Delivering Clean Air in Denver: Propane Trucks and Infrastructure in Mail Delivery Application

Andrew Kotz,[1] Matthew Jeffers,[1] Setayesh Fakhimi,[1] Eric Miller,[1] Anna Squires,[1] Sonja Meintsma,[2] Kristi Mladenovic,[2] Bonnie Trowbridge,[2] and Hunter Woodruff[2]

1 National Renewable Energy Laboratory
2 Drive Clean Colorado

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-88477
March 2024

Delivering Clean Air in Denver: Propane Trucks and Infrastructure in Mail Delivery Application

Andrew Kotz,[1] Matthew Jeffers,[1] Setayesh Fakhimi,[1] Eric Miller,[1] Anna Squires,[1] Sonja Meintsma,[2] Kristi Mladenovic,[2] Bonnie Trowbridge,[2] and Hunter Woodruff[2]

1 National Renewable Energy Laboratory
2 Drive Clean Colorado

Suggested Citation
Kotz, Andrew, Matthew Jeffers, Setayesh Fakhimi,Eric Miller, Anna Squires, Sonja Meintsma, Kristi Mladenovic, Bonnie Trowbridge, and Hunter Woodruff. 2024. *Delivering Clean Air in Denver: Propane Trucks and Infrastructure in Mail Delivery Application*. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 5400-88477. https://www.nrel.gov/docs/fy24osti/88477.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-88477
March 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photo by Matthew Jeffers: NREL 85267.

NREL prints on paper that contains recycled content.

Acknowledgments

This project and report would not have been possible without the support and cooperation of all the partnering organizations. The authors would like to thank the following individuals for their contributions:

Drive Clean Colorado
Bonnie Trowbridge
Steve Trowbridge
Sonja Meintsma
Kristi Mladenovic
Hunter Woodruff

Hi Pro, Inc.
Joshua Stoneback
Don Gonzales
Ty Porter
Ingred Rojas
Kaitlyn Turner

Roush CleanTech
Derek Whaley
Todd Mouw

AmeriGas
Chris Ransom
Byron Smith
Marshall Yungland

Rush Enterprises
Bobby Stanley

Propane Education and Research Council
Steve Whaley
Larry Osgood

U.S. Department of Energy's National Renewable Energy Laboratory (NREL)
Wendy Dafoe
Leslie Eudy
Setayesh Fakhimi
Matthew Jeffers
Andrew Kotz
Michael Lammert
Eric Miller
Anna Squires

List of Acronyms

CO_2	carbon dioxide
FleetREDI	Fleet Research, Energy Data, and Insights
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
LPG	Liquified Petroleum Gas
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
SCR	selective catalytic reduction
SO_x	sulfur oxides
USPS	U.S. Postal Service

Executive Summary

In 2021, Drive Clean Colorado, a Denver-based Clean Cities coalition, initiated the deployment of five Class 6 medium-duty propane Autogas delivery trucks into a United States Postal Service (USPS) mail delivery contractor fleet with the goal of providing a proof-of-concept demonstration for mail delivery fleets nationwide.

Funded by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy, the project, titled "Delivering Clean Air in Denver: Propane Trucks and Infrastructure in Mail Delivery Application," enabled the purchase and deployment of the propane-powered trucks, refueling infrastructure, and supporting Fleet Research, Energy Data, and Insights (FleetREDI) analysis by the National Renewable Energy Laboratory (NREL 2023). Key objectives of the analysis included calculating the propane vehicles' emissions reductions, analyzing the costs and operational performance of the propane fleet compared to conventional diesel-powered vehicles, and evaluating the viability of propane as a clean and cost-effective alternative to conventional diesel trucks (AFDC 2023b, 2023c).

In collaboration with Hi Pro, the operator of the mail hub delivery fleet, NREL installed data acquisition devices on the five new propane trucks along with a selection of existing diesel trucks to ensure a suitable comparison for evaluation. On-road operations data collected from both fleets included city and highway deliveries in the summer and winter periods.

NREL's on-road data analysis demonstrated that the propane trucks in this study achieved similar duty cycles as the baseline diesel fleet. They could attain the same maximum driving speeds, kinetic intensities, and comparable maximum daily driving distances.

In addition, NREL analysis revealed that propane trucks represent considerably lower—and in some cases, near-elimination of—tailpipe criteria pollutant emissions. Three primary forms of tailpipe and production emissions were considered in this study: sulfur oxides (SO_x), oxides of nitrogen (NO_x), and carbon dioxide (CO_2). Due to the negligible sulfur content in propane fuel, use of the propane fleet essentially eliminated tailpipe SO_x emissions. However, production emissions of SO_x are estimated to be higher for propane than for diesel. The propane fleet achieved a 98% reduction of NO_x tailpipe emissions on a per-mile basis. When combined with NO_x production emissions, which are estimated to be slightly higher for propane production versus diesel production, the propane fleet achieved a cumulative 87% reduction in per-mile NO_x emissions. Combined tailpipe and production emissions showed only a 3.7% net increase of per-mile CO_2 emissions. Comparing on an energy-specific basis, the propane vehicles showed a combined average of 199.2% increase in SO_x, 87.1% reduction in NO_x, and 24.5% reduction in CO_2 emissions per-unit engine-produced energy (g/bhp-hr) compared to the diesel vehicles. These reductions in tailpipe emissions could lead to lower local air pollution for the Denver Metro region and surrounding areas in which these vehicles operate.

While each propane truck represents a higher upfront investment than a comparable diesel truck— \$126,690 per propane vehicle compared to approximately \$100,000 per diesel truck— substantial rebates and lower operating costs both serve to lower the total cost of ownership. Hi Pro received a grant of \$282,500 to support the purchase of the five propane vehicles for this demonstration, which represented approximately 45% of the total fleet cost. Installation of a new

propane fueling station at Hi Pro's facility in Commerce City, Colorado, was required for the deployment of propane vehicles. The capital cost for the propane station equipment was approximately $54,200, and the cost for installation was approximately $86,500, for a total project cost of just over $140,700 for Hi Pro's new propane station.

In addition, diesel fuel varied between $4.00 per gallon and $5.00 per gallon during the study period, while propane fuel consistently remained below $2.00 per gallon of propane (or, less than $3.00 per diesel gallon equivalent [dge]). Propane fuel, at approximately $0.30 per mile, demonstrated an average per-mile cost 29% less than diesel, at more than $0.42 per mile on average. This represented a significant reduction in operating expenses for the propane truck fleet. The other major operating expense for the vehicle fleet—maintenance costs—will have to be tracked carefully over the coming years to quantify costs for both vehicle types and determine if the propane fleet offers savings compared to diesel fleet in this regard.

The new propane vehicles represent cost-effective and cleaner vehicle operations for the mail transport application. These results could be replicated by other commercial fleet operators, in this vocation and others, to help reduce local air pollution from vehicle tailpipe emissions.

Table of Contents

Executive Summary ..... **v**
1 Introduction **1**
1.1 Project Overview 1
1.2 Project Partners and Roles 2
2 Vehicle Duty Cycle Characterization **3**
2.1 Propane Vehicle Description 3
2.2 In-Use Vehicle Data Collection 4
2.3 Vehicle Duty Cycle Comparison 7
2.4 Emissions Estimation Methodology 14
2.5 Vehicle Emissions Comparison 17
3 Fleet Cost and Performance Comparison **21**
3.1 Vehicle Capital Costs 21
3.2 Propane Fueling Station Capital Costs 21
3.3 Vehicle Fuel Costs 22
3.4 Vehicle Maintenance Costs 24
3.5 Vehicle Utilization 25
4 Summary **27**
References **29**
Appendix **30**

List of Figures

Figure 1. Photo of the propane truck 4
Figure 2. Photo of the propane fuel station installed at the Hi Pro truck depot 4
Figure 3. Calendar plots showcasing the daily flywheel energy for diesel (top) and propane (bottom) vehicles during the data logging periods 5
Figure 4. Map showing routes traveled by diesel trucks (orange) and propane trucks (blue) during data collection periods 6
Figure 5. Map of USPS post office delivery locations 7
Figure 6. Daily distance distributions for diesel and propane vehicles 8
Figure 7. Average speed (left) and average driving speed (right) distributions for diesel and propane vehicles 9
Figure 8. Kinetic intensity (a) vs. average driving speed, (b) vs. daily distance, for diesel and propane vehicles 10
Figure 9. Flywheel energy distributions for diesel and propane 11
Figure 10. Daily fuel consumption (left) and fuel economy (right) for diesel and propane 12
Figure 11. Diesel thermal efficiency map 13
Figure 12. Propane thermal efficiency map 13
Figure 13. Comparison of calculated tailpipe and production emissions for diesel and propane vehicles on a per-mile basis 18
Figure 14. Comparison of calculated tailpipe and production emissions for diesel and propane vehicles on a per-unit energy basis 19
Figure 15. Diesel NO_X activity rate (left) and average ambient temperature (right) for summer and winter data collection periods 20
Figure 16. Monthly total fuel costs for diesel 22
Figure 17. Monthly total fuel costs for propane 23
Figure 18. Monthly average unit price for diesel and propane fuels 24
Figure 19. Monthly average cost per mile for diesel and propane fuels 24
Figure 20. Vehicle availability for the propane truck fleet 26

List of Tables

Table 1. Propane Vehicle Specifications 3
Table 2. Overview of Vehicle Operations from Valid Logged Datasets 6
Table 3. Diesel and Propane Per-Mile Emissions Estimates 18
Table 4. Propane Truck Costs 21
Table A-1. List of Diesel Vehicles Instrumented With Data Loggers 30
Table A-2. List of Diesel Vehicles To Be Retired by Hi Pro 30

1 Introduction

1.1 Project Overview

Growing awareness of the global imperative to reduce planet-warming emissions has put a spotlight on one of the largest contributors to global emissions: the transportation sector. While sales of light-duty electric vehicles are seeing increasing adoption by consumers, medium- and heavy-duty commercial vehicles are still largely dependent on internal combustion engines that run on fossil fuels and remain the second-largest source of U.S. transportation-related emissions (EPA 2023b; IEA 2023). However, while new clean energy technologies such as battery-electric and hydrogen fuel cell trucks are slowly gaining traction, a clean, efficient, and domestically produced alternative fuel has already powered commercial vehicles for decades: propane, also known as liquefied petroleum gas (LPG).

Propane-powered commercial vehicles can achieve the same duty cycles and match the power, acceleration, and cruising speeds of conventionally fueled vehicles while producing significantly reduced tailpipe oxides of nitrogen (NO_x) emissions. Due to the lower cost of propane compared to diesel or gasoline and the availability of tax incentives and government rebates for some less-polluting vehicles, propane-powered fleets can also provide significant operational and lifetime cost savings (AFDC 2023b, 2023c).

In addition to these considerations, the Denver Metro Area's regional ozone air quality rating was downgraded to "serious" by the U.S. Environmental Protection Agency in 2019, necessitating increased state efforts to reduce harmful criteria pollutants. In response, Drive Clean Colorado, a nonprofit organization committed to implementing programs to promote and support clean transportation, held a listening session with local fleets to discuss the growing interest in propane-fueled vehicles in the Denver area. Drive Clean Colorado collaborated with the Propane Education and Research Council to apply for a U.S. Department of Energy grant to support the deployment and evaluation of a propane-fueled truck fleet in the Metro Denver area. This grant, titled "Delivering Clean Air in Denver: Propane Trucks and Infrastructure in Mail Delivery Application," enabled the purchase and deployment of the propane-powered trucks, refueling infrastructure, and supporting Fleet Research, Energy Data, and Insights (FleetREDI) analysis by the National Renewable Energy Laboratory (NREL 2023).

The primary goal of the project was to demonstrate alternative fuel vehicles in a mail transport application and evaluate the viability of propane as a clean and cost-effective alternative to conventional diesel trucks. This proof-of-concept demonstration is expected to lead to improved understanding of the performance attributes, costs, and operational issues to inform technology adoption decisions, helping to spur market transformation toward lower-emission truck fleets. By reducing the risk of first adoption, potential exists to transform the U.S. Postal Service (USPS) mail delivery system into a lower-carbon national fleet.

Hi Pro, Inc., the operator of the mail hub delivery fleet based in the Denver suburb of Commerce City, served as the demonstration fleet for the project. This fleet operator transports mail from a USPS main hub to numerous post offices located in and around the Denver Metro region. AmeriGas, the largest retail propane distributor in the United States, provided the propane refueling infrastructure and supplied propane gas to fuel the demonstration fleet. NREL participated as the third-party evaluator, tasked with collecting data from the project partners and providing a technical analysis comparing the duty cycle, cost, performance, and emissions metrics.

The project was carried out from October 2020 to December 2023. Educational and awareness efforts are ongoing.

1.2 Project Partners and Roles

Drive Clean Colorado

Drive Clean Colorado, formerly Denver Metro Clean Cities Coalition, is a nonprofit member organization dedicated to delivering effective programs for stakeholders with the aim of promoting and supporting clean transportation and efficient mobility choices. Its mission is to empower diverse stakeholder collaboration to accelerate the equitable adoption of clean transportation. Drive Clean Colorado managed all aspects of the grant award and provided education and outreach activities relating to this project.

Roush CleanTech

Roush CleanTech provided the propane upfit for the vehicles in the demonstration fleet. Roush is a leading developer of liquid propane systems for Ford commercial trucks and Blue Bird school buses.

Hi Pro Inc.

Hi Pro Inc. purchased and operated the propane demonstration fleet and supported data collection for the project. Hi Pro Inc. is a postal service transportation contracting company that has serviced the Denver area for over 40 years. The company currently operates a hub in Commerce City. Its fleet largely comprises Class 6 and 7 diesel straight trucks.

AmeriGas

AmeriGas, the largest retail propane distributor in the United States, provided the propane refueling infrastructure and supplied propane gas to fuel the demonstration fleet.

NREL

NREL researchers provided a third-party FleetREDI evaluation of the propane vehicle operation to help assess the performance, cost, and viability as a low-emission alternative to diesel and an opportunity for fleets in the immediate future. NREL leveraged extensive in-house software and data analysis capabilities to analyze the data collected and provide detailed emission comparison information for well-to-wheel emissions.

Propane Education and Research Council

The Propane Education and Research Council created educational materials, including safety materials, a promotional video on the benefits of propane in postal route applications and public relations campaigning, including press releases, webinars, and pitching trade media in the contractor fleet association markets.

2 Vehicle Duty Cycle Characterization

In collaboration with Hi Pro, NREL identified and installed data acquisition devices on the 5 new propane trucks along with a total of 15 existing diesel trucks throughout the project to ensure a suitable comparison for evaluation. The NREL-installed data acquisition systems (data loggers) included controller area network and GPS connections, which captured second-by-second data, including vehicle location, speed, engine-related information, and emissions information (if available) to help assess the performance of each vehicle. Operations included both city and highway deliveries across two 1-month periods in the summer and winter to estimate the emission reductions within the delivery operation, investigate propane's feasibility as a long-term fuel choice, and compare the associated operational costs in the given market to the diesel fleet.

2.1 Propane Vehicle Description

Beginning with a Ford F-750 platform, Roush CleanTech upfitted the fuel system and delivered the five propane-powered Class 7 box trucks used in this study for mail delivery operations. The detailed vehicle specifications are shown in Table 1, and photos of the trucks and fueling station are shown in Figure 1 and Figure 2.

Table 1. Propane Vehicle Specifications

Specification	Details
Vehicle Model	Ford F-750
Model Year	2022
Engine Type	7.3L V8 Propane Engine
Class	6
GVWR	26,000 lbs
Body Type	Mickey Body 26' with Tuck-Under Liftgate
Fuel System	ROUSH 74 Usable Gallons 0.02 NO_x Emissions Certified LPG
Transmission	6R140 Transmission, TorqShift Heavy-Duty 6-Speed Automatic
Horsepower	350 hp at 3,900 rpm
Torque	468 lb-ft at 3,900 rpm

Figure 1. Photo of the propane truck

(photo by Matthew Jeffers)

Figure 2. Photo of the propane fuel station installed at the Hi Pro truck depot

(photo by Matthew Jeffers)

2.2 In-Use Vehicle Data Collection

Leveraging the FleetREDI data collection capabilities and methodologies, NREL deployed data loggers on vehicles in the Hi Pro fleet to capture on-road operational data for the mail transport application during different times of the year. Data loggers were installed on 5 propane trucks and 15 unique diesel trucks throughout the data collection periods to record GPS, engine, and emissions-related data. It is important to note that different diesel vehicles were used in each testing period due to fleet turnover and replacement of older diesel trucks by the new propane trucks. Data collection for the diesel vehicles included January 2021–February 2021 (winter months), July 2022–August 2022 (summer months), and March 2023–April 2023 (spring months). Subsequently, the propane data collection included data from March 2023–April 2023 (spring months) and July 2023–August 2023 (summer months). Useable on-road vehicle data was only available from two of the five instrumented propane vehicles during the data collection periods. A detailed calendar plot highlighting the recorded data for each logging period is shown in Figure 3, with the diesel vehicles shown in red (top), and the propane vehicles shown in blue (bottom). Intensity of color for each day indicates the cumulative fleet engine-produced energy as measured at the flywheel (flywheel energy). This is the energy required to move the vehicle, power accessory loads, and leads to losses within the drivetrain. Darker days indicate more vehicle use.

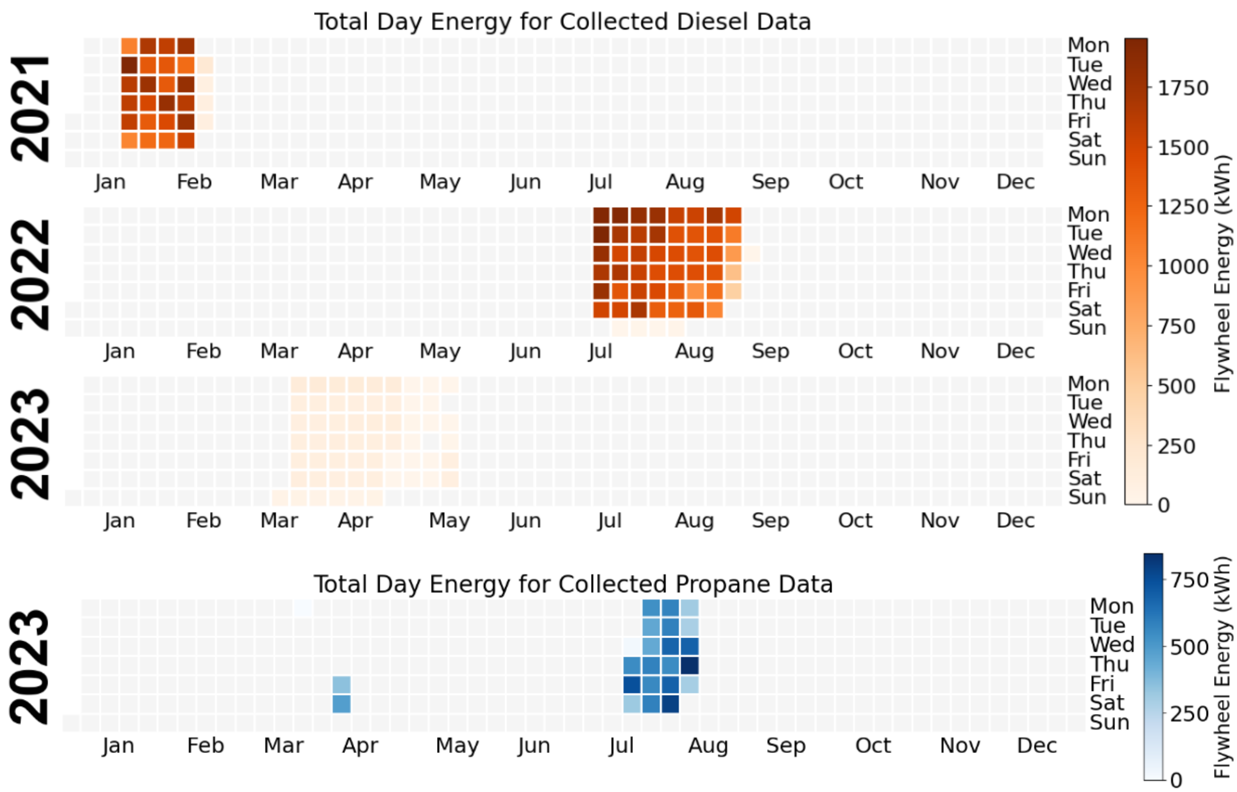

Figure 3. Calendar plots showcasing the daily flywheel energy for diesel (top) and propane (bottom) vehicles during the data logging periods

Once the data loggers were removed from the vehicles, raw data were segmented into daily files, meaning each file includes one unique date for each respective vehicle ID. Metrics were then calculated on each day of operation to analyze the daily performance of each vehicle and compare the powertrain technologies. Files were excluded from the analysis if, on the given day, the corresponding vehicle did not cover a minimum distance of 1 mile. This criterion was implemented to filter out short trips that did not accurately represent typical vehicle operations, such as refueling or reparking the vehicle in the truck yard. A summary of the data collection metrics is shown in Table 2, and a map of the captured vehicle operation is shown in Figure 4. While less data was captured on the propane vehicles due to the delayed deployment and limited operation, the propane vehicles were able to travel similar routes as the diesel trucks—to the eastern plains of Colorado along with the mountainous corridors—indicating these vehicles can meet the same duty cycle as the existing diesel vehicles. Detailed analysis of the trucks' duty cycles and their comparisons are quantified in the following sections.

Table 2. Overview of Vehicle Operations from Valid Logged Datasets

	Vehicle Count	Calendar Days	Vehicle Days	Miles of Data	Hours of Operation	Gallons Used (dge)
Diesel	15	185	444	86,034	5,675	3,805 [a]
Propane	2	24	41	7,922	491	918 [a]

[a] Gallons used by trucks reporting fuel rate.

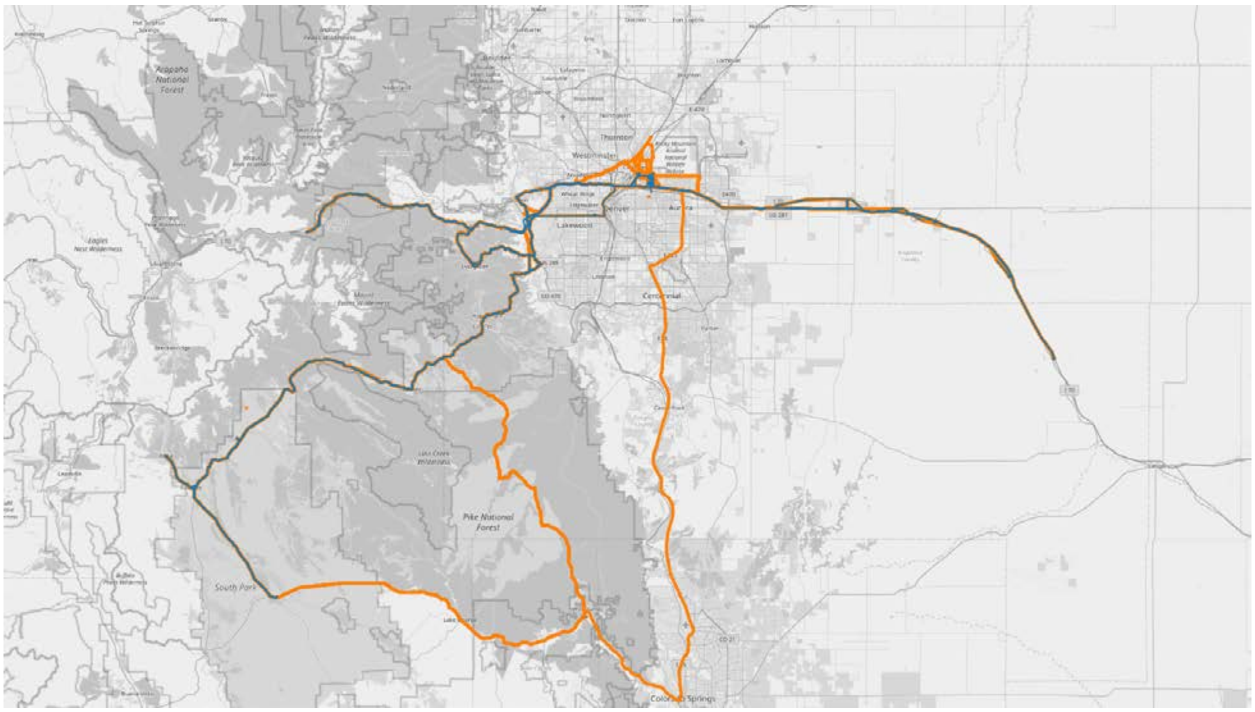

Figure 4. Map showing routes traveled by diesel trucks (orange) and propane trucks (blue) during data collection periods

The map in Figure 5 shows the locations of USPS post offices to which the Hi Pro fleet delivers mail on a regular basis. Post offices are displayed as blue stars, and Hi Pro's truck depot location north of Denver is shown as a green pin on the map. The truck fleet typically operates 6 days per week, Monday through Saturday. Figure 5 also suggests that the southernmost paths traveled by the diesel trucks in Figure 4 are not typical routes for post office deliveries and were, therefore, not traveled frequently.

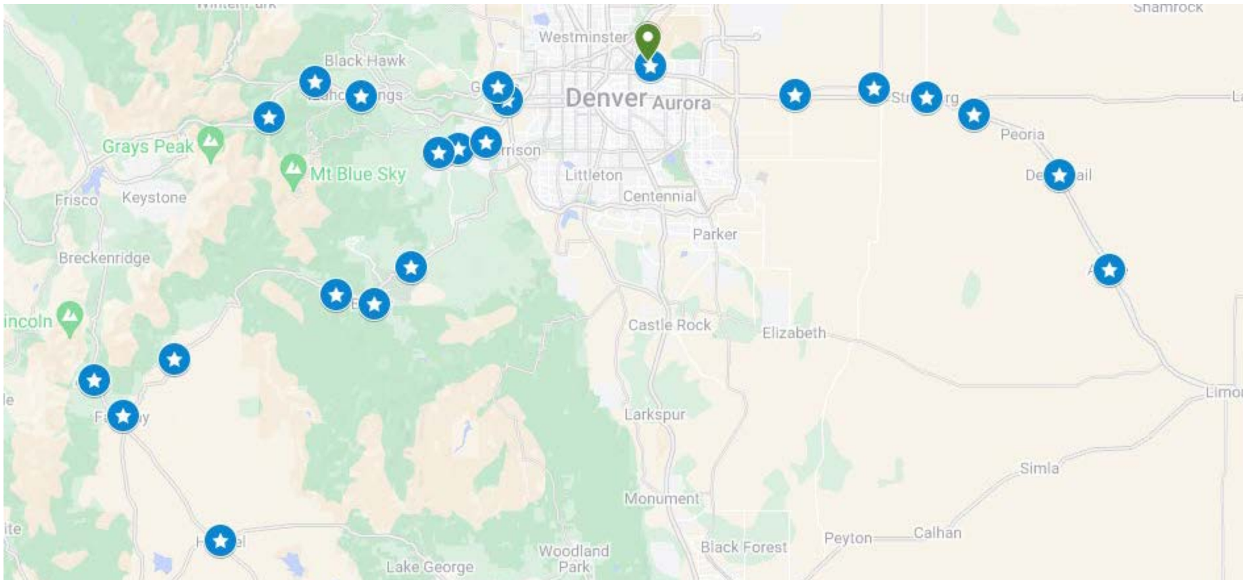

Figure 5. Map of USPS post office delivery locations

2.3 Vehicle Duty Cycle Comparison

Vehicle duty cycle is the measure of effort and intensity of vehicle operation. Metrics including vehicle speed, route length, and kinetic intensity help quantify the extent of a vehicle's work. With the intent of comparing the ability of the propane vehicles to meet the duty cycle requirements of the existing diesel vehicles, this analysis centers on comparing the duty cycles and performance by utilizing data from the controller area network data loggers for both diesel-powered and propane-powered delivery trucks. Daily distance is one of the key metrics for comparing duty cycle and is calculated by integrating the wheel-based vehicle speed over time. Daily distance for each vehicle is shown in Figure 6. The average daily distance traveled was approximately 193 miles for both diesel and propane. The maximum daily distance was 416 miles and 339 miles for diesel and propane, respectively. The taller peak for the propane vehicle distribution in the following plots is, in part, a reflection of fewer days of operation collected for this fleet. More vehicle operational days in the dataset would likely result in a smaller peak and smoother distribution for propane, more closely matching the diesel distribution, assuming similar route assignments continued between the fleets.

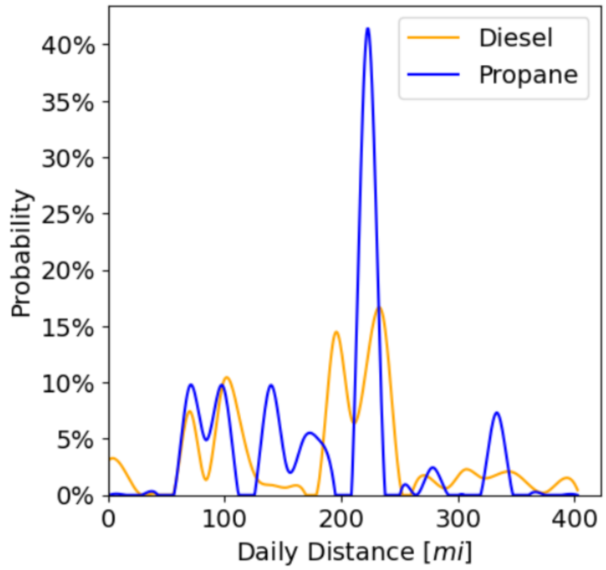

Figure 6. Daily distance distributions for diesel and propane vehicles

Average speed is another important metric for understanding vehicle duty cycle, as higher speeds require exponentially more power to overcome the forces of aerodynamic drag. Calculation of average speed used the time-average speed of wheel-based vehicle speed, and the distribution for each powertrain type is shown in Figure 7 (left). The median and maximum daily average speeds were 26 mph and 42 mph, respectively, for the diesel trucks, and the median and maximum average speeds were 29 mph and 33 mph, respectively, for the propane trucks. While the propane trucks had lower max daily average speeds, they had higher median speeds, indicating a tighter band of operation compared to the existing diesel vehicles. This is likely due to the limited data collected for the propane vehicles, resulting from those vehicles not being dispatched to all the routes the diesel vehicles operated on during the data collection periods. Further, both diesel and propane vehicles were able to attain the same maximum speed while driving. Figure 7 (right) also shows the distributions of average driving speed, which is the time-average speed while the vehicles are in motion (excluding zero speed, or idling, time). This plot shows very close agreement between diesel and propane vehicle operations.

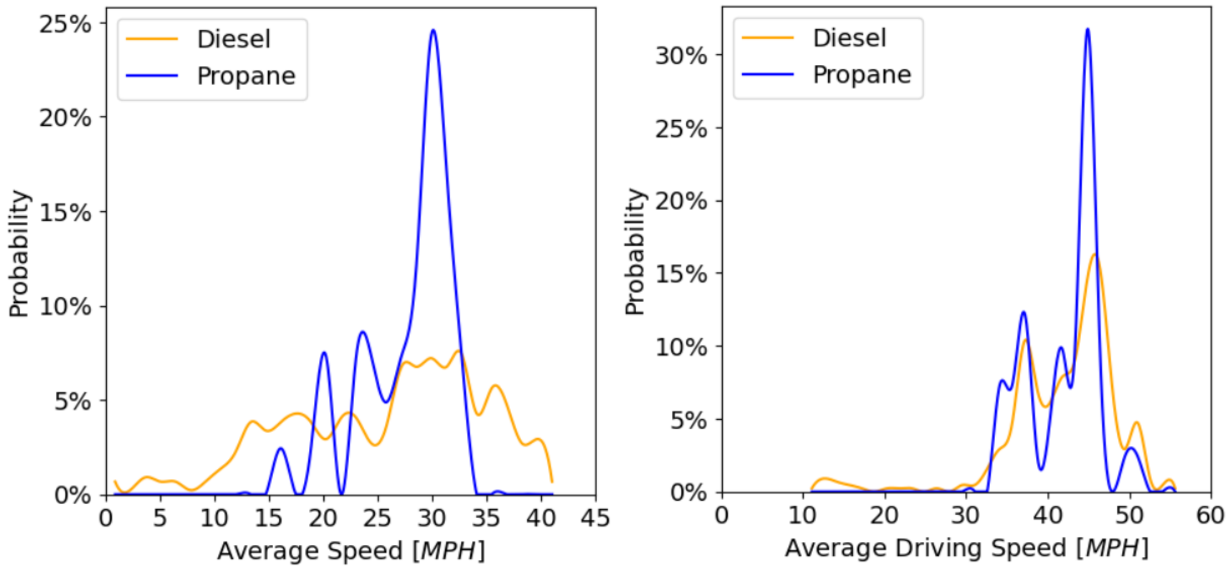

Figure 7. Average speed (left) and average driving speed (right) distributions for diesel and propane vehicles

Kinetic intensity is a measure of the drive cycle "aggressiveness," which is a ratio of characteristic acceleration to aerodynamic velocity (O'Keefe et al. 2007). While this metric is calculated only from vehicle speed, kinetic intensity is analogous to the ratio of power required for propulsion to that needed to overcome aerodynamic drag losses. High kinetic intensity is indicative of frequent starts/stops and lower average speeds. Aggressive acceleration and deceleration can also lead to higher kinetic intensity for the same average driving speed. Conversely, low kinetic intensity indicates sustained steady speeds such as on a freeway or interstate. Kinetic intensity for both the diesel and propane vehicles is shown in Figure 8—compared to average driving speed (left) and daily distance (right)—with relatively low kinetic intensity operation shown for both vehicle types. Both the diesel and propane trucks in this study had average driving speeds between 30 and 50 mph, which contributed to the low kinetic intensity of these vehicles and suggests a predominantly highway driving scenario with minimal stop-and-go. Similarly, the diesel and propane trucks have low kinetic intensity for operation above 50 miles per day, confirming that primary operation is on mid- to high-speed roads with limited stop-and-go driving, and the few low-mileage days do not represent typical driving for these vehicles.

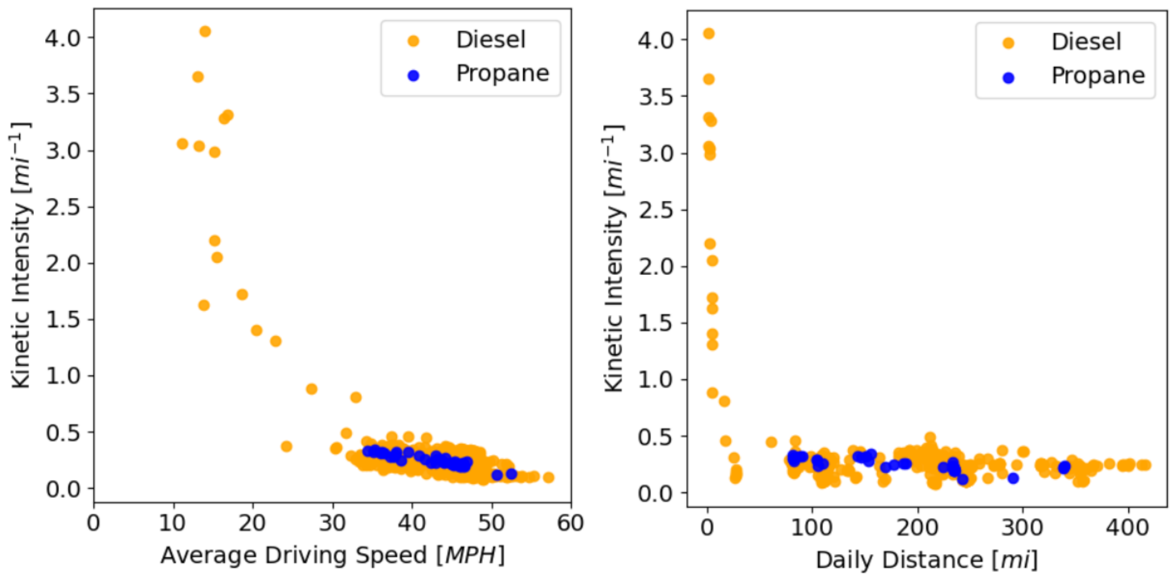

Figure 8. Kinetic intensity (a) vs. average driving speed, (b) vs. daily distance, for diesel and propane vehicles

Flywheel energy is important for understanding vehicle operation and duty cycle, as this is the energy output at the flywheel of the vehicle after thermal losses within the engine. For conventional and hybrid vehicles (excluding plug-in hybrids), all energy used to power, move, and perform the vehicle's operation comes from the engine, so it is important to understand what this requirement is to help compare each truck's operation. Flywheel energy was calculated from the collected engine data for the diesel and propane trucks by integrating the instantaneous engine power, defined in Equation 1. This includes engine angular velocity multiplied by engine torque to calculate power in watts. Using the recorded engine angular velocity in RPM, converted to radians per second and multiplied by the engine torque (N-m)—which is calculated using the logged actual engine percent torque, nominal friction percent torque, and reference torque—these values produce the engine power output at the flywheel where positive power is power production, and negative power indicates frictional losses within the powertrain.

$$P_i = \frac{(\tau_{act} - \tau_{fri})}{100} \bar{\tau}\omega_i$$

$$Power_i = Torque_i * Angular\ Velocity_i$$

Equation 1. Calculation of instantaneous engine power (watts)

Cumulative flywheel energy was summed over each day of operation to produce the distribution of total daily energy usage as shown in the left plot of Figure 9. The average daily flywheel energy was 264 kWh for the diesel trucks and 331 kWh for the propane, with both having an upper limit of 600 kWh per day. The propane trucks have a higher average engine-produced energy, despite a similar average daily distance traveled as the diesel trucks, which may contribute to higher daily fuel usage. The right plot in Figure 9 shows that the propane trucks also have a higher average energy output during engine idle periods. These differences for propane could be caused by increased vehicle loads on the recorded operational days; different engine thermal efficiency, calibration, and gearing; or a combination of these factors. The results may also be influenced by fewer operational days recorded for the propane vehicles.

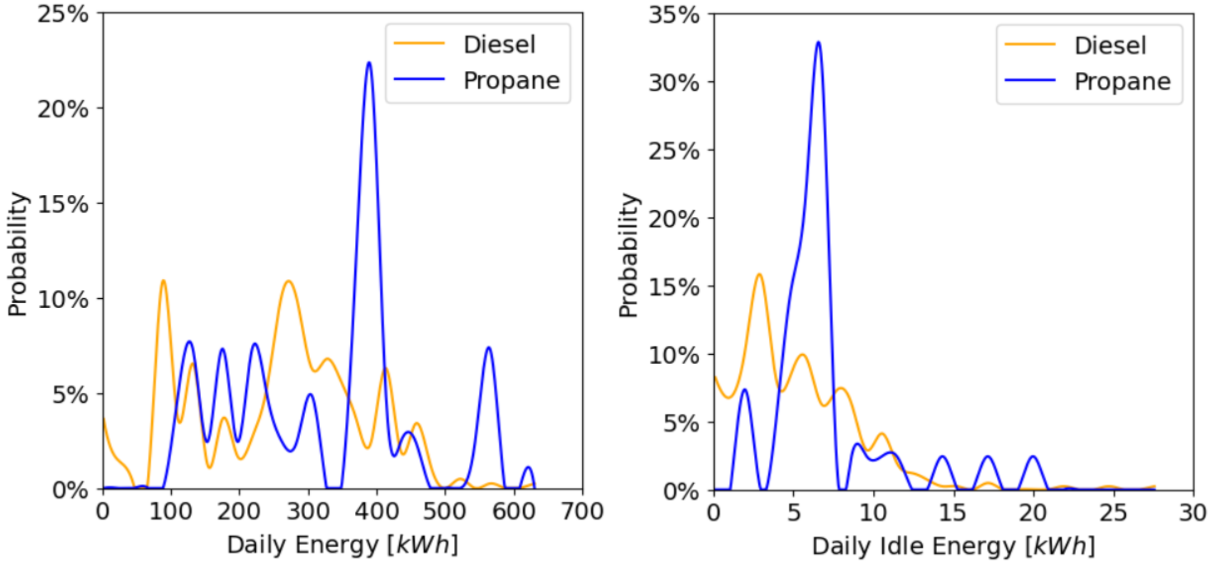

Figure 9. Flywheel energy distributions for diesel and propane

Comparing daily fuel consumption and fuel economy is critical for understanding the overall energy requirement and impact to the end user—the fleet operator. Fuel is part of the operating cost of the vehicle, and any new technology must be economically competitive with the conventional, or incumbent, technology to be widely adopted. Because different fuels have different energy densities, a conversion factor is required to compare them on an energy equivalent basis. Fuel consumption for each vehicle was calculated by analyzing files from the recorded second-by-second engine fuel rate data, measured in units of liters per hour for diesel and grams per second for propane vehicles. For diesel, the engine fuel rate was multiplied by the delta time (1 sec), converted to diesel gallons, and summed to obtain the daily fuel usage.

Propane consumption in gallons was calculated from the engine mass flow rate for propane (g/sec) divided by the density of propane (1,866.21 g/gal). In Equation 2, the conversion factor, which converts liquid gallons of propane to diesel gallons equivalent (dge), is obtained by dividing the energy content of propane (84,250 Btu/gal) by the energy content of diesel (128,488 Btu/gal), which is 0.656 (AFDC 2023a).

$$Conversion\ to\ dge = \frac{Energy\ Content\ of\ Propane}{Energy\ Content\ of\ Diesel}$$

Equation 2. Conversion factor to equate the energy content of a volume of propane to the energy content of an equivalent volume of diesel

Liquid propane consumption (gal/sec) was then multiplied by this conversion factor and the delta time (1 sec) and summed to obtain the daily fuel consumption in dge. Figure 10 showcases the distributions of daily fuel consumption and fuel economy calculated from the recorded data. The average daily fuel consumption was 17.5 diesel gallons and 22.4 dge for propane. Propane exhibited higher average daily fuel consumption, despite similar average daily distance traveled, compared to diesel. Daily fuel economy (mi/gal) was calculated by dividing the daily distance traveled (mi) by the daily fuel consumption (diesel gallons or dge) for each data file. The average daily fuel economy was 10.3 mi/gal for diesel and 8.7 mi/dge for propane. The lower average fuel economy for the propane vehicles also indicates lower engine thermal efficiency for propane compared to diesel.

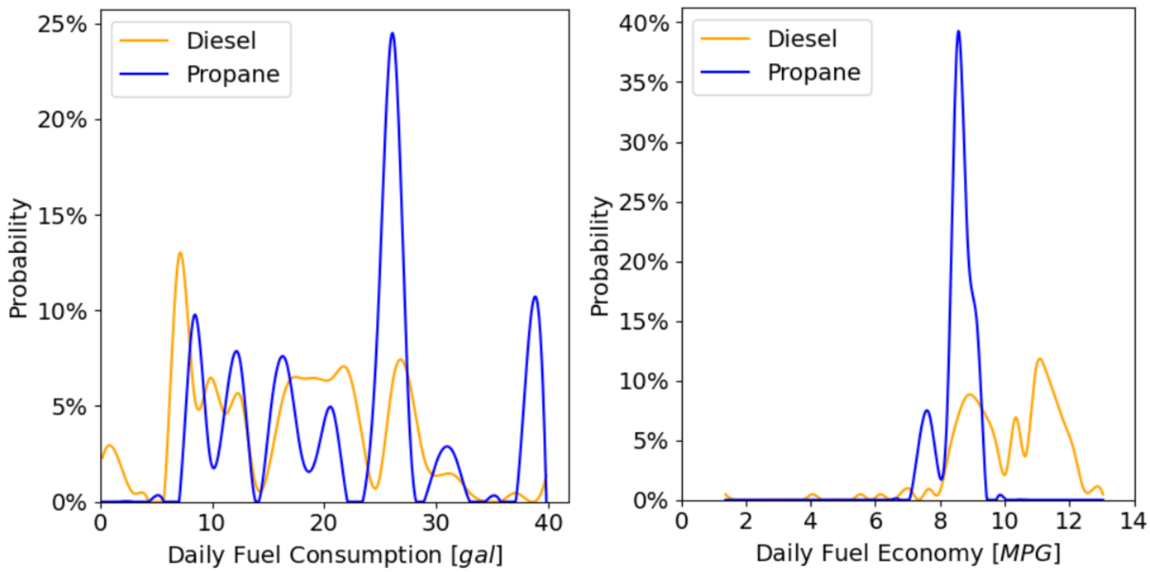

Figure 10. Daily fuel consumption (left) and fuel economy (right) for diesel and propane

Thermal efficiency of the engine is calculated as the ratio between the flywheel power and the fuel power, which is the fuel flowrate multiplied by its heat of combustion (Equation 3).

$$\eta = \frac{P_{shaft}}{P_{fuel}}$$

Equation 3. Calculation of engine thermal efficiency

The thermal efficiency maps shown in Figure 11 and Figure 12 display the calculated thermal efficiency across the engine speed and torque ranges recorded for the propane and diesel vehicles in this study. The diesel dataset includes a variety of vehicle make/model/year combinations (as listed in the Appendix), while the propane dataset includes only one vehicle make/model/year. The maps indicate that diesel (Figure 11) can achieve higher thermal efficiencies compared to propane (Figure 12), albeit over a smaller range of engine speed. It has been established that the high-frequency zone of engine operation for diesel trucks operating in the local delivery vocation is typically the engine speed range of 1,200-1,500 rpm and engine torque range of 100-500 Nm (Zhang, et al. 2021). This high-frequency operating zone does not necessarily match the peak thermal efficiency zone for the engine. In this high-frequency zone, the Hi Pro diesel trucks demonstrated thermal efficiencies up to 40-45%. Although the propane vehicles may have had a different high-frequency engine operating zone (likely, higher speed range and similar torque range), the efficiency map for propane shows virtually all recorded operation under 40% thermal efficiency.

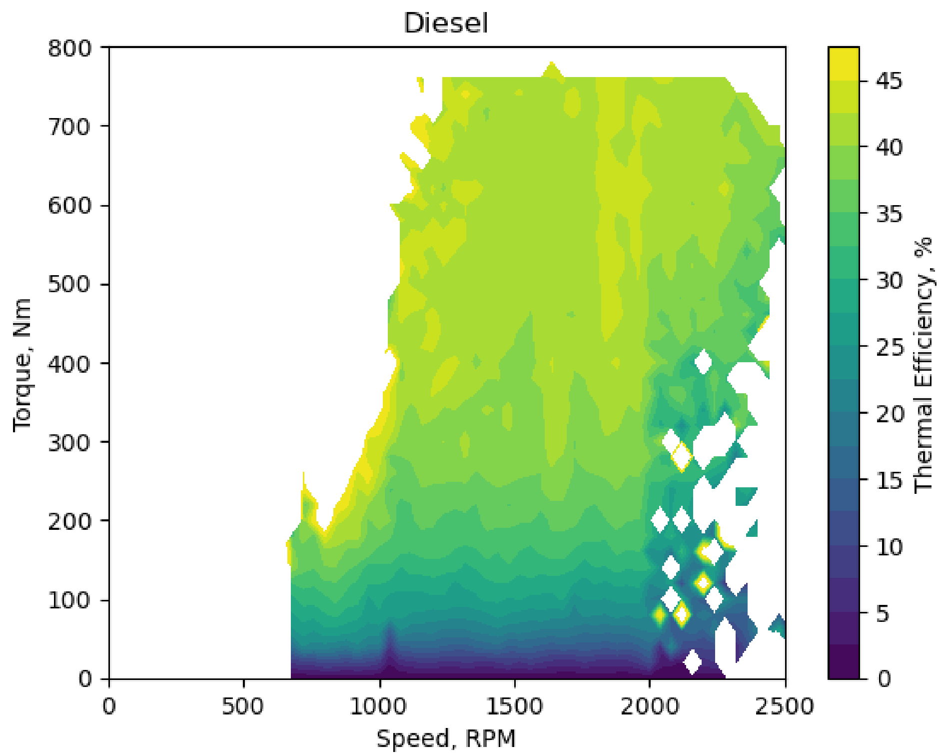

Figure 11. Diesel thermal efficiency map

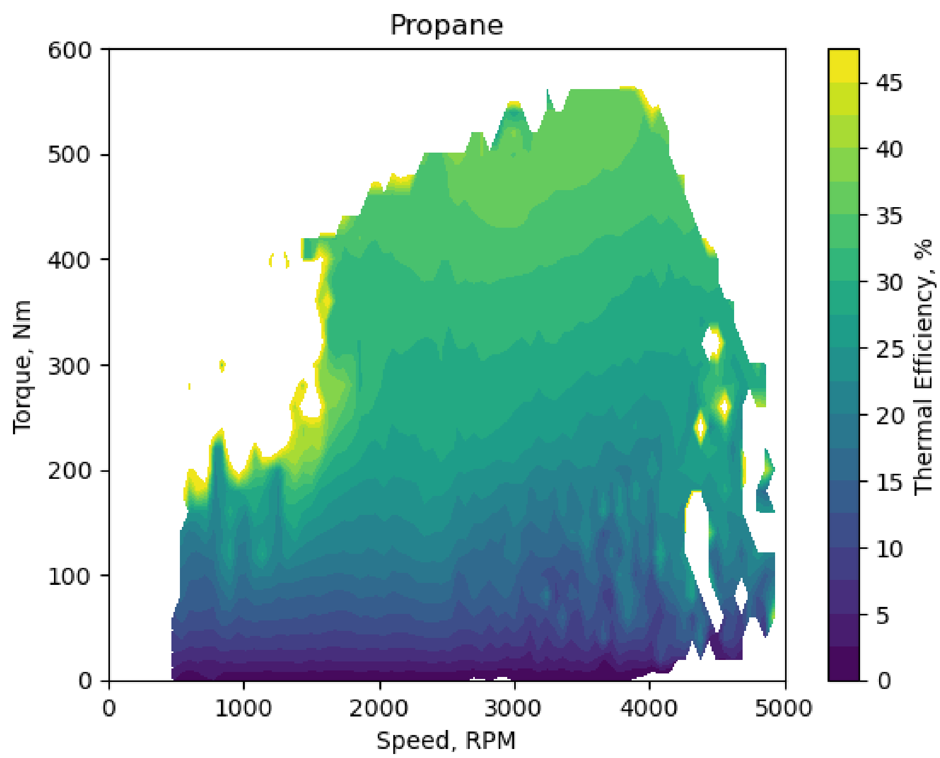

Figure 12. Propane thermal efficiency map

2.4 Emissions Estimation Methodology

Demonstrating emissions reduction with propane vehicles is a primary goal of this project. Diesel is an energy dense fuel that has been used for years to propel the nation's transportation network. However, due to the high flashpoint of diesel, higher compression is required to ignite the fuel, thus increasing combustion temperatures. Along with the lean fuel mixture (more air than needed) compression ignition of diesel fuel creates a substantial number of oxides of nitrogen (NO_x) compared to stoichiometric port injection which does a better job of vaporizing propane fuel. Further, direct injection of diesel fuel results in liquid droplets being present in the combustion mixture, resulting in increased diesel particulate and other unburnt hydrocarbons. Diesel particulate filters, exhaust gas recirculation, and selective catalytic reduction (SCR) emissions devices have been developed to reduce these emissions, but as emissions regulations become more stringent, these emissions control systems have become more complex and expensive.

Propane combustion engines use spark ignition and rely on port fuel injection which increases fuel vaporization. While these engines have lower thermal efficiency, they have substantially reduced emissions with relatively small amounts of particulate matter and a simpler emissions aftertreatment design that solely relies on a three-way catalyst to achieve the necessary emissions regulations.

The following sections describe the methods used to calculate the tailpipe and production emissions for diesel and propane fuels. The fuel production emissions, also described as "well-to-pump," represent the emissions generated during the extracting, refining, compressing (if applicable), and transporting processes required for a fossil-based transportation fuel to reach the end user at a fueling station. These are also considered to be upstream or indirect emissions. Tailpipe emissions, or "pump-to-wheel" emissions, represent the direct emissions exhausted through the tailpipe of a vehicle with an internal combustion engine. This evaluation did not consider any evaporative or vented emissions associated with refueling, which would be included in the "pump-to-wheel" category. The three primary emissions considered for this analysis include carbon dioxide (CO_2), sulfur oxides (SO_x), and NO_x.

For the diesel trucks, tailpipe NO_x emissions were directly measured using the SCR system's NO_x sensors. Tailpipe NO_x for the propane vehicles was estimated based on the engine-produced energy and the emissions certification for NO_x in g/bhp-hr. CO_2 and SO_x for both diesel and propane were calculated from the fuel consumption, assuming all carbon is converted to CO_2, and SO_x is based on typical fuel sulfur content. In actuality, some of the carbon will be converted to CO due to incomplete combustion, and the three-way catalyst will reduce the CO emissions produced by the engine. The engine certification by the California Air Resources board shows this to be around 1% of the carbon (CARB 2024). In addition, emissions for fuel production were calculated from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model for both vehicles.

Diesel Emissions Calculations

As mentioned, the NO_x emissions for the diesel vehicles were directly measured using the SCR system's NO_x sensors. The calculation for the NO_x tailpipe emissions included the NO_x measurements and engine mass air flow rate obtained from the controller area network loggers.

Tailpipe CO_2 emissions were calculated using Equation 4, which represents the combustion process, highlighting the relationship between diesel ($C_{12}H_{23}$ – average fuel composition assumed) and the resulting CO_2 and H_2O in a stoichiometric reaction. The molar mass of diesel and CO_2 were calculated as 167.31 g/mol and 44.01 g/mol, respectively.

$$C_{12}H_{23} + 17O_2 \rightarrow 12CO_2 + 11H_2O$$

Equation 4. Combustion equation of diesel

Equation 5 was used to estimate the amount of tailpipe CO_2 emitted in kg for the diesel consumed, where 3.79 is the unit conversion for gallons to liters, 0.85 kg/l is the density of diesel, 44.01 g/mol is the molar mass for CO_2, and 167.31 g/mol is the molar mass of diesel. This was multiplied by the daily fuel consumption in diesel gallons for the subset of vehicles that reported engine fuel rate.

$$CO_2\ tailpipe = \left(\frac{12 * 44.01 \frac{g}{mol}}{167.31 \frac{g}{mol}}\right) * 0.85 \frac{kg}{l} * 3.79 \frac{l}{gal} * Fuel\ Consumption\ (gal)$$

Equation 5. Tailpipe CO_2 emissions calculation for diesel vehicles

In addition, tailpipe SO_x emissions were calculated based on the typical sulfur fuel contents, which assumes that all sulfur in the fuel gets converted to SO_x. While these contents were not directly measured for the study, the quantity of emissions using the standard sulfur content is relatively low compared to other emissions quantities. Since 2010, on-highway diesel fuel is required to be ultra-low-sulfur diesel, for which the sulfur content must be 15 parts per million, or less, according to regulation by the U.S. Environmental Protection Agency (EPA 2023a). Equation 6 outlines the calculation for diesel tailpipe SO_x emissions (kg) and incorporates the following components: diesel density (converted from 0.85 kg/l to 3.22 kg/gal), sulfur content for diesel (15 ppm), a conversion factor representing grams of sulfur per gram of sulfur dioxide, and the daily fuel consumption (gal).

$$SO_x\ tailpipe = \frac{3.22 * 15 * 2}{1 * 10^6} * Fuel\ Consumption\ (gal)$$

Equation 6. Tailpipe SO_X emissions calculation for diesel vehicles

The GREET tool was utilized to calculate the production emissions to represent the environmental impact linked to the production phase of the transportation fuel.[1] The specific production emissions data for low-sulfur diesel from crude oil, including CO_2, SO_x, and NO_x were obtained from the 2022 GREET model. These values were 1.71 kg of CO_2/gal, 0.68 g of SO_X/gal, and 2.47 g of NO_x/gal, which were each multiplied by the fuel consumption (gal) for a subset of the vehicle fleet, as shown in Equation 7.

[1] Argonne National Laboratory. "Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model." https://greet.anl.gov/index.php.

$$CO_2\ production = 1.71\frac{kg\ CO_2}{gal} * Fuel\ Consumption\ (gal)$$

$$SO_x\ production = \left(\frac{0.68}{1000}\right)\frac{kg\ SO_x}{gal} * Fuel\ Consumption\ (gal)$$

$$NO_x\ production = \left(\frac{2.47}{1000}\right)\frac{kg\ NO_x}{gal} * Fuel\ Consumption\ (gal)$$

Equation 7. Production emission calculations for diesel vehicles

Propane Emissions Calculations

Unlike diesel vehicles, propane combustion engines do not need NO_x sensors for their aftertreatment control, so NO_x is not able to be directly measured without specialized external emissions equipment. As a result, NO_x emissions must be estimated from other parameters. In this report, tailpipe NO_x emission estimates for propane were calculated, as shown in Equation 8, by referencing the California Air Resources Board engine certification for Roush Industries, Inc. with Ford's ultra-low NO_x 7.3L V8 propane engine, which set the NO_x emission level as 0.02 g/bhp-hr (CARB 2024). This value was converted to g/kWh and multiplied by the daily flywheel energy (kWh) for each dataset, which calculates tailpipe NO_x (g). It should be noted that in-use numbers may vary based on duty cycle, catalyst age, and catalyst temperature.

$$NO_x\ tailpipe = 0.02\frac{g}{bhp - hr} * 1.34\frac{bhp}{kW} * Daily\ Energy\ (kWh)$$

Equation 8. Tailpipe NO_x emissions calculation for propane vehicles

Like the method employed for diesel, the calculation of propane tailpipe CO_2 emissions involved applying the stochiometric combustion equation tailored to propane (C_3H_8), as shown in Equation 9, and assuming all carbon gets converted to CO_2. Equation 10 was used to estimate the tailpipe CO_2 emissions in kg for propane, where 44.01 g/mol is the molar mass for CO_2 and 44.1 g/mol is the molar mass of propane. This was multiplied by the daily fuel consumption in grams (g) to get the total tailpipe of CO_2 produced.

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Equation 9. Combustion equation of liquid propane

$$CO_2\ tailpipe = \left(\frac{3 * 44.01\frac{g}{mol}}{44.1\frac{g}{mol}}\right) * \frac{1\ kg}{1000\ g} * Fuel\ Consumption\ (g)$$

Equation 10. Tailpipe CO_2 emissions calculation for propane vehicles

The 2022 GREET model was used to assess tailpipe SO_x emissions for propane, which shows zero tailpipe emissions (all SO_x emissions occur during the fuel production phase). Therefore, tailpipe SO_x emissions were estimated to be zero for propane in this analysis.[2]

Production emissions data for propane from crude oil also referenced the 2022 GREET model, where the following values were provided: 0.41 g of CO_2/g, 0.88 mg of SO_x/g, and 1.05 mg of NO_x/g. As shown in Equation 11, each of these values was converted to kg/g and multiplied by the propane fuel consumption in grams.

$$CO_2\ production = \left(\frac{0.41}{1000}\right)\frac{kg\ CO_2}{g} \cdot Fuel\ Consumption\ (g)$$

$$SO_x\ production = \left(\frac{0.88}{10^6}\right)\frac{kg\ SO_x}{g} \cdot Fuel\ Consumption\ (g)$$

$$NO_x\ production = \left(\frac{1.05}{10^6}\right)\frac{kg\ NO_x}{g} \cdot Fuel\ Consumption\ (g)$$

Equation 11. Production emission calculations for propane vehicles

The respective tailpipe and production emissions were calculated for each daily dataset and divided by the daily distance traveled to establish a standardized metric—emissions per mile (kg/mi and g/mi). This approach allowed a direct comparison of emissions impact between the two powertrain fuel types that may travel different distances for daily routes.

2.5 Vehicle Emissions Comparison

Average tailpipe and production emissions for the diesel and propane vehicles are compared in Figure 13, with corresponding values in Table 3. The propane vehicles have lower tailpipe criteria pollutant emissions (SO_x and NO_x) compared to conventional diesel, and a 6.5% increase in kg of CO_2 per mile. There is an estimated 98.3% reduction in grams per mile of NO_x, and the tailpipe SO_x is eliminated for propane. According to the GREET model, propane production emissions were higher than diesel except for the CO_2 emission component. Specifically, there was a 12.5% decrease in CO_2, a 52.2% increase in NO_x, and a 383.3% increase in SO_x for producing propane over diesel. Combining both tailpipe and production emissions, there was an 87.2% net decrease of NO_x emissions, 3.7% net increase of CO_2 emissions, and 322.1% net increase in SO_x emissions for propane over the baseline diesel operation.

---

[2] According to The Propane Education & Research Council (PERC), propane is dosed with ethyl mercaptan, which is a sulfur compound. A fuel sampling survey conducted by PERC showed that, on average in the U.S., propane's sulfur content is 34.5 ppm by weight.

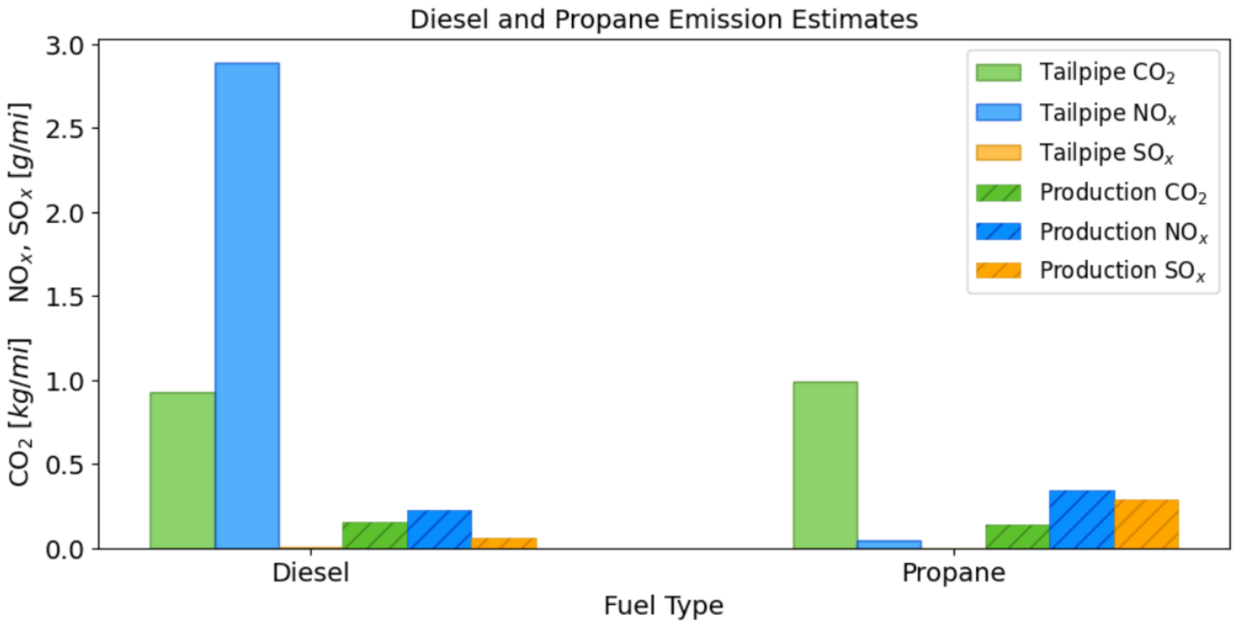

Figure 13. Comparison of calculated tailpipe and production emissions for diesel and propane vehicles on a per-mile basis

Table 3. Diesel and Propane Per-Mile Emissions Estimates

	Diesel	Propane
CO_2 tailpipe (kg/mi)	0.93	0.99
NO_x tailpipe (g/mi)	2.89	0.05
SO_x tailpipe (g/mi)	0.0088	0.0
CO_2 production (kg/mi)	0.16	0.14
NO_x production (g/mi)	0.23	0.35
SO_x production (g/mi)	0.06	0.29
CO_2 combined (kg/mi)	1.09	1.13
NO_x combined (g/mi)	3.12	0.40
SO_x combined (g/mi)	0.0688	0.29

However, it was shown in Figure 9 and Figure 10 that the propane vehicles had higher average engine-produced energy and higher fuel consumption, respectively, while still having similar average daily distance—indicating different engine efficiencies/calibrations, and potentially heavier loads or more intense operation. Comparing emissions on an energy-specific basis, Figure 14 shows the average emissions per-unit energy (g/bhp-hr) for diesel and propane. As expected, there is an 24.5% reduction in CO_2, 199.2% increase in SO_x, and 87.1% reduction in NO_x on a per-unit engine-produced energy basis, showing that, with a similar duty cycle the 2022 model year propane vehicle has lower emissions than the 2016 model year diesel for the captured data.

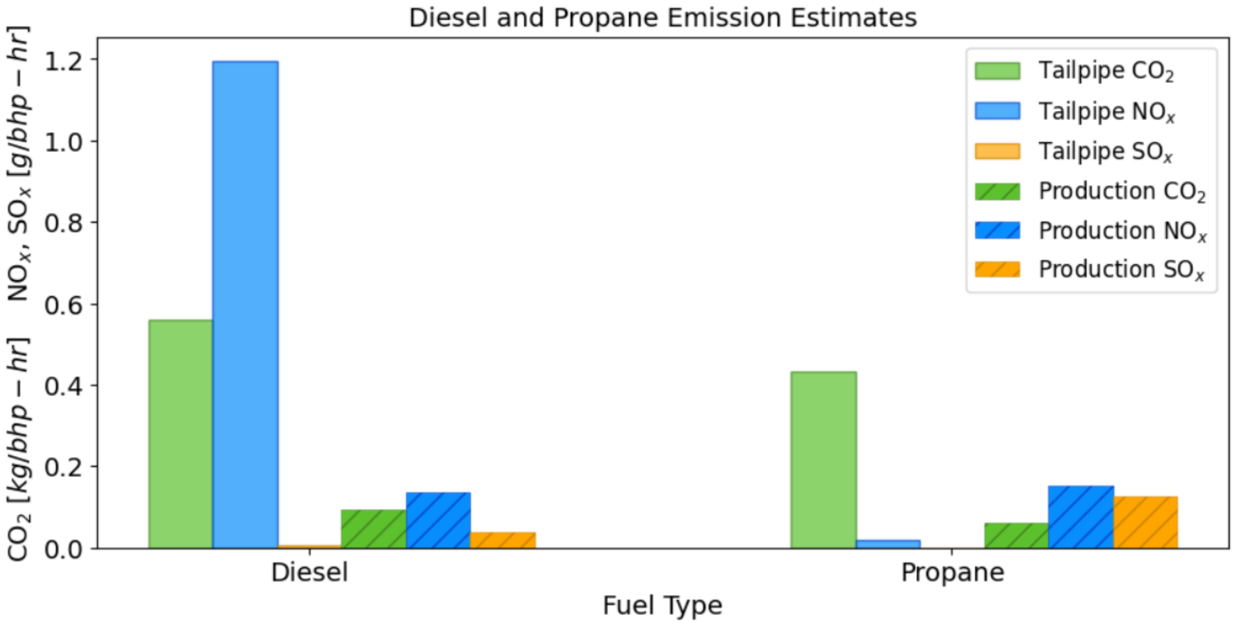

Figure 14. Comparison of calculated tailpipe and production emissions for diesel and propane vehicles on a per-unit energy basis

Tailpipe NO_x sensors on diesel vehicles have a ±10 ppm accuracy from 0–100 ppm and then a ±10% accuracy from 100 ppm to 2,000 ppm (Kotz et al. 2017). Additionally, tailpipe NO_x sensors will only be active when above 180°C to avoid damage from condensation. This means the sensors will not be able to read until they reach this temperature. Values were only used from the data if the sensor was active to avoid erroneous measurements. However, during this time of inactivity, the SCR system is not able to control or reduce NO_x actively, which can result in increased levels of emissions that are not quantified in this analysis, and these emission increases are highly dependent on load. In addition, colder external environments can further impact NO_x sensor activity by requiring more heat to maintain sensor temperature. Figure 15 shows the impact of external temperature on NO_x sensor activity, with summer months having over 95% activity on average, and winter months having less than 45% activity on average. This suggests that NO_x emissions are likely to be worse in the winter for diesel vehicles, resulting from the inability to actively control NO_x for greater than 50% of the time; however, those emissions were not able to be quantified within the scope of this work.

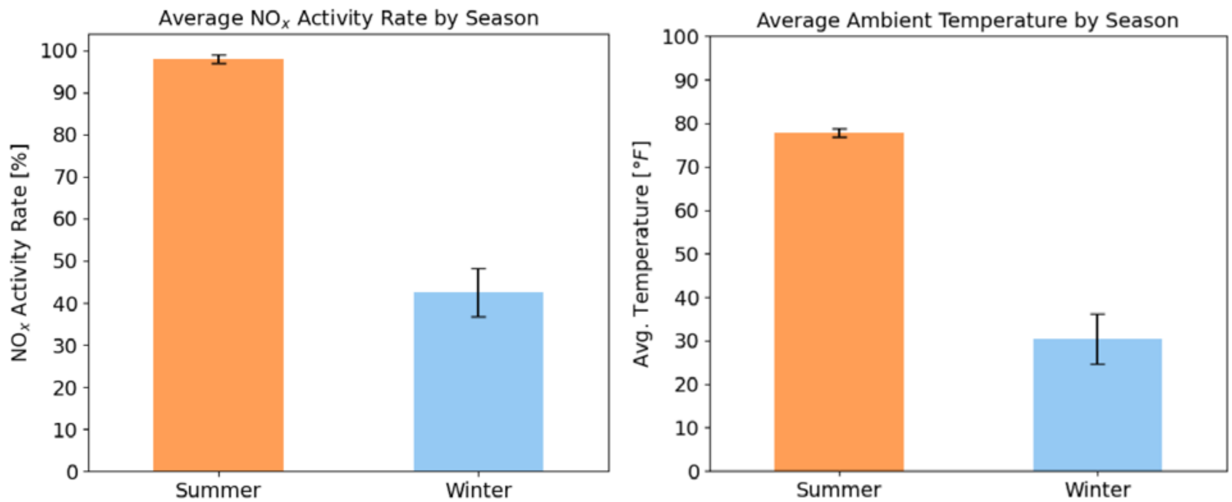

Figure 15. Diesel NO_x activity rate (left) and average ambient temperature (right) for summer and winter data collection periods

In this study, the latest diesel vehicles examined were 2016 model year, adhering to the 0.2 g/bhp-hr NO_x standard. In contrast, the 2022 propane vehicles comply with the 0.02 g/bhp-hr NO_x standard. A 2023 diesel vehicle is anticipated to show lower emissions compared to the 2016 model due to the upcoming adoption of the 0.02 g/bhp-hr standard for on-road medium- and heavy-duty engines.

Future research should focus on analyzing the in-use emissions of newer diesel engines with aftertreatments. Additionally, investigating emissions during periods when NO_x sensors are inactive and in cold climates can help further understand the emission profiles for each vehicle type.

3 Fleet Cost and Performance Comparison

Analysis of costs and operational performance of the new propane fleet compared to the baseline diesel fleet was another key objective of the project team. This section summarizes the upfront capital costs required to purchase and deploy the vehicles, the average fuel costs, and the average vehicle utilization. The results are derived from information provided by the fleet operator and other project partners.

3.1 Vehicle Capital Costs

The purchase of new propane vehicles and deployment into service transporting mail in the Denver Metro region was the primary purpose of this project. Hi Pro worked with the local Rush Truck Center to order the five propane box trucks according to their fleet needs. Table 4 outlines the upfront costs incurred for the purchase and registration of the new vehicles, which was approximately $126,690 per vehicle, resulting in a total fleet cost of nearly $633,500. For participating in this project, Hi Pro received a grant of $282,500 to support the purchase of these new vehicles, which represents approximately 45% of the total fleet cost. For reference, Hi Pro reports that a comparable new model diesel truck—such as a 2024 International MV607—costs approximately $100,000 per vehicle, based on recent data. This is 21% lower than the reported cost for the new propane vehicles.

Table 4. Propane Truck Costs

Description	Units	Unit Cost
Propane Truck Sales Price	$/vehicle	$118,364.00
Tax and Fees	$/vehicle	$5,451.38
Delivered Truck Cost	$/vehicle	$123,815.38
Truck Registration Cost	$/vehicle	$2,874.17
Subtotal	$/vehicle	$126,689.55
Number of Vehicles		5
Total Fleet Cost	**($)**	**$633,447.75**

3.2 Propane Fueling Station Capital Costs

Installation of a new propane fueling station at Hi Pro's facility in Commerce City, Colorado, was required for the deployment of propane vehicles. This was accomplished in 2022 by AmeriGas, working with Hi Pro and other project partners and contractors. The capital cost for the propane station equipment was approximately $54,200, and the cost for installation was approximately $86,500. These costs collectively covered the purchase, assembly, and installation of the fuel tank, dispenser, hoses, hose protectors, filters, as well as site preparation, electrical work, a new concrete pad, and labor. Some of the soft costs were covered by AmeriGas as in-kind support for the project. The costs also included key fobs, an annual website/cell fee, station startup, and training expenses. The total project cost for Hi Pro's new propane station was just over $140,700.

3.3 Vehicle Fuel Costs

Historical fuel transactions for each fleet were provided by Hi Pro to evaluate fuel costs for the diesel and propane truck fleets. Figure 16 shows the monthly total fuel costs incurred by Hi Pro for diesel fuel, which is purchased at public retail fueling stations along the truck routes. This data set covers all Hi Pro's Colorado fleet operations for the months of August 2022 through September 2023. This includes all the diesel trucks based at the Commerce City location, as well as diesel trucks based at Hi Pro's other Colorado hubs and, therefore, represents a much larger fuel quantity than the propane fleet.

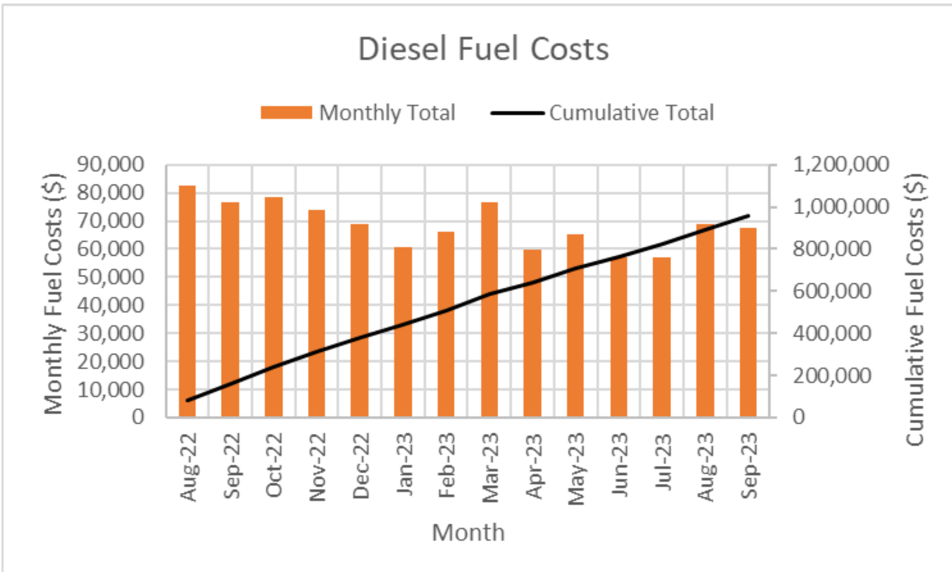

Figure 16. Monthly total fuel costs for diesel

Conversely, propane vehicles refuel on-site at the propane fueling station installed at Hi Pro's truck depot in 2022. Propane fuel is provided by AmeriGas via monthly deliveries to the station. Figure 17 shows the monthly total fuel costs incurred for the five-truck propane fleet at the Commerce City location, from August 2022 through September 2023.

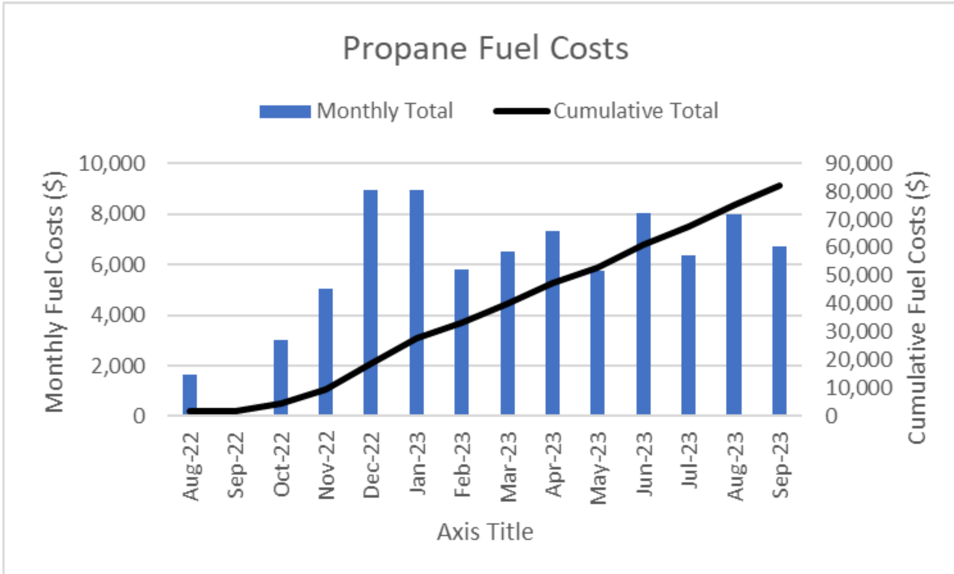

Figure 17. Monthly total fuel costs for propane

Propane fuel invoices provided by Hi Pro for the most recent 6 months (April 2023–September 2023) each included total fuel cost as well as total quantity of fuel delivered, which allowed for the direct calculation of the monthly average unit price ($/gallon) for propane, as shown in Figure 18. The price proved to be low and very stable during this period, staying below $2.00 per gallon of propane, as shown by the dashed line in the figure. When the propane fuel prices are converted to diesel gallon equivalent ($/dge) to account for the difference in energy content of the fuel, the relative price increases to approximately $2.45–$2.90 per dge (solid line), with an average of $2.60 per dge.

Fueling transactions available for diesel, however, included only total costs, not total gallons consumed, for each fueling event. Therefore, NREL utilized historical data available from the U.S. Energy Information Administration to estimate the monthly average unit price for diesel fuel used by the Hi Pro fleet during this period (EIA 2023). The values shown for diesel price in Figure 18 represent monthly average on-highway retail prices for ultra-low-sulfur diesel fuel in the Rocky Mountain region. During this period, diesel fuel varied between $4.00 per gallon and $5.00 per gallon, which is between 22% and 64% higher than the reported unit price of propane fuel, on an energy-equivalent basis.

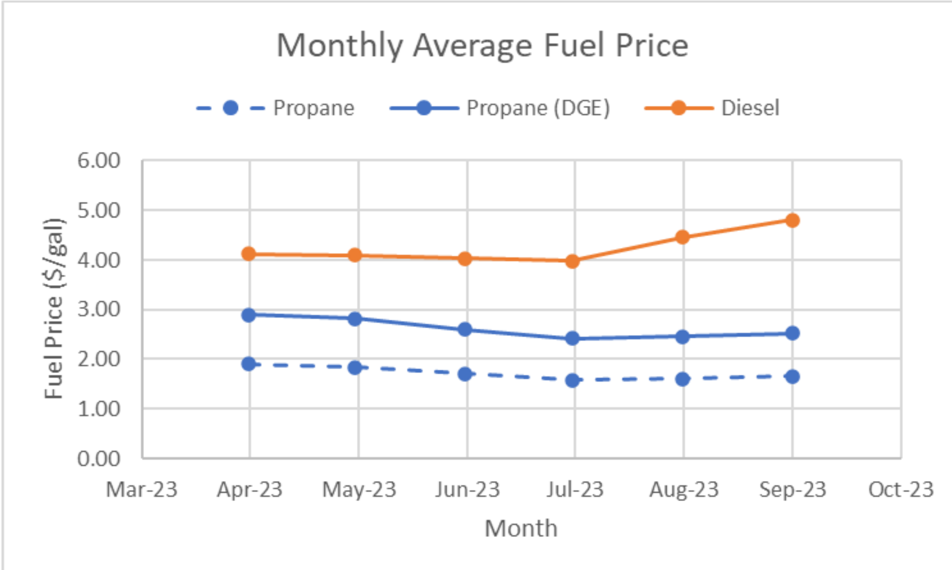

Figure 18. Monthly average unit price for diesel and propane fuels

The monthly average unit price for each fuel (with units of diesel gallons or dge) was multiplied by the fleet-average fuel economy for the corresponding vehicles—8.7 mi/dge for the propane fleet and 10.3 mi/gal for the diesel fleet—to determine the monthly average cost per mile for each type. Figure 19 reveals that propane fuel, at approximately $0.30 per mile, on average, was 29% less than the average per-mile cost for diesel, which was just more than $0.42 per mile. This represents a significant reduction in operating expenses for the propane truck fleet.

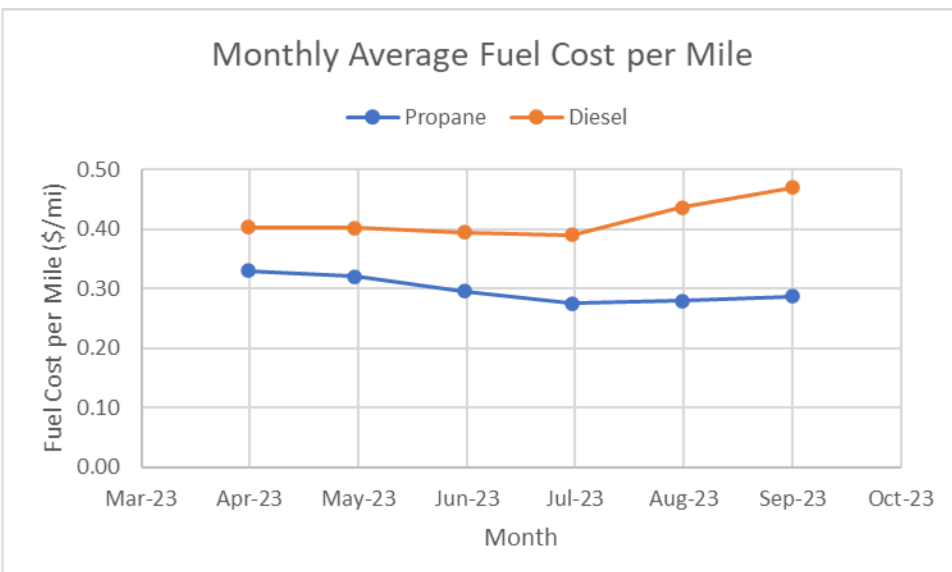

Figure 19. Monthly average cost per mile for diesel and propane fuels

3.4 Vehicle Maintenance Costs

At the outset of the project, the project team anticipated collecting detailed maintenance records for both the diesel and propane fleets in this evaluation to inform a comparison of the real-world costs required to maintain the respective truck types. Unfortunately, this aspect of the evaluation was not feasible, due to a combination of factors—including, but not limited to, several manufacturing and shipping delays for the propane trucks, which vastly reduced the in-service time for this fleet during the project's period of performance, as well as unexpectedly high vehicle turnover and use of rental vehicles in place of the diesel trucks, resulting in very inconsistent operation and incomplete service records for the baseline diesel fleet during the data collection period.

Hi Pro was able to provide a brief list of maintenance activities performed on propane vehicles during the early operation period, between February 2023 and October 2023. Most of the work performed consisted of scheduled preventive maintenance activities, such as oil changes, air filter cleaning, and tire rotations/replacements. The list of maintenance expenses also included numerous towing events; however, the root cause for many of these events could not be determined from the data. After initial delivery of the propane fleet, Hi Pro experienced several issues with the truck batteries not maintaining adequate charge while the vehicles were parked, requiring replacement of the batteries and rewiring in some cases. Other miscellaneous repairs that occurred during this time frame included repairs to windshields, liftgates, fuel gauges, and fuel tank sensors. Some of the maintenance work was covered under warranties. Hi Pro estimated average maintenance costs were less than $0.10 per mile for the propane vehicles during this initial deployment timeframe; however, this may not represent the average per-mile maintenance costs over the long-term operation of these vehicles.

Ultimately, the available data was insufficient to accurately quantify real-world maintenance costs or to compare those ongoing costs between the two vehicle technologies. Future evaluations should focus on the consistent and complete recording of maintenance data—including, at minimum, detailed repair costs, labor hours, and miles traveled for each vehicle with corresponding dates, times, work durations, and costs for each event over a sufficient time period—to determine the representative maintenance costs for the technology in this vocation.

3.5 Vehicle Utilization

Hi Pro utilizes telematic devices to track the operation of their fleet vehicles. To determine the utilization percentage for each of the fleet vehicles, Hi Pro staff conducted a review of the data recorded by the telematic devices and stored by the proprietary software. For each propane vehicle, they identified all days that the vehicle was operating on a route transporting mail to post offices, as well as days that the vehicle was not operating. When not in operation, the vehicle could be parked for a variety of reasons, including scheduled and unscheduled maintenance or because it was simply not needed for deliveries on that day. Therefore, the utilization percentage is a reflection of how often each vehicle was used, not necessarily how often the vehicle was available for service when planned to be used.

All five propane trucks were delivered to Hi Pro by August 1, 2022. This data review covered the date range of August 2022 through August 2023. The findings reported by Hi Pro to the NREL team are displayed in Figure 20. The average daily vehicle utilization varies from a low of 32.5% to a high of 84.2% during the data period, and the overall fleet average was 61.3% for the propane fleet. Comparable daily utilization numbers for the baseline diesel fleet were not available. Future efforts to compare the vehicle technologies should create daily records of vehicle availability and characterize the reasons for vehicle downtime to thoroughly evaluate the vehicle reliability during the data period.

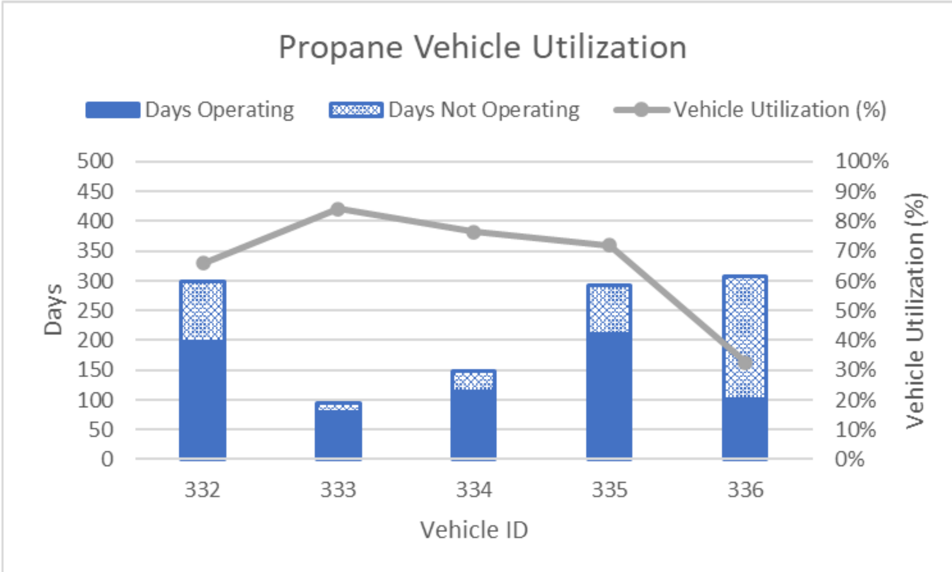

Figure 20. Vehicle availability for the propane truck fleet

4 Summary

NREL's FleetREDI analysis of collected on-road data demonstrates that the propane trucks in this study achieved similar duty cycles as the baseline diesel fleet, transporting mail to post offices from the eastern plains to the mountainous regions west of Denver. The propane and diesel vehicles had similar daily distances, average driving speeds, and kinetic intensities on these routes. The average fuel economy of the propane vehicles was lower than for diesel, which is expected due to the difference in engine thermal efficiency between the two transportation fuels. The propane trucks also had a higher average daily engine-produced energy, suggesting additional contributing factors (such as different engine calibration/gearing, and potentially heavier vehicle loads for propane) during the data collection periods.

Emissions reductions are an important aspect of adopting propane trucks. Results from this study indicate substantially lower NO_x emissions from the tailpipe compared to similar diesel truck operation—a 98% reduction on a per-mile basis. Tailpipe CO_2 emissions were slightly higher (approximately 6.5% increase), and the tailpipe SO_x emissions were eliminated with the propane fleet, due to the negligible sulfur content in propane fuel. Production emissions of NO_x and SO_x, however, were estimated to be higher for propane on a per-mile basis using values from the GREET model. However, it was noted that the propane trucks had increased average engine-produced flywheel energy. Comparing the emissions on a per-unit energy basis, the combined tailpipe and production emissions were 24.5% lower for CO_2, 87.1% lower for NO_x, and 199.2% higher for SO_x for the propane vehicles over the baseline diesel vehicles. The reductions in tailpipe emissions could lead to lower local air pollution for the Denver Metro region and surrounding areas where these vehicles operate.

This study also highlights the constraints of tailpipe NO_x sensors on diesel vehicles, revealing accuracy limitations within specific concentration ranges. These sensors activate only above 180°C to avoid damage from condensation, leading to periods of inactivity in which the SCR system cannot control or reduce NO_x emissions. This inactivity may result in unquantified increases in emissions, particularly during winter months, in which it was shown that the NO_x sensor activity drops below 45% on average vs. over 95% activity, on average, during summer months. While the data suggest potentially worsened NO_x emissions in winter, the exact impact remains unspecified within the study's scope. Additionally, the diesel vehicles included in this project, with a model year of 2016, emit higher levels of emissions compared to newer 2023 diesel vehicles. The difference is attributed to the expected adoption of the 0.02 g/bhp-hr NO_x standard in more recent vehicle models. Future research should analyze emissions during periods of NO_x sensor inactivity and in cold climates to better understand and quantify the additional NO_x emissions associated with lower temperatures.

The new propane vehicles deployed in this project are also achieving significant recurring savings in fuel costs for the fleet operator, based on available fueling records. During 6 months of operation in 2023, the propane fleet demonstrated consistently low fuel costs, averaging $0.30 per mile compared to the retail diesel average of $0.42 per mile during the same period. The other major operating expense for the vehicle fleet—in particular, maintenance costs—will have to be tracked carefully over the coming years to quantify costs for both vehicle types and determine if the propane fleet offers savings compared to diesel.

Drive Clean Colorado presented the initial findings of this project in webinars, conference presentations, and articles directed at fleets, especially USPS contractor fleets. There was significant interest due to the fuel cost savings that Hi Pro experienced, as well as the benefit of lowered tailpipe pollution, especially at the fleet facility where the trucks frequently traveled in and out. The new propane vehicles represent cost-effective and cleaner vehicle operations for the mail transport application. These results could be replicated by other commercial fleet operators, in this vocation and others, to help reduce local air pollution from vehicle tailpipe emissions.

References

Alternative Fuels Data Center (AFDC). 2023a. “Fuel Properties Comparison.” Accessed Dec. 29, 2023. https://afdc.energy.gov/fuels/properties.

———. 2023b. “Propane Benefits and Considerations.” Accessed Dec. 29, 2023. https://afdc.energy.gov/fuels/propane_benefits.html.

———. 2023c. “Propane Vehicles.” Accessed Dec. 29, 2023. https://afdc.energy.gov/vehicles/propane.html.

California Air Resources Board (CARB). 2024. “New Vehicle and Engine Certification: Executive Orders for MY2023 Medium-Duty and Heavy-Duty Engines.” Accessed Jan. 10, 2024. https://ww2.arb.ca.gov/new-vehicle-and-engine-certification-executive-orders-my2023-medium-duty-and-heavy-duty-engines.

IEA (International Energy Agency). 2023. “Transport.” https://www.iea.org/energy-system/transport.

Kotz, Andrew J., David B. Kittleson, William F. Northrop, and Niklas Schmidt. 2017. “Real-World NO_x Emissions of Transit Buses Equipped with Diesel Exhaust Aftertreatment Systems.” *Emission Control Science and Technology* 3: 153–160. https://link.springer.com/article/10.1007/s40825-017-0064-4.

National Renewable Energy Laboratory (NREL). 2023. “Fleet Research, Energy Data, and Insights (FleetREDI) platform data.” Accessed Dec. 15, 2023. *https://fleetredi.nrel.gov/*

O’Keefe, Michael P., Andrew Simpson, Kenneth J. Kelly, and Daniel S. Pedersen. 2007. “Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications.” NREL/CP-540-40929. Presented at the 2007 SAE World Congress and Exhibition, 16-19 April 2007, Detroit, Michigan. https://www.nrel.gov/docs/gen/fy07/40929.pdf.

U.S. Energy Information Administration (EIA). 2023. “Gasoline and Diesel Fuel Update.” Dec. 26, 2023. https://www.eia.gov/petroleum/gasdiesel/.

U.S. Environmental Protection Agency (EPA). 2023a. “Diesel Fuel Standards and Rulemakings.” Aug. 18, 2023. https://www.epa.gov/diesel-fuel-standards/diesel-fuel-standards-and-rulemakings.

———. 2023b. “Fast Facts on Transportation Greenhouse Gas Emissions.” Oct. 31, 2023. https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

Zhang, Chen, Kenneth Kelly, Andrew Kotz, and Eric Miller. 2021. “Development of In-Use Engine Speed/Torque Heat Maps Across Multiple Heavy-Duty Commercial Vehicle Vocations.” *International Journal of Engine Research* 23 (10): 1717–1731. https://doi.org/10.1177/14680874211029905.

Appendix

Table A-1. List of Diesel Vehicles Instrumented With Data Loggers

Truck #	Type	Make	Model	Model Year	Class	Gross Vehicle Weight Rating	Vehicle Days
026	Diesel	International	4400	2002	7	33,000	3
065	Diesel	International	4300	2004	7	33,000	21
116	Diesel	Hino		2019	6	26,000	48
232	Diesel	Hino		2019	6	26,000	46
265	Diesel	International	4300	2005	6	26,000	7
302	Diesel	Freightliner	FLD120	2012	8	33,000+	24
325	Diesel	Freightliner	M2	2009	7	33,000	17
391	Diesel	Hino	268	2018	6	26,000	31
525	Diesel	International	4300	2005	6	26,000	22
552	Diesel	Hino		2019	6	26,000	49
692	Diesel	International	MV607	2022	6	26,000	46
718	Diesel	International	MV607	2019	6	26,000	20
883	Diesel	Peterbilt	337	2015	6	26,000	22
954	Diesel	Freightliner	M2	2017	6	26,000	68
967	Diesel	Freightliner	M2	2006	7	33,000	20

Table A-2. List of Diesel Vehicles To Be Retired by Hi Pro

Make	Model	Model Year	Class	Gross Vehicle Weight Rating
International	4400/MA035	2002	7	33,000
International	4300/MA025	2004	7	33,000
International	4400/MA035	2005	7	33,000
International	4300/MA025	2005	6	26,000
International	4300/MA025	2005	6	26,000
International	4300/MA025	2005	6	26,000
Freightliner	M2	2012	6	26,000
Peterbilt	337	2015	6	26,000