REVIEW OF EXISTING TECHNOLOGIES (VEHICLE FUELS AND DEVICES): APPLICATIONS, BENEFITS AND LIMITATIONS[1]

Andrew Tam
Goods Movement Policy, Ontario Ministry of Transportation
(Disclaimer: The views expressed in this paper are those of the author only)

Introduction

Freight transport is identified as one of the largest contributors to Canada's greenhouse gas (GHG) emissions and air pollution. The share of transportation emissions from freight increased substantively (from 28% in 1990 to 44% in 2015) over 25 years. During this period, the proportional share of emissions from freight trucks, which are mostly diesel-powered, compared with the other freight modes (such as rail) also increased significantly (from 61% in 1990 to 83% in 2015)(1). Achieving meaningful reductions in Canada's emission and air pollution will therefore require a focus on freight trucking in particular.

This paper focuses on fuel efficiency and alternative fuels for heavy-duty road freight vehicles because as GHGs and air pollutants are derived from the burning of fuel, such technologies that directly reduce fuel consumption and emissions are practical mechanisms for the industry, *at least in the short to medium term*. In meeting shipper and consumer demand for more road freight as a result of population and economic growth, carriers base their decisions to adopt available technologies on their bottom-line considerations in addressing increased emissions resulted partly from more truck traffic.

To provide the context, the paper begins by looking at recent statistics on GHG and air pollutant emissions as well as regulatory developments at the federal level in Canada. After setting the parameters for technology selection and review, it identifies a list of alternative fuels and fuel-saving technologies and then focuses the review of some of them, including applications, key benefits and limitations. The paper will conclude with some specific observations and suggestions, drawn from research findings, including cross-jurisdictional program experiences, for accelerating technology adoption in trucking.

Road freight emissions: GHGs and Air Pollutants

Road freight vehicles here refer to on-road heavy-duty trucks powered by diesel. By burning diesel engine fuels, they emit GHGs (mainly CO_2, CH_4/methane and N_20/nitrous oxide) and air pollutants (principal ones are oxides of nitrogen /**NOx** and particulate matter/**PM)**, that contribute to climate change and cause smog or other kinds of air quality degradation. Heavy duty vehicles (HDVs), especially Class 8 line haul tractor-trailer combination trucks, contribute significantly to emissions and are a high-impact area.

GHG emissions - Canada and Ontario (Statistics from National Inventory Report 2016)

In Canada, the transportation sector accounts for about a quarter of total GHG emissions, making it the 2nd largest contributor of GHG emissions by economic sector with road transportation comprising the majority. In 2014 and 2015, 23% (171 Mt) and 24% (173 Mt) of Canada's GHG emissions came from transportation sources respectively. Heavy-duty freight trucking accounted for approximately 33% of the GHG emissions from the transportation sector in 2014. In 2015, GHGs from on-road heavy-duty vehicles totaled over 62 Mt or nearly 9% of total national emissions. In Ontario, the transportation sector had the largest or the second largest share of emissions (34-35%) in 2012-13. In 2015, it accounted for 37% of GHG emissions and 26% of Ontario's total transportation GHG emissions came from road-based freight.

[1] 54th Annual Meetings of the Canadian Transportation Research Forum, May 26 - 29, 2019 at Vancouver, British Columbia

Air pollutant emissions - Canada and Ontario

1. Data on road transport air pollutant emissions between 1990 and 2016 in Canada and Ontario below are broken down by vehicle weight and fuel type (Federal Air Pollutant Emissions Inventory)

	Heavy-duty diesel vehicles				**Gasoline cars and LD trucks**			
Emissions ***change***	NOx+VOCs		PM 2.5		NOx+VOCs		PM 2.5	
	1998-2010	1990-2016	1998-2010	1990-2016	1998-2010	1990-2016	1998-2010	1990-2016
Canada	-9%	-17%	-8%	-43%	-54%	-63%	-51%	-64%
Ontario	-12%	-31%	-7%	-52%	-56%	-67%	-47%	-64%

That passenger cars and LD (light duty) trucks have achieved comparatively faster emissions reduction is likely the result of more stringent standards introduced since 2015, which do not apply to heavy-duty diesel vehicles. (Volatile organic compounds/VOCs are organic chemicals that cause harm to the environment and can be produced by the use of fossil fuels)

Regulatory Developments in US and Canada

Over the past 15 years GHG and air pollutant emissions regulations and standards have been introduced and implemented in alignment by the US and Canada:

- In the US and Canada, regulations for heavy-duty vehicle and engine GHG emissions were introduced between 2014 and 2018 in two phases to reduce GHG emissions by establishing increasingly stringent mandatory emission standards for new on-road heavy-duty vehicles, trailers and engines in areas such as classes of vehicles, emissions standards, test procedures and compliance.
- Similarly, regulations for on-road vehicle and engine emissions were implemented by the US and Canada between 2004 and 2015 that set air pollutant emission standards for on-road vehicles commonly known as the "Tier 2 and 3" standards. These are progressively stringent standards against smog-forming emission from passenger cars, light trucks and some heavy-duty vehicles.

Technologies for review: fuel switch and fuel-saving

Demand-side measures are more concerned about managing the volume of the demand for transport services to reduce road transport emissions. As noted earlier, in identifying technologies that reduce emissions from heavy duty trucking, this paper focuses on the supply side/fuel use. The supply side/fuel use is more concerned about the energy intensity (correlated to efficiency) as measured in megajoules (or litres) per tonne-kilometre (MJ/t-km) and fuel carbon intensity (the carbon content of the fuels consumed) as measured by the amount of carbon emitted per unit of energy demand (g CO_2e/MJ) which differs, depending on the fuel used. The concern is about the average carbon intensity (kg CO_2 e/t-km).

GHGs and air pollutants are directly related to the power output of the engine and its relation to fuel consumption. In this regard, the review will be based on a list of relevant technologies chosen for their direct contribution to the reduction of truck GHG air pollutant emissions through either **fuel switch** or **fuel-savings,** i.e. switch to alternative fuels **or** reduced fuel use which will result in lower tailpipe GHG and air pollutant emissions or fewer emissions for a given number of kilometres travelled. It will focus on those considered more impactful and practical for the industry (e.g. those supporting zero-emission or significant emission savings, operational efficiency, market access and cost-competitiveness) with their **average impacts** expressed mainly in percentage (%)/range, where appropriate or information available.

- Most are established technologies that already exist while some have recently emerged but not been fully developed or commercialized - all relevant to on-road freight market operations such as refrigerated transport. A number of them are considered "disruptive", i.e. not currently broadly used but with the potential to achieve strong fuel and emissions reductions.

- They are applicable to on-road heavy duty diesel-powered commercial vehicles with a gross vehicle weight rating of more than 3856 kg (8500 lbs), i.e. Class 3 to 8 vehicles including line-haul trucks, Long Combination Vehicles (LCVs), vocational vehicles and trailers. Focus will be on Class 7-8.
- Only *tailpipe emissions* of freight/cargo transport vehicles are considered in the review.
- The review draws from extensive research, including cross-jurisdictional experiences from multiple technology funding programs in North America.

Technology	Status	Review
Fuel-switch (including conversions)		
Natural Gas: CNG, LNG, RNG	Established/Disruptive	√
Dual fuel (Natural Gas and diesel)	Established	√
Propane	Established	
Dimethyl ether (DME)	Emerging	
Hybrid-electric	Established/Disruptive	√
Hydrogen Fuel Cell (HFC)	Emerging/Disruptive	√
Electricity		√
Bio-diesel	Emerging	
Bi-fuel	Established	
Fuel-saving (tractors/trailers)		
Anti-idling/Idle-Reduction		
Auxiliary Power Unit, Cab Cooler, Cab Heater, Anti-idle systems	Established	
Aerodynamics		
Boat Tail, Side Skirt	Established	√
Under-body fairing, Roof and cab extenders, Gap reducer	Established	
Tire technology and System		
Low rolling resistance tires (LRRTs)	Established	√
Single Wide-base (WBS) ties	Established	√
ATIS, TPMS	Established	
Reefer Technologies		
Refrigeration Unit, Air delivery system Multi-compartment technology	Established	
Truck insulation, Eutectic systems Cryogenic system	Established	√

Review: applications, key benefits and limitations

Natural Gas (NG): CNG, LNG, RNG and Applications
These 3 forms of NG apply to the on-road heavy-duty trucking market including tractor-trailers, refuse, dump and regional delivery trucks. Seen as a more economical route for sector to transition from fossil fuel-based options to the zero-carbon options.
Benefits
Lower tailpipe emissions (12% from NRCAN's guide to MD and HD AFVs) and fuel cost than diesel. Offer levels of engine performance and fuel efficiency similar or comparable to diesel-powered trucks
Limitations
• Driving range generally less because of the lower energy density of natural gas

- Limited fuel delivery/refueling infrastructure in Canada. Mostly used in short haul return to base.
- Higher capital costs (engine, fuel storage and delivery system), extra storage tanks increase range increase vehicle costs, additional weights hinder vehicle performance and displace payload capacity.
- Volatility of diesel/fuel prices a disincentive
- Unavailability of a high horsepower natural gas engine

Dual Fuel (CNG and Diesel) and Applications

Dual-Fuel vehicles operate on both diesel fuel and CNG simultaneously; limited to applications such as over the road trucking, including Class 7- 8 trucks and LCVs. Vehicles start on diesel and then switch to a metered mix of natural gas and diesel. If out of CNG, automatically reverts to and operate on diesel.

Benefits

A very clean fuel with lower CO2 intensity compared to diesel. CO2 reduction very dependent on the level of gas substitution rate and the vehicle's operation. Increased benefits for heavy load and long-distance operations; GHG saving lower than NG but better than diesel heavy duty engine; overall range not limited and higher performance and fuel efficiency than that of spark-ignition NVs, similar to HPDI dedicated engines that matches diesel efficiency. Savings depend on CNG cost and mileage travelled.

Limitations

- a dual-fuel engine increases the complexity of the fuel-storage system
- the transient response/operation of the engine could deteriorate as substitution rates increase
- driving range in dual fuel mode less than comparable diesel vehicles. Extra storage tanks can increase range but additional weight can hinder vehicle performance and displace payload capacity.

Heavy-Duty Hybrid-Electric and Applications

Commercially available for medium duty applications including parcel delivery, beverage delivery, food distribution, uniform and linen delivery, propane pick-up and delivery and refuse hauler. Heavy duty applications largely at development or commercialization stage.

Two Heavy duty Hybrid systems:

(1) The **Hyliion system:** hybridization (6X4 HE) for long-haul over the road vehicles (Class 8) with fuel saving/emissions reduction. Hybridization achieves 15% fuel savings and reduced emissions with the Electric Axles helping to save or reduce fuel use. Increased vehicle stability and controllability.

(2) The **Effenco system**'s Active Stop-Start electric system designed to shut down the engine of heavy-duty (Class 7-8) vocational/refuse trucks when they are stationary (automatic idle-off operation) and to provide electric power to the vehicle equipment, cab and chassis accessories, even with engine off.

Benefits

Better fuel economy and lower fuel costs than similar conventional vehicles. Reduction in fuel use dependent on driving conditions and cycles. Can improve fuel efficiency by in standard in-city pickups and deliveries by medium-duty applications. Do not require special fueling infrastructure. Engine less exposed to accelerations and burns fuel under more stable conditions, thus emitting less pollution and CO2. Electricity produces no GHG emissions during consumption.

Limitations

- Highest uncertainty around the battery lifetime, the cost of replacement, and the maintenance of advanced electronics.
- The incremental cost can be very high for heavy-duty hybrids, depending on truck class, type of hybrid system and battery capacity, making payback time longer
- For heavy-duty applications, highway trucks gain comparatively less through hybridization. Little efficiency is gained from regenerative braking and idling in this type of drive cycle.

Heavy-Duty Electric and Applications

Battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs). Offerings now primarily focused on medium-duty urban delivery trucks involved in short haul, predictable, multi-drop pickup and delivery operations for mail/parcel, food service and home delivery, less constrained by battery range

- Companies such as AT&T, Frito-Lay, and Staples have all added electric delivery trucks to their

fleets. Fully electric on and off-road heavy-duty terminal tractors by **Orange EV in Missouri.**

- Tesla announced in 2018 a battery-powered semi-truck, claiming a range of 475 to 800 km, autonomous driving capabilities. Nikola Motor Company's electric drivetrain for Class 8 trucks (Nikola One) powered by a custom-built hydrogen-electric 800V fuel cell for markets in US and Canada, using electrolysis to create hydrogen from water to power batteries for electric motors.
- Others: Peterbilt (Electric Model 567) and Volvo (VNR Model) have announced product models.

Benefits

Highly dependent on the load carried and the duty cycle, electric engines are typically 45% more efficient than internal combustion engines (2). Also, electric vehicles use no other fuel which thus reduces diesel consumption and fuel costs; 100% lower tailpipe emissions

Limitations

- Trade-off between vehicle and cargo weight and the range of electric vehicles; battery technologies must develop to reduce their weight as they extend their storage capacity.
- Vehicle and system costs big impediment. HFCVs with high cost fuel cells, high-pressure tanks and on-board storage technology. High battery costs for BEVs;
- Limited range (up to 250 kilometers) and lower maximum speed (about 80 km/hour). Extreme outside temperatures tend to reduce range as more energy used to heat or cool the cabin.
- Unstable fuel prices as disincentive and high hydrogen fuel price (unless self-provided e.g. Nikola)
- Limited refueling and related infrastructure (unless self-provided e.g. Nikola's plan)

Aerodynamic Technology (Boat Tail and Side Skirt) and Applications

Attached to the trailer to provide more streamlined shape, reduce drag, increase fuel efficiency and lower consumption & emissions. Highly complementary technologies (i.e., the side and under-body versus the rear end of the trailer). Mostly used by Class 8 tractor-trailers on highways at high speeds: 100 km/h or over to reduce the fuel use and lower emissions for vehicles. Can meet the California's regulation that requires SmartWay verified aerodynamic technologies and LRR tires on vehicles.

Benefits

Side skirts:

- Estimated fuel savings: SmartWay average 5% fuel savings
- Reliability and durability much improved; simple mechanical designs require less maintenance

Boat tails:

- Estimated fuel savings: SmartWay average 4% fuel savings
- 3 or 4 panel boat-tail systems, fuel savings will increase

Limitations

Side skirts

- It cannot be used with other under trailer devices or no additional benefits will be provided when used concurrently with under-body devices.
- Service, inspection, tire storage, and tire maintenance hindered by lack of easy access to the trailer underside. Also prone to damage and breakage in the harsh environment where trailers must operate, e.g. in snow and ice or at steep loading docks.

Boat tails:

The main drawback is manual deployment by drivers; fleets prefer no driver intervention. Newer generations offering the option to automatically deploy once the tractor-trailer exceeds a certain speed

Energy efficient tire technology (LRRTs and WBS tires) and Applications

Low rolling resistance tires (LRRTs), whether in a dual or a wide-base configuration, reduce vehicle rolling resistance, save significant fuel use and reduce emissions. Mainly used by heavy duty vehicles such as line haul tractor-trailer on-road operations, mostly at high speeds. Can meet the California's regulation that requires SmartWay verified aerodynamic technologies and LRR tires on vehicle.

LRRTs (Duals): widely accepted for most hauling applications and a number of trailer types. Used for

tractor drive tires and in trailer applications; majority of all tires sold are LRRTs and SmartWay-verified.
WBS Tires, a subset of LRRTs, are 17-inch wide tires and substitutes for standard dual tires. Popular for hauling bulk commodities such as liquid, grain, gravel, sugar beets, distillers' grain and feed. Presently not available for use on Class 3 to 6 vehicles

Benefits

LRRTs (Duals): potential higher fuel savings over standard tires, especially on a tractor-trailer combination from. No adverse effects on safety and extend the tire's lifetime. New-generation LRRTs require no new or additional maintenance. US EPA SmartWay's verifies at least 3% or more cost-saving
WBS Tires: fuel economy improvements influenced by the vehicle type, driving cycle, both the tractor and trailer wheel positions and baseline tire; OTA suggested 4% - 5% fuel savings equal to annual greenhouse gas reductions in the range of seven to eight tonnes per vehicle per year. Weight savings (hauling capacity) for a typical combination truck range from 800 to 1,000 pounds versus duals. Cost advantage (tire cost, set up and tire assembly cost, truck purchase cost)

Limitations

LRRT Duals:

- Improvement in fuel economy decreases as the tires wear.
- Tire replacement more frequent and to run fewer miles overall
- A premium of about 10% for the upfront purchase (NACFE 2015 Confidence Report on LRRTs)
- Concerns about reduced winter road traction performance compared to non-LRR tires, particularly in snow and ice conditions and even in rainy weather

WBS tires:

- Conversion cost high; decreased lifespan, higher maintenance costs, and potential tire problems
- Averse pavement impact due to their higher pressure and smaller contact area versus dual tires
- More sensitive to over- and under- inflation than dual tires
- Do not offer the limp-home capability that dual tires do

Zero-emission Reefer Technology (Truck insulation, Eutectic & Cryogenic) and Applications

Road transport refrigeration technologies required to operate and keep refrigerated vehicle (reefers) under harsh environments ice-cooled such as vans, trucks or semi-trailers. Technologies that have zero-emissions and/or complement or support mechanical refrigeration systems:
Truck body insulation, usually in the form of insulated rigid boxes, minimizes the heat transferred from the environment to the refrigerated space
Two Canadian Manufacturers:

- **Transit Truck Bodies Inc**.: FrioTM Refrigerated truck bodies
  It offers a wider interior and lighter body weight so loading capacity is increased. Frio™'s rivet-free sandwich panels make application of decals quick and inexpensive. The technology offers a 10% fuel savings, complements the mechanical refrigeration system.
- **Transforcool Industries:** Composite technology with multiple product offerings. The technology is exclusively dedicated to cold and combines composite materials of complex production and high insulating properties.

Eutectic systems, like cold plates, use an eutectic solution (phase change material) to store energy and provide a cold source/heat absorption and cooling effect whenever necessary to maintain the correct temperature in the refrigerated container. Majority of cold plates in the US produced by Dole Refrigeration.
Cryogenic cooling systems, as an alternative to mechanical refrigeration, use liquid nitrogen or carbon dioxide injection. A cryogenic fuel (liquid nitrogen, liquid carbon dioxide or liquid air) is contained in a refillable storage tank on the truck or trailer near the cargo space to provide cooling when needed.

Benefits

Truck body insulation reduces the cooling load or cooling capacity and power consumption of refrigeration system, the operating cost and emissions. It has zero-emissions.
Eutectic systems a cost-effective, more reliable, and "greener" alternative. Near-constant temperatures

maintained throughout delivery day; could lead to efficiency savings by reducing the number of on/off control cycles and extend delivery range if used with mechanical refrigeration systems. Zero-emissions. **Cryogenic cooling systems** extremely quiet due to the absence of the diesel engine and associated equipment; much faster cool downs and temperature recovery. Minimum defrosting needs. Maintenance, repair and down-times significantly reduced. Zero-emission and no high GWP refrigerant.
Limitations
Truck body insulation • time-consuming, expensive and quality of the final product highly dependent on installer's skills; the insulating material age and deteriorate over time, raising heat load on the refrigeration system. **Eutectic systems:** • It may work best for certain applications: cold plates for private return-to-base fleets and generally do not meet the needs for for-hire fleets or long-haul, e.g. charge times, compatible power infrastructure. • Payload space impacted by cold plates and fans, reducing the amount of goods that can transported. Cold plate mounting can also affect the ability to easily load and unload goods from the cargo space. **Cryogenic cooling systems:** • In the U.S., the cost of diesel fuel is generally much less expensive than the cost of the cryogenic fuel • Operating range is limited and restricts application to return to base operation. • Vehicle parts which contact the cryogenic fuel must be fabricated with materials that can withstand the low temperatures associated with cryogenic materials. Storage tanks require periodic certification.

Program experiences: key observations

The key observations and lessons learned from a review of 20+ funding programs across the US and Canada and their experiences reflect and reinforce the understanding that business needs and priorities of the trucking companies dictate or significantly influence their decision on adopting the technologies as the "user".

- Industry stakeholders recognize the importance of the environmental factor but they also know very well that they still have their business to run. The potential cost implications are their number one consideration in making decisions on adopting new equipment or technologies. If the emission-reducing equipment does not positively contribute to their bottom-line (cost, business opportunities and efficiency), they would not adopt unless required by regulation. They look for benefits such as better performance, fuel/cost savings, market access, shipper preference or quick ROI, e.g. adopting LNG because it is expected to provide cost-savings of 25-50% and according to Freightliner, an LNG truck driven 50,000 miles per year could save US$85,000 in annual fuel cost.
- These business considerations underlie almost all the barriers to adoption they have identified, their particular interest in and preference for technologies eligible for funding, the funding levels and approach as well as their adoption patterns e.g. withdrawing because of the cost impact. Such concerns were well-captured in CTA's white paper on the federal proposed Phase II GHG Emission Regulation which lamented the negative impacts of the air quality emission standards between 2003-2010 on overall engine performance, fuel efficiency, reliability, operating cost and productivity.

Considerations for accelerating technology adoption in freight trucking

There has been tremendous interest in and momentum for de-carbonizing freight transport, particularly heavy-duty trucking, from low carbon tailpipe to zero-carbon, life-cycle emissions. Today, governments have been providing funding for technologies and regulating emissions and standards. The industry has been increasing adoption, likely incurring and absorbing financial losses similar to the way in which they handle the cost of border delays. However, there are limits to what can and should be done. Regulation and program funding are not the ultimate solutions but can be an accelerator. It is also unfair that only the trucking industry has to cut their profit levels.

- In that regard, there is one piece of the adoption puzzle which seems to have been overlooked: *vehicle and technology developers and manufacturers.* Since the single most important barrier to adoption is the cost/price of the technology, they could take on a more leading role and consider scaling down their prices and profit levels instead of waiting for commercializing the technologies through demand and economies of scale. This is in line with the developments to date that, in order to tackle climate change and air pollution, there has been so much intervention in the market where business imperatives such as demand and supply or profitability are no longer the main driver.
- As the supplier, the technology developers and manufacturers have their share in the pie and should support accelerating adoption, not just by investing in R&D but also by *making their advanced technologies affordable for the user*. Such a move will go a long way in de-carbonizing trucking.

Bibliography

1. The Conference Board of Canada. Greening Freight. Pathways to Reducing GHG Emissions From Trucking. May 2018.
2. Energy Transitions Commission. Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century. November 2018