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Examining the role of natural gas and advanced vehicle technologies in mitigating CO_2 emissions of heavy-duty trucks: Modeling prototypical British Columbia routes with road grades

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ABSTRACT

This study presents a simulation framework for estimating on-road CO_2 emissions of compressed natural gas (CNG) and diesel tractor-trailer heavy-duty trucks under various operational conditions. A second-by-second component-level model was developed and then used to simulate seven distinct drive cycles. This paper specifically considers road grade, and develops a novel technique to pair road grade profiles with given speed vs. time data when gradient data are not available. Six routes around the Canadian province of British Columbia were used as case study drive cycles, including an extreme hill climb route. Results showed that omission of road grade under-estimates CO_2 emissions by as much as 24% for both CNG and diesel drivetrains. Simulations indicated that CNG trucks emit 13–15% less CO_2 than comparable diesel trucks, depending on weight class and drive cycle. Sensitivity analyses highlighted the importance of aerodynamic drag, rolling friction, and engine efficiency for all cycles. An assessment of advanced vehicle technology options for CNG trucks showed achievable CO_2 reductions of 28–35% in the near-term and 41–51% over the longer term, compared to current diesel technology. The same advanced technology options would reduce diesel drivetrain CO_2 emissions by 17–23% and 31–42% over the near and long-term respectively. It is worthwhile to emphasize that with commensurate technology developments, CNG drivetrains offer the same 13–15% CO_2 reductions compared to diesels over the near and long term. The results demonstrate that CO_2 reductions in heavy-duty trucks depend primarily on drivetrain technology, while operational conditions play a less significant role.

1. Introduction

Worldwide, freight transport by trucks has been steadily growing as a result of globalization of trade and supply chain changes, and now constitutes a major source of greenhouse gas (GHG) emissions (Kahn Ribeiro et al., 2007). In the United States and Canada, more than 70% of domestic freight volume is moved via trucks (Jaffe et al., 2015; Transport Canada, 2015). Trucks also carry 75% of the total freight volume in the European Union (EU) and account for 30% of total EU on-road GHG emissions (Muncrief and Sharpe, 2015). By 2030, their contribution to EU on-road emissions is projected to increase to 40% without any additional policy (Muncrief and Sharpe, 2015). In 2015, Canadian freight trucks emitted 37% of on-road GHG emissions (63.2 Mt CO_2eq) and 9% of the total GHG emissions respectively. In contrast, in 2005, the GHG emissions from Canadian freight trucks were 30% of on-road emissions (49.5 Mt CO_2eq), a 28% decadal increase in GHG emissions from this sector (Environment and Climate Change Canada, 2017). Heavy-duty[1] trucks are the most significant contributor to on-road freight volume in

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[1] Heavy-duty refers to the Class 8 category of trucks with gross mass of 15,000 kg or more.

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Nomenclature

F	force (N)
V	engine displacement (L)
a	acceleration (m/s^2)
g	gravitational acceleration (9.81 m/s^2)
t	time (s)
C_D	drag coefficient
A	frontal area (m^2)
K	engine friction factor
K_o	constant coefficient of engine friction factor
C_{r0}	zero order of rolling friction coefficient
C_{r2}	second order of rolling friction coefficient
N	engine rotational speed (rps)
P_{br}	engine braking power (kW)
P_{fr}	engine friction power (kW)
P_{tr}	tractive power (kW)
$\dot{m}_{FR}$	mass flow rate of fuel consumption (g/s)
M_{CO2}	specific CO_2 emissions (kg/100 km)
m	gross mass of a vehicle (kg)
C_f	carbon content of fuel (%)
SR	vehicle speed ratio (rpm/mph)
φ	fuel–air equivalence ratio
T	engine torque (N.m)

Greek letters

ν	vehicle speed (m/s)
ρ	density (kg/L)
ε	mass correction factor
Δ	Delta
θ	road grade angle (°)
η_i	indicated thermal efficiency
η_t	vehicle transmission efficiency

Subscripts

fr	friction
tr	tractive
br	braking
FR	flow rate

Acronyms

WOT	Wide Open Throttle
CNG	Compressed Natural Gas
DGE	Diesel Gallon Equivalent
TD	Traveling Distance (km)
GHG	Greenhouse Gas
LNG	Liquefied Natural Gas
LHV	Lower heating value (kJ/g)

the United States and Canada (Baldwin, 2002) and are employed for a broad range of applications such as long-haul, short-haul[2] and port drayage.[3]

This research focuses on the Canadian province of British Columbia as a case study, which also aligns with Canada, the United States, and EU trends in terms of GHG emissions from freight trucks. Heavy-duty trucks contribute to 33% and 8% of on-road and total provincial GHG emissions, respectively (British Columbia Climate Action Secretariat, 2015). The fleet of 42,000 heavy-duty trucks in British Columbia plays important role in the economy and moves $3 billion of commodities every year (BC Ministry of Transportation and Infrastructure, 2015). In recent years, the increased economic feasibility of extracting natural gas resources has brought this fuel to the attention of decision makers and industries globally, due to the potential for lower costs and less carbon intensity for heavy-duty vehicles (Jaffe et al., 2015; Delgado and Muncrief, 2015; Park and Tak, 2012). For example, FortisBC, a natural gas utility company in British Columbia, has started to pay an incentive in 2012 for the adoption of natural gas vehicles, which can cover up to 90% of the incremental cost over a diesel vehicle (FortisBC, 2012). On the other hand, many governments around the world including British Columbia have set an ambitious GHG reduction target of 33% below 2007 levels by 2020, and 80% below 2007 levels by 2050 (B.C. Government, 2008). Meeting these targets will require aggressively adopting low and zero emission technologies for this sector. Many people have proposed natural gas as a transitional fuel because hydrogen fuel cell and battery electric trucks may not be available in this market for several decades (Cannon, 2012; Ogden et al., 2018).

Natural gas combustion produces approximately 32% fewer CO_2 emissions than the combustion of diesel fuel per heating unit (Camuzeaux et al., 2015). Since the major GHG intensive stage in the life cycle of a vehicle with a combustion engine is the tailpipe CO_2 emissions, the focus of the present study is on the vehicle on-road stage. In the literature available to date, there has been no consensus with regard to the absolute CO_2 benefits of natural gas vehicles over comparable diesel ones, in part due to difference in lifecycle modeling assumptions, assumed drive cycles and technology characteristics, as well as whether one uses a lifecycle emissions model or measures emissions in the field.

For example, Rose et al. (2013) and Shahraeeni et al. (2015) assessed the potential of natural gas for refuse and light-duty trucks, respectively, in British Columbia (the city of Surrey), Canada and applied the GHGenius model as a life cycle analysis tool. Although Shahraeeni et al. (2015) demonstrated that light-duty CNG trucks produce 34% fewer on-road GHG emissions compared to the baseline diesel, Rose et al. (2013) used the same methodology and found a 15% on-road GHG reduction for a heavy duty CNG refuse truck compared to the baseline diesel. Shahraeeni et al. (2015) clarified that the discrepancy was due to a difference in fuel efficiency assumptions in the GHGenius tool for light and heavy duty vehicles. The default setup of the GREET.net model (Argonne National Laboratory, 2015), on the other hand, predicts a 19% reduction in CO_2 emissions for a long-haul CNG heavy-duty truck during the

[2] By British Columbia government definition any trip for heavy-duty Class 8 truck exceed 160 km from home terminal then it consider as long-haul trip and below this limit consider as short-haul trip (Interpretation Guidelines Manual British Columbia Employment Standards Act and Regulations).

[3] Drayage refer to a short trip that is a part of longer trip such as delivery of goods from a seaport into a warehouse (Wikipedia).