the large battery pack of a battery electric long haul trucks will reduce their payload capacity, this was not seen as a show stopper for this application, as there are many companies trucking goods that are volume constrained, rather than weight constrained.

Significant reductions in operational costs were predicted for the step van and the refuse truck (see Table 5). Long-haul trucks on diesel still had the lowest operational costs, mainly due to the high price for ultra-fast charging and hydrogen.

All electrified vehicles achieved substantial to drastic emission reductions.

Table 5: Annual results for diesel, battery electric and hydrogen fuel cell trucks

	Courier/step van		Refuse truck			Long-haul truck		
	Diesel	Elec.	Diesel	Elec.	Hydr.	Diesel	Elec.	Hydr.
Distance driven (km/year)	24,000	24,000	25,000	25,000	25,000	150,000	150,000	150,000
Fuel cons. (L/100 km)	32		84			39		
Fuel cons. (L)	7,680		21,000			58,500		
Elec. cons. (kWh/km)		0.8		2.5			2	
Electricity cons. (kWh)		19,200		62,500			300,000	
H2 cons. (kg/100 km)					21.0			10
H2 consumption (kg)					5,250			15,000
Fuel ($/L, $/kWh, $/kg)	1.20	0.10	1.20	0.35	15	1.20	0.50	15
Fuel costs ($)	9,216	1,920	25,200	21,875	78,750	70,200	150,000	225,000
Maintenance costs ($)	4,800	2,880	15,000	3,000	3,000	18,700	9,400	9,400
Operational costs ($)	14,016	4,800	40,200	24,875	81,750	88,900	159,400	234,400
Cost saving ($)		9,216		15,325	-41,550		-70,500	-145,500
Cost savings (%)		66%		38%	-103%		-79%	-164%
GHG emissions (tCO_2eq)	20.7	2.9	56.7	9.4	41.5	158.0	45.0	118.5
Em. Reduction (tCO_2eq)		17.9		47.3	15.2		113.0	39.5
Em. Reduction (%)		86%		83%	27%		72%	25%

3.4 Construction Vehicles

There are many types and sizes of construction vehicles, such as compact rollers, dump trucks, backhoe loaders, motor graders, bulldozers, and excavators. Excavators are the most abundant type of construction vehicle. A small excavator (based upon the CAT 304E3 CR model [44]) and a large excavator (based upon a CAT 390F L [44]) were therefore taken as examples for the evaluation of the electrification potential of construction vehicles.

For each type of excavator, the characteristics of the battery electric and hydrogen fuel cell alternatives were determined based upon assumed energy conversion efficiencies. Given the highly intermittent mode of operation of excavators, a 20% efficiency was used for the diesel engine, an 80% efficiency for the battery electric excavator, and 40% for the hydrogen fuel cell one. Electrified excavators were assumed to have 20% lower maintenance costs than diesel excavators.

Table 6 presents result for annual operational costs savings and GHG emissions reduction for the battery electric and hydrogen fuel cell alternatives. Construction vehicles need to be refuelled on-site, regardless of the type of fuel used. This creates additional challenges and associated higher costs for electrified versions. Consequently, only the small battery electric excavator had significant operational cost savings.

Table 6: Annual results for diesel, electric and hydrogen fuel cell excavator variants

	Small excavator			Large excavator		
	Diesel	Electric	Hydrogen	Diesel	Electric	Hydrogen
Equivalent full load hours	1,000	1,000	1,000	1,000	1,000	1,000
Fuel consumption (L/hr)	2.55			39.6		
Fuel consumption (L)	2,550			39,600		
Electricity cons. (kWh/hr)		6.3			98	
Electricity consumption (kWh)		6,300			98,000	
H2 consumption (kg/hr)			0.38			5.9
H2 consumption (kg)			380			5,900
Fuel price ($/L, $/kWh, $/kg)	1.20	0.35	18	1.20	0.50	18
Fuel costs ($)	3,060	2,205	6,840	47,520	49,000	106,200
Maintenance costs ($)	1,900	1,520	1,520	10,200	8,160	8,160
Operational costs ($)	4,960	3,725	8,360	57,720	57,160	114,360
Cost saving ($)		1,235	-3,400		560	-56,640
Cost savings (%)		25%	-69%		1%	-98%
GHG emissions (tonnes CO_2eq)	6.9	0.9	3.0	106.9	14.7	46.6
Em. Reduction (tonnes CO_2eq)		5.9	3.9		92.2	60.3
Em. Reduction (%)		86%	56%		86%	56%

3.5 Sensitivity for the Price of Hydrogen

The economic results for the hydrogen fuel cell MD/HD vehicles seems to be impacted by the current high price of 15 $/kg of hydrogen used in the evaluations. The price of hydrogen is expected to decrease over the next decade(s) through both technology development and an increase of the scale of production. [45-46], for instance, indicates a future price in the range of 1-5 $/kg for large-scale, on-site production. Additionally, a further penetration of low-cost renewable power generation may reduce electricity costs and consequently hydrogen production costs.

Figure 1 displays the impact a lower hydrogen price would have on the operational cost savings for hydrogen fuel cell city buses, refuse trucks and long haul trucks. The results of Figure 1 should be used with care because there still is considerable uncertainty on the actual hydrogen consumption rates of those vehicles.

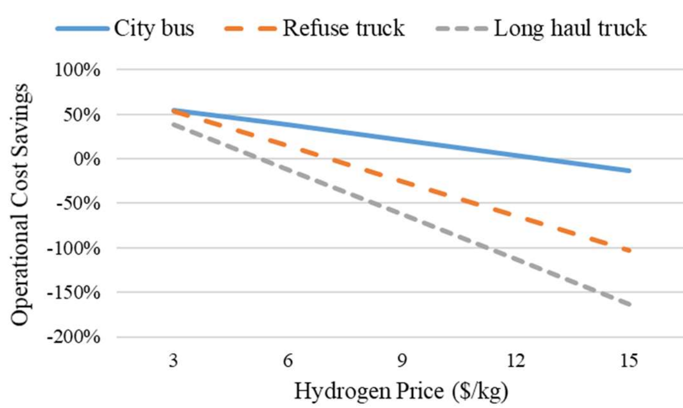

Figure 1: Impact of hydrogen price on operational cost savings of MD/HD fuel cell vehicles in comparison to diesel versions of these vehicles

4 Conclusions

The results of the high-level evaluation of twelve battery electric or hydrogen fuel cell alternatives to conventional diesel MD/HD vehicles broadly indicated a greater potential for operational cost savings and drastic emissions reduction for battery electric vehicles than for hydrogen fuel cell vehicles.

All fuel cell vehicles had higher operating costs than diesel vehicles at the current relatively high price of hydrogen. Lower hydrogen costs in the future could potentially enable operational costs savings for these vehicles.

Battery electric city buses and school buses saved close to 50% on fuel and maintenance costs, providing good prospects on lower total cost of ownership in the future.

The high cost of (ultra-)fast charging is a disadvantage for the larger MD/HD vehicles with intense duty cycles. The electrification of smaller vehicles (step vans) or of school buses (having lower daily distances) is favoured, because they can benefit from cheaper recharging options.

The requirement to deliver the fuel for construction vehicles to the actual construction site is a major challenge for the electrification of this sector.

The results of the twelve feasibility studies should be seen as a first indication of the potential to electrify MD/HD vehicles, rather than a fully consistent set of precise numerical results, because some studies heavily relied on assumptions due to a lack of real-world data. A regular update of these studies with more accurate performance and costing data is recommended.

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