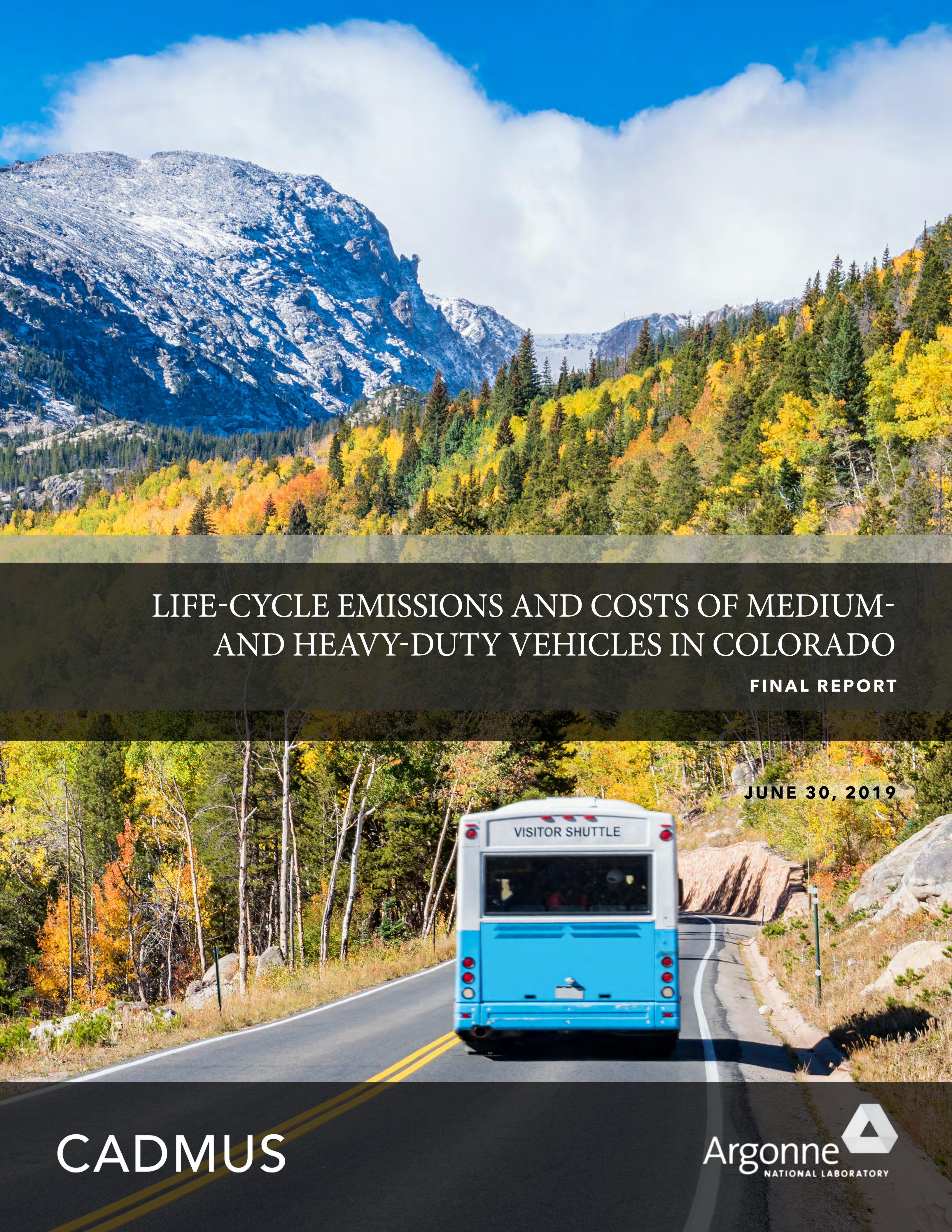

LIFE-CYCLE EMISSIONS AND COSTS OF MEDIUM- AND HEAVY-DUTY VEHICLES IN COLORADO

FINAL REPORT

JUNE 30, 2019

CADMUS

Argonne NATIONAL LABORATORY

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ABBREVIATIONS

Table 1. Table of abbreviations.

Abbreviation	Definition
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool
CARB	California Air Resources Board
CBD	Central Business District
CEO	Colorado Energy Office
CNG	Compressed natural gas
CO	Carbon monoxide
DEF	Diesel emission fluid
DPF	Diesel particulate filter
EPA	Environmental Protection Agency
GGE	Gallon gasoline equivalent
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GVWR	Gross vehicle weight rating
H2	Hydrogen
H2-NG	Hydrogen from natural gas reformation
H2-Renew	Hydrogen from renewable energy produced via electrolysis
HC	Hydrocarbon
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
HHD	Heavy-heavy duty
HHV	Hydraulic hybrid vehicle
kW	kilowatt
LCA	Life-cycle assessment
LEM	Life-cycle emissions model
LHD	Light-heavy duty
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MHD	Medium-heavy duty
MHDV	Medium- and heavy-duty vehicle
MOVES	Motor Vehicle Emission Simulator
MPDGE	Miles per diesel gallon equivalent
MPG	Miles per gallon
MY	Model year
NG	Natural gas
NHTSA	National Highway Transportation Safety Administration
NOX	Nitrogen oxides
OEM	Original Equipment Manufacturer
PM	Particulate matter
PTW	Pump-to-wheel
RNG	Renewable natural gas produced via landfill biogas
QSR	Qualified system retrofitter
QVR	Qualified vehicle modifier
SCAQMD	South Coast Air Quality Management District
SCR	Selective catalytic reduction
TWC	Three-way catalyst
UDDS	Urban Dynamometer Drive Schedule
VIUS	Vehicle Inventory and Use Survey
VOC	Volatile organic compound
WECC	Western Electricity Coordinating Council
WTP	Well-to-pump
WVU	West Virginia University

Executive Summary

This document describes the background, methodology, and results of the study *Life-cycle Emissions and Costs of Medium- and Heavy-Duty Vehicles in Colorado*, prepared by the Cadmus Group and Argonne National Laboratory for the Colorado Energy Office. Life-cycle emissions and costs are examined for the categories of vehicles shown in Table 2. A supplemental Excel spreadsheet provides additional details and calculations.

This study is required under Colorado Statute §§ 39-22-516 C.R.S., which states:

> *In the event that category 4, 4A, 4B, 4C, 7, 7A, or 9 medium or heavy-duty trucks are shown to generate life-cycle emissions materially greater than comparable traditional fuel trucks, then the Colorado Energy Office shall notify the Department of Revenue that no tax credit specified in this section is available for such trucks. See Appendix A for full text.*

Table 2. Fuels/powertrains included in study.

Fuel/Powertrain	Comparison Vehicle	Colorado Vehicle Category (per §§ 39-22-516 C.R.S.)
Compressed Natural Gas (CNG)	Diesel	Category 4, 4A
Renewable Natural Gas from landfill gas (RNG)	Diesel	Category 4, 4A
Liquefied Petroleum Gas (LPG)	Diesel	Category 4, 4A
Liquefied Natural Gas (LNG)	Diesel	Category 4B, 4C
Hydrogen from Natural Gas Reformation (H_2-NG)	Diesel	Category 4B, 4C
Hydrogen from Renewable Sources (H_2-Renew)	Diesel	Category 4B, 4C
Electric	Diesel	Category 7, 7A
Hydraulic Hybrid Vehicle (HHV)	Diesel	Category 9

The primary tool used in this analysis is the Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool (AFLEET) 2017 Tool, developed by Argonne National Laboratory. For each alternative fuel category shown in Table 2, the authors estimate the following:

- **Emissions (in grams per mile)** of carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM10 and PM2.5), volatile organic compounds (VOCs), greenhouse gases (GHGs). Both upstream and vehicle operations are estimated. Upstream emissions are those associated with fuel production and delivery, while vehicle operation emissions are those from the tailpipe, tires, and other vehicle components. When summed together, upstream plus vehicle operation emissions equals life-cycle emissions;
- **Total cost of ownership (in dollars per mile)** including depreciation, financing, fuel, diesel exhaust fluid (if applicable), maintenance and repair, insurance, license, and registration;
- **Payback period (in number of years)** for the alternative fuel relative to the representative diesel vehicle; and
- **Marginal damage cost (in dollars per mile)** of using a given fuel in Colorado. Marginal damage costs include costs associated with negative human health outcomes (e.g., increased hospitalization, increased mortality), loss of agricultural productivity, and lowered tourism and recreation. Marginal damage cost is a common method in economics and epidemiology of converting emissions to costs. To determine whether a given fuel has "materially greater" emissions than diesel, the authors sum the marginal damages costs for all pollutants for the alternative fuel and for diesel.

The AFLEET tool includes data fields for several medium- and heavy-vehicle types, including:

- School buses;
- Transit buses;
- Refuse trucks;
- Single-unit, short-haul trucks;
- Single-unit, long-haul trucks;
- Combination short-haul trucks; and
- Combination long-haul trucks.

For each fuel category shown in Table 2, the authors aggregate the relevant AFLEET vehicle types into a "representative vehicle" and then compare emissions and costs of that representative vehicle with a similar diesel vehicle. The emissions per mile of the alternative fuel and diesel comparison vehicle are shown in Figure 1 on the following page.

Figure 1 highlights the difficulty of comparing alternative fuels and diesel emissions based on emissions per mile alone. For example, CO emissions are much higher for CNG than diesel (top-right panel), whereas NOx are lower (mid-left panel). However, when each of these emissions is converted into a marginal damage cost, a clearer comparison emerges. As described in the report below, CO has a marginal damage cost of only $886 per short ton, whereas NOx has a marginal damage cost of over $14,000 per short ton. As a result, CNG's relatively low NOx emissions outweigh CNG's relatively high CO emissions.

Definition of Materially Greater

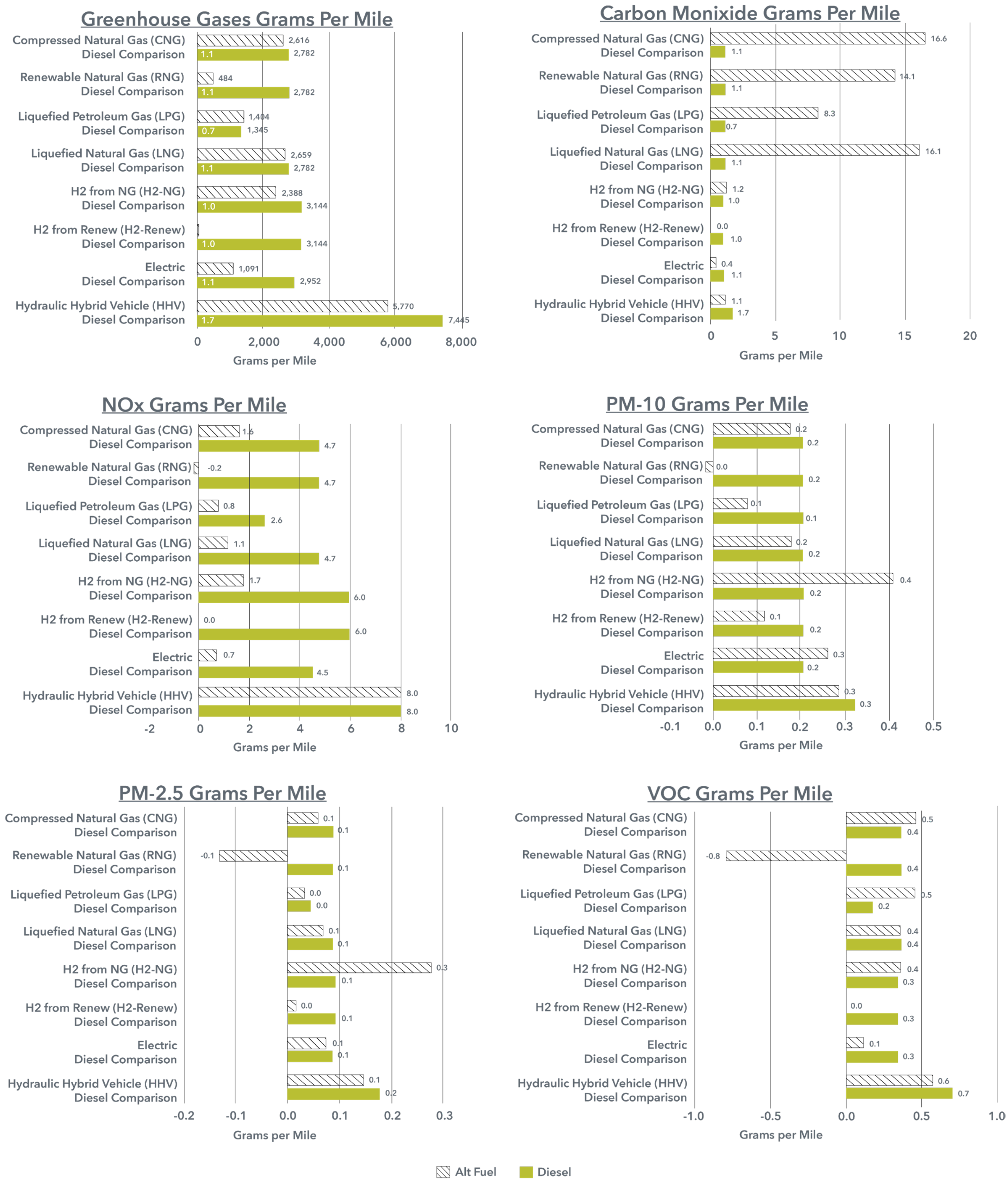
This study defines "materially greater" as the condition in which aggregated marginal damages caused by the lifecycle emissions of one fuel type exceed those of another.

Final results of this study are given in Table 3. A lower marginal damage cost implies a more attractive fuel for society. As shown, all alternative fuel categories have marginal damage costs that are lower than the diesel comparison vehicle. The largest societal benefits on a per mile basis arise from switching from diesel to hydrogen from renewables; marginal damages from the hydrogen from renewables are estimated to be $0.22 per mile lower than the diesel comparison vehicle. On the other hand, switching from diesel to LPG only provides a $0.01 per mile benefit.

Table 3. Marginal damage cost alternative fuel with comparison fuel ($ per mile).

Vehicle Category	Alternative Fuel	Diesel	Difference
Compressed Natural Gas	$0.17	$0.19	$0.02
Renewable Natural Gas	$0.04	$0.19	$0.15
Liquefied Petroleum Gas	$0.09	$0.10	$0.01
Liquefied Natural Gas	$0.16	$0.19	$0.03
Hydrogen from Natural Gas Reformation	$0.14	$0.22	$0.08
Hydrogen from Renewables via Electrolysis	$0.004	$0.22	$0.22
Electric	$0.06	$0.20	$0.13
Hydraulic Hybrid	$0.37	$0.46	$0.09

Figure 1. Lifecycle emissions per miles of the representative vehicle for alternative fuels (dashed line) and diesel (green solid line).



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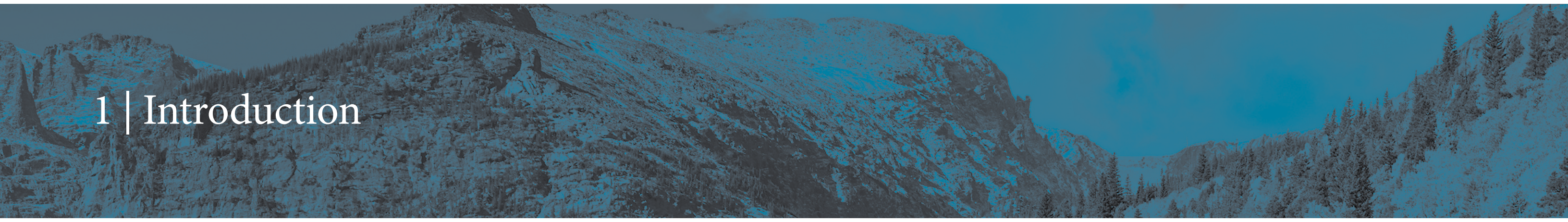


1 | Introduction

1a. Purpose of Report

This report describes the background, methodology, and results of the *Life-Cycle Emissions and Costs of Medium- and Heavy-Duty Vehicles in Colorado analysis*. This was conducted on behalf of the Colorado Energy Office pursuant to 39-22-516.8 (14)(a) C.R.S. The primary purpose of this study is to understand and compare the life-cycle emissions from alternative and traditionally-powered medium- and heavy-duty vehicles.

The vehicle categories considered under this statute include: Categories 4, 4A, 4B, 4C, 7, 7A, and 9 vehicles, which are described in Table 4. The relevant text of statute is in Appendix A. Additionally, §§ 39-22-516 C.R.S. define medium- and heavy-duty as follows:

- Medium-duty – gross vehicle weight ratings (GVWRs) between 10,000-26,000 pounds (lbs.);
- Heavy-duty – GVWRs above 26,000 lbs.

This GVWR-based definition is consistent with the federal definition under the Federal Highway Administration (FHWA). However, unlike the FHWA, statute §§ 39-22-516 C.R.S does not further disaggregate vehicles into size classes (i.e., Class 3 to 8), but rather categorizes them by the attributes listed in two right-most columns of Table 4. Due to a lack of data, this study does not attempt to distinguish between original equipment manufacturer (OEM) and conversion vehicles, nor dedicated versus multi-fuel vehicles.

Table 4. Categorization of medium- and heavy-duty vehicles under §§ 39-22-516 C.R.S.

Vehicle Category	Fuel/Powertrain	Original or Conversion	Fueling System
Category 4	CNG, LPG	OEM	Dedicated or multi-fuel
Category 4A	CNG, LPG	Conversion	Dedicated or multi-fuel
Category 4B	LNG, H_2	OEM	Dedicated or multi-fuel
Category 4C	LNG, H_2	Conversion	Dedicated or multi-fuel
Category 7	Electric	OEM	Dedicated or multi-fuel
Category 7A	Electric	Conversion	Dedicated or multi-fuel
Category 9	Hydraulic hybrid	Not specified	Not specified

1b. Background on Medium- and Heavy-Duty Vehicles

Summary statistics on the medium- and heavy-duty vehicle population in Colorado and at the national level are quite limited because, unlike light-duty vehicles, no government organization tracks or surveys these vehicles on a regular basis. Some authors have estimated medium- and heavy-duty vehicle summary statistics by merging several different datasets. Figure 2 shows the estimated number of medium- and heavy-duty vehicles in 2014 for the entire U.S. from Kast et al. (2017) by vocation and weight class. Numerical values in the figure are 1,000s of vehicles. Of all size classes and vocations, Class 8 tractor trailers constitute the largest single segment, with over 2.6 million vehicles. Other vehicle segments with relatively high populations including Class 3 and 6 flatbeds, and Class 3 and 6 step and enclosed vans.

Figure 2. Estimated medium- and heavy-duty vehicle population in 1,000s of vehicles in 2014 in the United States. Data is extrapolated from the 2002 VIUS survey to correspond with today's population. The colors represent the relative market share of each vehicle category. Figure taken from Kast et al. (2017).

		Vans					Weight Vehicles						Freight			Other
Class	Weight (1,000 lbs)	Step	Enclosed	Insulated	Open top	Other	Flatbed	Dump	Concrete	Tow	Utility	Garbage	Tank	Beverage	Tractor	Other
8	60+	2	4	2	6	1	33	203	122	2	2	32	19	0	2,670	29
8	50-60	1	4	3	22	1	41	160	49	4	7	73	28	0	314	21
8	40-50	1	14	4	69	2	81	187	17	7	11	49	51	2	279	24
8	33-40	2	18	6	38	1	100	101	2	11	31	26	41	8	131	15
7	26-33	5	87	40	78	4	203	181	0	16	73	20	130	46	64	40
6	19.5-26	127	294	60	89	20	475	315	0	78	106	14	96	32	31	104
5	16-19.5	101	175	23	19	7	157	80	0	31	70	6	14	5	0	49
4	14-16	98	80	7	12	11	185	114	2	36	46	2	13	3	0	69
3	10-14	234	256	21	11	43	341	204	0	65	117	5	13	4	0	151

1c. Background on LCA Models for Transportation Fuels

Life-cycle assessments (LCAs) of transportation fuels has been an area of research for more than two decades (Wang 1996). The primary goal of an LCA of a fuel (also known as a "well-to-wheels analysis") is to quantify the environmental impact from all stages of fuel production and use, from primary energy to end-use. The system boundary of a typical transportation LCA includes:

- **Wells-to-pump (WTP) stage** – the supply chain between feedstock recovery, feedstock transportation, fuel production, and fuel transportation;
- **Pump-to-wheels (PTW) stage** – refueling and use of the fuel by a vehicle.

Early research on the environmental impacts of transportation fuel focused on light-duty vehicles (LDVs). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model

(GREET) Model, developed by Argonne National Laboratory, initially focused exclusively on light-duty vehicles (Wang 1999, Brinkman 2005; Cai 2015). A version of GREET that included medium- and heavy-duty vehicles (called GREET 3) was developed in the late 1990s but was not publicly released.

Other life-cycle models were being developed concurrently to GREET, including the Life-cycle Emissions Model (LEM) and the GHGenius model – a model based on LEM but adapted to Canada. LEM and GHGGenius are capable of simulating life-cycle emissions of medium- and heavy-duty vehicles as an aggregated group of buses or trucks or a combination of both (Delucchi, 2003; (S&T)2 Consultants, 2014). Later, the GREET model was modified to assess the energy and emissions of diesel-powered and five alternative fuel-powered Class 8 heavy-duty vehicles in New York in a case study (Meyer et al., 2011) and later in an analysis of CNG heavy-duty vehicle emissions (Alvarez et al., 2012).

In 2015, Argonne released a public version of its medium- and heavy-duty vehicles module for GREET (Cai 2015). The GREET expansion included the fuel consumption, GHG emissions, and air pollutant emissions of a variety of conventional (i.e., diesel and/or gasoline) medium- and heavy-duty vehicle types, including Class 8b combination long-haul freight trucks, Class 8b combination short-haul freight trucks, Class 8b dump trucks, Class 8a refuse trucks, Class 8a transit buses, Class 8a intercity buses, Class 6 school buses, Class 6 single-unit delivery trucks, Class 4 single-unit delivery trucks, and Class 2b heavy-duty pickup trucks and vans. These vehicle types were selected to represent the diversity in the US medium- and heavy-duty vehicle market, and specific weight classes and body types were chosen on the basis of their fuel consumption using the 2002 VIUS database.

In addition, the new version of GREET included the fuel consumption and emissions of a portfolio of alternative fuel and hybrid options that were being developed and deployed, as well as petroleum-fueled comparison vehicles. The alternative fuel options include biodiesel, dimethyl ether, renewable diesel, CNG, LNG, LPG, hydrogen, ethanol, and electricity. The hybrid options include hybrid electric and hydraulic hybrid technologies. Fuel consumption and emissions of alternative fuel vehicles from the literature were reviewed and the results were generally presented in the form of changes relative to the conventional baseline vehicles in the GREET model.

AFLEET is a related tool that is used in this study and described in more depth below. AFLEET allows users to model lifecycle emissions and costs and emissions from light-, medium-, and heavy-duty vehicles.

1d. Organization of Report

This report begins by describing the fuel technologies in Section 2. It then provides the methodology for estimating the life-cycle emissions and costs in Section 3. Section 4 provides results and conclusions.

2a. Compressed, Renewable, and Liquefied Natural Gas – Categories 4, 4A, 4B, 4C

Natural gas (NG) engines can run on CNG, LNG, and RNG fuel. Outside of fuel tank weight, there is little difference between a spark-ignited NG vehicle using CNG versus LNG, as the engines will operate similarly. With a volumetric energy content roughly 2.5 times that of CNG at 3,600 psi, LNG can deliver more range with smaller fuel tanks compared to CNG, and thus has been used as an alternative fuel for long-haul trucking operations. LNG vehicles will typically weigh less than CNG vehicles with the same range, owing to the lower weight of the storage tanks and fuel, though the difference is small.

Compressed RNG has similar chemical properties and is fully interchangeable with fossil-based CNG. However, whereas CNG is extracted from an oil and gas field, RNG comes from the decomposition of organic matter typically from wastewater treatment facilities, landfills, or livestock operations. The RNG pathway modeled in this study is derived of landfill gas, which is the most common feedstock for RNG. In Colorado, some cities – such as the City of Grand Junction – use wastewater-based RNG in their fleet vehicles (Guardian, 2016). Regardless of the feedstock, however, every RNG pathway has lower GHG emissions than diesel. For example, the approved pathways in California's Low Carbon Fuel Standard policy lower GHGs compared to diesel by between 57 to 93 percent for wastewater-based RNG, 41 to 70 percent for landfill-based RNG. Other pathways (e.g., from anaerobic digestion of dairy waste) offer even greater reductions in GHGs (CARB, 2018).

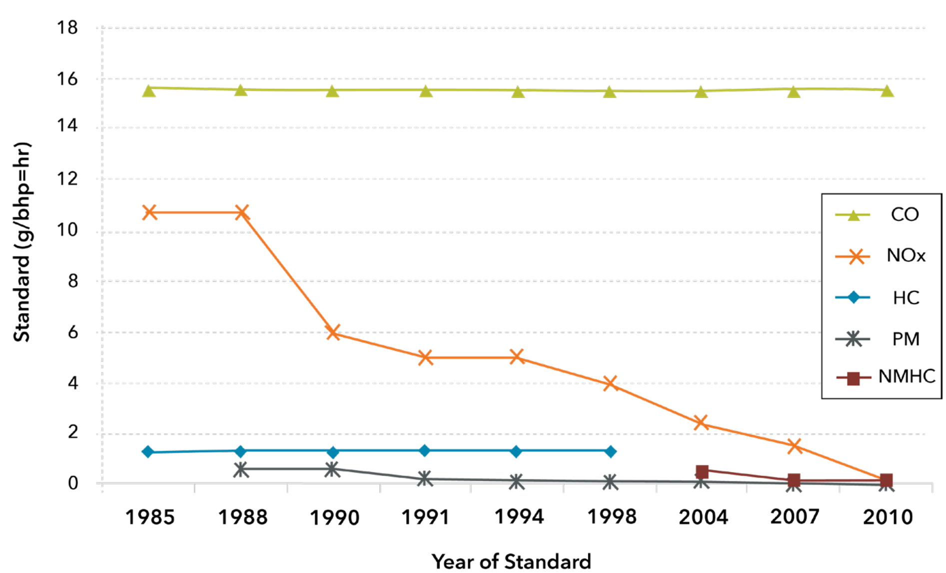
In the past few decades, NG engines have undergone significant changes in their performance, emissions, and fuel economy (Boyce, 2013). Numerous published studies have shown that NG vehicles, especially those developed prior to the issuance of 2007/2010 standards from the Environmental Protection Agency (EPA) and California Air Resources Board (CARB), generally have worse fuel efficiency than their diesel counterparts. Some of the reasons for the lower efficiency of spark-ignited NG engines are their lower compression ratio, slower combustion speeds, and need for throttling at partial loads as compared to compression-ignition diesel engines (Gao et al., 2013; Zhang et al., 1998).

Currently-available NG engines, such as the Cummins Westport's 8.9-L ISL G and 11.9-L ISX12 G, have exhibited higher fuel economy than older models, largely owing to the introduction of closed-loop control and optimization of the air-fuel control system (Yoon et al., 2013). Gao et al. (2013) compared the fuel consumption of NG and diesel Class 8 trucks using Argonne's *Autonomie* model to simulate the vehicles on various drive cycles. The results of those simulations showed that the NG heavy-duty trucks had 6 to 13 percent lower fuel economy relative to the diesel heavy-duty vehicles.

At the West Virginia University vehicle laboratory, several types of NG and diesel heavy-duty vehicles – including transit buses and refuse trucks – were tested on various duty cycles (Carder et al., 2014). This testing showed that a single NG refuse truck had 32 percent better fuel economy than the diesels tested. However, the engines were not all from the same OEM, nor did they have the same displacement, and only one NG truck was tested. Therefore, it is difficult to draw conclusions from these results when nearly all other testing shows a reduction in NG fuel economy relative to diesel.

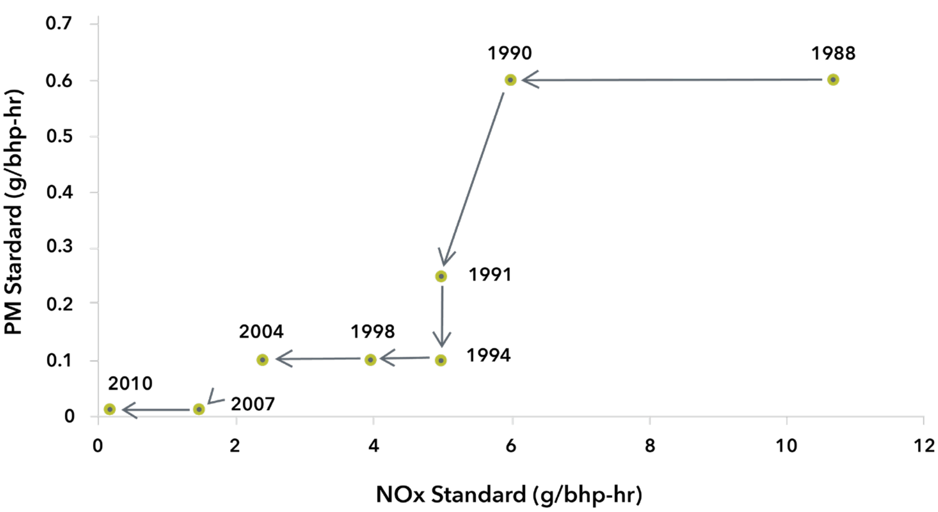
As mentioned previously, NG engines have changed significantly over the past few decades. A key factor that drove NG engine development was their ability to reduce air pollutant emissions relative to diesel engines. Numerous studies show that NG vehicles, especially those developed prior to the issuance of the EPA and CARB 2007/2010 standards, have significantly lower PM emissions (Clark et al., 1995, 1998b; Frailey et al., 2000; Wang et al., 1993) and lower

Figure 3. EPA heavy-duty vehicle emission standards, 1998-2010.



NOx emissions (Clark et al., 1998a, 1999) than equivalent diesel engines, but increased CH_4 emissions (Clark et al., 2007). With the implementation of stricter emission standards (see Figure 3 and Figure 4), the emissions of diesel heavy-duty vehicles have decreased and thus the absolute emission benefits of NG vehicles have also decreased (Cai et al., 2013). However, more recent studies have found that in real-world operation, diesel medium- and heavy-duty vehicles can emit NOx at much higher rates than what their engines were certified to meet the EPA/CARB 2010 standards (Miller et al., 2013; Carder et al., 2014; Quiros et al., 2016). The EPA's current version of the Motor Vehicle Emission Simulator (MOVES) model 2014a does not incorporate those or other recent diesel medium- and heavy-duty vehicle test results and therefore most likely is underestimating their NOx emissions. While data for in-use NOx of new diesels is limited, analyses have shown that the MOVES model is most likely underestimating diesel NOx (Anenberg 2017, Sandhu 2017). For AFLEET 2017, the option to use diesel in-use multipliers is available to provide sensitivity cases as compared to the default MOVES results.

Figure 4. EPA PM and NOx emission standards for heavy-duty engines, 1988–2010



In order to meet 2007/2010 EPA and CARB emission standards, Cummins-Westport developed a NG engine with stoichiometric combustion, cooled exhaust gas recirculation, and a three-way catalyst (TWC). The benefit of the stoichiometric/TWC engine design is that it does not require diesel particulate filters (DPFs) or selective catalytic reduction (SCR) to meet the standards. Several studies have examined in-use emissions of stoichiometric NG vehicles meeting the EPA/CARB 2010 standard (Nylund and Koponen, 2012; Yoon et al., 2013; Carder et al., 2014; Wang et al., 2015; Quiros et al., 2016). In October 2016, Cummins Westport began production of an 8.9-L stoichiometric engine with an improved TWC and a new closed crankcase ventilation system and calibration, branded the "ISL G Near Zero," and meeting CARB's lowest optional NOx standard of 0.02 g/bhp-hr (Cummins Westport Inc, 2016). A recent study examined the in-use emissions of a NG vehicle using this "near-zero" stoichiometric engine (Johnson et al., 2016).

Compared to NG lean-burn engines with an oxidation catalyst, NG stoichiometric engines with a TWC have significantly lower levels of non-methane hydrocarbon (NMHC) emissions, owing predominately to the higher conversion efficiency of a TWC compared to an oxidation catalyst, and had about 95 percent less CH_4 emissions, owing primarily to the larger size and higher precious-metal loadings for the TWC (Hajbabaei et al., 2013). Significantly lower NMHC and CH_4 emissions from stoichiometric engines with TWCs compared to lean-burn engines with oxidation catalysts were also measured on both the Heavy-Duty Urban Dynamometer Driving Schedule (HD-UDDS) and steady-state driving cycles (Yoon et al., 2013). Moreover, about 80 percent lower CH_4 emissions from stoichiometric engines with TWCs compared to lean-burn engines with oxidation catalysts were measured for European NG buses (Nylund and Koponen, 2012).

Unlike other pollutants, CO is considerably higher in NG engines than diesel engines. This is due to diesel engines using lean-burn technologies, which means the fuel is burned in an excess of oxygen, resulting in lower CO than NG engines using a TWC. According to the EPA's engine certification testing data, Cummins NG engines have significantly higher CO emissions, 8–14 g/bhp-hr (these engines meet the 15.5 g/bhp-hr standard), compared to diesel engine counterparts having 0.1 g/bhp-hr (U.S. Environmental Protection Agency, 2014). A review study on emissions from CNG and diesel transit buses showed that CNG transit buses with a TWC had much higher CO emissions, 4.9 g/mi, compared to their diesel counterparts with DPF, having 0.6 g/mi (Hesterberg et al., 2009). Further tests of CNG transit buses found CO emissions to be 27.4 g/mi (standard error of 3.4 g/mi) for the HD-UDDS drive cycle and 5.0 g/mi (standard error of 0.7 g/mi) for a steady-state 45 mi per hour cruise test (Yoon et al. 2013). Carder et al. (2014) also showed that NG freight trucks had significantly higher CO emissions, 7.1–9.4 g/mi, than diesels, with 0.2–0.8 g/mi, depending on the duty cycle. Furthermore, Carder et al. (2014) found very high CO emissions for CNG transit buses, 14.4–19.9 g/mi, and CNG refuse trucks, 22.7–36.6 g/mi, depending on the duty cycle. CARB testing showed that a heavy-duty CNG vehicle with a TWC had very high CO emissions, 30 g/mi, compared to a diesel with SCR and a DPF, with 0.2 g/mi (Herner et al., 2012).

Results from EPA/CARB 2010 compliant freight trucks showed that the heavy-duty NG vehicles had PM emissions ranging from 80 percent lower to 40 percent higher than diesels equipped with DPFs, depending on the duty-cycle (Carder et al. 2014; Quiros et al. 2016). In absolute terms, the PM emissions from all the tested natural gas vehicles and diesels with DPFs were very low, ranging from about 1–10 mg/mi for all vehicles, which agrees well with MOVES2014 (Cai et al., 2015).

The testing also showed that the current NG freight trucks using TWCs had 42–95 percent lower NOx emissions and that a NG refuse truck had NOx emissions ranging from 70 percent lower to 116 percent higher than their diesel counterparts depending on the duty-cycle (Carder et al. 2014; Thiruvengadam et al., 2015; Quiros et al., 2016). However, using relative ratios can be misleading as all the current natural gas vehicles consistently had low NOx ranging from 0.2–0.9 g/mi, while the diesel freight trucks' NOx ranged from 0.6–9.0 g/mi and diesel refuse ranged from 0.7–1.3 g/mi. In high-speed duty cycles, the SCR system performs well and the diesel trucks have relatively low NOx emissions. The test results showed that diesel engine temperatures did not reach levels to support sustained SCR performance in duty-cycles with significant amounts of idling, low speeds, and low engine loads, resulting in very high NOx emissions. For example, in duty-cycles representing near-dock port and local drayage operations, the exhaust gas temperatures were below 250°C for more than 95 percent of the time, which limited SCR activity and resulted in NOx emissions of 9.0 g/mi and 5.4 g/mi, respectively (Carder et al., 2014; Thiruvengadam et al., 2015). The natural gas vehicles typically had much lower NOx emissions in duty-cycles with low speeds and low engine loads, as diesel engine temperatures did not support sustained SCR after treatment performance in those operations. Table 5 shows a summary of the GREET 1 2017 summary of ratios of air pollutant emissions for spark-ignited NG HD combination short-haul truck relative to their diesel counterpart. The relative emissions for this vehicle type are representative of other MDHVs.

The main differences between CNG and LNG emissions occur in upstream processes. Specially designed cryogenic sea vessels (LNG carriers) or cryogenic road tankers are used for LNG transportation and distribution. LNG is principally used for transporting natural gas to markets, where it is re-gasified and distributed as pipeline natural gas. LNG can be used in natural gas vehicles, although it is much more common to design vehicles to use CNG. LNG's relatively high cost of production and the need to store it in expensive cryogenic tanks have hindered widespread commercial use. Similarly, the advantages of RNG over CNG or LNG arise from benefits in upstream process. Although the tailpipe emissions of RNG are similar to those of CNG and LNG, in most LCA frameworks, RNG receives an emissions credit for avoided emissions. For example, if the RNG is derived from a landfill methane capture, the RNG fuel lowers the total release of the methane into the atmosphere at the landfill which is credited towards the fuel.

2b. Liquefied Petroleum Gas – Category 4 / 4A

LPG (often called "propane") has been used for several decades as a transportation fuel and is well suited for spark-ignition engines. The LPG vehicles available today use converted gasoline engines and will typically have similar engine efficiencies (Nylund et al., 2004). Recently, the University of California-Riverside tested a model year (MY) 2009 LPG school bus equipped with TWC for the South Coast Air Quality Management District (SCAQMD) and compared it with a model year 2007 diesel school bus with a DPF (and no SCR). The LPG school bus utilized an 8.1-L engine based on a General Motors gasoline engine, which was available between 2008 and 2011 (Laughlin and Burnham, 2014). Results showed that the LPG school bus had 12 percent lower fuel economy, 7.1 miles per gallon (MPG) for diesel vs. 4.1 MPG or 6.2 miles per diesel gallon equivalent (MPDGE) for LPG, on the Central Business District (CBD) drive cycle. The LPG bus exhibited much lower NOx emissions and lower PM emissions, but higher CO, hydrocarbon (HC), and CH4 emissions than its diesel counterpart (Miller et al., 2013).

Table 5. Summary of ratios of air pollutant emissions* for spark-ignited NG medium- and heavy-duty vehicles relative to their diesel.

Vehicle Type	MY	VOC Exhaust	NOx	PM_{10}, Exhaust	$PM_{2.5}$, Exhaust
Spark-ignited Natural Gas medium- and heavy-duty vehicle	2015	100 percent	16 percent	100 percent	100 percent
	2020	100 percent	4 percent	100 percent	100 percent

In addition, Miller et al. (2013) tested a MY 2005 port truck that had been converted using a MY 2009 LPG 8.1-L engine and compared it to various post-2007 and post-2010 diesels. The researchers found the LPG truck difficult to test; it nearly overheated, as the engine was not properly sized for the chassis and duty cycle (loads were set at 69,500 pounds for goods movement testing). The LPG truck had significantly higher emissions than the diesel trucks (Miller et al., 2013). It is difficult to draw any conclusions from the LPG port vehicle tests, as the engine was not designed for that application.

Owing to the limited test data available, Cai et al. (2015) assumed that LPG medium- and heavy-duty vehicles have the same fuel economy on a gallon of gasoline (GGE) basis as their gasoline counterparts. In addition, analysis of heavy-duty LPG engine certification data shows similar emissions in comparison to their gasoline counterparts (U.S. Environmental Protection Agency, 2014g). Therefore, Cai et al. (2015) adopted the emissions of gasoline school buses, which were estimated with the EPA's MOVES model. A model year 2017 gasoline school bus in MOVES has about 50 percent lower NOx than a model year 2017 diesel school bus. In 2017, the Roush 6.8-liter engine was first LPG engine to meet the CARB's second lowest optional NOx standard, 0.05 g/bhp-hr, which is 75 percent lower than the EPA standard (Bebon 2017). Further testing expanding on the work of Miller et al. (2013) is needed to see whether LPG engines operating on the correct duty cycles can provide in-use emission benefits. In 2018, West Virginia University began testing one post MY-2010 propane school bus and one post MY 2010 diesel school bus. No results are available at the time of this writing.

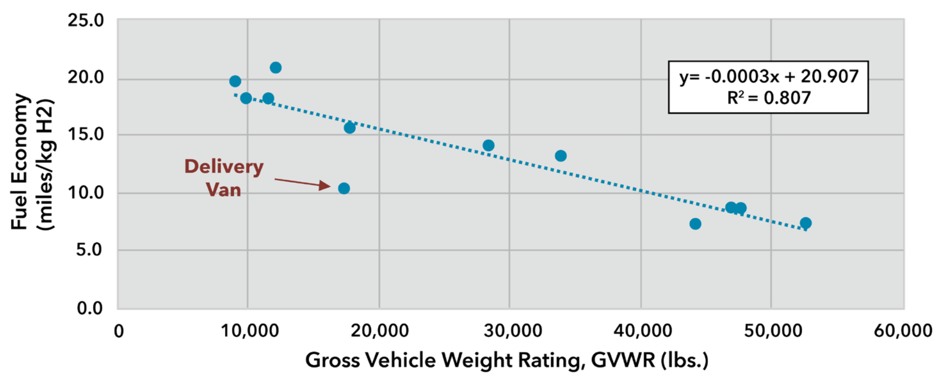
2c. Hydrogen – Category 4 B & 4 C

Hydrogen fuel cell electric vehicles are zero emission vehicles that currently use high-pressure (i.e., 5000 psi) compressed hydrogen gas storage tanks, a fuel cell stack, balance of plant components, and a battery to power the vehicle. As with other gaseous fuels, the limited volume capacity onboard medium- and heavy-duty vehicles, as well as the impact of these components on the vehicle's weight and aerodynamic drag, results in a complex vehicle design space which must be customized to each vehicle's specific vocation, duty cycle, and purpose.

Only limited numbers of studies measure the vehicle efficiency of hydrogen fuel cell electric trucks. As a result, Argonne National Laboratory only incorporated fuel cell electric medium- and heavy-duty vehicles powered by gaseous hydrogen in GREET 2017. Fuel cell technology was added for combination short-haul trucks, heavy-heavy-duty vocational vehicles, medium-heavy-duty vocational vehicles, light-heavy-duty vocational vehicles, heavy-heavy-duty pickup trucks and vans, refuse trucks, and school buses. Representative US average fuel efficiency ratios for fuel cell and conventional diesel medium- and heavy-duty vehicles were developed using real-world idle fuel rates, Autonomie simulation results, EPA/National Highway Traffic Safety Administration (NHTSA) vehicle fuel efficiency standards, and county-by-county regional aggregation.

Figure 5 demonstrates how the fuel economy of fuel cell electric vehicles varies with GVWR. Results are from the Autonomie model and reported in Kast et al. (2017). Note the outlier cases are attributed to unique truck design considerations, such as the Class 4 delivery truck that has low relative fuel economy at 65 mph due to the large aerodynamic drag. The Autonomie simulations in Kast et al. (2017) demonstrate that fuel cell electric vehicles are technically feasible for most medium- and heavy-duty vehicles.

Figure 5. Autonomie-based simulation results for medium- and heavy-duty hydrogen fuel economy as a function of GVWR.



This study examines two hydrogen pathways. The first is derived from natural gas via reformation, while the second uses renewable electricity via electrolysis. Because the natural gas reformation pathway uses a fossil fuel as its feedstock, its life-cycle emissions are higher than the renewable electricity via electrolysis route.

2d. Electric – Category 7 / 7 A

Electric vehicles store energy onboard in a battery, which is charged from an electricity source. These vehicles have no emissions at the tailpipe but can produce emissions "upstream" at the electricity source. Colorado's electricity generation is largely a mix of coal, natural gas, wind, and hydro-electricity. Even though coal accounts for 53 percent of Colorado's generation mix, coal's emissions-intensive nature means it accounts for a disproportionate fraction (88 percent) of greenhouse gas emissions (CDPHE, 2014).

However, this mix is changing in favor of greater renewable energy. In 2004, Colorado passed a renewable energy standard, requiring electricity providers to obtain a minimum percentage of their power from renewable energy sources. The legislature has increased the amount of renewable energy required several times since 2004. House Bill 10-1001 required investor-owned utilities to generate 30 percent of their electricity from renewable energy by 2020, of which 3 percent must come from distributed energy resources. (Colorado, 2017a). Cooperative utilities are required to generate 20 percent of their electricity from renewable sources (Colorado, 2017b). Simple online emissions calculators, such as from Union of Concerned Scientists (UCS, 2018), suggest that electric vehicles charged with electricity from Colorado's grid have lower life-cycle greenhouse gas emissions than equivalently sized gasoline or hybrid electric vehicles.

Additionally, electric vehicles are often coupled with onsite solar panels to help shift load from the grid and lower emissions. Some estimates suggest that up to 39 percent of household electric vehicles are coupled with residential solar panels (CSE, 2013). No similar estimate was found by the research team regarding electric medium- and heavy-duty vehicles.

Medium- and heavy-duty electric vehicles are quite limited in availability. The first all-electric refuse truck in the U.S., manufactured by Motiv Power Systems, began operations in Chicago in 2014. The all-electric refuse truck is equipped with 200 kilowatt-hours of energy that supplies enough electricity to move the truck and power the hydraulics, with a payload capacity of nine tons and 1000 pounds per cubic yard of compaction (Motiv Power Systems, 2014). Proterra's EcoRide BE35 transit bus is the world's first heavy-duty, fast-charge, battery-electric bus. Currently BYD and New Flyer also produce battery electric transit buses. In 2016, Denver Regional Transportation District deployed 36 electric shuttle buses (Starcic 2016). Currently the AFLEET Tool estimates that electric medium- and heavy-duty vehicles have a fuel economy of about 255 percent of that of the diesel medium- and heavy-duty vehicle, when taking into account a charger efficiency of 88 percent and battery-in and battery-out efficiency of 95 percent (Burnham 2017).

2e. Plug-In Hybrid Electric - Category 7 / 7 A

The Plug-In Hybrid Medium-Duty Truck Demonstration and Evaluation Program was sponsored by the U.S. Department of Energy using American Recovery and Reinvestment Act of 2009 (ARRA) funding. The program was to develop plug-in hybrid vehicle technology for medium-duty vehicles through demonstration and evaluation in diverse applications. From this effort, plug-in hybrid pickup trucks, vans, and Class 6-8 medium-duty utility trucks were demonstrated. The Class 6-8 trucks were found to improve fuel economy by up to 50 percent in duty-cycles that replicate utility vehicles (Kosowski 2015).

Limited emission testing has been performed on plug-in hybrid medium- and heavy-duty vehicles, when running in hybrid mode. Nylund and Koponen (2012) suggested that there was a wide variation in the relative emission ratios of NOx, HC, and PM, and no conclusions could be reached on emission differences between hybrid-electric vehicles (HEVs) and diesel vehicles equipped with SCR and DPFs, running under different duty cycles. Cai et al. (2015) analyzed this testing of hybrid trucks and assumed that post-MY 2010 hybrid vehicles do not have NOx, PM, or HC emission reduction benefits. Furthermore, no studies focus on evaporative VOC emissions of diesel hybrid electric medium- and heavy-duty vehicles. Cai et al. (2015) assumed that diesel hybrid electric medium- and heavy-duty vehicles have the same evaporative VOC emissions, while having 50 percent lower CO as compared to their diesel counterparts.

2f. Hydraulic Hybrid - Category 9

Unlike HEVs, which use electrochemical (battery) or electrostatic (ultracapacitor) energy storage, HHVs capture kinetic energy during braking events, store it in hydro-pneumatic accumulators, and return energy to the driveline during vehicle acceleration (Boretti and Stecki, 2012). The EPA and its partners have successfully installed hydraulic hybrid technology in a variety of vehicles, including delivery trucks and work trucks. Their testing has shown real-world fuel economy improvements of 30 percent to over 100 percent over their conventional counterparts (U.S. Environmental Protection Agency, 2014). Kim and Rousseau (2013) evaluated the performance of Class 6 HHVs and compared it to conventional diesel and diesel HEVs. The results demonstrated that HHVs achieve about 25–190 percent higher fuel economy than their diesel counterparts on aggressive drive cycles like the Urban Dynamometer Drive Schedule (UDDS), Central Business District CBD, Manhattan, and New York cycles. The 190 percent fuel economy gain seems unlikely to be achieved in practice. Also, HHVs achieve higher fuel savings than HEVs when driven on these aggressive drive cycles because of higher system efficiency during regenerative braking events, as well as a higher charging power.

HHV technology has been demonstrated in the past few years as a viable technology for brake energy recovery for transit buses and refuse trucks, which are engaged in heavy urban stop-and-go or highly transient duty cycles, regenerating a large portion of the energy that is dissipated during braking. For extremely short driving cycles, as are common with refuse vehicles, the use of hydraulic regenerative systems reduces fuel consumption by up to 30 percent for Class 8 refuse trucks, equivalent to a fuel economy gain of 43 percent (Baseley et al., 2007). The City of Denver has employed the Peterbilt Model 320 hydraulic hybrid refuse truck, which utilizes Eaton's hydraulic launch assist system. The truck has achieved 25 percent better fuel economy than its non-hybrid counterparts, supporting the assessment of DOE's Clean Cities Program (Lauron, 2009; Shea, 2011).

Parker (2013) reported that replacing Class 8 refuse trucks, with conventional drivetrains, with its RunWise hydraulic hybrid drivetrains resulted in a fleet average 43 percent (35 percent–50 percent) reduction in diesel consumption, depending on route density and operating conditions (Parker, 2013). The company reports that high fuel saving is achieved by decoupling the engine from the wheels at speeds under 45 mph, which allows the engine to operate at its peak efficiency, and by recovering brake energy to reduce the total vehicle fuel consumption. Emission testing of the Parker hydraulic hybrid refuse truck showed significant reductions in CO and NOx emissions relative to its conventional counterpart (Parker, 2013). However, information was not presented regarding the MY or specific vehicle technologies used for these fuel economy and emissions comparisons.

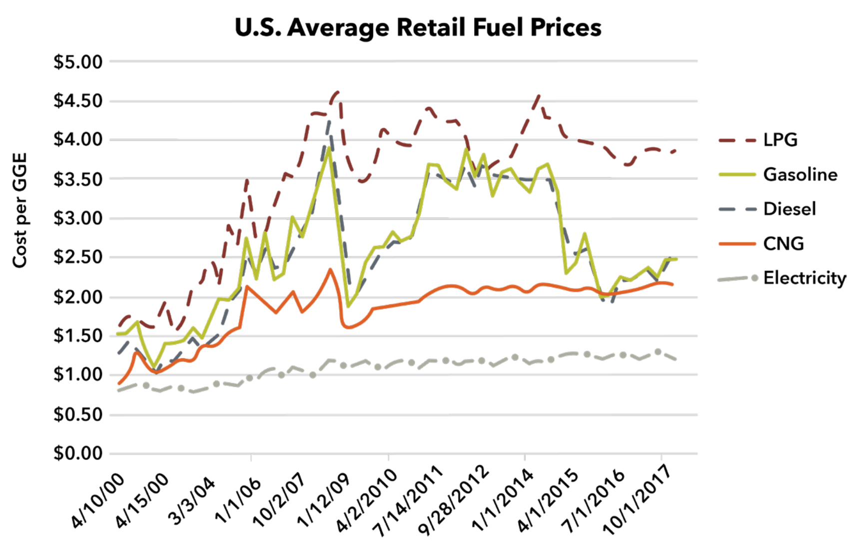
Another study found that heavy-duty diesel-powered refuse trucks equipped with hydraulic regenerative braking systems provided fuel economy improvements of 4.0 percent relative to their conventional diesel counterparts on the West Virginia University (WVU) Refuse Truck Cycle and 7.2 percent on the New York City Garbage Truck Cycle, compared to a fuel economy improvement upper limit of 25.1 percent on an ideal driving cycle consisting of a high proportion of low-speed, stop-and-go driving with little idling, PTO or transient operation (New West Technologies, LLC, 2011).

Cai et al. (2015) assumed that hydraulic hybrid trucks have a 25 percent higher fuel economy (20 percent lower fuel consumption) than their diesel counterparts. While the study by Parker (2013) showed CO and NOx emission reductions of 47 percent and 34 percent, respectively, Cai et al. (2015) used emission assumptions for diesel HEVs for this vehicle type, since there was a limited amount of vehicle testing of HHVs. Currently Lightning Systems are the major providers of hydraulic hybrid trucks. With a 20 percent fuel saving, Cai et al. (2015) assumed that the tailpipe CO emissions are reduced by 50 percent for hydraulic hybrid trucks compared to their diesel counterparts.

2g. Costs of Fuels

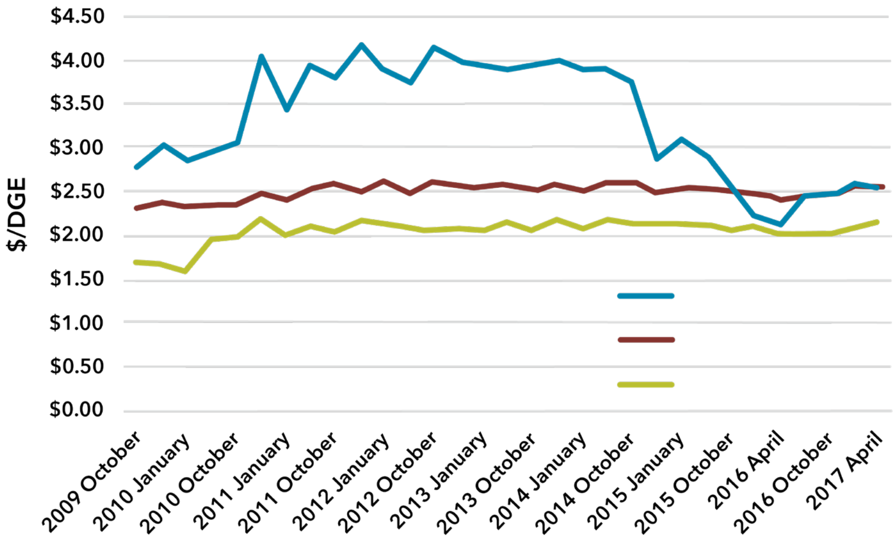
The cost differential between fuel types varies over time and by fuel type. Figure 6 gives trends over time for the average US retail price of fuels between 2000 and 2017. Note that electricity price has been reduced by 3.4 times to account for the higher engine efficiency of plug-in electric vehicles. Hydrogen and LNG are not shown in Figure 6 because data is much more limited on these fuels. The US DOE reports that the current unsubsidized cost of hydrogen from natural gas reformation is $13-16 per kilogram, roughly equal to $13-$16 per gallon of gasoline. Since hydrogen fuel cell vehicles are roughly 2.4 times more efficient than internal combustion engines, this equates to a cost of $5.40 to $6.67 gallon for the same mileage (US DOE, 2015). The DOE reports that the US Average Retail Price of LNG is $2.36 per gallon of gasoline equivalent in January 2018 (US DOE, 2018a).

Figure 6. Average US fuel prices in GGE for five fuels from April 2000 to October 2017. Note: electricity prices have been reduced by 3.4 to account for higher vehicle efficiency.



Fuels like natural gas and propane are less expensive when fleets build private fueling infrastructure. They can also be less expensive when securing long-term fueling contracts. Figure 7 shows the reduction in fuel price of CNG from public versus private stations.

Figure 7. CNG and Diesel fuel prices in diesel gallon equivalent (DGE) (Burnham 2017).



2h. Conversion versus OEM, and Dedicated versus Bi-Fuel

Vehicles can be modified through the use of a conversion kit to run on a fuel or power source that is different from the one it was originally designed to operate on. The process of converting vehicles depends on the type of alternative fuel selected, but typically involves the addition of fuel-specific supply lines, storage system components and controllers, and engine recalibrations or software adjustments to the electronic engine control system.

Most commonly available conversion kits today modify gasoline and diesel vehicles for operation on CNG and LPG. Vehicles and engines can be converted to "dedicated" configurations so that they operate exclusively on one alternative fuel. They can also be converted to "bi-fuel" configurations that include two separate fuel systems—one for a conventional fuel and another for an alternative fuel. In this type of configuration, either fuel can be used by flipping a switch.

All vehicle and engine conversions must meet standards instituted by the EPA, the National Highway Traffic Safety Administration (NHTSA), and state agencies like CARB (DOE, 2017). To achieve emission benefits, the conversion equipment must be designed and calibrated specifically for the engine and emission control system on which it has been installed, and the installation and setup must be performed so as not to adversely affect the vehicle's original emission performance (DOE, 1998).

When a buyer purchases a newly converted alternative fuel vehicle through a dealer, the conversion kit is installed by the system manufacturer or by a company designated as a qualified system retrofitter or vehicle modifier (QSR or QVM). These companies have met strict requirements in order to convert certain vehicles from an OEM.

In other cases, individual vehicle owners convert the vehicles themselves using a conversion kit. Conversion-kit manufacturers must submit applications to the EPA, including test data, certification fees, and other information. Vehicles and engines in this category need an EPA or CARB Certificate of Conformity to qualify for an exemption from the EPA's tampering prohibition. The EPA or CARB then issues a certificate to verify that the appropriate regulations and requirements have been met.

In our literature search, we only identified a study that examined emissions from aftermarket conversions of alternative fuel vehicles (i.e., Dondero, L., and J. Goldemberg, 2005). However, this study examines emissions from aftermarket light-duty vehicles in Brazil so the applicability to Colorado is minimal.

Given the limited data available to differentiate the in-use emissions of new OEM versus new conversions and the fact that aftermarket vehicles have to meet the same emissions standards as OEM vehicles, most life-cycle emission modeling (including GREET and AFLEET) assumes the two have the same air pollutant emissions. There is a similar lack of data to compare dedicated versus multi-fuel alternative fuel vehicles.

Bi-fueled vehicles are omitted from this study due to a lack of data. Bi-fuel vehicles are capable of running on two different fuel (for example, CNG and diesel). This provides flexibility if one fuel is unavailable or is higher price. Emissions studies of bi-fuel vehicles require more intensive data collection than studies on dedicated fuel vehicles. Those studies need to analyze the emissions using each fuel type is needed. In addition, there is limited information on the fraction of time vehicles run on each fuel, as this can vary significantly by operator. This information was not available for the authors at the time of this study.

2i. Advances in Vehicle and Fuel Technology

The discussion above describes many of the recent advances in vehicle technology that are penetrating the market place. On one hand, vehicles and engines that use certain fuel types – such as CNG, RNG, LPG, and LNG – are well-understood and technology is advancing at a slow and steady pace.

A notable exception is the emergence of low NOx engines and their ability to provide substantially lower emissions than diesel equivalent engines. Other quickly moving technology development areas impact all medium- and heavy-duty vehicles and therefore do not change the relative benefits of a given fuel category. These developments include: aerodynamics, hybridization, improved thermal management, friction and wear, and data collection and modeling. Because these improvements apply to any medium- and heavy-duty vehicle type, they will not materially affect the conclusions of this study. More information on these sector-wide advances is available in DOE (2015).

On the other hand, emerging fuels like electricity and hydrogen are experiencing much more rapid change. The following bullets describe advances that could alter the life-cycle emissions and/or costs of these vehicles:

- **Electricity grid changes.** Today, the electricity grid in Colorado is composed of natural gas (28 percent), coal (48 percent), hydroelectricity (4 percent), and non-hydroelectric renewables (20 percent) (EIA, 2018). The grid is moving towards greater percentages of non-hydroelectric renewables, such as wind and solar. Additionally, several jurisdictions like Pueblo and Fort Collins are considering implementing or have already implemented stringent renewable energy goals. Together, these changes will lower the life-cycle emissions of electric vehicle powertrains in the future relative to diesel powertrains.
- **Batteries.** Battery costs are falling rapidly and play a major role in the purchase price of vehicles. One study demonstrates that the cost of batteries for electric vehicles is dropping 14 percent per year on average (Nykvist and Nilsson, 2015). R&D efforts, including pack design optimization and simplification, manufacturing improvements at the cell and pack level, materials production cost reduction, and novel thermal management technologies, can also contribute to battery cost reduction. Concurrently, the size and weight of electric vehicle battery packs have also been reduced by more than 60 percent. The battery pack energy density has increased from 60 watt-hours (Wh) per liter in 2008, to more than 150 Wh per liter in 2014. Despite recent progress, current battery technology is still far from its theoretical energy density limit. In the next roughly five years, advances in lithium-ion technology could more than double the battery pack energy density from 120 Wh per kilogram to 250 Wh per kilogram through the use of new high-capacity cathode materials, higher voltage electrolytes, and the use of high-capacity silicon or tin-based intermetallic alloys to replace graphite anodes (DOE, 2015a). Lower battery costs will mean that electric and diesel medium- and heavy-duty vehicles may begin reaching cost parity within the next five years on a life-cycle basis (DOE, 2016).
- **Fuel cells and hydrogen production.** R&D has reduced automotive fuel cell cost from $124 per kilowatt (kW) in 2006 to $55 per kW by 2015, based on high-volume manufacturing projections. The DOE estimates that automotive fuel cell systems must cost $30 per kW or less to be cost-competitive with petroleum-powered vehicles (DOE, 2015b). Hydrogen production is still more expensive than needed for cost parity with diesel-powered vehicles. Today's retail hydrogen from natural gas reformation costs are about $13 per gallon of diesel equivalent. After factoring in the higher vehicle efficiency of fuel cells than diesel vehicles, this equates to around $5-$6 per gallon for a similar distance traveled. Even though costs continue to drop each year, hydrogen fuel cells likely will not reach life-cycle cost parity with diesel vehicles in the next five years (DOE, 2016).
- **Vehicle-to-Grid.** The opportunity for vehicle-to-grid (V2G) or vehicle-to-building (V2B) in the case of electric vehicles and hydrogen fuel cell electric vehicles has largely been unexplored. V2G and V2B systems would enable these vehicles to provide power to the electricity grid or building, respectively, when needed, such as during peak electricity load times or when backup power is needed. The concept of a power offtake unit could allow an electric vehicle or hydrogen fuel cell electric vehicle to power a home for several days. These technologies, although promising, are still in their infancy in terms of market adoption and are not expected to make a material impact on costs or emissions in the next five years.

Overall, electricity and hydrogen pathways show the greatest emission and cost reduction potentials from 2015 to 2030. Fuel cell technology shows the largest reduction in cost over time, due to both the expected drops in fuel cell costs and hydrogen costs. Moultak et al. (2017) report that the reduced vehicle costs for electric tractor-trailers result in upfront costs that are similar to conventional diesel trailers in the 2025–2030 timeframe. Moultak et al. (2017) suggest that the gap in costs between conventional diesel and electric technology will further widen as diesel tractor-trailers become incrementally more advanced and as compliance with future efficiency regulations becomes more expensive.

2j. Pollutants in Study

An air pollutant is a material in the air that has adverse effects on humans and the ecosystem. Studies link pollutants to adverse impacts on nearly every organ system in the body. Furthermore, air pollution has been linked to loss in agricultural productivity and decreases in tourism. Table 6 provides a description of each pollutant included in this study and summarizes the key impacts.

Table 6. Summary descriptions of pollutants and their impacts.

Pollutant	Description	Primary Impacts
GHG	Includes CO_2, methane, N_2O, and black carbon, primarily from combustion of fossil fuels.	Global climate change.
CO	Colorless and odorless by-product of combustion.	Reduced ability of red blood cells to carry oxygen; negative impacts on development of fetuses and young children; headaches and nausea.
NOx	Includes NO and NO_2 and is formed when nitrogen and oxygen in the atmosphere is exposed to intense heat, such as combustion. Acts as a catalyst for ozone and PM formation.	NOx impacts include: respiratory irritation; formation of photochemical smog. Ozone and PM impacts include: respiratory irritation; aggravation of existing respiratory conditions; suppression of immune system, cancer.
PM-2.5/ PM-10	Solid or liquid pollutant from a variety of sources, including direct combustion as "soot" from a car's engine. Diesel exhaust is a major contributor to PM pollution.	Respiratory and cardiovascular impacts. Smaller particles (e.g., PM-2.5) pose serious human health threats because they penetrate deep into the lungs.
VOCs	Reacts with ultraviolet sunlight and NOx to create ground-level ozone, a main ingredient of smog.	Diverse set of impacts, including: respiratory irritation; aggravation of existing respiratory conditions; suppression of immune system, and cancer.

3 | Methodology for Calculating Life-cycle Emissions and Costs

3a. Summary of Methodology

The overarching task of this study is to determine if the life-cycle emissions of Categories 4, 4A, 4B, 4C, 7, 7A, or 9 medium- or heavy-duty trucks are materially greater than comparable traditional fuel trucks. To accomplish this, the authors used the following steps below:

1. Use AFLEET Tool to model all potential vehicle-fuel categories in AFLEET.
    a. The vehicle types include: school bus, transit bus, refuse truck, single unit short-haul truck, single unit long-haul truck, combination short-haul truck, combination long-haul truck. See Table 7.
    b. The fuel/powertrain types include: electric, H_2-NG, H_2-Renew, diesel HHV, LPG, CNG, RNG, LNG, and conventional diesel.
    c. For all vehicle-fuel combinations, the authors estimate the life-cycle emissions of the following pollutants: GHGs, NOx, HC, PM, and CO. Note that HCs is a diverse emissions category. In AFLEET, HC are represented by VOC emissions. The selection of these pollutants for this study was made based on the authors' expert knowledge of the transportation-related pollutants with the highest probable impact on society.
    d. For all vehicle-fuel combinations, the authors estimated the net present value of all life-cycle costs, including vehicle, fuel, maintenance, and disposal.
    e. The authors use Colorado-specific inputs to the modeling when possible. For electricity, the authors use the electricity mix from the Western Electricity Coordinating Council (WECC). Note that this mix may not reflect the actual electricity mix of where the vehicle charges.
2. Calculate the arithmetic mean of emissions and costs for each vehicle category defined in §§ 39-22-516 C.R.S.
3. To understand whether a vehicle had materially greater emissions than another, the authors developed a methodology to weigh each

Table 7. Vehicle-fuel combinations modeled in AFLEET Tool.

medium- and heavy-duty vehicle in AFLEET	Definition	Fuels Represented in AFLEET							
		CNG	RNG	LPG	LNG	H_2-NG	H_2-Renew	Electric	HHV
School bus	Passenger vehicle with a capacity of 15 or more persons used primarily for transport of students	x	x	x	x			x	
Transit bus	Passenger vehicle with a capacity of 15 or more persons primarily used for transport within cities	x	x		x	x	x	x	
Refuse truck	Truck primarily used to haul refuse to a central location	x	x		x			x	x
Single unit short-haul truck	Single unit truck with more than four tires with a range of operation of up to 200 miles	x	x	x	x			x	
Single unit long-haul truck	Single unit truck with more than four tires with a range of operation of over 200 miles	x	x	x	x			x	
Combination short-haul truck	Combination tractor/trailer truck with more than four tires with a range of operation of up to 200 miles	x	x		x			x	
Combination long-haul truck	Combination tractor/trailer truck with more than four tires with a range of operation of over 200 miles.	x	x		x				

pollutant by the cost of the pollutant to society in Colorado (i.e., the marginal damage cost).

4. Compare the marginal damage cost of each averaged vehicle Category defined in §§ 39-22-516 C.R.S. with the that of the diesel comparison vehicle. The higher marginal damage cost is defined as materially greater.

Table 8. Summary of life-cycle pathways of fuels in study.

Fuel	Primary Energy and Feedstock Recovery	Feedstock Transport to	Post-Recovery Processing	Fuel Delivery	End Use
Diesel	Crude extraction from North America	Pipeline or train	Crude upgrading to diesel	Pipeline, train, or truck	Combustion in vehicle
CNG	Mix of conventional and shale gas	Pipeline	Natural gas upgrading and compression	Pipeline to refueling station followed by compression	Combustion in vehicle
RNG	Modeling in this report assumes landfill gas.	Pipeline or truck	Filtering, upgrading, and compression	Pipeline to refueling station followed by compression	Combustion in vehicle
LPG	Mix of conventional and shale gas recovered from North America	Pipeline	Propane upgrading	Truck	Combustion in vehicle
LNG	Mix of conventional and shale gas	Marine carrier or pipeline	Natural gas liquefaction	Truck	Combustion in vehicle
H_2-NG	Mix of conventional and shale gas recovered from North America	Pipeline or truck	Steam methane reforming	Pipeline or truck	Use in vehicle's fuel cell, producing electricity for vehicle's battery
H_2- Renew	Solar or wind to electricity	n/a	n/a	Pipeline or truck	Use in vehicle's fuel cell, producing electricity for vehicle's battery
Electric	Coal, natural gas, solar, wind, hydro, petroleum	Transport of coal, natural gas, and petroleum to power plant. Others N/A	Electricity production	Power lines	Use in vehicle's battery
HHV	Crude extraction from North America	Pipeline or train	Crude upgrading to diesel	Pipeline, train, or truck	Combustion in vehicle

Note that a more robust method of developing the emissions profile of a representative vehicle would be to weight the vehicles by their respective vehicle population in Colorado. For example, if there are more combination long-haul trucks than refuse trucks, the emissions of combination long-haul trucks would be weighted more than refuse trucks. This ideal methodology is not possible, however, due to the lack of statistics about Colorado's medium- and heavy-duty vehicle population. The last publicly-available survey of medium- and heavy-duty vehicles is the Vehicle Inventory and Use Survey (VIUS), conducted by the US Department of Commerce in 2002. While the VIUS dataset provides a rich set of information on medium- and heavy-duty vehicles, most of the vehicles in the survey are retired by 2018. In addition, VIUS only examines private and commercial trucks and does not analyze public vehicles including school buses, transit buses. The only other report the authors identified that describes the medium- and heavy-duty vehicle population in Colorado focuses on public fleet vehicles (Vision Fleet, 2015).

3b. Description of AFLEET Tool

The AFLEET tool was developed by Argonne and uses data from models such as GREET and MOVES. The main outputs from the AFLEET tool include: petroleum use, greenhouse gas emissions, air pollutant emissions, and costs of ownership for light-duty vehicles and medium- and heavy-duty vehicles. Argonne has released three versions of AFLEET in 2013, 2016, and 2017.

AFLEET allows the user to update the following input parameters:

- Primary vehicle location (user chooses the state and/or county);
- Vehicle type (e.g., refuse truck);
- Vehicle fuel type (e.g., CNG);
- Number of vehicles;
- Annual vehicle mileage;
- Fuel economy;
- Vehicle purchase price;
- Public or private fuel station pricing;
- Fuel and diesel emission fluid (DEF) price.

Using these data and other hard-coded formulas and data lookup tables, AFLEET calculates the life-cycle emissions, petroleum use, and life-cycle costs in output sheets.

3c. Methodology to Determine Life-cycle Emissions

The basis of the life-cycle emissions in the AFLEET tool comes from Argonne's GREET fuel-cycle model (Argonne 2016a). The well-to-wheel (WTW) analysis in GREET is divided into two stages: well-to-pump (WTP) and pump-to-wheels (PTW). The WTP stage starts with the fuel feedstock recovery, followed by fuel production, and ends with the fuel available at the pump, while the PTW stage represents the vehicle's operation activities. It is important to examine emissions of transportation fuels and technologies on a WTW basis to properly compare alternatives, since activities upstream of vehicle operation can use significant amounts of energy and subsequently produce large quantities of emissions.

For air pollutant emissions, such a CO and NOx, the location of the emission source is directly related to health and environmental impact. Air quality management organizations and their stakeholders are primarily interested in vehicle operation emissions, since upstream (WTP) emissions often occur a significant distance from where humans are impacted. By default, AFLEET's air pollutant calculations have been for vehicle operation only. EPA's MOVES model is used to generate emission factors by state for gasoline and diesel vehicle types. In some cases, there are no emissions data for vehicles as they are not available in the marketplace (e.g., no gasoline refuse or combination trucks) and therefore in AFLEET Tool the calculation will show the not applicable error sign "#N/A".

Recent analyses have found that diesel in-use emissions are much higher than their laboratory certification results (Cai 2017, Anenberg 2017). Diesel NOx is driven by the type and performance of its aftertreatment systems, which can be highly duty-cycle dependent. For diesel medium- and heavy-duty vehicles, long idle times, low speeds, and low loads can cause higher NOx (Cai 2017). Data for in-use NOx of new diesels is limited, but analyses have shown that the MOVES model is most likely underestimating diesel NOx (Anenberg 2017, Sandhu 2017).

To estimate life-cycle emissions for the fuels, the GREET model sums the emissions for each stage of the life-cycle shown in Table 8. Note that Table 8 simplifies the stages and the boundaries of the life-cycle analysis. For the full description of each fuel's life-cycle, visit the GREET documentation available at https://greet.es.anl.gov/.

3d. Methodology to Determine Life-cycle Costs

The TCO metric is an industry-standard approach to assessing the overall cost and efficiency of a fleet's operations based on the full life-cycle cost accounting of each vehicle. In addition to the upfront purchase cost of each vehicle, it considers the annual and lifetime costs of fuel, maintenance and eventually residual value upon disposition of that vehicle. All of these costs are then divided by the appropriate mileage (either annual or lifetime) to assess the levelized cost per mile ($/mile) for the fleet to own and operate that vehicle.

The authors use the tabs in AFLEET related to TCO to perform the life-cycle cost analysis. In AFLEET, TCO is the net present value of the operating and fixed costs of a new vehicle over the years of planned ownership. A simplified form of TCO in dollars per mile is:

$$TCO = \frac{Depreciation + Operating + Liscense/Insurance}{Lifetime\ Miles}$$

Where Depreciation is the lifetime depreciation cost, Operating is the sum of fuel, maintenance and repair, and diesel exhaust fluid cost (if applicable), License/Insurance is the sum of vehicle registration and insurance costs, and Lifetime Miles are the number of miles driven until the time of resale. All costs are discounted in the future to reflect a real discount rate.

The structure of the TCO calculations is to look at the operating and fixed costs on an annual basis for every year of planned ownership of a new vehicle purchase. The user of AFLEET can examine costs of financing a loan, depreciation, insurance, license, and registration, in addition to the operating and acquisition costs. Using assumptions of inflation for various costs and a discount rate, the tool calculates the net present value of a vehicle purchase. The user of AFLEET also has the option of adding refueling infrastructure to the TCO. However, because this infrastructure cost is ultimately reflected in the cost of the fuel, the authors do not include infrastructure costs in this study.

3e. Methodology to Define Materially Greater

Colorado statute §§ 39-22-516 C.R.S. require the Colorado Energy Office to determine if the life-cycle emissions of alternative fuel categories 4 to 9 vehicles are materially greater than the traditionally fueled vehicle. While emissions estimates of CO, NOx, PM2.5, PM10, VOCs, and GHGs are a helpful first pass, they did not answer the question of whether an alternative fuel vehicle category was materially greater than the diesel comparison vehicle. For example, Category 4/4A LPG vehicles have lower NOx, PM2.5, PM10 than the diesel comparison vehicle, but higher CO, VOCs, and GHGs.

Given the statute's requirements and the inconclusive comparison of the emissions, the authors utilized the marginal damage cost approach, which weighs each pollutant by its associated cost to society To do this, the authors reviewed epidemiological studies on "marginal damages" and estimated those damages using the dollars ($) per metric ton of emissions (see Table 9) . Note that estimates in Table 9 reflect a statewide average. These marginal damages values are multiplied by the grams-per-mile of each pollutant and summed to get a single, composite marginal damage cost of each vehicle category.

Table 9. Statewide average marginal damages cost for six pollutants in study.

Pollutant	$2016 per short ton	Externalities included in Estimate	Reference
CO	$886	Authors account for damages associated with environmental impact, mortality, and morbidity (using a $6 million value of statistical life); and assess location-specific damages in the regions where emissions take place. See Supplemental Material for authors' methodology[1].	Michalek et al. (2011)
NOx	$14,719	Using concentration response functions, author estimates impact on human health end points such as premature mortality, chronic bronchitis, and hospital admissions. Damages also include impacts on agriculture, forestry, and recreation. All damages listed in Appendix C of NAS (2009).	Muller, N. (2014)
PM_{10}	$9,735		
$PM_{2.5}$	$86,807		
VOC	$7,248		
GHGs	$46	Net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning.	EPA (2016)

[1] Because CO valuation at a location-specific level is not available in other studies, the authors use the national-level CO valuation from Matthews and Lave (2000).

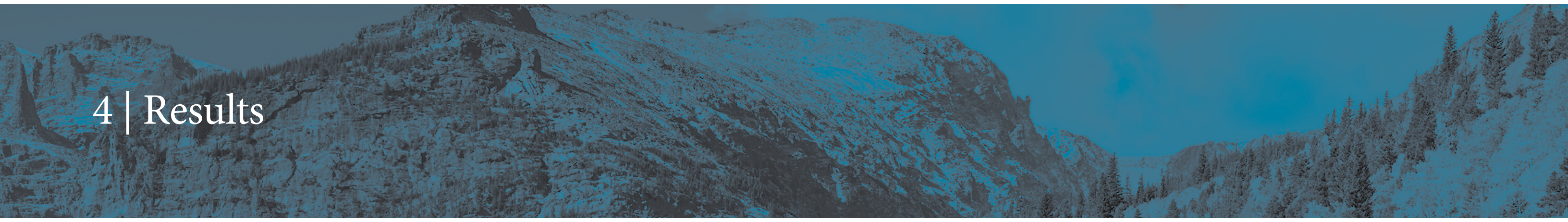
A marginal damage cost is defined as the damages to human health (e.g., increased mortality, reduced health care), agriculture (e.g., reduced yields), and visibility per ton of pollutant. The word "marginal" implies that the damage cost is measured when one additional ton of pollutant is emitted. The other way to measure damage cost is "on average." On average simply means the damage costs are averaged across the entire year's-worth of emissions. Marginal and average costs are both in $/ton and often have similar or equal values. However, sometimes they are not equal.

To provide a simple example, suppose that Colorado vehicles emit 1,000,000 tons of NOx per year. The marginal damage cost would be the damage caused by the 1,000,001st ton emitted in the state (in $ per ton). The average damage cost would be estimated by taking the sum all damages from the 1,000,000 tons emitted and dividing by 1,000,000 tons to get $/ton. The marginal cost is the preferred approach because it more closely linked to the cause-and-effect relationship between the tax credit and the emissions damages. In this example, suppose there is a threshold effect in which above a certain ton of emissions, the impact of NOx becomes much more severe. Perhaps the first 900,000 tons of NOx in Colorado have very little impact on human health, agriculture, etc. because they are absorbed or dispersed in the atmosphere, but above 900,000 tons per year the impacts become severe. In this case, the average damages would be lower than marginal damages and would misrepresent the impact of the tax credit. In all cases, academic literature recommends using marginal instead of average.

Definition of Materially Greater

This study defines "materially greater" as the condition in which aggregated marginal damages caused by the lifecycle emissions of one fuel type exceed those of another.

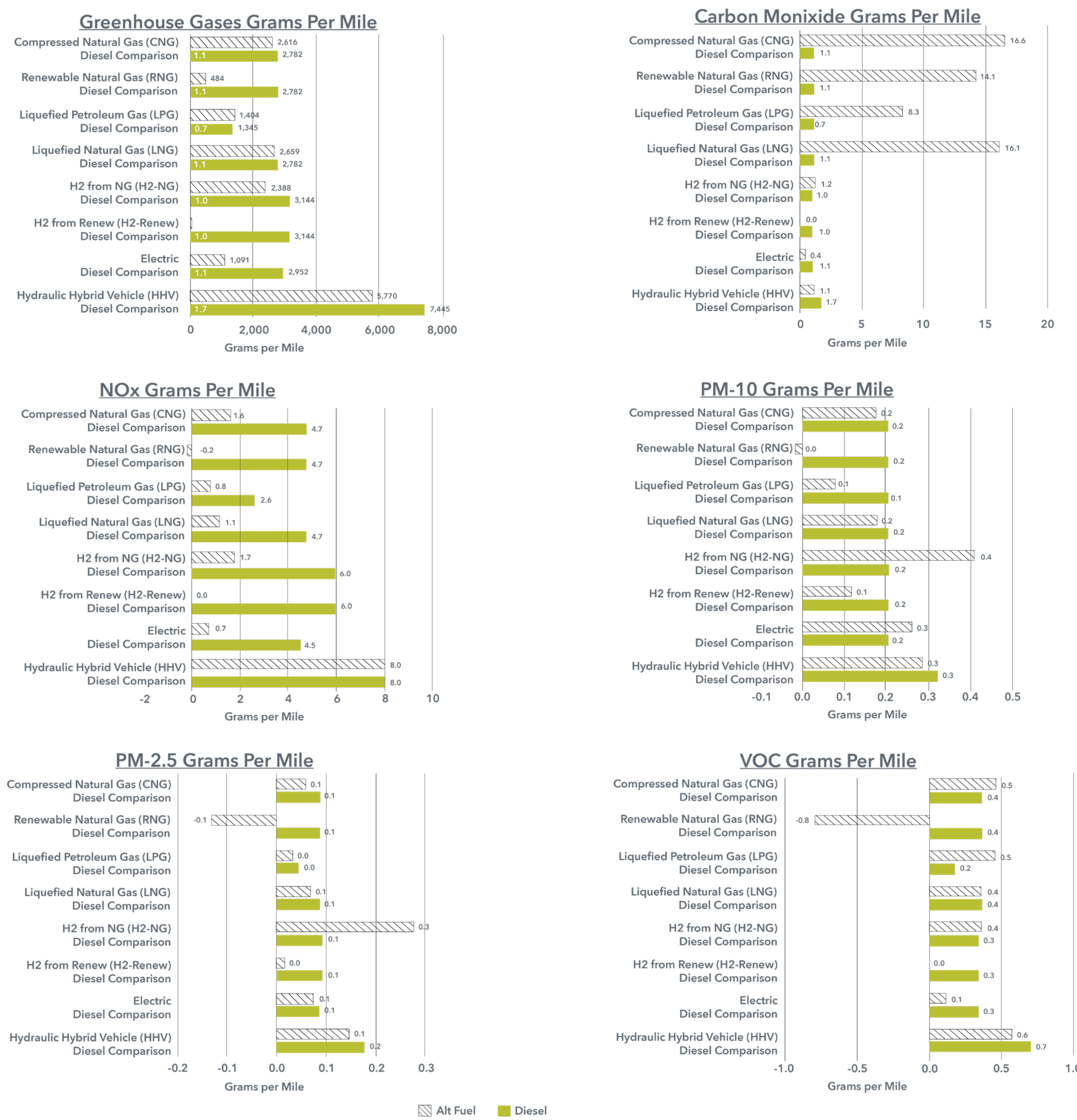
Muller (2014) estimated marginal damage costs of NOx, PM_{10}, $PM_{2.5}$ and VOCs at the county-level. To aggregate these costs to a state-level average as shown in Table 9, the authors weighed each county in Colorado by its projected population in 2025 using historical data for 2010 to 2017 from the Colorado State Demography Office (2018) and the author's own trend analysis.



4 | Results

Figure 8 below provides the initial comparison of the life-cycle emissions of the alternative fuels (black dashed line) and diesel (solid green line). Note this figure only shows emissions, not marginal damage costs. Figure 8 illustrates that results are mixed when only considering emissions – diesel is higher for some pollutants and the alternative fuel is higher in other cases (the only exception being H_2-Renew).

Figure 8. Life-cycle emission per miles of the representative vehicle for alternative fuels (black dashed) and diesel (solid green)



A general conclusion from Figure 8 is that alternative fuels are sometimes higher than the diesel comparison but are more often lower. Detailed tables in Appendix B provide pollutant-specific findings, as well as the total cost of ownership and payback period. Other insights from Figure 8 include:

- **CNG, LNG,** and **LPG** have much higher life-cycle CO emissions than diesel, lower NOx emissions, and about the same emissions for other pollutants.
- **RNG** from landfill gas has much lower life-cycle emissions for all pollutants except CO. RNG's negative emissions are due the LCA methodology behind it's emissions factor. By the avoiding methane flaring at landfills, the RNG receives an emission "credit" resulting in a negative number for certain pollutants.
- **H_2-NG** has higher $PM_{2.5}$ and PM_{10} emissions than diesel, lower NOx, and similar levels of other pollutants.
- **H_2-Renew** has lower life-cycle emissions for all pollutants due to the nature of its zero-emission feedstock. Note that $PM_{2.5}$ and PM_{10} are positive due to emissions associated with vehicle operations (e.g., tires).
- **Electric vehicles** have lower GHG, NOx, and VOC life-cycle emissions than diesel and similar emission levels for other pollutants.
- **HHVs** have slightly lower life-cycle emissions for all pollutant categories.

Except for the H_2-Renew pathway, no alternative fuel outperforms diesel across all pollutants on a life-cycle basis. This creates difficulties in identifying which alternative fuels have "materially greater" emissions than diesel.

A cost-based metric – marginal damage cost – is useful in this case. By converting grams-per-mile to marginal damage cost-per-mile, the impacts of all pollutants can be aggregated into a single value, which represents a fuel's total impact on society. Use of marginal damage costs is an appropriate and accepted method of weighing multiple pollutants (NAS, 2007).

Table 10 below demonstrates that the marginal damage costs of alternative fuels are uniformly lower than those of diesel. H_2-Renew has near-zero marginal damages since the emissions associated with this fuel pathway are near-zero and thus has the highest differential benefit compared to diesel. LPG, on the other hand, has only a slight benefit over diesel. A supplemental Excel spreadsheet provides all results and calculations used in the study and breaks out emissions by vehicle type and by upstream versus downstream.

Table 10. Marginal damage cost of alternative fuel and diesel comparison fuel ($ per mile).

Vehicle Category	Alternative Fuel	Diesel	Difference
CNG	$0.17	$0.19	$0.02
RNG	$0.04	$0.19	$0.15
LPG	$0.09	$0.10	$0.01
LNG	$0.16	$0.19	$0.03
H_2-NG	$0.14	$0.22	$0.08
H_2-Renew	$0.004	$0.22	$0.22
Electric	$0.06	$0.20	$0.13
HHV	$0.37	$0.46	$0.13

ELECTRIC VEHICLES POWERED BY XCEL ENERGY'S GRID, 2017-2027

Purpose: This analysis examines the emissions and benefits of electric vehicles powered by Xcel Energy – one of two investor-owned utilities in Colorado. In 2017, Xcel Energy's energy mix was largely coal, natural gas, and wind (Table 11). Xcel Energy's Colorado Clean Energy Plan Portfolio will grow wind and solar generation and retire coal and gas generation through 2027, according to its electric resource plan.[3] As discussed below, this means the emissions per mile of electric vehicles powered by Xcel Energy will decrease over time, while the relative benefits compared to diesel vehicles will increase.

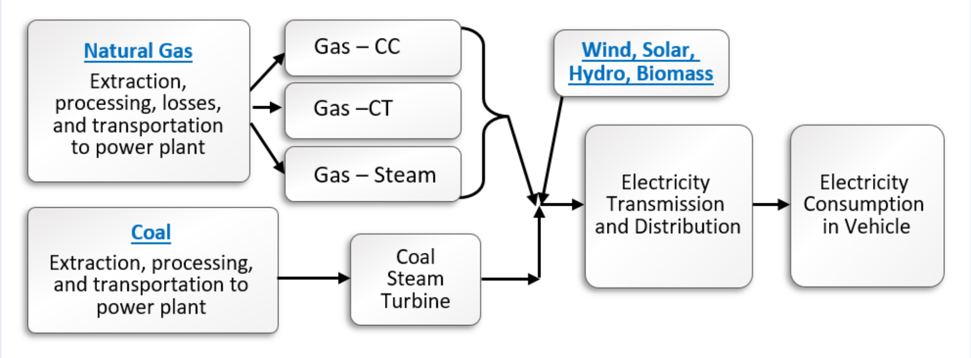
Table 11. Xcel Energy's energy mix in 2017 and projected for 2027. Values are estimates and reflect fraction of energy generation (i.e., kWh).

Electricity Resource	2017[1]	2027[2]
Residual oil	0%	0%
Natural gas	28%	22%
Coal	44%	23%
Nuclear power	0%	0%
Biomass	<1%	<1%
Wind	23%	39%
Hydro	2%	<1%
Solar	3%	13%

Methodology: To estimate Xcel Energy's emissions and marginal damage costs compared to the representative diesel vehicle, the authors estimated emissions at each stage of Xcel Energy's electricity generation, as shown in Figure 9. Natural gas and coal are extracted, processed, and transported to the power plants where they are combusted. The electricity is sent to the end user through the electricity transmission and distribution system. Emissions associated with each stage in Figure 9 were estimated separately using Argonne's GREET model.

Consistent with the GREET model, renewable pathways – such as solar, hydroelectric, and wind – are assumed to have zero emissions associated with resource extraction, processing, electricity production, and delivery. Biomass electricity accounts for a very minor share of Xcel Energy's electricity mix (less than 0.5%) and the upstream emissions associated with biomass collection, transportation, and land-use change were ignored in this analysis.

Figure 9. Life-cycle stages of electricity generation in Xcel Energy's grid energy mix.



The emissions from Xcel Energy's grid mix are summed together to a grams per kWh at the electrical outlet. As in the analysis in the main text of this report and consistent with the AFLEET tool, grams per kWh is converted to grams per mile for each vehicle type in AFLEET using efficiency factors in kWh per mile. The six medium- and heavy-duty electric vehicle categories in AFLEET include: Combination Short-Haul Truck, Single Unit Long-Haul Truck, Single Unit Short-Haul Truck, Refuse Truck, Transit Bus, and School Bus. The three greenhouse gases (GHGs) included in this analysis are: CO_2, N_2O, and CH_4, which are summed together using the following 100-year global warming potentials of 1, 265, and 28, respectively.[4]

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[1] Xcel Energy (2018) Colorado Energy Plan: Advancing our state's clean energy future. Available at: https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Resource%20Plans/CO-Energy-Plan-Fact-Sheet.pdf

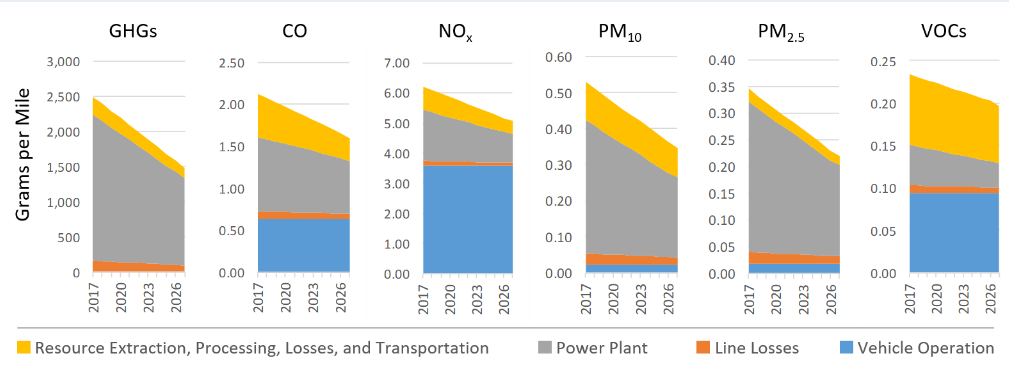
[2] Note that Xcel Energy (2018) provides an estimate for the energy mix in the year 2026, but phone communications with Xcel Energy staff indicate the plan for 2027 is as shown in Table 11.

[3] Public Service Company of Colorado (2016) Electric Resource Plan, Volume 2, Proceeding No. 16A-0396E, May 27, 2016. Available at: https://www.xcelenergy.com/staticfiles/xe/PDF/Attachment%20AKJ-2.pdf

[4] IPCC (2017), Assessment Report 5 values. Available at: https://www.ipcc.ch/pdf/assessmentreport/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf (p. 73-79).

Findings: As shown in Figure 10, all emissions decrease as Xcel Energy's renewable generation grows between 2017 and 2027, with the most dramatic reductions for GHGs, PM_{10}, and $PM_{2.5}$, which decrease by 41 percent, 35 percent, 36 percent, respectively. For most pollutants, the largest emission source is from the combustion of coal and natural gas at the power plant (grey). Resource extraction, processing, losses, and transportation is the second largest. Vehicle operation is an important contributor to PM_{10}.

Figure 10. Emissions per mile (g/mile) for medium- and heavy-duty electric vehicles powered by Xcel Energy's electricity, 2017-2027. Emissions are shown by lifecycle stage.



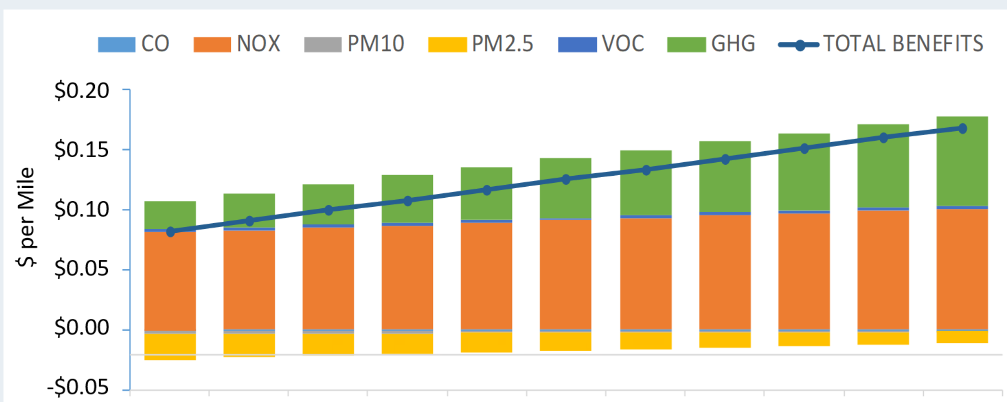
Values in Figure 10 are summed and compared with the representative diesel vehicle in Table 12. As shown, emissions of CO, PM_{10}, and $PM_{2.5}$ are higher for the electric vehicle in 2017 but decrease rapidly through 2027. As the renewable penetration in Xcel Energy's grid mix increases between 2017 and 2027, emissions per mile decline for all pollutants.

Table 12. Emissions per mile for medium- and heavy-duty electric vehicles powered by Xcel Energy's grid, 2017-2027.

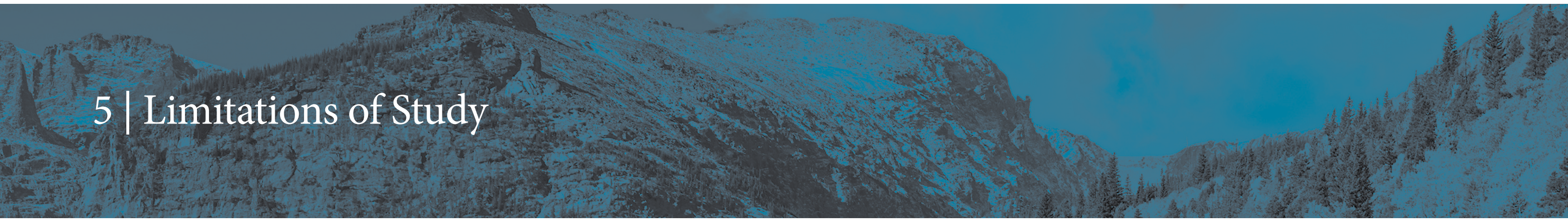
	Diesel	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
CO (g/mile)	1.05	1.50	1.45	1.39	1.34	1.29	1.24	1.18	1.13	1.08	1.02	0.96
NOx (g/mile)	4.06	2.64	2.52	2.40	2.29	2.17	2.05	1.94	1.82	1.70	1.58	1.48
PM_{10} (g/mile)	0.20	0.51	0.49	0.47	0.45	0.44	0.42	0.40	0.38	0.36	0.34	0.33
$PM_{2.5}$ (g/mile)	0.09	0.33	0.31	0.30	0.29	0.28	0.26	0.25	0.24	0.22	0.21	0.20
VOC (g/mile)	0.33	0.14	0.14	0.13	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.10
GHGs (g/mile)	2,952	2,495	2,394	2,292	2,190	2,089	1,987	1,885	1,784	1,682	1,580	1,479

The emissions per mile in Table 12 are converted to marginal damages costs. Figure 11 shows the benefits (positive values) and costs (negative values) when comparing electric vehicles powered by Xcel Energy's grid to diesel vehicles. The dark blue line indicates the net benefits, which slowly increase over time as Xcel Energy's grid becomes more reliant on renewable energy. For comparison, the analysis above in the main text shows that electric vehicles powered by the 2025 WECC electricity grid have an estimated net benefit of $0.13 per mile, whereas Xcel Energy's grid has benefits of $0.15 per mile in 2025 and $0.17 per mile in 2027.

Figure 11. Estimated benefits per mile of medium and heavy-duty electric vehicles powered by Xcel Energy's grid, 2017-2027. Figure calculated by subtracting marginal damage cost of electric vehicle from diesel. Dark blue line indicates net benefits.



	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
GHG	$0.02	$0.03	$0.03	$0.04	$0.04	$0.05	$0.05	$0.06	$0.06	$0.07	$0.07
VOC	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
PM2.5	-$0.02	-$0.02	-$0.02	-$0.02	-$0.02	-$0.02	-$0.01	-$0.01	-$0.01	-$0.01	-$0.01
PM10	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
NOX	$0.08	$0.08	$0.08	$0.09	$0.09	$0.09	$0.09	$0.09	$0.10	$0.10	$0.10
CO	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL BENEFITS	$0.08	$0.09	$0.10	$0.11	$0.12	$0.13	$0.13	$0.14	$0.15	$0.16	$0.17



5 | Limitations of Study

While the findings in this study are based on the state-of-the-art emissions and cost models and tools, the authors acknowledge several data- and calculation-related limitations of the study. These limitations are described below.

- **Electricity grid mix simplifications.** The research team assumed that emissions from the electricity used for the electric vehicles is based on the average WECC generation mix. Using average emissions ignores an important feature of how electricity markets function and how grid operators continuously balance load. This means that if demand for electricity is low, the cheapest units are deployed (usually coal). As demand increases, more expensive sources of generation are brought online (e.g. natural gas). As a result, the location of the charging matters, as does the time of the day. The generation mix can also vary across time of the year (e.g., spring vs summer) even for the same time of day. Relatedly, the location of the charging event determines the grid resources used to satisfy the demand. Charging in regions with high renewable generation offers environmental benefits over charging in regions with high fossil fuel generation.
- **Few vehicle categories modeled.** Similarly, only seven vehicle models are represented in the AFLEET tool, whereas in reality, hundreds of different medium- and heavy-duty vehicle types operate within Colorado, each with different duty-cycles and vocations. Again, the impact of this simplification on the study's conclusions is unknown.
- **General limitations of life-cycle assessment models.** Results of an LCA model, like GREET, are always model-based representations of the real environmental impact. LCA results are only valid under the assumptions of the study and are still associated with substantial uncertainty.

6 | Areas of Future Study

The research team has several recommendations for areas of future study.

- **Improve robustness of marginal damage estimation.** Future work that uses the marginal damage framework could expand the number of studies and develop a range of potential impacts. Similarly, future work could provide greater detail about the impacts that are expected from emissions in Colorado and the timing of those impacts.
- **Improve data about Colorado's vehicle population.** The authors recommend future studies spend greater effort on obtaining summary statistics about Colorado vehicle populations. This data would allow the research team to properly weigh the emissions and costs of the various vehicle types in the study.
- **Incorporate vehicle manufacturing emissions.** This current study only examined emissions associated with fuel production, delivery, and use. A more rigorous comparison of alternative fuels would also consider differences in vehicle manufacturing emissions. For example, as demonstrated by past studies (e.g., UCS, 2015), emissions from battery manufacturing means the vehicle production emissions are higher for electric vehicles than conventional-powered vehicles.
- **Conduct emission analyses of special equipment.** As suggested in public comments related to the Volkswagen Settlement, the authors recommended a follow-up study to include emissions and cost modeling of certain special-use equipment, such as airport ground support equipment (GSE) and forklifts. Both types of equipment are important contributors to urban and indoor air quality. A better understanding of the benefits of alternative fuels in these applications could help steer decision-making around public policy.

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Appendix A

The following text forms the basis of this study and is taken directly from to 39-22-516.8, (14) C.R.S., which was enacted through HB 14-1326:

(14) (a) During the calendar year ending December 31, 2018, the Colorado Energy Office created in section 24-38.5-101, C.R.S., shall determine whether category 4, 4A, 4B, 4C, 7, 7A, or 9 medium- or heavy-duty trucks generate life-cycle emissions materially greater than comparable medium or heavy duty trucks using traditional fuel. Such a life-cycle analysis must include the direct emissions regulated by the United States Environmental Protection Agency or by the Department of Public Health and Environment that are associated with producing, transporting, and using the alternative or traditional fuels. The Colorado Energy Office shall consider the likely adoption of future technology at each stage of the life-cycle.

(b) In making the determinations described in paragraph (a) of this subsection (14), the Colorado Energy Office shall consider public input, any analysis or reports prepared by the department of public health and environment, other states, or the united states environmental protection agency, and any peer-reviewed studies conducted in the united states that evaluate similar matters.

(c) In the event that category 4, 4A, 4B, 4C, 7, 7A, or 9 medium or heavy duty trucks are shown to generate life-cycle emissions materially greater than comparable traditional fuel trucks, then the Colorado Energy Office shall notify the Department of Revenue that no tax credit specified in this section is available for such trucks for the income tax years commencing on or after January 1, 2019, but before January 1, 2022; except that the Colorado Energy Office may determine if a particular category 4, 4A, 4B, 4C, 7, 7A, or 9 truck model or engine does not generate life-cycle emissions materially greater than a comparable traditional fuel truck model or engine and is thus allowed a credit for a given income tax year, or the Colorado energy office may allow a credit if the taxpayer can demonstrate that the taxpayer has a long-term fuel contract for his or her category 4, 4A, 4B, 4C, 7, 7A, or 9 truck from a green fuel provider, such that the life-cycle emissions from such truck are not materially greater than the emissions of a comparable traditional fuel truck. For purposes of this paragraph (c), "green fuel provider" means the alternative fuel is produced and delivered by providers that have adopted best practices for low life-cycle emissions on or before January 1, 2019, and on or before each January 1 thereafter through January 1, 2021, the Colorado Energy Office and the Department of Revenue shall, through their respective web sites, specify which category 4, 4A, 4B, 4C, 7, 7A, or 9 medium or heavy duty trucks are not allowed a credit for a given income tax year.

Table 13. Emissions, damage costs, ownership costs, and payback periods of CNG (Category 4 / 4A).

Compressed Natural Gas

Vehicles modeled: School Bus, Transit Bus, Refuse, SU-Short, SU-Long, Comb-Short, Comb-Long

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**CNG**	**Diff**	**Diesel**	**CNG**	**Diff**	**Diesel**	**CNG**	**Diff**
CO (g/mile)	1.14	16.55	(15.41)	0.40	1.10	(0.70)	0.75	15.46	(14.71)
NOx (g/mile)	4.73	1.59	3.14	0.87	1.46	(0.59)	3.86	0.13	3.73
PM10 (g/mile)	0.21	0.18	0.03	0.06	0.03	0.03	0.15	0.15	0.00
PM2.5 (g/mile)	0.09	0.06	0.03	0.05	0.02	0.03	0.04	0.04	0.00
VOC* (g/mile)	0.37	0.46	(0.10)	0.23	0.34	(0.11)	0.14	0.13	0.01
GHGs (g/mile)	2,782	2,616	166	*GHGs not broken out between upstream and vehicle operation.*					
Total Damages (2016$/mile)	$0.19	$0.17	$0.02	$0.01	$0.01	($0.00)	$0.04	$0.01	$0.03
Total Cost of Ownership ($/mile)	$1.96	$2.15	($0.19)						
Cost per ton GHGs ($/ton)		$1,171							
Avg Upfront Cost	$125,033	$164,432	($39,399)						
Avg Annual Operating Cost	$63,386	$55,966	$7,420						
Net present value ($)	$885,661	$836,019.23	$49,642						
Payback period (years)		5.3							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 14. Emissions, damage costs, ownership costs, and payback periods of RNG (Category 4/4A).

Renewable Natural Gas

Vehicles modeled: School Bus, Transit Bus, Refuse, SU-Short, SU-Long, Comb-Short, Comb-Long

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**RNG**	**Diff**	**Diesel**	**RNG**	**Diff**	**Diesel**	**RNG**	**Diff**
CO (g/mile)	1.14	14.12	(12.97)	0.40	(1.23)	1.62	0.75	15.34	(14.60)
NOx (g/mile)	4.73	(0.19)	4.92	0.87	(0.31)	1.18	3.86	0.12	3.74
PM10 (g/mile)	0.21	(0.02)	0.22	0.06	(0.16)	0.22	0.15	0.15	0.00
PM2.5 (g/mile)	0.09	(0.13)	0.22	0.05	(0.17)	0.22	0.04	0.04	0.00
VOC* (g/mile)	0.37	(0.79)	1.15	0.23	(0.95)	1.18	0.14	0.17	(0.03)
GHGs (g/mile)	2,782	484	2,298	*GHGs not broken out between upstream and vehicle operation.*					
Total Damages (2016$/mile)	$0.19	$0.04	$0.15	$0.01	$0.01	($0.00)	$0.04	$0.01	$0.03
Total Cost of Ownership ($/mile)	$1.96	$2.15	($0.19)						
Cost per ton GHGs ($/ton)		$0							
Avg Upfront Cost	$125,033	$164,432	($39,399)						
Avg Annual Operating Cost	$63,386	$55,966	$7,420						
Net present value ($)	$125,033	$164,432.35	($39,399)						
Payback period (years)		5.3							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 15. Emissions, damage costs, ownership costs, and payback periods of LNG (Category 4 / 4B).

Liquefied Natural Gas

Vehicles modeled: School Bus, Transit Bus, Refuse, SU-Short, SU-Long, Comb-Short, Comb-Long

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**LNG**	**Diff**	**Diesel**	**LNG**	**Diff**	**Diesel**	**LNG**	**Diff**
CO (g/mile)	1.14	16.08	(14.94)	0.40	0.64	(0.25)	0.75	15.44	(14.69)
NOx (g/mile)	4.73	1.15	3.58	0.87	1.02	(0.15)	3.86	0.13	3.73
PM10 (g/mile)	0.21	0.18	0.03	0.06	0.03	0.03	0.15	0.15	0.00
PM2.5 (g/mile)	0.09	0.07	0.02	0.05	0.03	0.02	0.04	0.04	0.00
VOC* (g/mile)	0.37	0.36	0.01	0.23	0.23	(0.01)	0.14	0.13	0.01
GHGs (g/mile)	2,782	2,659	123	*GHGs not broken out between upstream and vehicle operation.*					
Total Damages (2016$/mile)	$0.19	$0.16	$0.03	$0.01	$0.01	($0.00)	$0.04	$0.01	$0.03
Total Cost of Ownership ($/mile)	$1.96	$2.73	($0.78)						
Cost per ton GHGs ($/ton)		$6,298							
Avg Upfront Cost	$125,033	$154,900	($29,867)						
Avg Annual Operating Cost	$63,386	$80,495	($17,109)						
Net present value ($)	$885,661	$1,120,842.06	($235,181)						
Payback period (years)		none							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 16. Emissions, damage costs, ownership costs, and payback periods of LPG (Category 4B / 4C).

Liquefied Petroleum Gas

Vehicles modeled: School Bus, SU-Short, SU-Long

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**LPG**	**Diff**	**Diesel**	**LPG**	**Diff**	**Diesel**	**LPG**	**Diff**
CO (g/mile)	0.73	8.29	(7.56)	0.19	0.26	(0.07)	0.53	8.03	-7.49
NOx (g/mile)	2.59	0.75	1.84	0.45	0.49	(0.04)	2.14	0.26	1.87
PM10 (g/mile)	0.12	0.08	0.04	0.03	0.02	0.01	0.09	0.06	0.04
PM2.5 (g/mile)	0.04	0.03	0.01	0.02	0.02	0.01	0.02	0.01	0.01
VOC* (g/mile)	0.18	0.46	(0.28)	0.11	0.19	(0.08)	0.07	0.27	-0.20
GHGs (g/mile)	1,345	1,404	(60)	*GHGs not broken out between upstream and vehicle operation.*					
Total Damages (2016$/mile)	$0.10	$0.09	$0.01	$0.00	$0.00	($0.00)	$0.02	$0.01	$0.02
Total Cost of Ownership ($/mile)	$1.11	$1.31	($0.20)						
Cost per ton GHGs ($/ton)		($3,277)							
Avg Upfront Cost	$75,043	$83,939	($8,897)						
Avg Annual Operating Cost	$22,569	$23,624	($1,054)						
Net present value ($)	$345,873	$367,423.05	($21,550)						
Payback period (years)	none								

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 17. Emissions, damage costs, ownership costs, and payback periods of H2-NG (Category 4B / 4C).

Hydrogen from natural gas reformation

Vehicles modeled: Transit Bus

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**H2-NG**	**Diff**	**Diesel**	**H2-NG**	**Diff**	**Diesel**	**H2-NG**	**Diff**
CO (g/mile)	0.96	1.23	(0.26)	0.45	1.23	(0.78)	0.52	0.00	0.52
NOx (g/mile)	5.96	1.74	4.22	1.02	1.74	(0.72)	4.94	0.00	4.94
PM10 (g/mile)	0.21	0.41	(0.20)	0.07	0.29	(0.22)	0.14	0.12	0.02
PM2.5 (g/mile)	0.09	0.28	(0.18)	0.06	0.26	(0.21)	0.04	0.02	0.02
VOC* (g/mile)	0.34	0.36	(0.02)	0.26	0.36	(0.10)	0.09	0.00	0.09
GHGs (g/mile)	3,144	2,388	756	*GHGs not broken out between upstream and vehicle operation.*					
Damages (2016$/mile)	$0.22	$0.14	$0.08	$0.01	$0.02	($0.01)	$0.05	$0.00	$0.05
Total Cost of Ownership ($/mile)	$2.47	$7.40	($4.93)						
Cost per ton GHGs ($/ton)		$6,523							
Avg Upfront Cost	$273,733	$1,608,221	($1,334,488)						
Avg Annual Operating Cost	$73,714	$125,024	($51,309)						
Avg net present value ($)	$1,158,307	$3,108,503.31	($1,950,197)						
Payback period (years)		none							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 18. Emissions, damage costs, ownership costs, and payback periods of H2-Renew (Category 4B / 4C).

Hydrogen from Renewables via Electrolysis

Vehicles modeled: Transit Bus

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**H2-Renew**	**Diff**	**Diesel**	**H2-Renew**	**Diff**	**Diesel**	**H2-Renew**	**Diff**
CO (g/mile)	0.96	0.00	0.96	0.45	0.00	0.45	0.52	0.00	0.52
NOx (g/mile)	5.96	0.00	5.96	1.02	0.00	1.02	4.94	0.00	4.94
PM10 (g/mile)	0.21	0.12	0.09	0.07	0.00	0.07	0.14	0.12	0.02
PM2.5 (g/mile)	0.09	0.02	0.08	0.06	0.00	0.06	0.04	0.02	0.02
VOC* (g/mile)	0.34	0.00	0.34	0.26	0.00	0.26	0.09	0.00	0.09
GHGs (g/mile)	3,144	29	3,115	*GHGs not broken out between upstream and vehicle operation.*					
Damages (2016$/mile)	$0.22	$0.00	$0.22	$0.01	$0.00	$0.01	$0.05	$0.00	$0.05
Total Cost of Ownership ($/mile)	$2.47	$7.40	($4.93)						
Cost per ton GHGs ($/ton)		$0							
Avg Upfront Cost	$273,733	$1,608,221	($1,334,488)						
Avg Annual Operating Cost	$73,714	$125,024	($51,309)						
Avg net present value ($)	$273,733	$1,608,220.86	($1,334,488)						
Payback period (years)		none							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 19. Emissions, damage costs, ownership costs, and payback periods of electric vehicles (Category 7 / 7A).

Electric Vehicles

Vehicles modeled: School Bus, Transit Bus, Refuse, SU-Short, SU-Long, Comb-Short

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**EV**	**Diff**	**Diesel**	**EV**	**Diff**	**Diesel**	**EV**	**Diff**
CO (g/mile)	1.05	0.39	0.66	0.42	0.39	0.03	0.63	0.00	0.63
NOx (g/mile)	4.50	0.70	3.80	0.92	0.70	0.22	3.58	0.00	3.58
PM10 (g/mile)	0.20	0.26	(0.06)	0.06	0.14	(0.08)	0.14	0.12	0.02
PM2.5 (g/mile)	0.09	0.07	0.01	0.05	0.06	(0.01)	0.03	0.02	0.02
VOC* (g/mile)	0.33	0.12	0.22	0.24	0.12	0.12	0.09	0.00	0.09
GHGs (g/mile)	2,952	1,091	1,861	*GHGs not broken out between upstream and vehicle operation.*					
Damages (2016$/mile)	$0.20	$0.06	$0.13	$0.01	$0.01	$0.001	$0.04	$0.00	$0.04
Total Cost of Ownership ($/mile)	$2.18	$2.63	($0.45)						
Cost per ton GHGs ($/ton)		$243							
Avg Upfront Cost	$129,905	$321,923	($192,018)						
Avg Annual Operating Cost	$53,100	$40,709	$12,391						
Avg net present value ($)	$767,108	$810,436.12	($43,328)						
Payback period (years)		15.5							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value

Table 20. Emissions, damage costs, ownership costs, and payback periods of Hydraulic Hybrid Vehicles (Category 9).

Diesel Hydraulic Hybrid
Vehicles modeled: Refuse

	ALL EMISSIONS			UPSTREAM			VEHICLE OPERATION		
	Well-to-Wheel (Low NOx, diesel in-use, 2025 grid)			Well-to-Pump (Low NOx, diesel in-use, 2025 grid)			Pump-to-Wheel (Low NOx, diesel in-use, 2025 grid)		
	Diesel	**Diesel HHV**	**Diff**	**Diesel**	**Diesel HHV**	**Diff**	**Diesel**	**Diesel HHV**	**Diff**
CO (g/mile)	1.70	1.15	0.55	1.07	0.66	0.42	0.63	0.49	0.13
NOx (g/mile)	8.01	8.01	0.00	2.10	2.10	0.00	5.92	5.92	0.00
PM10 (g/mile)	0.32	0.29	0.04	0.16	0.12	0.04	0.16	0.16	0.00
PM2.5 (g/mile)	0.18	0.15	0.03	0.13	0.10	0.03	0.04	0.04	0.00
VOC* (g/mile)	0.71	0.57	0.14	0.61	0.47	0.14	0.10	0.10	0.00
GHGs (g/mile)	7,445	5,770	1,675	*GHGs not broken out between upstream and vehicle operation.*					
Total Damages (2016$/mile)	$0.46	$0.37	$0.09	$0.02	$0.02	$0.001	$0.06	$0.06	($0.0000)
Total Cost of Ownership ($/mile)	$5.42	$5.09	$0.32						
Cost per ton GHGs ($/ton)		$193							
Avg Upfront Cost	$193,664	$229,250	($35,586)						
Avg Annual Operating Cost	$126,449	$100,108	$26,341						
Net present value ($)	$1,711,057	$1,430,549.65	$280,507						
Payback period (years)		1.4							

Lengend	
Yellow cell	Marginal damage
Grey cell	Difference between alt fuel and diesel
Blue cell	Other results
Black text	Positive value
Red text	Negative value


VISITOR SHUTTLE