NGV UP-TIME Analysis:
Updated Performance Tracking Integrating Maintenance Expenses

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Executive Summary

Natural gas engines offer a significant opportunity to reduce the greenhouse gas (GHG) emissions produced by the heavy-duty freight and goods movement industry. This space is dominated by large diesel engines that produce large amounts of GHGs and require complicated exhaust aftertreatment systems to meet modern emissions standards. Switching from diesel to natural gas (NG) engines can reduce CO_2 emissions by up to 27%.[1]

The main purpose of this study was to evaluate one of the biggest barriers to NG engine adoption: maintenance. Specifically, the project team sought to evaluate the differences in maintenance frequency and costs between various generations of heavy-duty NG engines and current diesel engines in the freight and goods movement sector. The natural gas vehicle (NGV) industry currently lacks comprehensive analysis and metrics regarding maintenance costs due to the fact that users tend to be siloed by various use cases or competing in similar verticals. In addition, vehicle and engine manufacturers have been reticent to make this data widely available. There is little publicly available data that clearly compares the relative maintenance costs of NGVs and current diesel trucks with modern exhaust aftertreatment systems (post-2010) to effectively capture recent NGV technology advancements, evaluate NGVs' potential to lower operating costs, and investigate claims of NGVs' lower total cost of ownership.

The objective of the NGV UPTIME project—UPTIME stands for "Updated Performance Tracking Integrating Maintenance Expenses"—is to bridge this information gap and complete a comprehensive data-analysis study that documents vehicle maintenance costs, technology solutions, and best practices for reducing maintenance and other related ongoing costs for medium- and heavy-duty NGVs used in freight and goods movement. This project evaluates these vehicles alongside comparable diesel models, including emissions aftertreatment systems. The project evaluates NGV maintenance costs on both a system-wide and component level to help improve total-cost-of-ownership calculations and determine maintenance cost differences between NGV technology generations and current advanced clean-diesel engines, specifically for medium- and heavy-duty freight and goods movement applications.

This study of real-world maintenance costs of NGVs is funded by the U.S. Department of Energy and led by Clean Fuels Ohio. Energetics Incorporated served as the data analysis lead, while the National Renewable Energy Laboratory provided the project with vehicle and maintenance data analysis and alternative fuel expertise.

The data-collection stage of this project proved to be particularly challenging. The project team spent the majority of the first two project years actively trying to recruit fleets. A total of 138 fleets were identified and pursued by the network of Clean Cities project partners. The project kicked off in March 2020—just as the COVID-19 pandemic was beginning. This presented a serious challenge for fleet-data-partner recruitment. Many fleets that were contacted were focused on and struggling to maintain their businesses and did not have the available bandwidth to learn about the NGV UPTIME project—or, if they did learn about it, most felt that the time investment would be too great. Unfortunately, the final count of participating fleets did not reflect the amount of time and effort invested in recruitment. Project

[1] Puneet Singh Jhawar, "Natural Gas Engines vs. Diesel Engines," Cummins Inc., published May 4, 2022, https://www.cummins.com/news/2022/05/04/natural-gas-engines-vs-diesel-engines.

recruitment was somewhat successful in the first ~1.5 years in terms of securing the contract-required number of vehicles. However, this included only three fleets—one of which is very large.

Despite having only three fleets willing to provide data at the end of the recruitment period, the data collection resulted in a dataset that included over 1,800 vehicles with at least one repair order (RO). Model years of vehicles in the dataset ranged from 2010 to 2021 (though over 95% of the vehicles fell between 2014 and 2019). Total vehicle miles traveled for trucks in the dataset was just shy of 780 million miles, and the total number of ROs analyzed was approximately 244,500 useable ROs.

The project team modified our analysis approach due to the limited number of participating fleets and the various data-quality issues. In many instances, it was also not possible to make direct comparisons between the three fleets due to the differences in data completeness. Despite these data issues, the team was still able to make interesting observations from the project's dataset.

Our initial expectations were that NG trucks would require higher amounts of baseline maintenance earlier on in their lifespan, while diesel trucks would require more maintenance toward the end of their lifespan due to exhaust system failures. This prediction was based on our assumptions that NG engines have shorter oil change intervals and require more routine maintenance for their ignition and fuel systems. In contrast, the project team anticipated that the complicated exhaust aftertreatment systems required for diesel engines would become more expensive to maintain as the trucks age. NG engines, by comparison, have much simpler three-way catalytic converters for exhaust aftertreatment and are typically maintenance-free for the life of the truck.

The study's maintenance analysis revealed that NG trucks required more maintenance than their diesel counterparts, but the maintenance costs never reached the expected parity between the two fuel types. The NG trucks in this dataset generated more ROs and required more maintenance expenditures than their diesel counterparts at almost every odometer range. This trend was observed in the maintenance data from all three participating fleets. Further investigation revealed that the powerplant, cooling, ignition, and exhaust systems accounted for most of these observed differences.

The specific component-level analysis for all of these systems revealed some interesting differences between the two fuel types. The powerplant system required the most maintenance for both fuel types, but the NG trucks had significantly more ROs for the cylinder head component than the diesel trucks. Cummins mentioned that their NG engines generally require more valve adjustments than their diesel engines, which could explain the differences in cylinder head-related maintenance.

The cooling system also had large differences in maintenance frequency and cost between the two fuel types. The NG trucks in this dataset experienced significantly more cooling system failures than the diesel trucks. Cummins does not provide the cooling system components with their NG engines, and it is possible that the cooling systems installed by the original equipment manufacturers (OEMs) are not adequately equipped to handle the additional thermal load from NG combustion.

These higher temperatures could also be affecting turbocharger reliability for NG engines, as the NG trucks accumulated three times as many turbocharger-related ROs compared to the diesel trucks. The higher exhaust-gas temperature from NG combustion could be creating additional wear within the turbocharger. The costs associated with the additional turbocharger maintenance required for NG trucks offset most of the advantages gained from the simpler exhaust aftertreatment system. The diesel trucks generated three times as many exhaust system-related ROs, but the average exhaust system-related costs were very similar between the two fuel types.

This study was able to quantify some of the key differences in maintenance frequency and costs between NG and diesel trucks, but the data limitations did not allow us to perform the comprehensive analysis desired. Gaining access to a dataset with greater variety and granularity would allow for better tracking of the reliability improvements across NG engine generations and make it possible to pinpoint areas that would benefit from additional development. This information would in turn allow OEMs to make the improvements necessary to better align the maintenance requirements for diesel and NG engines. Eliminating this maintenance disparity between the two fuel types would remove one of the biggest hurdles for NG adoption.

Abbreviations List

CNG	compressed natural gas
DOC	diesel oxidation catalyst
DSL	diesel
ECM	electronic control module
GHG	greenhouse gas
GPS	Global Positioning System
MY	model year
NG	natural gas
NGV	natural gas vehicle
NREL	National Renewable Energy Laboratory
NTEA	National Truck Equipment Association
OE	original equipment
OEM	original equipment manufacturer
PAC	Project Advisory Committee
PM	preventative maintenance
RO	repair order
SCR	selective catalytic reduction
UPTIME	Updated Performance Tracking Integrating Maintenance Expenses
VMRS	Vehicle Maintenance Reporting Standards

Project Overview

This study of real-world maintenance costs of natural gas vehicles (NGVs) was funded by the U.S. Department of Energy and led by Clean Fuels Ohio (https://cleanfuelsohio.org/). The objective of the **NGV UPTIME** "**Updated Performance Tracking Integrating Maintenance Expenses**" project was to collect maintenance cost data from a wide range of goods and freight movement fleets and complete a comprehensive data-analysis study that documents vehicle maintenance costs, technology solutions, and best practices for reducing maintenance and other related ongoing costs for medium- and heavy-duty NGVs. The project evaluated NGVs alongside comparable diesel vehicles.

The study also aimed to identify specific freight and goods movement applications or duty-cycle variables that affect maintenance costs significantly and disproportionately when comparing natural gas and diesel engine systems.

Project Background

The NGV industry currently lacks comprehensive analysis and metrics regarding maintenance costs since users tend to be siloed by various use cases or competing in similar verticals. In addition, vehicle and engine manufacturers have been reticent to make this data widely available. This has led to a paucity of available information for current and prospective NGV users.

There is little publicly available data that clearly compares the relative maintenance costs of NGVs and current advanced diesel trucks with modern exhaust aftertreatment systems (post-2010) to effectively capture recent NGV technology advancements, evaluate NGVs' potential to lower operating costs, and investigate claims of NGVs' lower total cost of ownership (ultimately improving cost-effectiveness and national energy security). NGV UPTIME's purpose was to bridge this information gap and facilitate an unbiased analysis drawing on a diverse dataset of national fleets to provide robust, real-world results for the broadest possible group of stakeholders.

The project implemented a proven, multi-dataset analysis approach at both the system- and component-levels to determine the maintenance repair frequencies and cost differences between compressed natural gas (CNG) engines (including previous and current state-of-the-art generations) and advanced clean-diesel engines (including post-2010 and post-2017 generations).The study aimed to capture the impacts of different technology solutions and best practices used by project partner fleets capable of impacting or reducing maintenance costs. The project results provide fleets, NGV industry stakeholders, and other end users relevant with current real-world information.

The project results showcase the analysis findings (broken down by engine and/or fuel type) at the system, assembly, and component levels to better determine the NGV industry's current status and to identify specific research, development, and outreach needs.

Project Team

The core project team was comprised of three primary organizations with complementary expertise.

- Clean Fuels Ohio is the NGV UPTIME project prime awardee and lead. Clean Fuels Ohio also led the fleet-data-partner outreach coordination among the Clean Cities Coalition partners. Clean

Fuels Ohio is a 501(c)3 not-for-profit organization focused on improving air quality and health, reducing environmental pollution, and strengthening Ohio's economy by increasing the use of cleaner, domestic fuels and energy-saving vehicles. Clean Fuels Ohio partners with organizations of all sorts to implement advanced transportation fuels for fleets and facilitates development of statewide infrastructure to support advanced fuels.

- Energetics is a full-service clean energy consultancy focused on clean energy solutions for transportation, advanced manufacturing, grid, and more. Energetics collaboratively works with state and local entities to help smartly and cost-effectively integrate clean energy technologies and strategies into their real-world operations. Energetics is the NGV UPTIME data analysis lead and provided its expertise in engines, vehicles, fuel systems, and fleets.
- The National Renewable Energy Laboratory (NREL) is a U.S. Department of Energy National Laboratory whose mission is to advance the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies, and to provide the knowledge to integrate and optimize energy systems. NREL's expertise includes sustainable transportation, renewable power, energy efficiency, and energy systems integration. NREL provided the NGV UPTIME project with vehicle and maintenance data analysis and alternative fuel expertise.

Project Advisory Committee

Clean Fuels Ohio assembled a Project Advisory Committee (PAC) that brought together key NGV industry stakeholders including the following:

- NGVAmerica is a national trade association dedicated to the development of a growing and sustainable American market for vehicles powered by natural gas (NG) or hydrogen.
- The Natural Gas Vehicle Technology Forum is an industry workgroup facilitated by NREL to provide insights into advanced NGV technologies and create opportunities to discuss data and research on NG engines, vehicles, and infrastructure.
- The National Truck Equipment Association (NTEA) is The Association for the Work Truck Industry, representing 2,100 companies that manufacture, distribute, install, sell, and repair commercial trucks, truck bodies, truck equipment, trailers, and accessories. NTEA supports both the vehicle/equipment manufacturer industry and vehicle buyers; provides in-depth technical information, education, and member programs and services; and produces Work Truck Week.
- Geotab is a Global Positioning System (GPS), telematics, and data analysis provider.
- AssetWorks provides fleet-management, maintenance-tracking, and GPS/telematics software as well as data-analysis services.
- AFV International is a leading NGV training provider across North America.
- Yborra & Associates, LLC is led by Stephe Yborra, a former NGV industry expert who served as both NGVAmerica's Director of Marketing and the Clean Vehicle Education Foundation's Director of Market Analysis, Education & Communications. Stephe's consulting firm has continued this core area of expertise in NGVs.
- Cummins is a medium- and heavy-duty diesel and spark-ignited NG engine manufacturer.
- Hexagon Agility is an NG fuel-system provider (for dedicated NG systems).
- ICOM North America is an NG fuel-system provider (for dual-fuel diesel/NG systems).
- Clean Energy Fuels is an NG fuel and fueling-station vendor/provider.

- Trillium is an NG fueling-station vendor/provider.
- Columbus State Community College in Columbus, Ohio, is an Alternative Energy Automotive Technician training provider.

Key PAC members were interviewed to help determine crucial areas that the project should focus on. The phone interviews included the following PAC members, with multiple people attending most calls: (1) Cummins, (2) Natural Gas Vehicle Technology Forum, (3) Yborra & Associates, (4) AFV International, (5) AssetWorks, (6) NTEA, and (7) Hexagon Agility. The purpose of these interviews was to maximize the cost effectiveness and benefits of the U.S. Department of Energy's funding, and to focus the project on engines representing the majority of the NGV market (in terms of vehicle sales, fuel/energy use, etc.).

The following summarize some of the key PAC interview findings:

- Data Collection:
  - Vehicle Maintenance Reporting Standards (VMRS)-coded maintenance data is key.
  - Compile electronic records (.csv or .xlsx files) for import into database.
  - Conduct webmeeting/phone interviews with fleets and collect follow-up data.
  - Collect vehicle and engine info (e.g., model, model year [MY], original equipment [OE], engine aftertreatment systems).
  - Collect duty and application info (e.g., application/job type, average speed, typical maximum gross combined vehicle weight, route type, percent deadhead operation).
  - Focus on Cummins engines (current and last generation only).
  - Focus on heavy-duty, stoichiometric, dedicated spark-ignition CNG engines.
  - Focus on MY 2010+ or possibly MY 2014+ diesel engines (with diesel particular filters, selective catalytic reduction).
  - Focus on the trucks' first owner.
  - Collect fleet-wide data including vehicle/engine inventories, maintenance data, fueling data, and duty-cycle/operations summaries.
  - Key systems and components include the fuel system (tank to injectors), spark plugs (for NG vehicles), pistons, and the exhaust system (including the aftertreatment system).
- Industry Metrics:
  - Total cost of operation is key to fleets. This includes the vehicle acquisition costs, maintenance costs (parts and labor), and fuel costs. (By contract, the NGV UPTIME project is focused exclusively on the maintenance-costs component.)
  - Cost per mile is the primary metric that fleets use to track vehicle costs, both at the vehicle level and the system/component level.
- Maintenance:
  - It is crucial to understand if/how well the fleet follows the manufacturers' maintenance schedule and specifications—and whether it follows the (separate requirements for diesel and NGVs.
  - Determine whether the fleet provides burdened or unburdened labor rates. It was suggested that the project use regional or national average labor rates, which would remove a variable and better anonymize the data.
  - Identify and bin scheduled versus unscheduled maintenance.
  - Ignore labor-only jobs.

- Focus on recurring failures over isolated failures; exclude accidents.
- A parts cost and labor cost is needed for each job.
- NG fueling-station maintenance should not be included in vehicle maintenance.
- It is important to understand how each fleet's technicians are trained to code repairs and what internal quality-assurance standards are in place to verify and enforce this.

- Warranty:
  - Need to understand warranty terms/maintenance arrangement
  - In-house or manufacturer shop
  - Understand how warranty work is documented in the maintenance tracking system (including courtesy repairs)
- Operations:
  - Need to understand if/how fleets start and operate NG vehicles differently from diesel.
  - Need information on normal days, hours of operation, and holidays to understand downtime versus normal days off.

Fleet Data Partner Recruiting Efforts

Structure and Resources

The core project team was supported by a strong group of regional Clean Cities Coalitions with strong NGV usage. The Clean Cities Coalitions executed the grassroots fleet-data-partner recruitment using their established and broad lists of local relationships and connections with fleet operators. The Clean Cities Coalition partners involved in the fleet-recruiting process included the following:

- Clean Fuels Ohio (OH)
- Wisconsin Clean Cities (WI)
- Dallas-Fort Worth Clean Cities (TX)
- Central Oklahoma Clean Cities (OK)
- Tulsa Clean Cities (OK)
- Virginia Clean Cities (VA)
- Empire Clean Cities (NY)
- Clean Communities of Central New York (NY)
- Clean Communities of Western New York (NY)
- St. Louis Clean Cities (MO)

The fleet recruitment was purposefully broad to attract and secure fleets from small to large, local to regional to national, and basic to more sophisticated fleet management and maintenance operations. Fleets had to meet the requirements for engine types and operations defined in the project charter and guided by the PAC input and had to operate both NGVs and diesel vehicles.

Clean Cities Coalitions were given a project overview to thoroughly understand the project's focus and needs as well as training on the outreach materials available to them. These outreach materials include the following:

1) The NGV UPTIME project website (https://cleanfuelsohio.org/ngv-uptime/) describes the project's purpose, sponsor, goals, partners, and points of contact for follow-ups.

2) The NGV UPTIME Data Partner Fact Sheet (included in this report as Appendix A) is a high-level summary that quickly describes the project, fleet data-sharing needs, and what fleets receive in exchange for participation.
3) The NGV UPTIME Data Partner Two-Pager (included as Appendix B) is a more detailed description of the project, data-sharing needs, and what fleets receive for participation.
4) The NGV UPTIME Data Sharing Agreement is a formal agreement template between Clean Fuels Ohio and the participating fleet that describes how shared data and other information would be treated. This was important, as many fleets were concerned about data security and anonymity.
5) The NGV UPTIME Data Partner Step by Step Process (included as Appendix C) is a detailed description of the requirements of the data-collection process to answer fleets' questions. This was important because many fleets were concerned about the time investment to participate.

The purpose of the website and documents summarized above was to broadly share project information with fleets, with the goal of recruiting the maximum number and breadth of fleets while minimizing the time spent in phone/email discussions by Clean Cities Coalitions and others involved in recruiting.

Process and Results

A total of 138 fleets were identified and pursued by the network of Clean Cities project partners. The project kicked off in March 2020—just as the COVID-19 pandemic was beginning. This presented a serious challenge for fleet-data-partner recruiting. Many fleets that were contacted were focused on, and struggling to, maintaining their businesses and did not have the available bandwidth to learn about the NGV UPTIME project. Or, if they did learn about the project, most felt that the time investment would be too great. The fleet-recruiting team (Clean Fuels Ohio, Clean Cities Coalitions, and Energetics) were very flexible and persistent about speaking with all interested fleets, answering their questions, and worked to allay their concerns about participating in the project and providing the necessary operational data.

The main, and reoccurring, reasons that fleets decided to not share data with the project included a lack of availability outside of their core business focus, concerns about the time investment being too high, and concerns about data anonymity and/or the Data Sharing Agreement's complexity.

Fleet data partner recruiting was somewhat successful in the first ~1.5 years in terms of securing the contract-required number of vehicles. However, this included only three fleets—one of which is very large.

To expand the search and improve these results, the PAC and NG fueling-provider colleagues were requested to leverage their industry contacts and clout to introduce potential fleet data providers to the project team. Energetics also supported the expanded recruiting effort, which identified an additional 30 fleets based on staff contacts/relationships, fleets with industry-sustainability accolades, and related paths. However, only three fleets ultimately decided to participate in the project and share operational data.

Despite having maintenance cost data from only three fleets, the number of vehicles a dataset included over 1,800 vehicles with at least one repair order. Model years of vehicles in the dataset ranged from 2010 to 2021 (though over 95% of the vehicles fell between 2014 and 2019). Total vehicle miles traveled for trucks in the dataset was just shy of 780 million miles, and the total number of repair orders analyzed was approximately 244,500 useable repair orders.

Data Collection

Once participating fleets signed data-sharing agreements, calls were scheduled with the fleet managers to get an overview of available data and operational practices, and to establish a data transfer process. The project team developed a standardized fleet questionnaire and vehicle-specification worksheet that were used to guide conversations during these data calls. Fleet managers were also encouraged to share their overall experiences with operating NG trucks. This anecdotal information helped aggregate the raw data collected from each fleet and corroborate trends identified during the analysis process.

Data Analysis Methodology

Key Objectives

The two main objectives of this study are to identify maintenance frequency and cost differences between diesel- and NG-powered heavy-duty vehicles used for freight and goods movement. The analysis process is divided into repair-frequency and repair-cost components, along with additional considerations to account for the hierarchical nature of the VMRS data collected. Both the frequency and cost analyses begin by evaluating overall differences between the two fuel types before delving into more specific component-level differences. Additional analysis is done to compare breakdown frequency and cost differences.

Collection Methods

A secure Microsoft SharePoint site was used to transfer data from the participating fleets to the project team. This raw data was reviewed and verified to ensure that it met the criteria required for this project. Follow-up calls were scheduled with fleet managers to address any questions or concerns identified by the project team. The Python programming language was used to perform preliminary data cleaning and anonymization. The cleaned data from each fleet was then aggregated and transferred to a Microsoft SQL Server database.

The first step of the data-cleaning process involved mapping the fields in the raw data to those in the project database. The complexity of this mapping process varied depending on the structure of the raw data. Some of the raw data fields simply needed to be renamed to the field name used in the database, while others required additional transformations (i.e., unit conversion from kilometers to miles). Some of the fleets provided a single table with all vehicle and maintenance information, which needed to be separated into vehicle-specific and repair-order-level information before being sent to the database. Data aggregation was avoided during the data-cleaning process to maintain the highest resolution of data possible. Anonymization was the final step in the data-ingestion process. Any identifiable attributes, such as location information or fleet-specific codes, were scrubbed from the dataset. New identifiers were also assigned to each fleet, vehicle, and repair order (RO).

Data Limitations and Validation Methods

Once all the raw data had been cleaned and ingested into the SQL Server database, a thorough data-quality analysis was performed. This analysis revealed several issues within the collected dataset. Some of these issues, such as the odometer-reading issue described below, were able to be corrected through imputation and statistical techniques. Others, such as discrepancies in RO duration, were not able to be corrected, and the analysis had to be tailored to work around these issues.

The biggest limitation with the dataset collected for this project is the lack of fleet and vehicle variety. The analysis below includes data from three fleets with varying sizes and maintenance practices. Fleet 1 was the largest fleet in the dataset and had the most sophisticated maintenance tracking data. They also had the most detailed VMRS data of all the fleets in the study, which made it possible to do component-level analysis between the two fuel types, but their data was not free of errors. The data from Fleet 1 had a significant number of odometer and RO-duration inconsistencies. Fleet 0 was the smallest in this dataset in terms of the number of vehicles, but they are operationally larger than Fleet 2 and had more robust maintenance tracking capabilities. Although their data was not as detailed as the data from Fleet 1, it had the fewest number of outlier and erroneous data points. Data from Fleet 2 had the largest vehicle age range but also had the largest number of erroneous and missing data points.

Figure 1: Miles Between Consecutive Repair Orders for Fleet 2

Figure 1 provides an indicator of the missing maintenance data from Fleet 2. The plot shows the number of elapsed miles between consecutive ROs for each vehicle. The metric was calculated by first sorting Fleet 2's maintenance data by vehicle ID code and RO open date. Then the odometer value from the current RO was subtracted by the odometer value from the previous RO to calculate the number of miles traveled between them. The points circled above likely indicate missing data, as it is improbable for a vehicle to travel more than 50,000 miles without any maintenance. These variations in data errors and completeness made it difficult to make representative comparisons across fleets for much of the analysis below.

Key Assumptions

Given the scope of the project, it was not possible to get a fully complete picture on fleet operations or vehicle duty cycles through the data that was provided. The analysis process relied on the information regarding fleet operation, vehicle duty cycles, and general maintenance practices gathered from the data calls to determine if comparisons between fleets were possible and fair. An overview of analysis assumptions for each fleet is provided below.

Fleet 0 was the only fleet in the study that restricted their NG trucks to certain routes and regions, but their fleet manager indicated that all of their trucks have similar duty cycles. All have a mix of regional and 'over the road' type routes. The trucks typically operate five days a week, from Monday to Friday. The maintenance for all of their vehicles is handled in-house, and their engine shop is Cummins-certified. All of their technicians are trained to code maintenance in the same manner, so there should not be variations between technicians. The RO open and close dates are indicative of when the vehicle entered and left the shop. The reported labor costs are all-inclusive.

Fleet 1 was the largest fleet in the dataset, and their trucks operate out of several hubs across the country. The diesel and NG trucks are interchangeable (i.e., there are no designated drivers or routes). All of the routes are regional, with every truck returning to the hub at the end of the day. Most maintenance is performed in-house, but major work (e.g., engine replacements) is outsourced to vendors. Fleet 1's maintenance tracking software employs a degree of automation to ensure that data is captured consistently across all hubs. The fleet manager also indicated certain ROs relating to routine maintenance are not closed when the vehicle leaves the shop but are instead kept open until the next time the vehicle comes in for the same service. This practice was consistent between both fuel types. Their reported labor costs include overhead but are not fully inclusive.

Fleet 2 was the smallest fleet in this study in terms of business size. Almost all of their trucks are used to transport dedicated freight. This means certain trucks are assigned to certain customers, but the routes and loads are similar for all trucks. The fleet manager indicated they were still developing their VMRS recording procedures and currently only had confidence in the accuracy of the first three digits. This fleet also does not employ in-house mechanics and outsources all maintenance to local vendors. The vendors range from 'mom and pop' shops to original-equipment-manufacturer- (OEM-) operated shops for their diesel trucks, while NG truck maintenance is handled by shops trained to work on NG engines.

All of this information from the data calls was used to develop the following assumptions:

- Odometer and RO duration errors are consistent between NG and diesel vehicles within a fleet.
- Duty cycles are consistent between NG and diesel vehicles within a fleet.
- Labor rates are the same for NG and diesel technicians within a fleet.
- Diesel engines have similar maintenance requirements/intervals regardless of manufacturer.

Odometer Errors and Corrections

One of the key metrics in the NGV UPTIME project is the odometer data for each vehicle. All fleets in this study collected odometer data as supplementary information during the creation of ROs. Fleet 1 implemented an automated procedure to auto-populate the odometer through their telematics equipment, but this system was not perfect and occasionally recorded erroneous values. The other fleets relied on the technicians to manually populate the odometer values.

The odometer data is vital to evaluating repair frequency differences between diesel- and NG-powered trucks, so it is important that this data is free of errors before analysis can begin. In previous studies that relied on odometer data, the project team was able to corroborate the RO odometer values from other sources (such as fueling or telematics data). Unfortunately, this approach was not possible for this study, as the participating fleets were not able to provide another reliable source of this data. As a result, the project team used statistical methods to correct odometer inconsistencies in the maintenance data.

Figure 2 below plots odometer readings over repair-order creation date for an example vehicle from the dataset. Barring any significant changes in vehicle usage patterns, odometer values should increase linearly over time. While there is clearly a linear trend, there are also several erroneous spikes and dips present in the data. It is important to correct these erroneous points because they could lead to misleading statistics further along in the analysis.

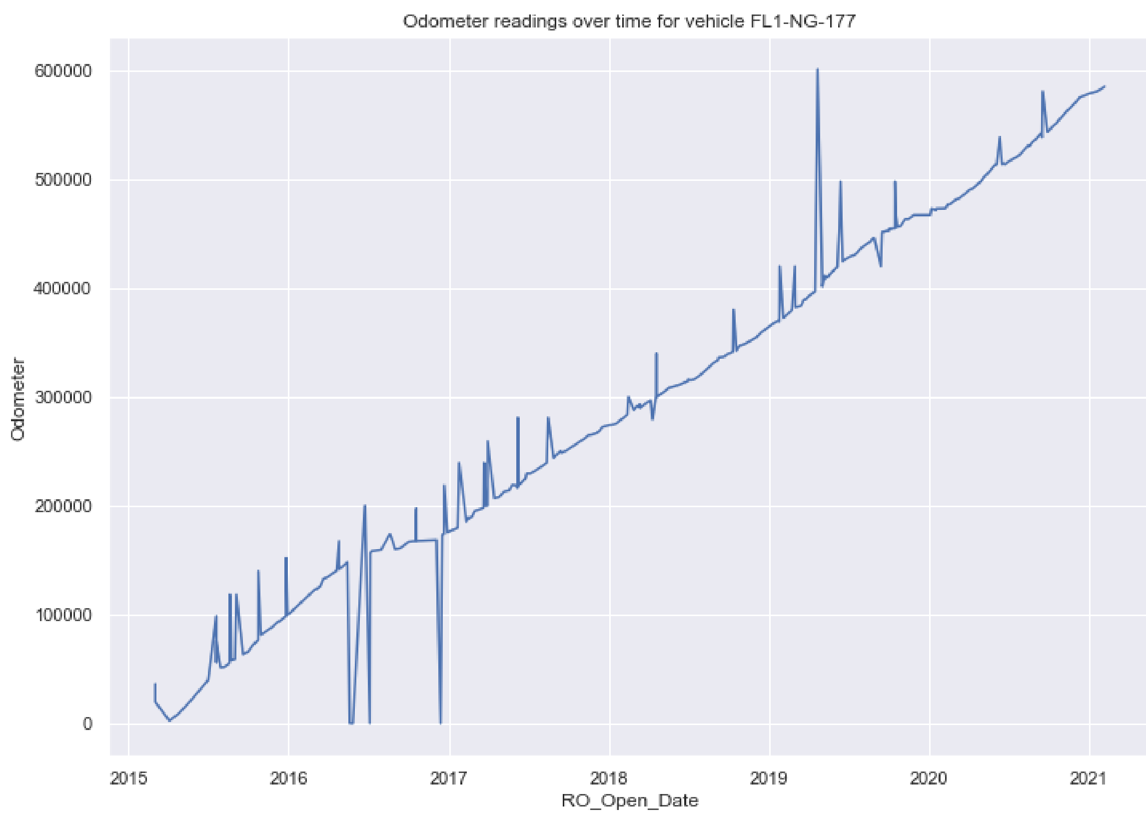


Figure 2: Plot of Raw Odometer Readings for Example Vehicle in the Dataset

The project team explored several different approaches to correcting the odometer data but settled on nulling the erroneous values and then using linear interpolation to predict the null values. This approach resulted in most of the original raw data being preserved and only the erroneous data being replaced with predicted values. The erroneous values were identified programmatically by recognizing the fact that odometer values cannot decrease over time. Any odometer value that decreased was first flagged for each vehicle. If the flagged value was creating a valley, then the flagged value was nulled. If there was a peak prior to the flagged value, then the previous value was nulled. This process was repeated until there were no more peaks or valleys in the odometer data. The nulled values were then populated through linear interpolation. The results of this approach are shown in Figure 3 below. The predicted odometer line retains the majority of the original data points while eliminating the peaks and valleys.

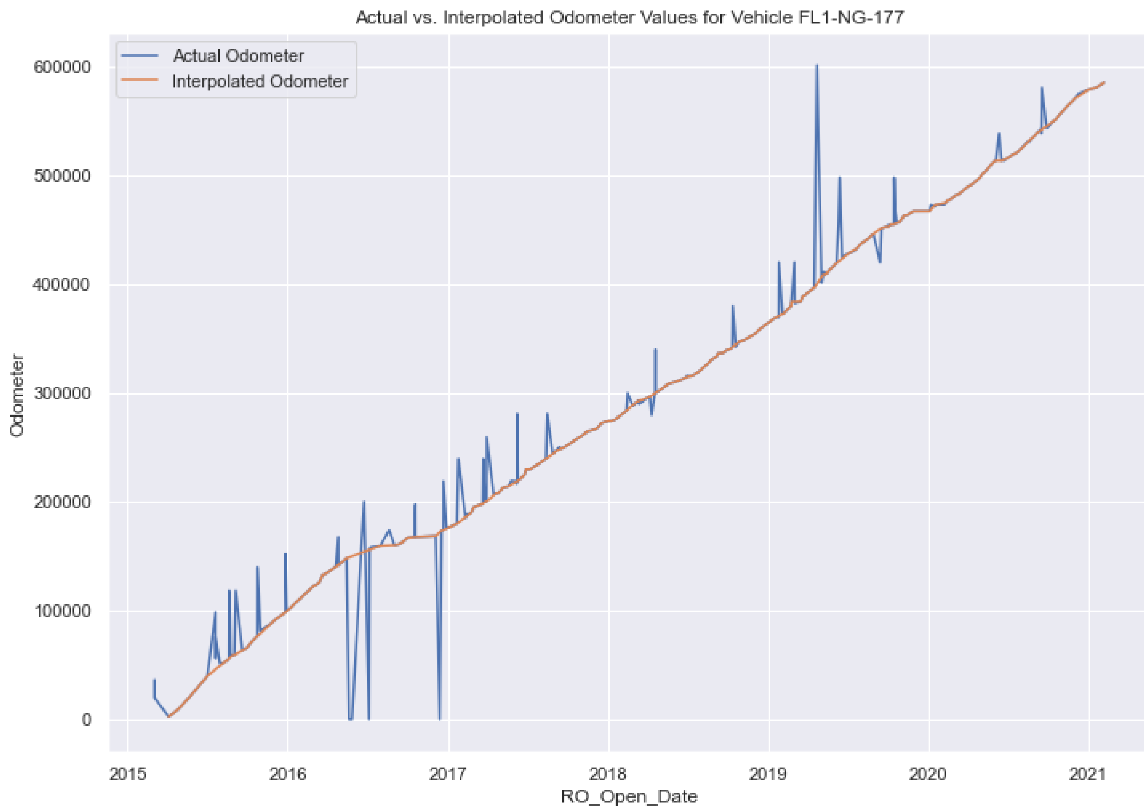


Figure 3: Plot of Actual vs. Corrected Odometer Readings for Example Vehicle in the Dataset

Statistical Tests

Simple statistical tests were used to compare fleets and vehicles by fuel type throughout the analysis. These statistical tests provide a quantitative comparison of the differences seen on a plot. A two-sample t-test was used to determine if the means between fleets and fuel types were statistically different. In the results below, a positive t-value indicates that the first group had a higher mean value, while a negative t-value indicates the second group had a higher mean. T-test results also have an associated p-value, which is the probability that these mean differences occurred by chance (expressed as a decimal). A p-value significance level of 0.05 (i.e., 5%) was used to evaluate these test results. If the p-value is less than 0.05, then the difference seen between the two populations is considered statistically significant.

Dataset Profiles

Vehicle specifications and maintenance records were requested from each participating fleet. The maintenance data was collected in the rawest format possible. This was done to capture as much detail as possible and to decrease the effort required from the fleet managers to participate in this study. Energetics also provided a standardized worksheet to collect vehicle specification and overall duty cycle information from each fleet. The fleet managers completed the worksheet to the best of their abilities, but some vehicle specifications and many of the fields relating to vehicle duty cycle were left blank.

Unit_ID	Fleet_ID	Model_Year	Make	Model	Engine_Year	Engine_Make_Model	Engine_Size_L	Engine_Size_HP	Fuel_System	Exhaust_Aftertreatment	Application	Typical_Load_lbs	Avg_Terrain	Deadhead	Operating_Region
DSL-0	1	2015	FREIGHTLINER	NULL	NULL	12.8L L6 D13	13	NULL	NULL	NULL	NULL	NULL	NULL	NULL	Mid-America
DSL-1	1	2015	FREIGHTLINER	NULL	NULL	12.8L L6 D13	13	NULL	NULL	NULL	NULL	NULL	NULL	NULL	North-West
DSL-10	1	2015	VOLVO	NULL	NULL	12.8L L6 XE13	13	NULL	NULL	NULL	NULL	NULL	NULL	NULL	South-East
DSL-100	1	2016	VOLVO	NULL	NULL	12.8L L6 XE13	13	NULL	NULL	NULL	NULL	NULL	NULL	NULL	South-East

Figure 4: Example of Missing Vehicle Information

Vehicle Data Profile

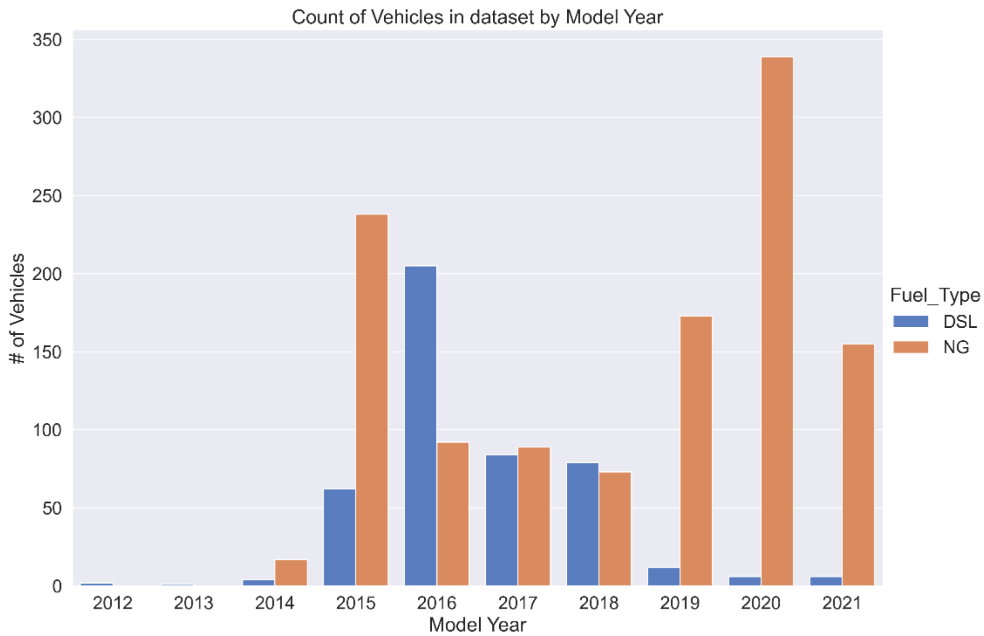


Figure 5: Distribution of Vehicles by Model Year from All Participating Fleets

The overall model-year range for all the vehicles in this dataset is relatively small, with almost all of the vehicles falling within a 6-year timeframe from 2015 to 2021. This condensed range made it difficult to make comparisons between different generations of NG and diesel vehicles. Another important note is that the average NG truck is newer than the average diesel truck in this dataset. This can be attributed to Fleet 1's prioritization of purchasing NG-powered trucks starting in 2019.

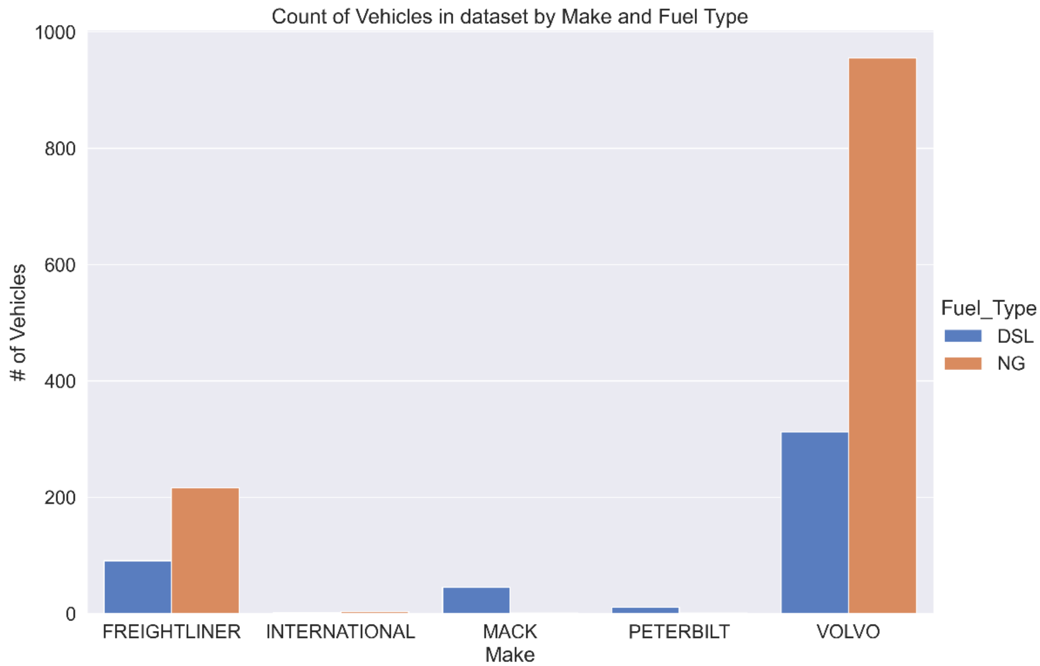


Figure 6: Distribution of Vehicles by Make and Fuel Type from All Participating Fleets

Over 70% of the vehicles in this dataset were manufactured by Volvo. Once again, Fleet 1 had an outsized influence on the diversity of the dataset. This lack of diversity in vehicle manufacturers did not have a significant influence on the NG vehicle analysis given that all engines in the study were produced by Cummins. The various diesel engine models included in the dataset were assumed to be analogous to each other in terms of their general reliability and required maintenance needs.

Maintenance Data Profile

The maintenance data was stored at the RO level as well as at the VMRS-code level. The RO-level table provides aggregated information on repair-order duration, cost, and labor hours for all maintenance that was performed during a shop visit. The VMRS-code-level data provides the most granular level of data that was available. This data includes unique rows for every VMRS code and labor category that was recorded for a RO. For ROs that had multiple VMRS codes, it was not possible to identify the main reason for the RO creation. As noted, the quality of the VMRS codes differed from fleet to fleet.

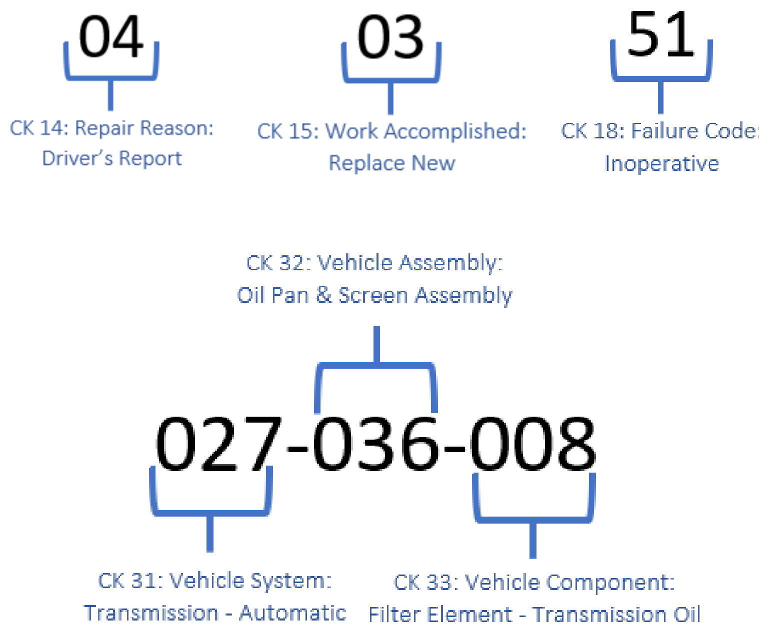


Figure 7: Example of VMRS Codes and Descriptions

An example of a complete component-level VMRS code is provided above in Figure 7. Examples of the supplementary codes that provided additional information regarding Repair Reason, Failure Type, and Work Accomplished are also included.

Data Distributions by Fleet, Fuel Type, and Cost Category

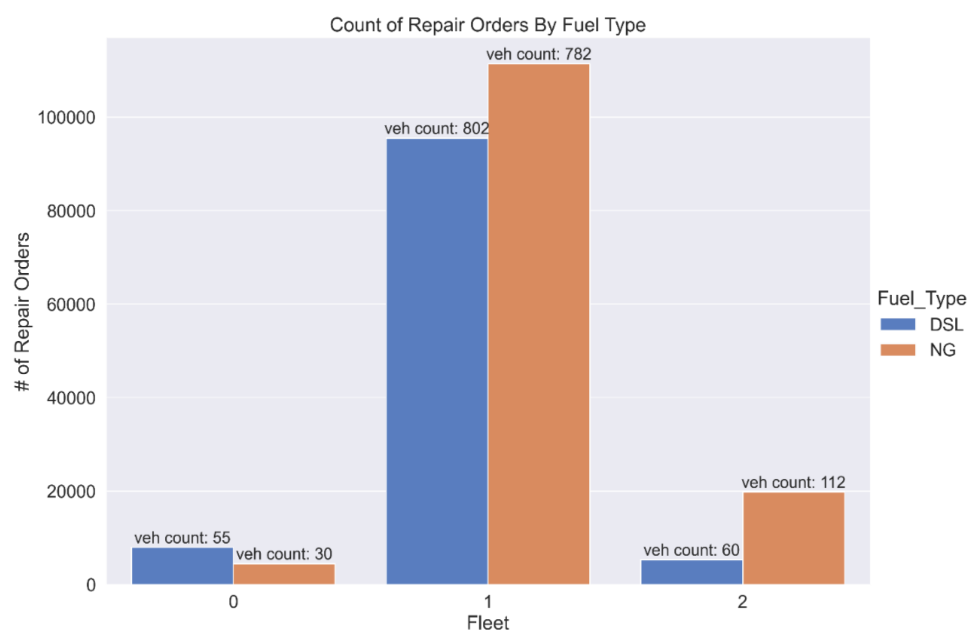


Figure 8: Number of ROs by Fleet and Fuel Type

Fleet 0 is operationally larger than Fleet 2 but only provided data for vehicles that have comparable duty cycles. This led to them having the smallest number of vehicles and ROs in the dataset. Fleet 1 had the most vehicles and contributed 85% of the maintenance data collected. Fleet 2 had some of the oldest NG vehicles in the dataset, which led to this fleet having the highest number of ROs per vehicle.

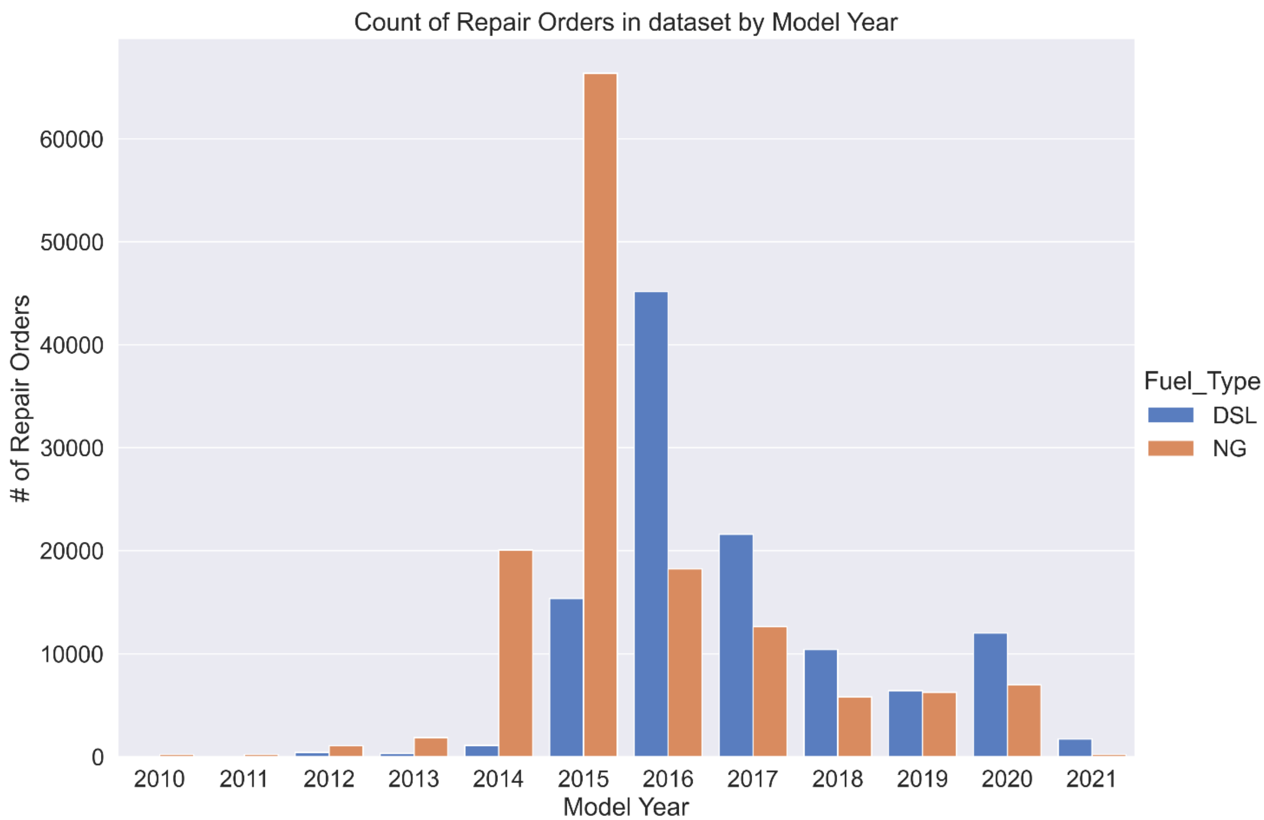


Figure 9: Number of ROs by Vehicle Model Year and Fuel Type

The distribution of ROs by model year provides an idea of how much maintenance data is available by vehicle age. Almost 80% of maintenance records in this dataset were generated by trucks that were manufactured between 2014 and 2017. This condensed timeframe of available data made it difficult to make comparisons between different vehicle generations.

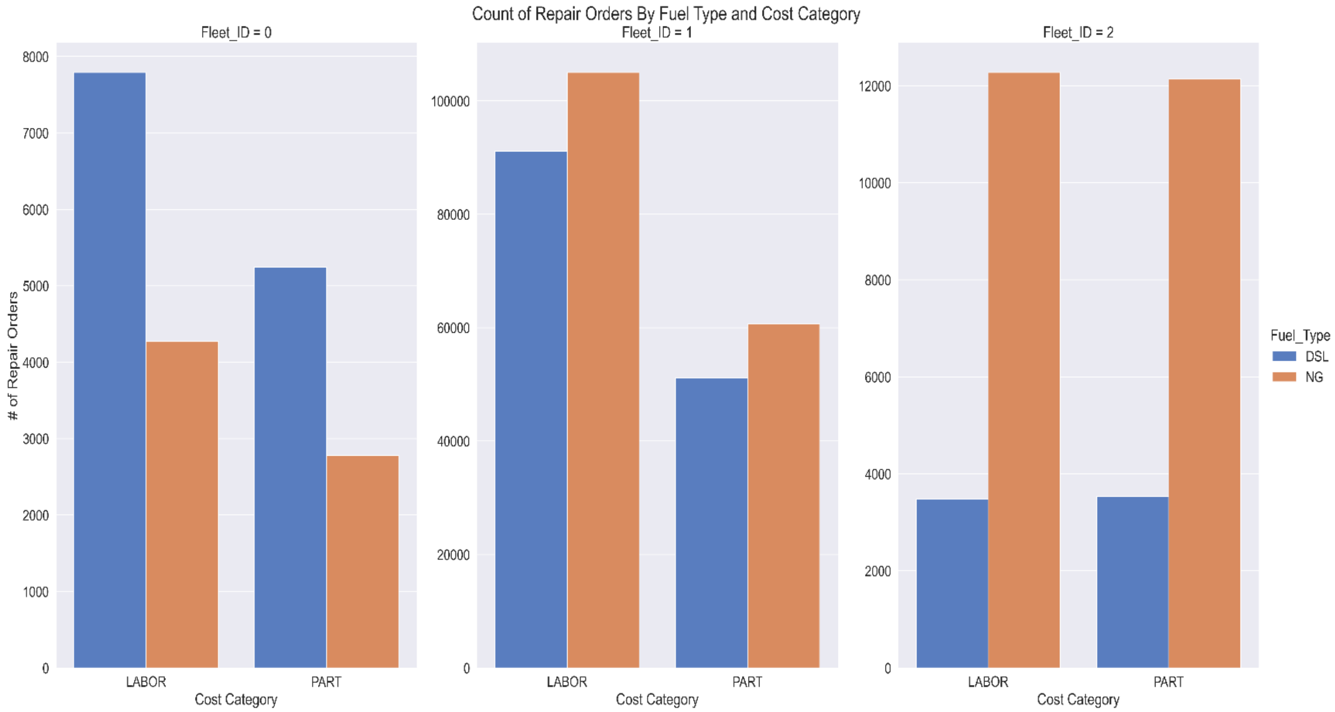


Figure 10: Labor- and Parts-Related ROs by Fleet and Fuel Type

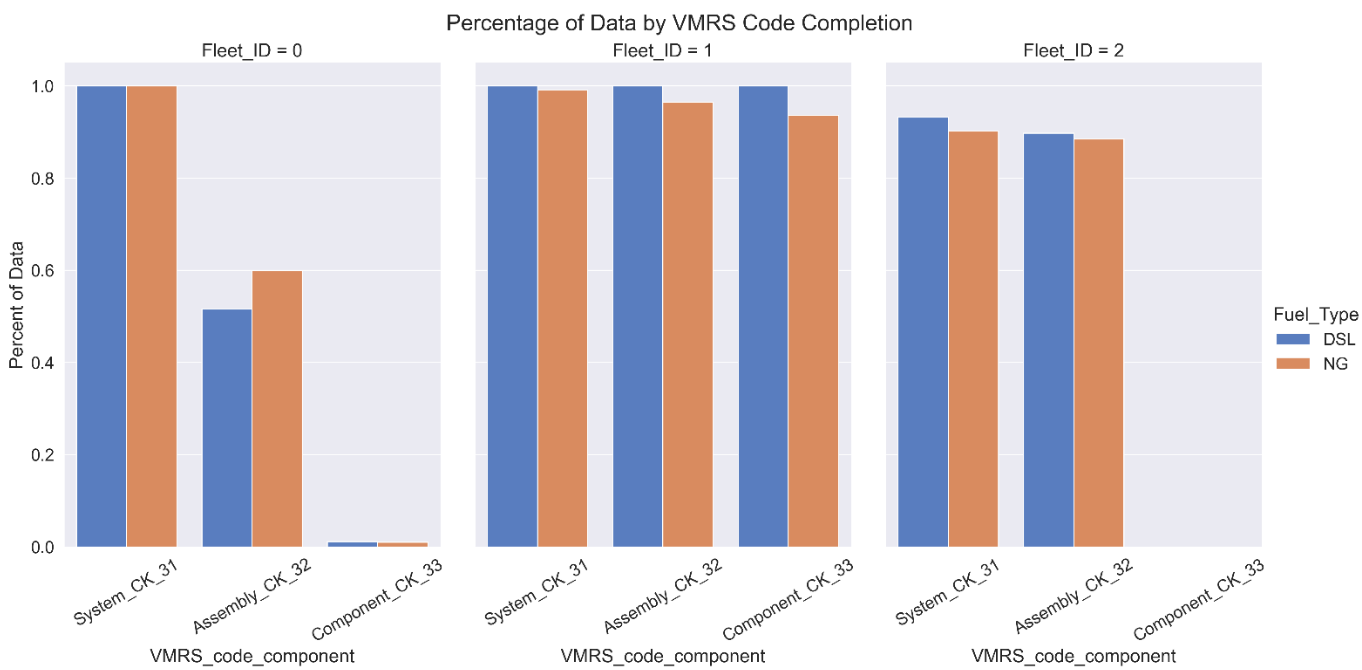


Figure 11: Percentage of Maintenance Data's VMRS Code Completeness by Fleet and Fuel Type

Maintenance data from Fleet 1 was the most complete and had the highest overall quality. 100% of their diesel data and 90% of their NG data contained the full 9-digit VMRS code used to identify the specific parts that required service. Fleet 0 also had high-quality data, but most of the ROs were only coded to the assembly level. Several data-quality issues were identified in Fleet 2's data. For example, 23% of the records were either coded as '000' or were null, which made it impossible to determine the cause of the repair order.

Repair Frequency Analysis

The analysis below focuses on identifying differences in repair frequency between diesel- and NG-powered trucks. The evaluation starts at the overall level before focusing on specific component-level differences. A breakdown-frequency analysis is also performed at the overall and component levels.

Overall Repair Frequency

All ROs, including warranty and breakdown repairs, are included in the analysis below. Both Fleet 0 and Fleet 1 indicated that their maintenance data includes warranty work, but it was not easy to separate this out from the regular maintenance work. Fleet 1's data identified breakdown-related maintenance through the VMRS repair-reason codes, but the other two fleets did not provide this information.

Distribution of ROs by Fleet and Fuel Type

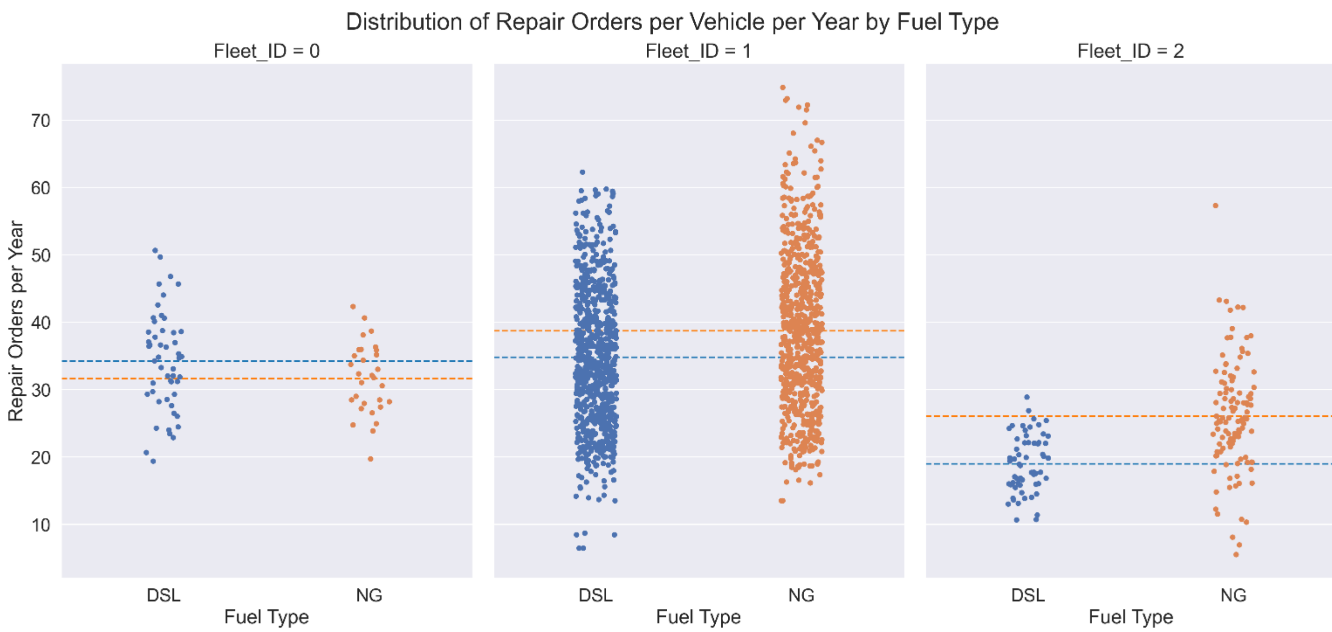


Figure 12: Distribution of ROs Normalized by Vehicle Count and Number of Active Years per Vehicle

Maintenance intervals for vehicles typically have both a time and mileage component. Figure 12 shows differences in the number of ROs generated over time by fleet and fuel type. Fleet 0's diesel-powered trucks generated slightly more ROs per year than their NG trucks. Fleet 1 and Fleet 2 had more ROs for their NG trucks. The overall spread of the distribution is also wider for NG trucks in Fleet 1 and Fleet 2. This suggests these NG vehicles exhibited more variability in the amount of maintenance required.

T-tests:

ROs per Year by Fleet

Groups Compared	T-value	P-value
Fleet 0 vs. Fleet 1	4.339	3.326e-05
Fleet 0 vs. Fleet 2	10.010	3.641e-19
Fleet 1 vs. Fleet 2	19.651	1.915e-52

Statistical t-tests were performed to compare the differences between fleets and fuel types. The results of the t-tests comparing the averages between fleets all had p-values less than 0.05 (corresponding to a confidence level above 95%). This indicates there is enough statistical evidence to conclude the mean ROs generated per year per vehicle are different for each fleet.

ROs per Year by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: diesel (DSL) vs. NG	-7.223	8.177e-13
Fleet 1: DSL vs. NG	1.817	0.073
Fleet 2: DSL vs. NG	-7.311	1.035e-11

A second set of t-tests was performed to compare the annual ROs for diesel and NG trucks within each fleet. The results showed that the mean numbers of annual ROs generated for diesel and NG trucks in Fleet 0 and Fleet 2 were greater for natural gas, with statistical confidence. Given the p-value greater than 0.05 for Fleet 1, there was not sufficient statistical evidence to conclude diesel and NG trucks in this fleet generated different amounts of annual ROs.

Average Distance Traveled Between ROs

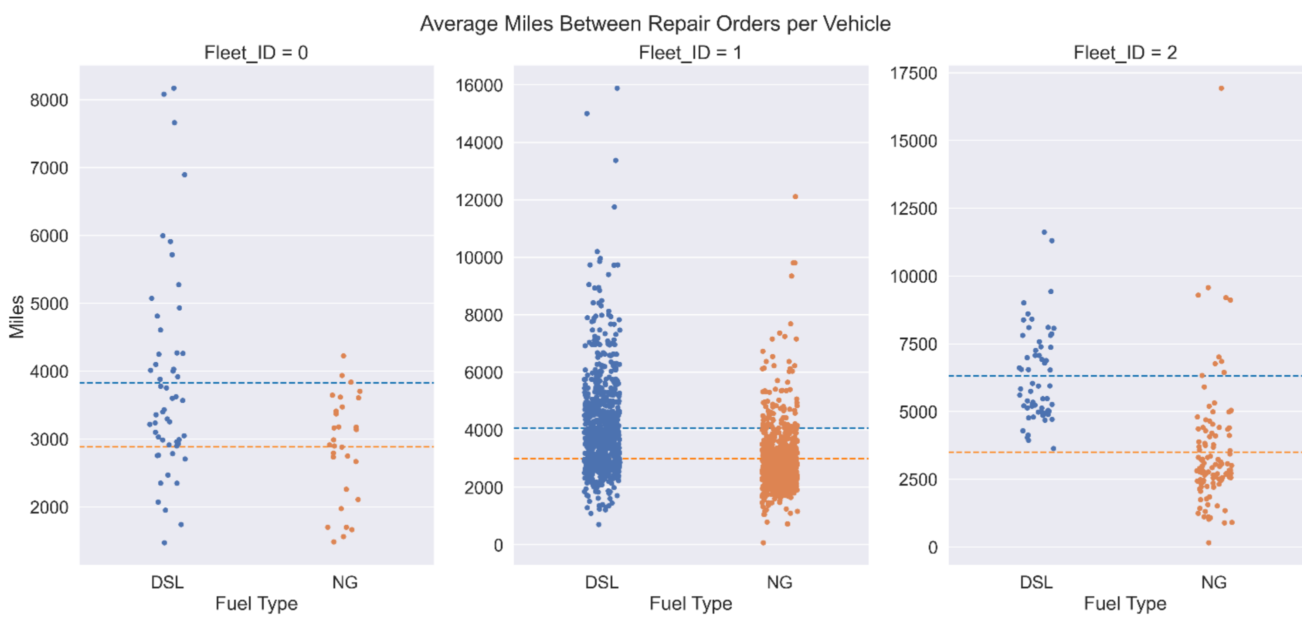


Figure 13: Average Distance Travelled Between ROs per Vehicle by Fuel Type
(Each point represents the average for a single vehicle.)

The average distance traveled between ROs provides an indication of service-interval-length differences between diesel and NG trucks. This metric was calculated by taking the average of the differences in odometer values reported by consecutive ROs for each vehicle. The interpolated odometer values were used in this calculation to account for the odometer errors encountered with Fleet 1 and Fleet 2.

The diesel vehicles in all three fleets travelled a greater distance between ROs. The difference in average distance travelled between the two fuel types was around 1,000 miles for Fleet 0 and Fleet 1. Fleet 0 had a few outlier diesel vehicles that traveled almost twice the average distance between ROs. Most of their vehicles traveled on average between 2,000 and 4,500 miles between ROs regardless of fuel type.

Fleet 1 had the most similar distributions for average distance travelled between ROs between the two fuel types. The majority of Fleet 1's trucks travelled between 1,500 and 4,500 miles between ROs. A small number of vehicles had very low values for this metric. This was mainly due to new vehicles in their fleet that had multiple ROs before becoming fully operational.

The difference between the two fuel types in Fleet 2 was much larger at 2,800 miles. The distributions for Fleet 2 also had the smallest overlap. All of the points for their diesel vehicles were above the mean line for their NG vehicles.

T-tests:

Miles Between Consecutive ROs by Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0 vs. Fleet 1	2.734	0.006
Fleet 0 vs. Fleet 2	-8.510	1.807e-17
Fleet 1 vs. Fleet 2	-12.401	3.217e-35

Miles Between Consecutive ROs by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	5.787	7.357e-09
Fleet 1: DSL vs. NG	42.803	0.0
Fleet 2: DSL vs. NG	24.759	7.390e-99

The t-test results are all statistically significant, with a greater than 99% confidence level. As such, there is enough evidence to conclude that the averages between fleets and between fuel types within fleets are all statistically different.

Average Distance Traveled Between ROs by Model Year

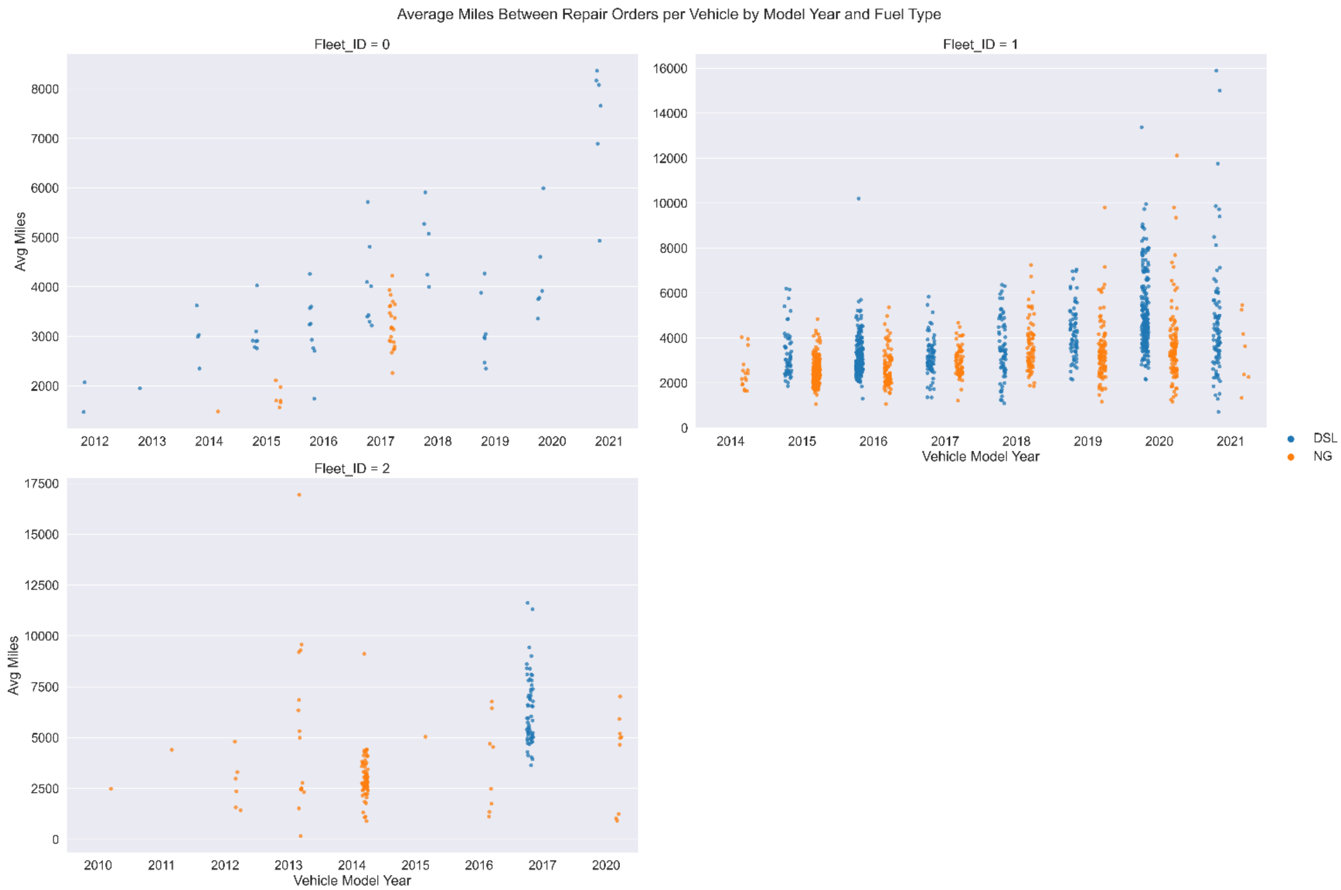


Figure 14: Average Distance Traveled Between ROs by Vehicle Model Year
(Each point represents a single vehicle.)

Figure 14 above shows the distribution of miles travelled between ROs by vehicle model year. Fleet 0's distribution clearly shows that older vehicles travelled fewer miles between ROs than newer vehicles. This follows the expected pattern that older vehicles require more maintenance than newer ones.
The distributions for Fleet 1 get broader as the model year increases. The maintenance data from Fleet 1 had a significant number of instances where vehicles accumulated multiple ROs within a short odometer range. This is likely due to the nuances in how ROs are created and closed for Fleet 1. The fleet manager indicated that ROs related to routine maintenance items (e.g., oil changes) are kept open until the next time the vehicle comes in for the same service. This leads to instances where multiple ROs are opened at very short odometer intervals, which skews the distribution. An example of this can be seen in Figure 15 below. These two ROs were likely created at the same time but have slightly different odometer values.

Unit_ID	RO_Number	RO_Open_Date	RO_Close_Date	RO_Duration_days	Predicted_Odometer
FL1-NG-211	FL1-NG-RO-59443	2016-07-19 14:01:05.000	2016-07-21 05:36:38.000	1.6496875	54230.9
FL1-NG-211	FL1-NG-RO-59438	2016-07-19 14:37:33.000	2017-07-27 21:53:23.000	373.302662037037	54812.2333333333

Figure 15: Example of Maintenance Data Details from Fleet 1

Fleet 2 had the largest variation between the two fuel types for miles traveled between ROs, but their diesel trucks were newer than most of their NG trucks. Their diesel vehicles were very tightly clustered compared to the NG vehicles. It is also possible for the newest vehicles to show a very small value for average distance traveled between ROs due to minor 'break-in'-related maintenance.

Average Days Between ROs

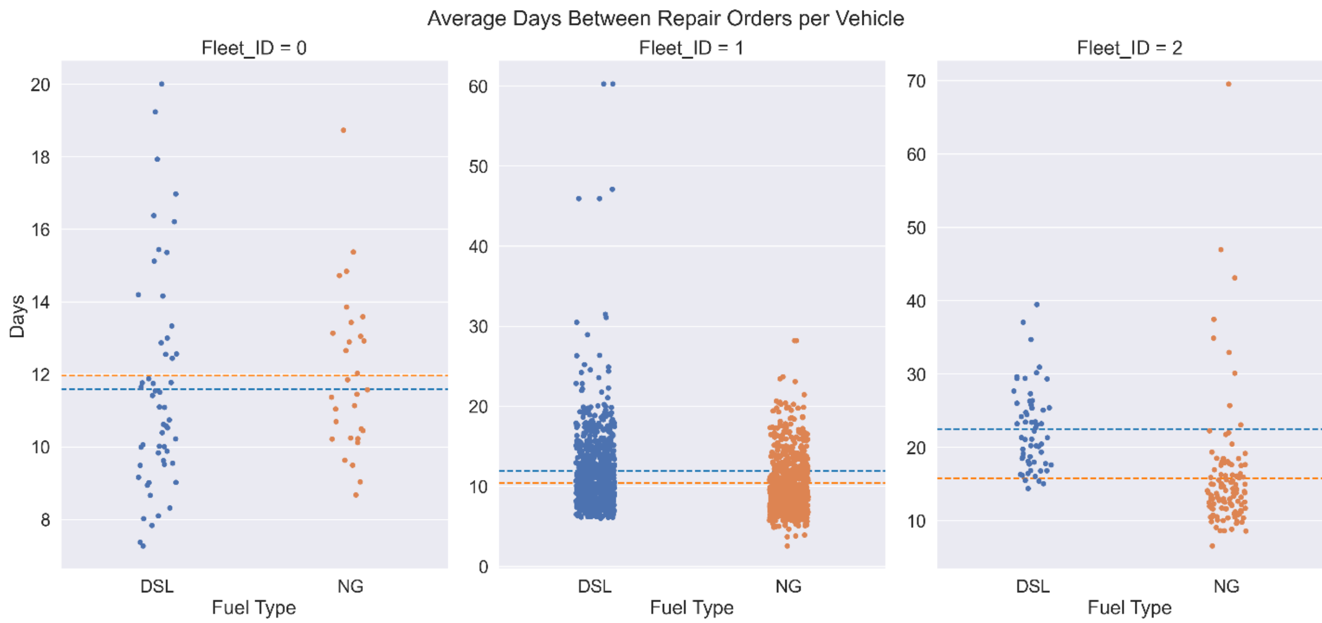


Figure 16: Average Days Between Consecutive RO Open Dates by Fleet and Fuel Type
(Each point represents the average for a single vehicle.)

The days-between-ROs metric allows for comparing service interval lengths on a time-based scale. This metric is based on the differences in days between consecutive RO open dates for each truck. Each point in Figure 16 represents the average number of days between ROs for a single truck.

Many of the same trends from the distance-based service interval metric are still prevalent, but there are a few key differences. Both fuel types for Fleet 0 average around 12 days between ROs, but the diesel vehicles tend to travel longer distances between ROs. This suggests that Fleet 0 may be assigning shorter, more local routes to their NG fleet. Both fuel types have very similar averages and distributions for Fleet 1, suggesting their trucks run similar routes regardless of fuel type. Fleet 2's diesel trucks have significantly longer service intervals, both in terms of time and distance, than their NG counterparts.

T-tests:

Days Between Consecutive ROs by Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 1 vs. Fleet 0	-13.950	6.283e-44
Fleet 1 vs. Fleet 2	-29.126	1.558e-183
Fleet 0 vs. Fleet 2	-18.942	1.257e-79

Days Between Consecutive ROs by Fuel Type for Each Fleet

Groups Compared	T-value	P-value
Fleet 0: DSL vs. NG	-5.855	4.946e-09
Fleet 1: DSL vs. NG	18.361	3.101e-75
Fleet 2: DSL vs. NG	17.144	6.464e-65

The t-tests show that the average days between ROs are significantly different between diesel and NG vehicles for all three fleets.

Distribution of ROs per 10,000 Vehicle Miles

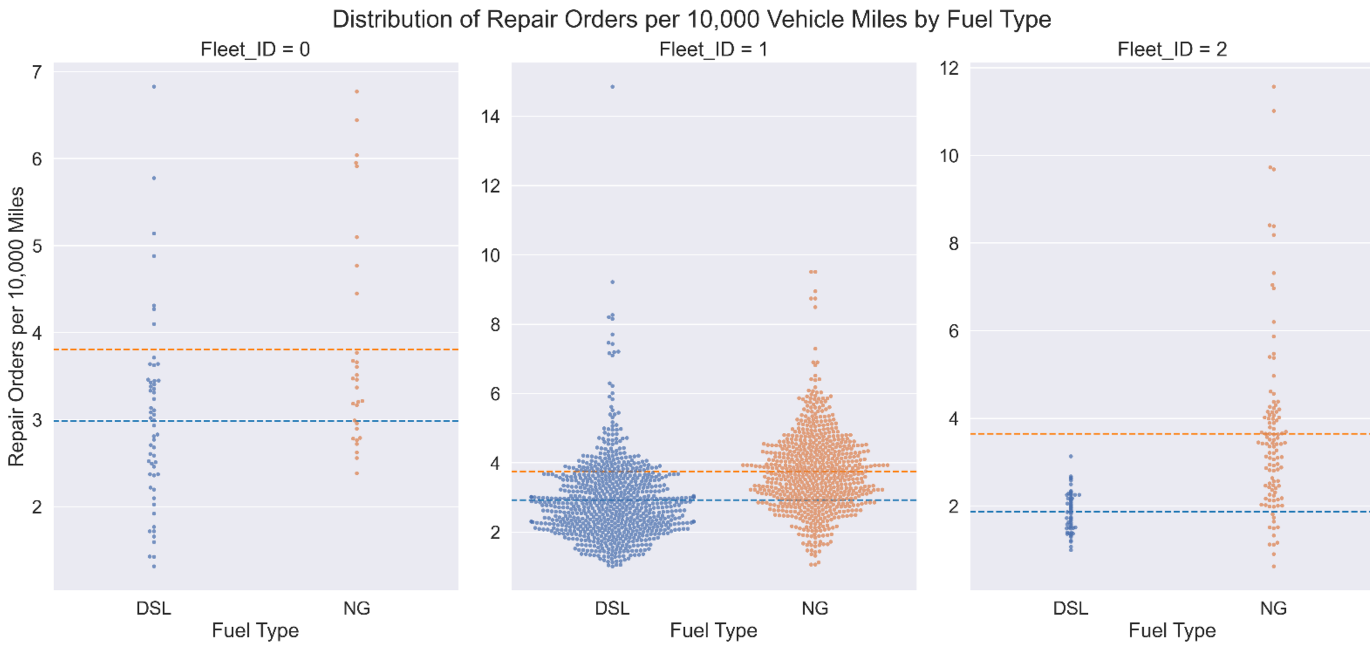


Figure 17: Average Count of ROs per 10,000 Vehicle Miles
(Each point represents a single vehicle.)

The average number of ROs generated per 10,000 vehicle miles were between approximately 2 and 4 for both fuel types in the three fleets. The NG vehicles had a higher average in all three fleets. Fleet 0 had the fewest number of outliers, with the average for all of their vehicles falling between 1 and 7 ROs. The ROs for the diesel trucks in Fleet 1 had a more right-skewed distribution than the NG trucks, meaning that a greater percentage of diesel trucks had average RO counts less than the mean. All of the diesel vehicles in Fleet 2 were of the same age, produced by the same manufacturer, and had similar duty cycles. These factors led to these vehicles having a very tight distribution of ROs. Fleet 2's NG trucks, on the other hand, spanned multiple generations and had more varied duty cycles, which led to a much wider distribution of ROs. The newest vehicles that accumulated less than 10,000 miles were excluded from this visual to reduce noise and outliers.

T-tests:

ROs per 10,000 Miles by Fleet		
Groups Compared	**T-value**	**P-value**

Fleet 1 vs. Fleet 0	0.299	0.765
Fleet 1 vs. Fleet 2	2.008	0.046
Fleet 0 vs. Fleet 2	1.307	0.192

The t-tests show that all the participating fleets have a similar number of ROs per mile. The difference in average ROs between Fleet 1 and Fleet 2 was the only one that was marginally significant.

ROs per 10,000 Miles by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	-3.016	0.004
Fleet 1: DSL vs. NG	-13.647	5.681e-40
Fleet 2: DSL vs. NG	-8.863	-5.552e-15

The average counts of ROs per 10,000 miles were statistically different between the fuel types for all three fleets. These results provide a significant amount of evidence that NG vehicles require more maintenance than diesel vehicles regardless of variations in duty cycles and maintenance practices.

Average Number of Days Out of Service per 10,000 Miles

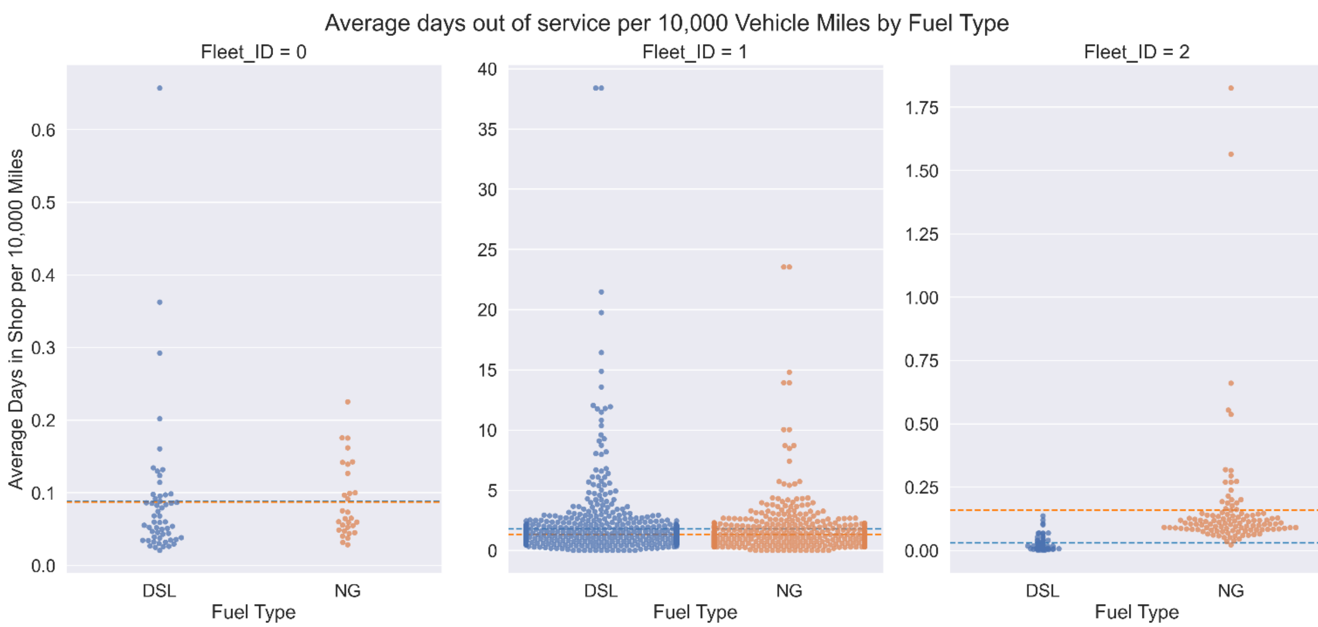


Figure 18: Average Number of Days Between RO Open and Close Dates
(Each point represents a single vehicle.)

Figure 18 is intended to show any differences that may exist in overall RO duration between the two fuel types. This metric is calculated by first counting the number of elapsed days from RO open date to RO completion date for each repair order. Values are then grouped by fleet, fuel type, and Unit ID, and the average is calculated for each group. Approximately 15% of the ROs from Fleet 1 had null completion dates, and 31% of the ROs from Fleet 2 had an erroneous completion dates. These values were omitted from this visual.

In general, both fuel types appear to spend a similar number of days out of service due to maintenance. The average-days-out-of-service-per-10,000-miles metric is identical for diesel and NG trucks for Fleet 0. Diesel trucks in Fleet 1 have a slightly higher average time out of service than their NG counterparts. Fleet 2 exhibited the most substantial difference in RO durations between diesel and NG trucks.

Fleet 1 : Top Repair Orders by Average Duration		
Fuel Type	RO Description	Average RO Duration in Days
DSL	OIL ANALYSIS KIT	267.226713
DSL	ELEMENT - OIL FILTER, FULL FLOW	255.9688248
DSL	OIL ANALYSIS	224.2544555
DSL	BRACKET - MOUNTING, FRONT LICENSE	186.3187269
DSL	KIT - SEAL, GEAR, STEERING	180.7669676
DSL	SLEEVE - EXHAUST MANIFOLD	180.2237153
DSL	TRACTOR, 240K SCHED SVC, ENGINE OVERHEAD	177.2540865
DSL	FILTER ASSEMBLY - OIL, FULL FLOW	172.0750193
DSL	FLEET 1 LABOR CODES	168.1179255
DSL	ELEMENT OIL FILTERS	158.3701633
DSL	OIL - REAR AXLE	147.2900347
DSL	A PM	139.4061556
NG	HOSE - HYDRAULIC, FRONT BRAKE	213.0935532
NG	ASSEMBLY - COMPLETE, TRANSMISSION, AUTOM	142.6259582
NG	NECK - FILLER, TANK, GASEOUS FUEL	141.5061774
NG	FILTER ELEMENT - TRANSMISSION OIL	135.7477567
NG	B PM	127.0655211
NG	A PM	127.0320152
NG	TUBE - DIP STICK	125.0043287
NG	OIL ANALYSIS	124.2041627
NG	HEAD - CYLINDER	123.7803494
NG	FILTER - CRANKCASE VENTILATION	120.1083179
NG	ELEMENT - FUEL FILTER, PRIMARY	119.4710908
NG	FLUID - AUTOMATIC TRANSMISSION	107.4486715

Figure 19: Examples of Lengthy RO Durations from Fleet 1
(Note: PM refers to preventative maintenance.)

The y-axis scale in Figure 18 for Fleet 1 is vastly different due to differences in data recording procedures for the RO completion dates. The data manager for Fleet 1 indicated that their technicians leave open certain ROs for routine maintenance (e.g., oil changes) until the next time the vehicle comes in for the same service. This practice results in very lengthy ROs, which skew the average RO duration to be higher than expected. There was no evidence that this practice differed between their diesel and NG trucks, so it was still possible to make comparisons between the two fuel types.

T-tests:

Days in Shop per Mile by Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0 vs. Fleet 1	-34.109	8.343e-99
Fleet 0 vs. Fleet 2	-1.497	0.135
Fleet 1 vs. Fleet 2	31.967	1.647e-99

Days in Shop per Mile by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	0.056	0.956
Fleet 1: DSL vs. NG	5.793	8.627e-09
Fleet 2: DSL vs. NG	-5.812	5.420e-08

Not surprisingly (based on the abovementioned RO practices), the results of the t-test show that Fleet 1 had statistically higher average-days-in-shop from Fleet 0 and Fleet 2. The diesel and NG vehicles had statistically different averages for this metric within Fleet 1 (higher diesel) and Fleet 2 (higher NG).

Average Cumulative Count of ROs by Fleet and Fuel Type

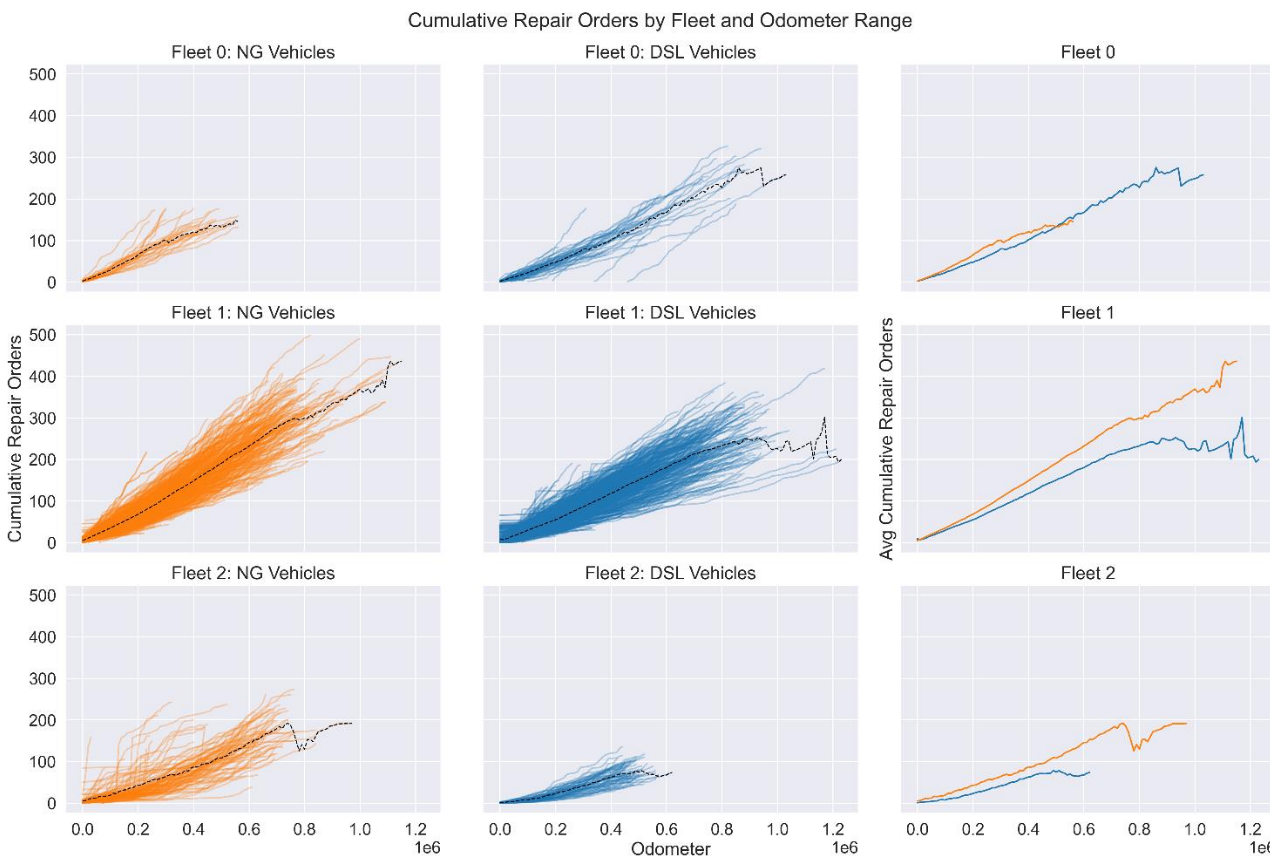


Figure 20: Cumulative Count of ROs per Vehicle by Fleet and Fuel Type
(Each line for the plots in the first two columns represents the RO accumulation for a single vehicle.)

Figure 20 shows the differences in the rate of RO accumulation by fleet and fuel type. Each one of the orange and blue lines in the left and middle column of plots represent a single vehicle. The black dotted line represents the average and is calculated by first grouping together all ROs generated by fleet, fuel type, and odometer range, and then taking the average. The plots in the rightmost column show the average lines for both fuel types on the same plot for easier comparison. Note that the variability of the average lines increase as the odometer range gets higher due to the decreasing sample size of vehicles.

The NG trucks in all three fleets accumulated ROs at a faster rate than the diesel trucks for most of the odometer range. For Fleet 0 and Fleet 1, the cumulative count of ROs was relatively similar between the two fuel types prior to the 200,000-mile mark. This was expected because newer vehicles typically require less maintenance, regardless of fuel type. Fleet 1 had the most comparable maintenance data in terms of number of vehicles, ages, and duty cycles. The gap between the NG and diesel vehicles within Fleet 1 continued increasing after the 200,000-mile mark. By the end of their life (around the 1,000,000-mile mark), the average NG vehicle accumulated 80 more ROs than the equivalent diesel vehicle. Fleet 2 had showed a large difference between the two fuel types even before the 200,000-mile mark. This fleet had the largest age range for NG trucks and the smallest age range for diesel trucks in the dataset.

ROs Generated per Vehicle by Odometer Range

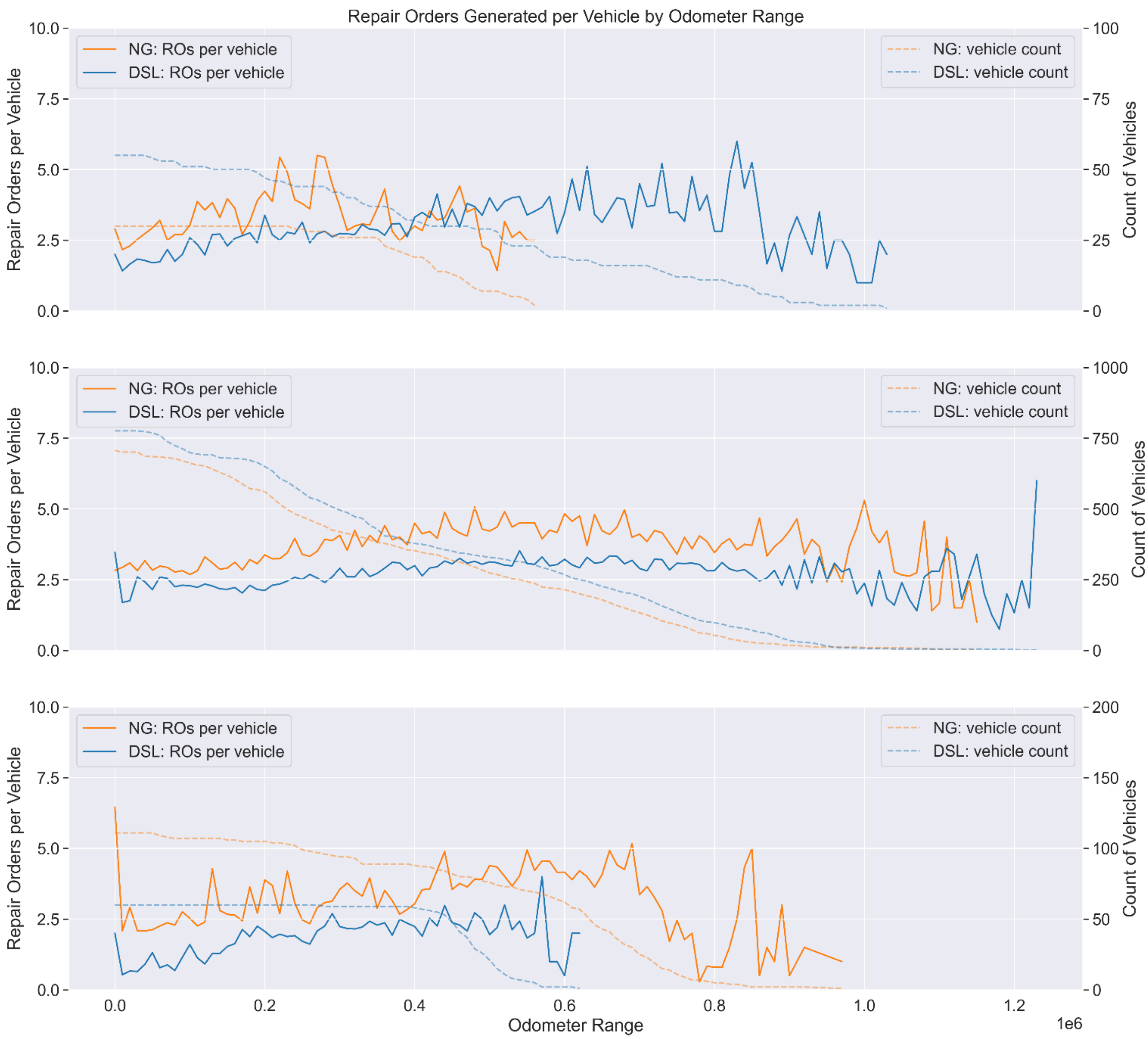


Figure 21: Average Number of ROs Generated per Active Vehicle by Fleet and Fuel Type
(Fleet 0 is shown in the topmost graph, followed by Fleet 1 and Fleet 2.)

Figure 21 shows the average number of ROs generated per all active vehicles over the total accumulated mileage (odometer range). This metric is calculated by first grouping the maintenance data by fleet, fuel type, and odometer range (rounded to the closest 10,000 miles) . Then the number of ROs in each group are counted and divided by the number of active vehicles. Active vehicles are a count of total vehicles that were operating in the fleet in a given mileage range regardless of whether they had a RO occur within that range. The dashed lines show the number of active vehicles per fuel type and by odometer range in each fleet.

It was hypothesized that NG-powered trucks would require more maintenance in the beginning of their lifespan and that diesel-powered trucks would require more maintenance toward the end of their life. This trend was not observed in this dataset. The NG trucks in all three fleets required more overall maintenance than the equivalent diesel trucks throughout the odometer range. The variation in ROs generated per vehicle increases as the sample size of active vehicles gets smaller.

Percent Uptime

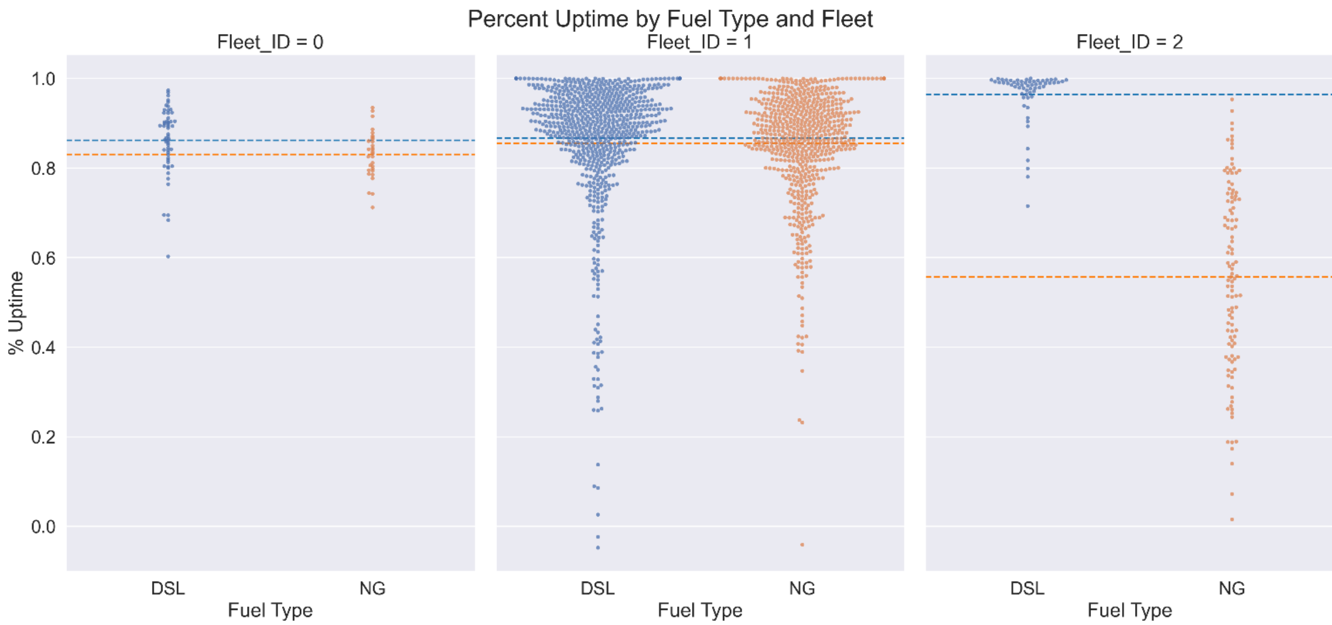


Figure 22: Distribution of Vehicles by Percent Uptime
(Each point represents a single vehicle.)

Figure 22 shows operational differences between diesel and NG trucks for each fleet. It is calculated by dividing the number of active days by the total days for each truck. Total days equals the number of days between the first RO and last RO for each truck. Active days is equal to the total days minus the sum of RO duration days. The accuracy of this metric is highly dependent on the accuracy of the RO open and RO completion dates.

Fleet 1: Average Repair Order Duration by Fuel Type and Repair Reason Type		
Repair Reason Type	Avg. RO Duration in Days	
Fuel Type	DSL	NG
Scheduled Service	259.42	130.7
Preventive maintenance	144.3	219.75
Scheduled Inspection	78.98	167.05
Scheduled Repair	15.83	11.72
Breakdown	6.08	1.12
PM Repair	5.97	6.42
Unscheduled Repair	3.58	3.55

Figure 23: Average RO duration by Repair Reason for Fleet 1

As noted earlier, Fleet 1 had different methods of recording RO completion dates depending on the type of maintenance that was being performed. ROs for routine maintenance items with set intervals were left open until the next time the vehicle needed the same service. This made it challenging to calculate accurate uptime metrics for this fleet. The ROs for these routine maintenance items were excluded from the uptime calculations for Fleet 1.

Fleet 2 had the biggest differences in uptime between their diesel- and NG-powered trucks, but there were a significant number of inconsistencies in the RO close date and RO duration fields from this fleet. 84% of the reported RO duration values did not match the differences between RO open and completion dates. These data errors are likely the biggest contributors to the extraordinarily low uptime values for their NG trucks.

Fleet 0 had the most accurate RO duration data and therefore the most reliable uptime metric. The average uptime percentage for both fuel types hovered between 83% and 86%. Their diesel trucks had a larger range for uptime percentages than their NG trucks. Fleet 1 had very similar distributions for both fuel types, and their averages were within 1% of each other. There were a few outlier vehicles that had uptime-percentage values that were close to or below zero. This is due to errors in the RO duration field where certain ROs were left open for an improbable amount of time.

T-tests:

% Uptime by Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 1 vs. Fleet 0	1.251	0.213
Fleet 1 vs. Fleet 2	7.983	1.541e-13
Fleet 0 vs. Fleet 2	7.106	1.762e-11

The average percentage uptime was statistically different for Fleet 0 and Fleet 1 compared to Fleet 2, while differences between Fleet 0 and Fleet 1 were not significant. The Fleet 2 results are likely due to the variations in maintenance record-keeping practices rather than actual uptime variation between the vehicles.

% Uptime by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	2.223	0.029
Fleet 1: DSL vs. NG	1.660	0.097
Fleet 2: DSL vs. NG	19.108	1.153e-40

Fleet 1's data did not demonstrate statistically different uptimes between their diesel and NG trucks. Fleet 0 had statistically significant results, but this was only around the 5% significance level. The uptime for diesel and NG trucks for Fleet 2 was statistically different at any significance level. In all three cases, the diesel vehicles generally exhibited greater uptime percentages than the NG vehicles.

Overall Breakdown Frequency (Fleet 1 Only)

In addition to overall maintenance frequency, fleets are also very sensitive to breakdown frequency. Breakdowns are generally the most problematic type of maintenance because they usually involve expensive towing charges and can disrupt fleet operations. Only Fleet 1 provided sufficiently detailed maintenance data to identify ROs related to breakdowns.

Total Breakdowns per Vehicle

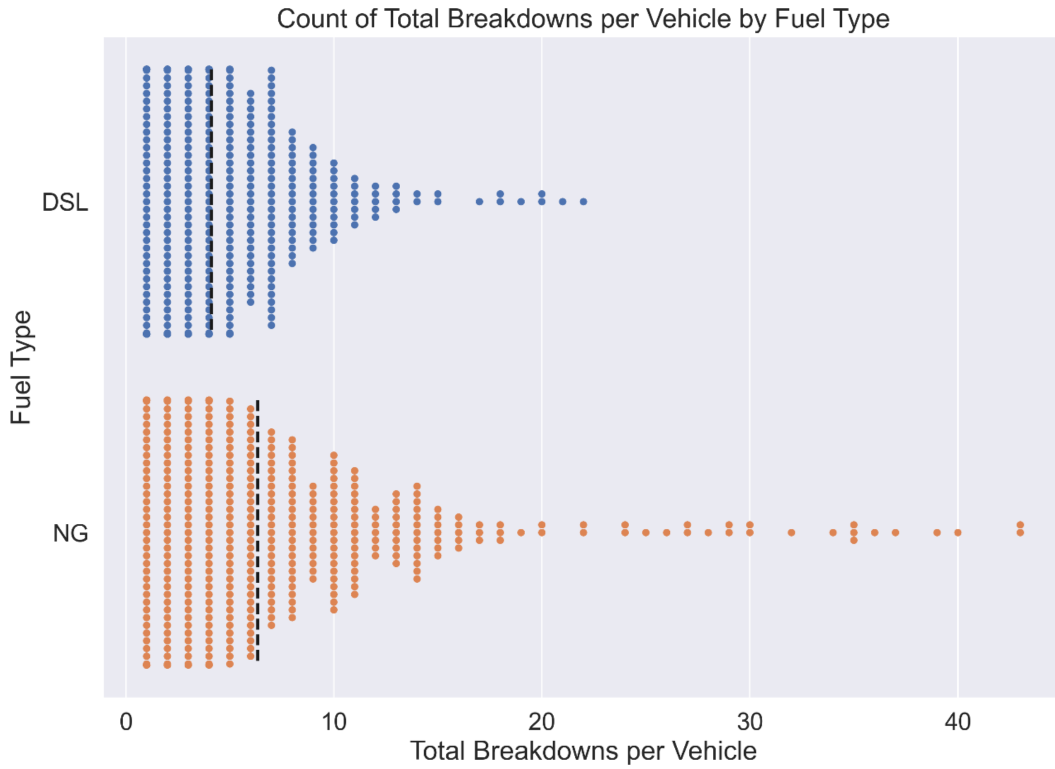


Figure 24: Distribution of Total Breakdowns per Vehicle
(Each point represents one vehicle.)

Fleet 1 operates their NG trucks in the same manner as their diesel trucks. No exceptions are made in terms of routes, loads, or overall duty cycles based on the fuel type. This makes comparing differences in breakdowns between the two technologies as fair as possible.

The majority of NG and diesel trucks have less than 10 recorded breakdown incidents, but there were a higher number of outlier NG trucks that had more breakdowns than expected. The highest number of breakdowns for a diesel truck was 22. There were 24 NG trucks that had more than 22 breakdowns. The overall age and mileage of diesel and NG trucks were comparable for Fleet 1.

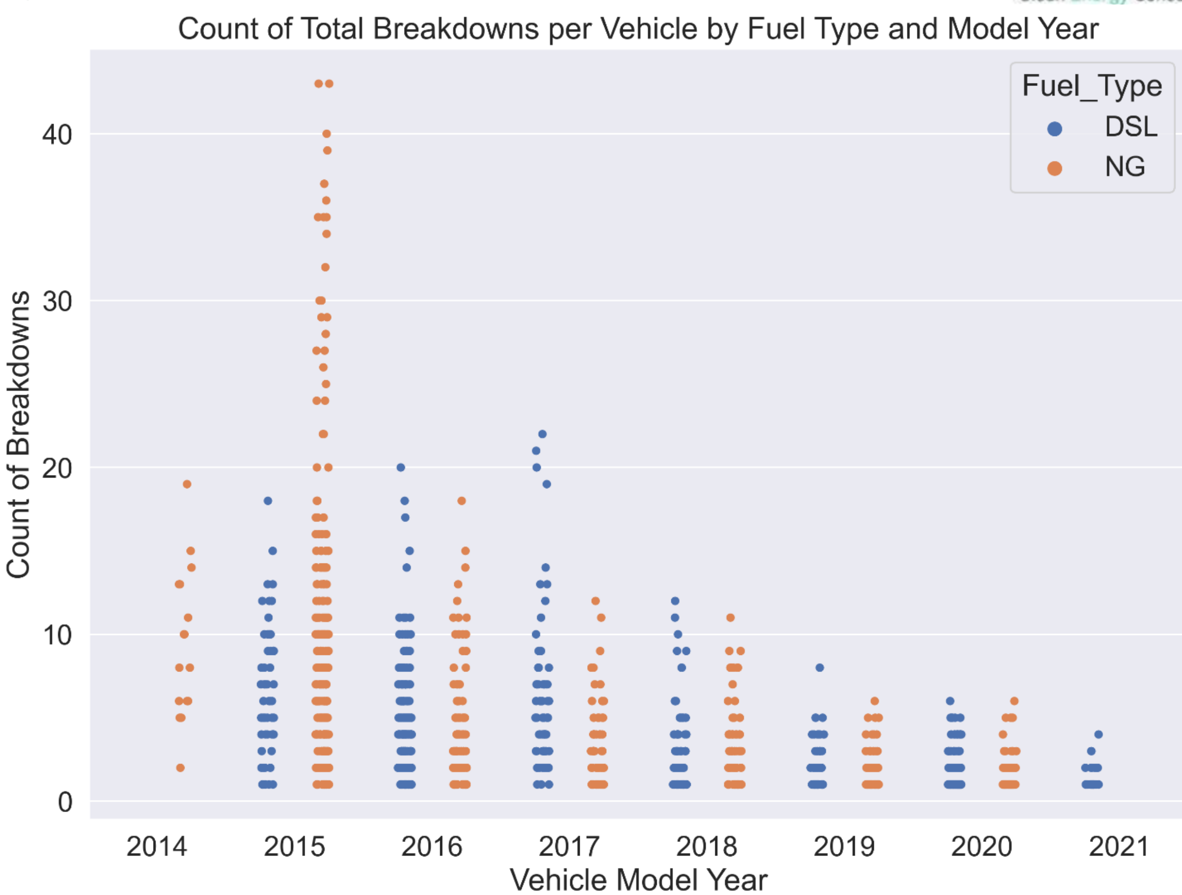


Figure 25: Distribution of Total Breakdowns per Year by Vehicle Model Year and Fuel Type

Separating the breakdown data by vehicle model year revealed NG trucks with the model year 2015 accounted for nearly all the outliers seen in Figure 24. NG trucks and diesel trucks from model year 2016 onward exhibited very similar breakdown numbers. This plot additionally follows the expected trend for breakdowns where newer vehicles accumulate fewer breakdowns than older vehicles.

T-tests:

Total Breakdowns by Fuel Type (all vehicles)		
Groups Compared	**T-value**	**P-value**
Fleet 1: DSL vs. NG	-6.676	4.573e-11

Total Breakdowns by Fuel Type (excluding model year 2015)		
Groups Compared	**T-value**	**P-value**
Fleet 1: DSL vs. NG	0.465	0.642

The t-test results above demonstrate the outsized impact of the 2015 NG trucks. The results of the test are statistically significant when all trucks from Fleet 1 are considered, but they are not significant when the trucks from model year 2015 are excluded.

Fleet 1: Vehicles with the Largest Number of Breakdowns					
Model Year	Unit_ID	Number of ROs	Count of Breakdowns	Miles Travelled	Days in Fleet
2015	NG-56	354	43	638,207	2,351
2015	NG-58	329	43	693,129	2,379
2015	NG-52	352	40	751,154	2,381
2015	NG-55	326	39	671,949	2,369
2015	NG-142	287	37	669,918	2,146
2015	NG-146	296	36	701,640	2,143
2015	NG-149	277	35	605,128	2,156
2015	NG-168	287	35	783,208	2,164
2015	NG-57	335	35	726,127	2,379
2015	NG-151	284	34	586,912	2,162
2015	NG-150	287	32	656,465	2,128
2015	NG-62	328	30	675,915	2,313
2015	NG-61	356	30	741,240	2,385
2015	NG-93	306	29	741,314	2,394
2015	NG-60	312	29	708,779	2,383
2015	NG-233	231	28	673,923	2,066
2015	NG-94	293	27	638,140	2,378
2015	NG-147	281	27	753,852	2,159
2015	NG-51	301	26	684,145	2,387
2015	NG-59	310	25	691,274	2,388
2015	NG-108	284	25	659,490	2,095
2015	NG-180	259	24	674,323	2,162

Figure 26: Summary Metrics for Total Breakdown Outlier Vehicles

Figure 26 above provides additional information on the trucks that recorded the largest number of breakdowns. The mileage range for these trucks ranged from 600,000 – 800,000 miles, and all of these vehicles were in operation for over five (5) years. In examining the associated data, there did not appear to be any single point of failure that caused these additional breakdowns.

Cumulative Breakdowns

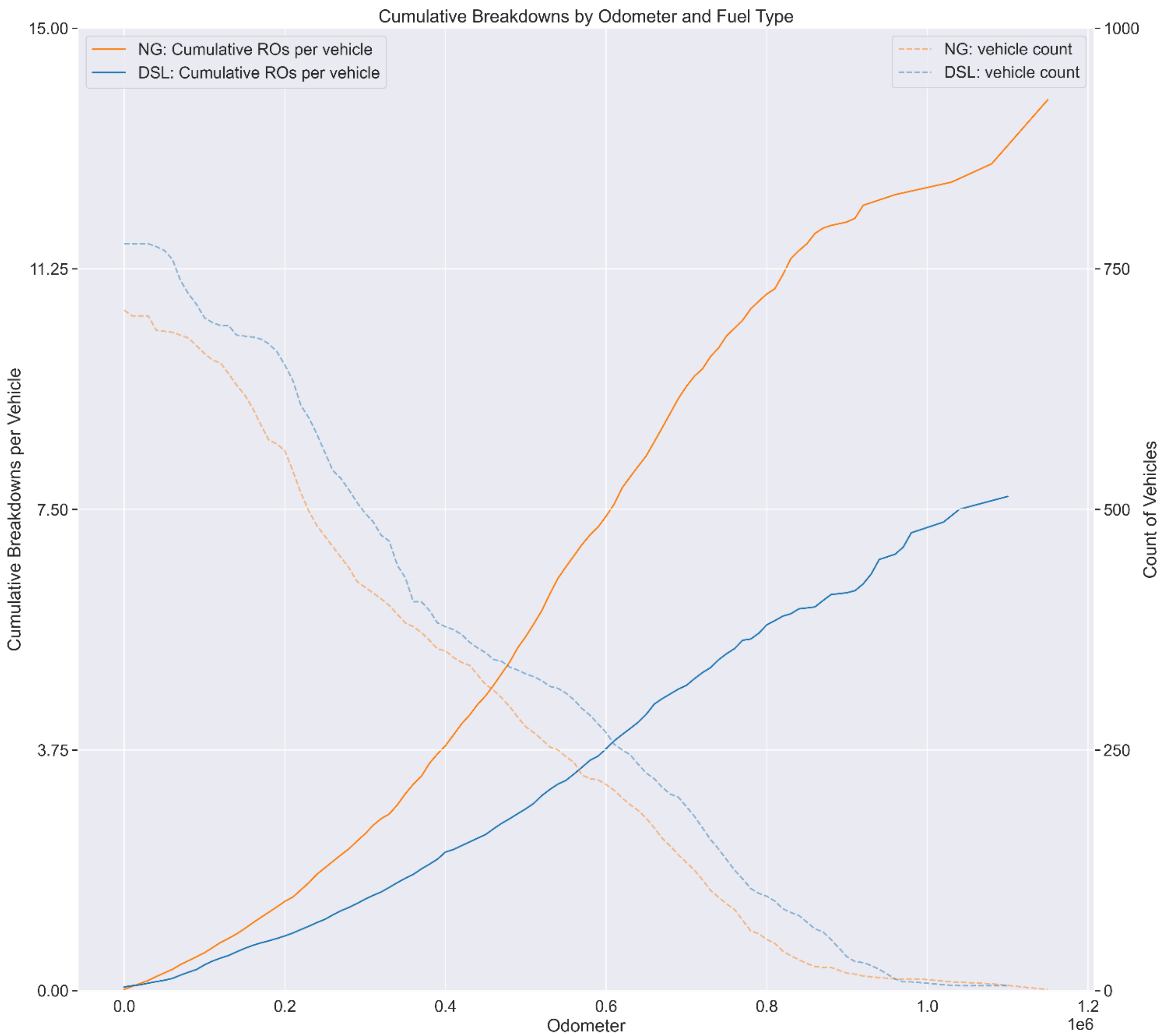


Figure 27: Average Cumulative Breakdowns per Active Vehicle by Fuel Type and Odometer Range

Figure 27 shows the accumulation of breakdown incidents over the vehicle odometer range. This metric was calculated by first grouping the breakdowns by fleet and fuel type, and then counting the number of incidents in each mileage interval. This value was then divided by the total number of trucks that were active through the mileage interval to get the average count of breakdowns per vehicle. Finally, these values were sorted by mileage range for each fuel type, and the cumulative sum was calculated. The dashed lines in the visual represent the count of active vehicles used as the denominator.

The average cumulative number of breakdowns for each fuel type shows that NG-powered trucks had more breakdowns than diesel-powered trucks from very early in the odometer range. The gap between diesel and NG trucks only increases as the vehicles accumulate more miles. By the million-mile mark, a typical NG truck accumulated 5 more breakdowns than the typical diesel truck in this dataset.

Total Breakdowns Cluster Chart

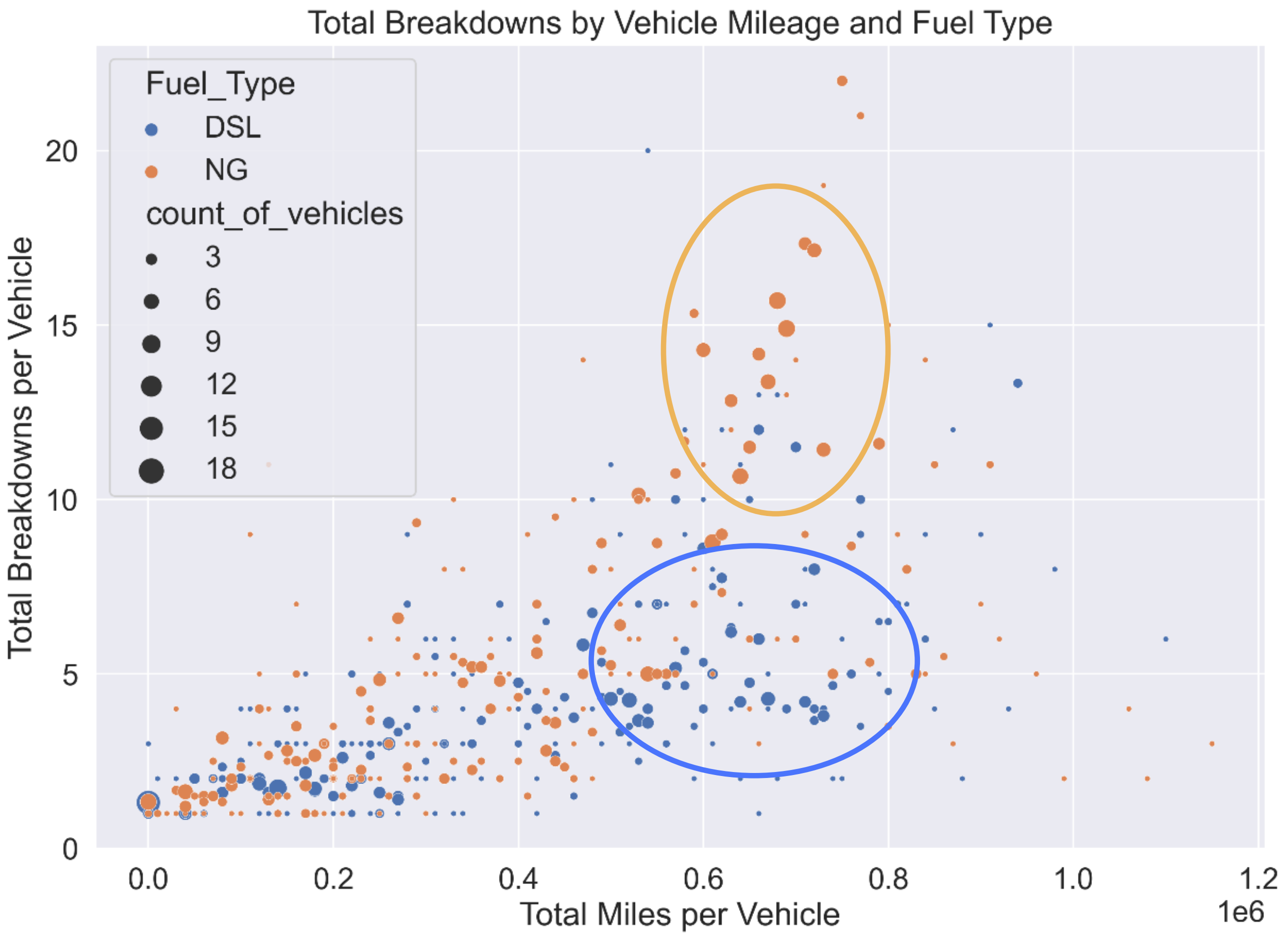


Figure 28: Scatter Plot of Total Breakdowns (intended to show clustering)

The clustering of the vehicles by number of breakdowns by mileage range shows that NG-powered trucks that reached 600,000 miles have almost double the number of breakdowns as their diesel-powered counterparts with the same mileage. A large portion of the NG-powered trucks that accumulated over 600,000 miles experienced 10 or more breakdowns. In contrast, most of the diesel-powered trucks in this same mileage range experienced less than 8 breakdowns.

Component-Level Repair Frequency (Fleet 1 Only)

The goal for this analysis section was to identify and compare the maintenance areas that caused the biggest differences in maintenance frequency between diesel- and NG-powered trucks. All of the non-propulsion-related systems and components (e.g., chassis and cab) are generally identical between both fuel types and were not included in the component-level analysis. Only Fleet 1 was able to provide data at the VMRS component level, so only their data is used for the specific component-level analysis.

Average Count of ROs per Vehicle by VMRS System

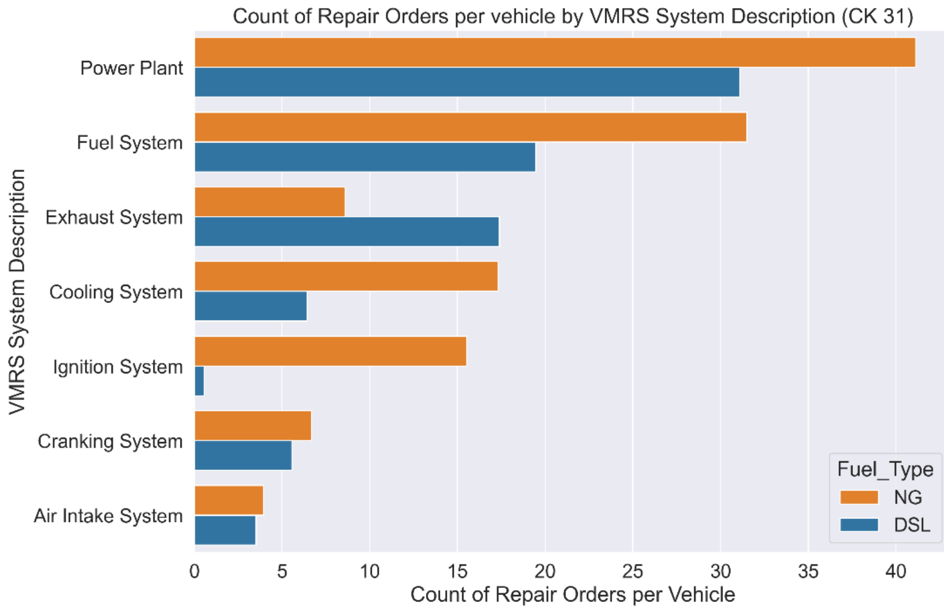


Figure 29: Average Count of ROs by Fuel Type and VMRS System

The component-level analysis began by identifying differences at the broadest VMRS system level. Figure 29 shows the average count of ROs for each of the fuel-type-significant VMRS system codes. As expected, the average count of ROs for the ignition and exhaust systems were significantly different between the two fuel types. Diesel engines have more complex exhaust systems, and NG engines have more complex ignition systems. The differences seen in the number of ROs for the power plant, fuel, and cooling systems were unanticipated.

Average Count of ROs by VMRS System and Odometer Range

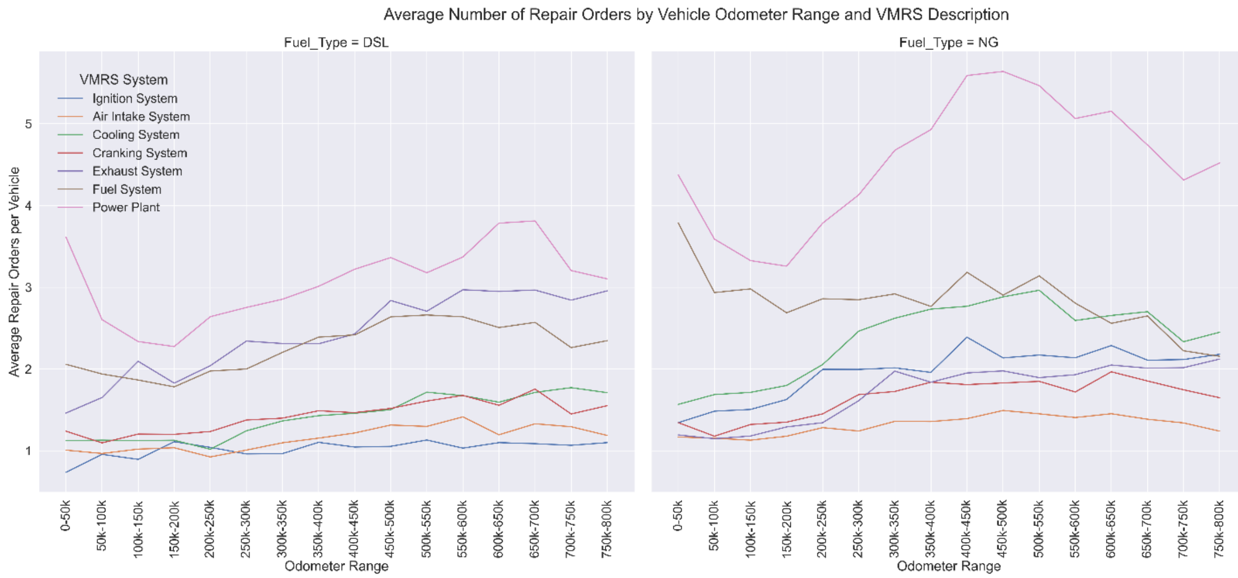


Figure 30: Average Count of ROs per Vehicle by VMRS System and Odometer Range
(Note: ROs recorded after the 800,000-mile mark were excluded from this visual,
as only a few vehicles in the dataset accumulated this many miles.)

Adding odometer range as a dimension shows how the average count of ROs for each system changed over a vehicle's lifespan. Figure 30 above shows that there is a slight positive trend in the count of average ROs for most systems. This trend was expected, as older vehicles generally require more maintenance. Interestingly, there are peaks in the average ROs for powerplant and cooling systems of NG trucks around the 500,000-mile mark. The average number of fuel-system-related ROs for NG trucks also decreased over the odometer range. Overall, the NG trucks generated more ROs for most systems and odometer ranges.

Cumulative ROs by VMRS System and Fuel Type

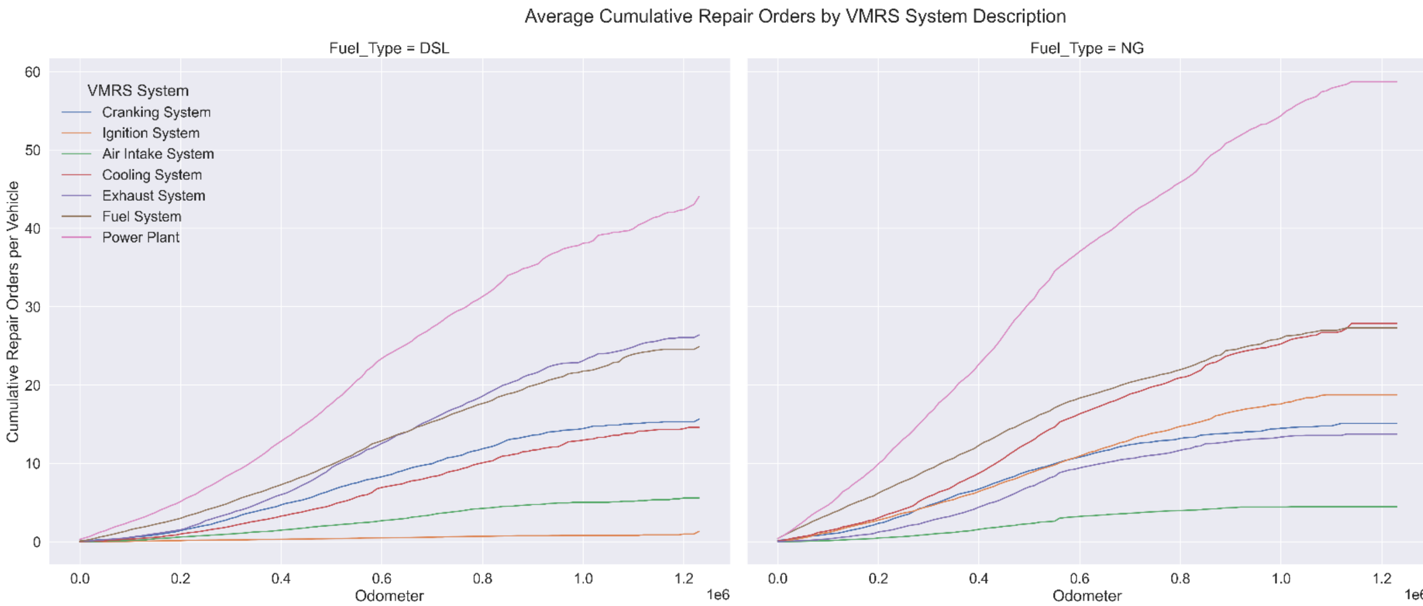


Figure 31: Average Cumulative Count of ROs per Vehicle by VMRS System

The cumulative-count-of-ROs metric, shown in Figure 31, highlights the extent of the maintenance differences between the two fuel types. A typical NG-powered truck in the dataset generated around 20 ignition-system-related ROs, but a typical diesel truck only had around two ROs for this system. The scale of the difference is even larger for exhaust system-related ROs. A typical diesel truck had around 26 exhaust system-related ROs, while a typical NG truck only had around 13 exhaust system-related ROs by the same mileage mark. The differences observed in some of the other systems, such as cooling and power plant, are more indicative of reliability and uptime. NG-powered trucks accumulated ROs at a faster rate than diesel trucks for these systems throughout most of the odometer range.

Area Charts of VMRS System and Assembly Levels

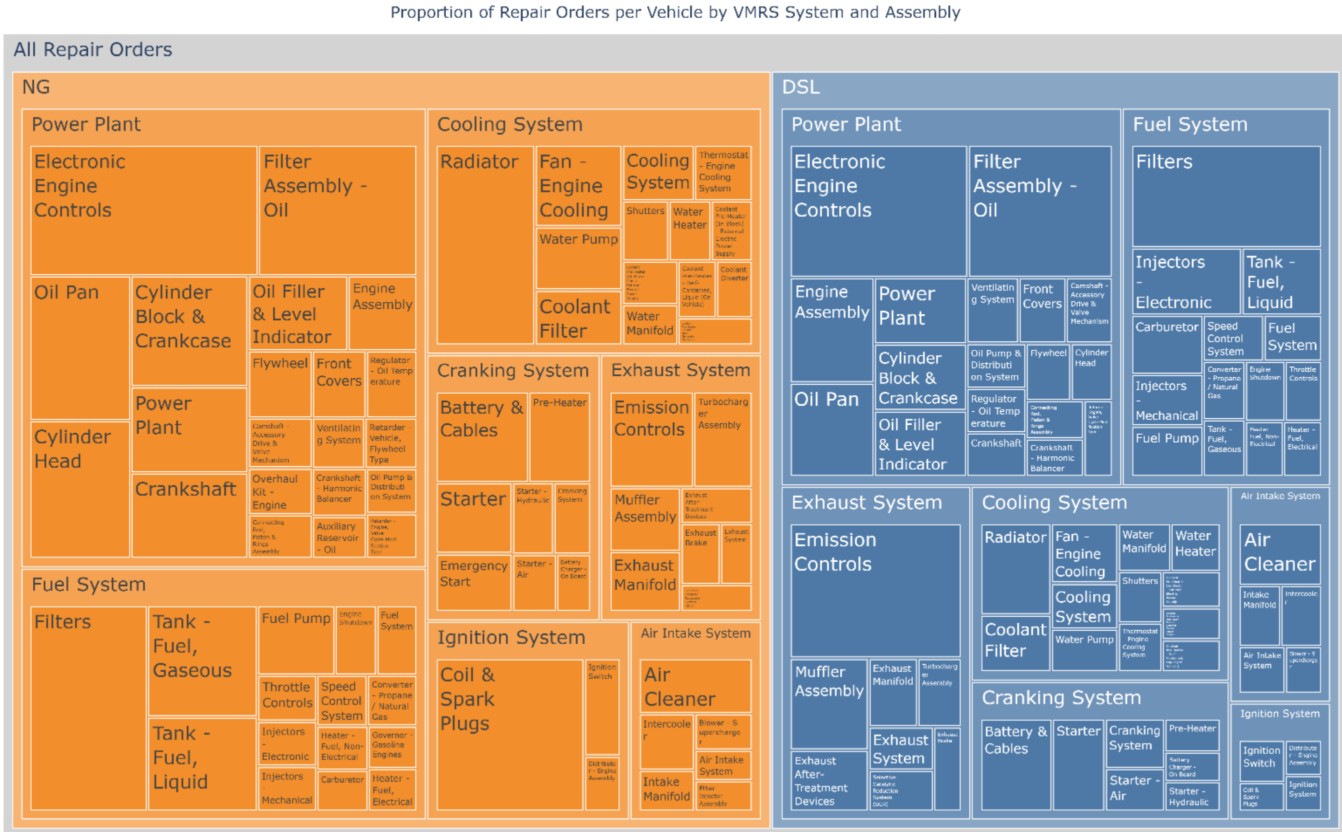


Figure 32: Area Chart of Proportions of VMRS System and Assembly-Level ROs for Each Fuel Type

Figure 32 above identifies the proportion of ROs created by each VMRS assembly. The largest proportion of powerplant-related ROs for both fuel types was generated by the electronic-engine-controls assembly. Interestingly, the cylinder head assembly was one of the top assemblies that contributed to powertrain-related ROs for NG trucks—but not for diesel trucks. This assembly was also anecdotally identified as a common failure point for the NG trucks by some of the fleet managers.

Ignition coils and spark plugs contributed to most ignition-system-related ROs for NG trucks. Emission controls made up the largest proportion of exhaust system-related ROs for both fuel types, but this assembly accounted for a much larger proportion of the overall maintenance (in terms of number of ROs) for diesel vehicles. Similarly, the radiator assembly was the largest contributor to cooling system-related maintenance for both fuel types but accounted for a much larger proportion of ROs for the NG vehicles.

Average Cumulative ROs by Engine Generation and Odometer Range

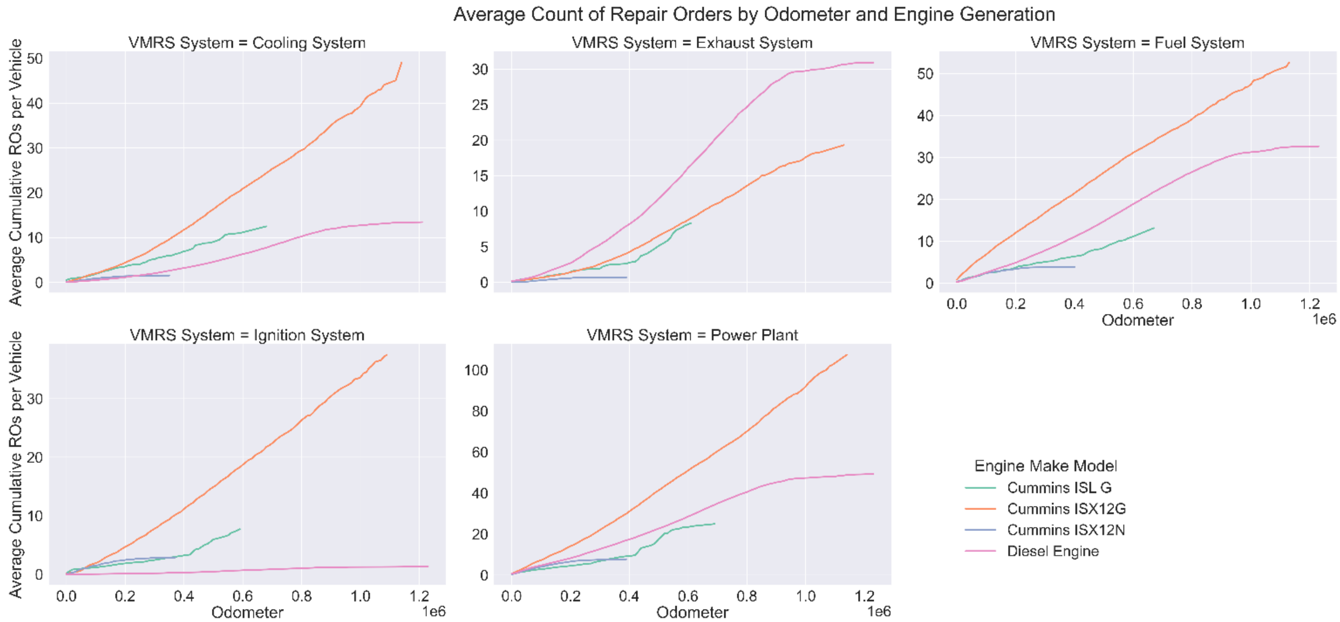


Figure 33: Average Cumulative Count of ROs by NG Engine Generation
(Diesel engines were assumed to be homogeneous and are included on the plot for reference.)

One of the main objectives for this study was to evaluate maintenance differences between different generations of NG and diesel engines. Unfortunately, the vehicle composition of the dataset limited this analysis, as 80% of the maintenance data was generated by trucks manufactured between 2014 and 2017. This timeframe was not wide enough to properly represent multiple NG- and diesel-engine generations.

Natural gas is a much newer technology compared to diesel and is expected to have considerable improvements between engine generations. Cummins is the only OEM in the United States that offers NG engines for class-8 applications. Their earliest offering was the 9-liter ISL G engine, which was not as fit for purpose as the later 12-liter ISX12G engines. The ISX12G was followed up by the ISX12N model in 2018. Approximately 50% of the NG trucks in this study were equipped with the ISX12G engine, and these vehicles accounted for 79% of the NG ROs. The vehicles with the newer ISX12N engine did not have a chance to accumulate as many miles as the trucks with the older ISX12G engine. As a result, it was not possible to make detailed comparisons of maintenance frequency between these different engine generations.

Specific Components Causing Repair Frequency Differences

The figures below are intended to highlight the specific components that caused maintenance frequency differences between diesel- and NG-powered trucks. Only Fleet 1 data is represented in these visuals. The Repair Reason, Failure Description, and Technician Work Accomplished descriptions were also analyzed where possible. The Repair Reason provides insight into whether the repair frequency differences stem from routine maintenance intervals or unexpected part failures. For unexpected part failures, the Failure Reason provides more details regarding how the part failed. The Work Accomplished code describes what the technicians did to correct the maintenance issue.

Ignition-System ROs

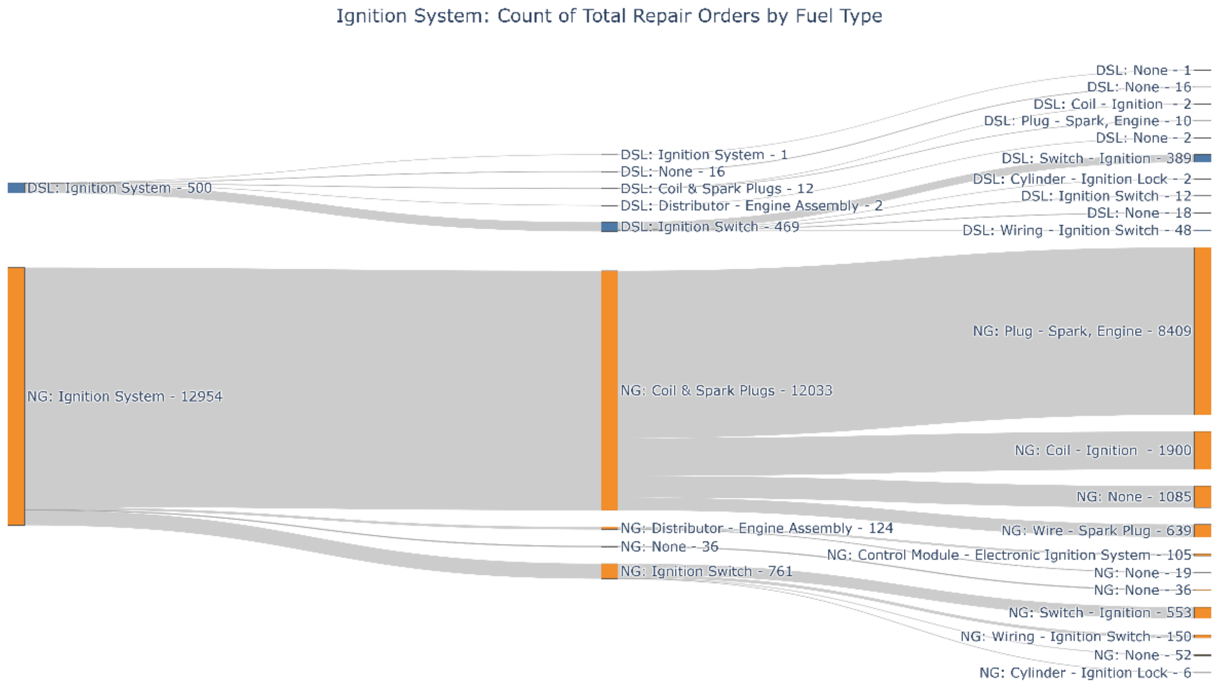


Figure 34: Sankey Plots of Component-Level Differences for the Ignition System
(Note: These plots only include Fleet 1 data.)

As expected, Figure 34 shows that the majority of the ignition-system-related ROs for NG trucks are due to spark plugs and ignition coils, which are routine maintenance items for spark-ignited engines. Around 65% of the ignition-system-related maintenance was due to spark plug replacement. If these routine maintenance items were ignored, the diesel and NG trucks would have very similar amounts of ignition-system-related maintenance.

Cooling System ROs

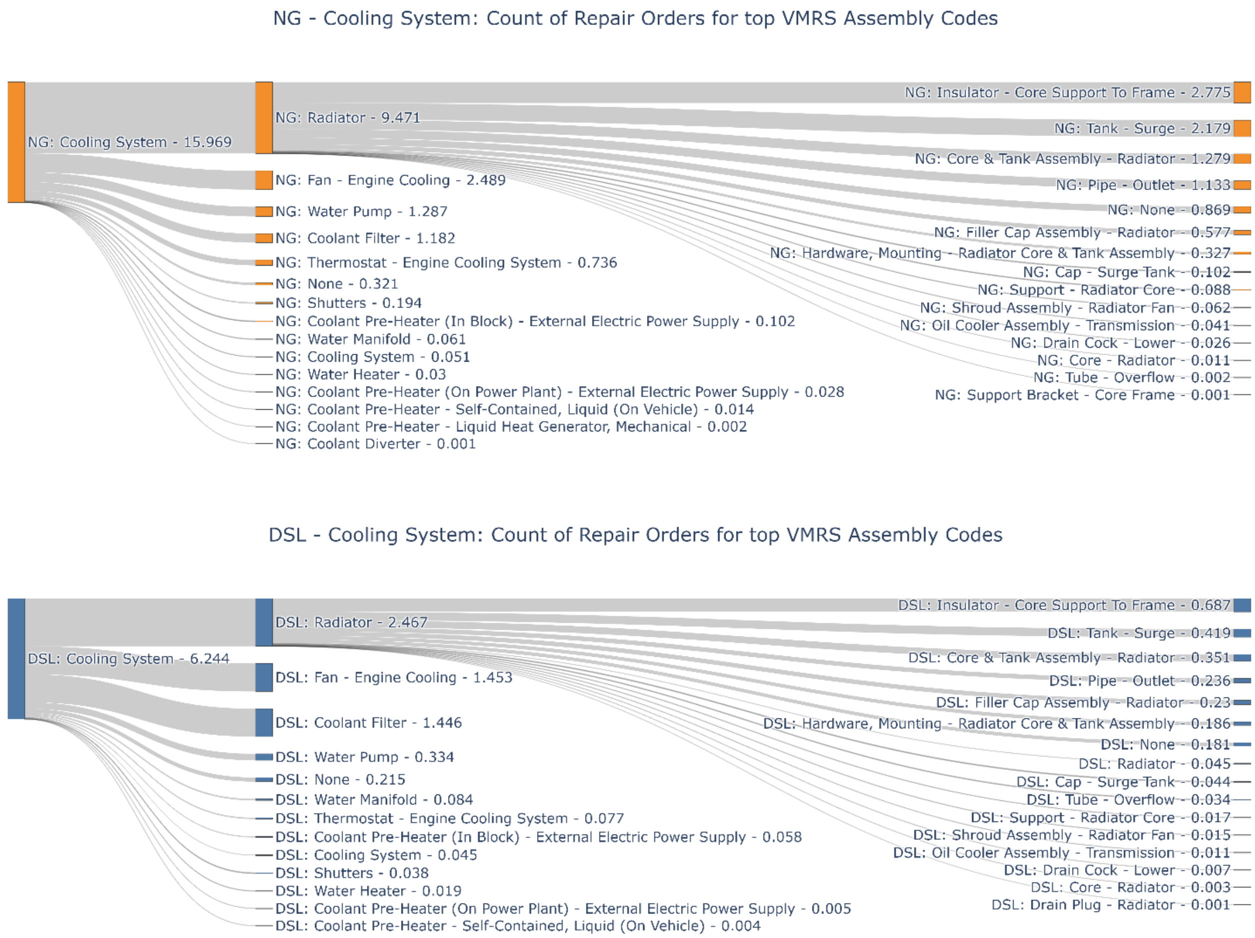


Figure 35: Sankey Plots of Component-Level Differences for Top Assemblies in the Cooling System (Note: These plots only include Fleet 1 data.)

Figure 35 shows that the radiator assembly was the biggest contributor to cooling system-related maintenance for both fuel types, but NG vehicles required almost four times as many ROs as the diesel vehicles in this dataset. The insulator core and surge tanks were the components requiring the most maintenance in the radiator assembly for both fuel types. The cooling system design and components are very similar for both fuel types.

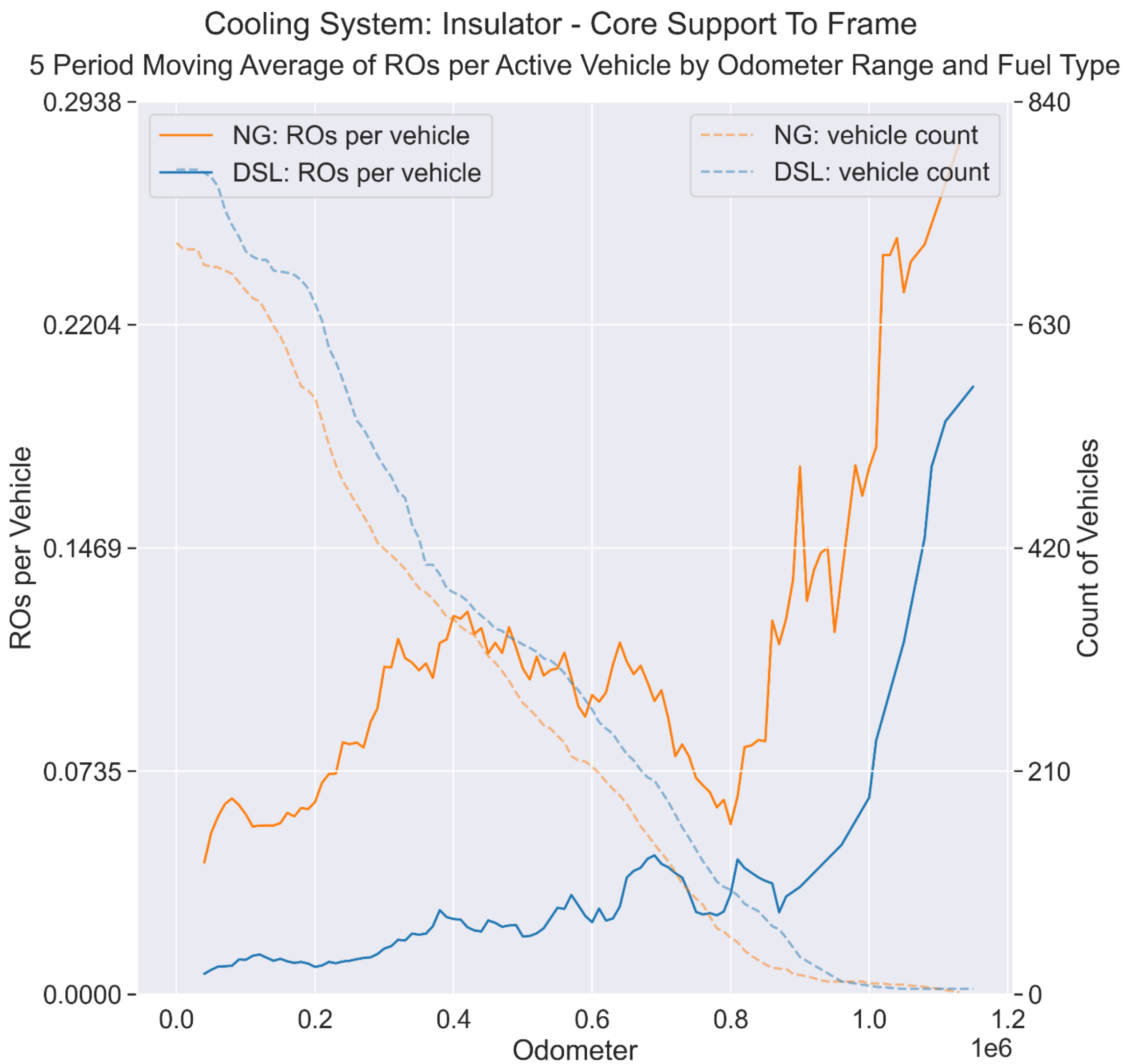


Figure 36: Average ROs per Active Vehicle for the Radiator Core Component

Figure 36 shows the average amount of maintenance required by the radiator core component over the odometer range for each fuel type. This component required more maintenance for NG trucks throughout most of the odometer range. The sharp increase after the 800,000-mile mark is heavily influenced by the rapidly decreasing vehicle sample size.

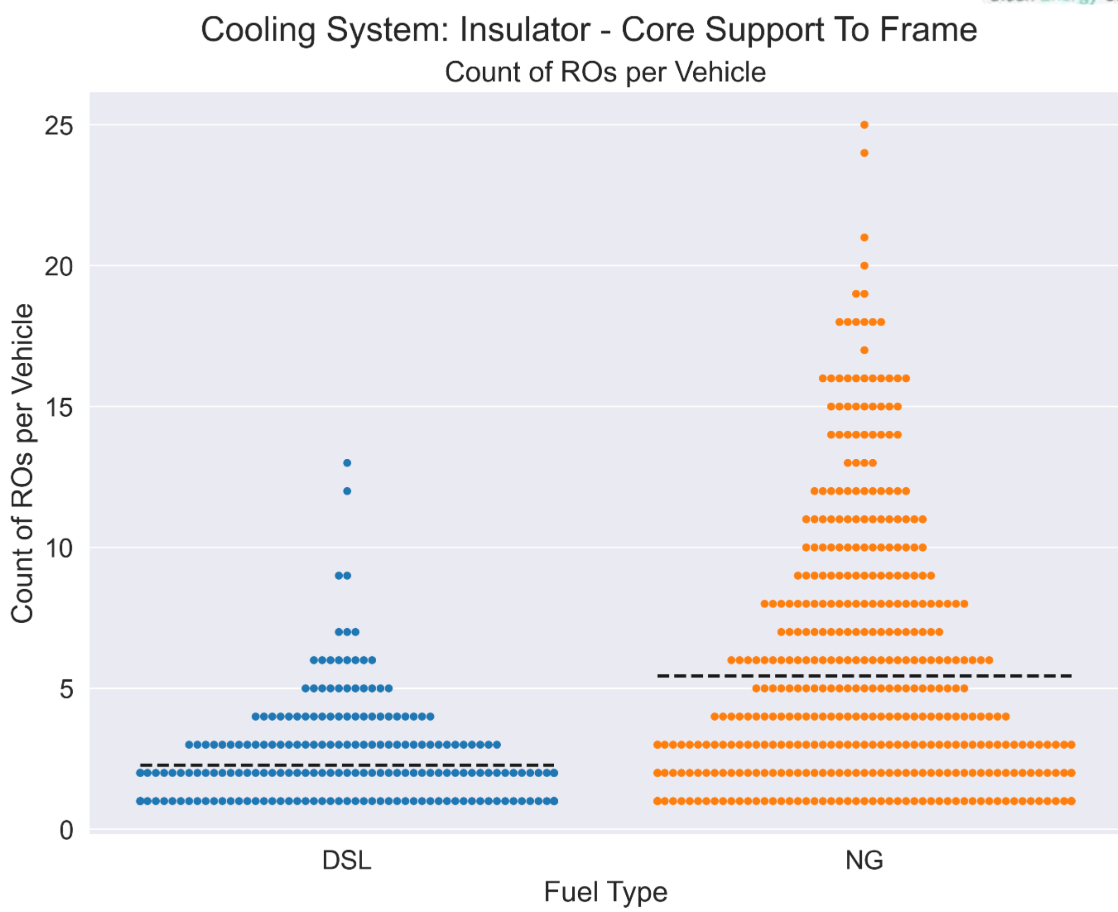


Figure 37: Distribution of Radiator-Core-Component-Related ROs per Vehicle

T-test:

Radiator Core: Count of ROs per Vehicle by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-13.068	7.744e-35

The distributions of radiator-core-related ROs, shown in Figure 37, are right-skewed for both fuel types, which indicates that a larger portion of trucks accumulated less than their respective means of radiator-core-related ROs. But there were significantly more examples of NG vehicles experiencing more than 10 radiator-core-related ROs. The results of the t-test confirm the average numbers of radiator-core-related ROs are statistically different between the diesel and NG vehicles.

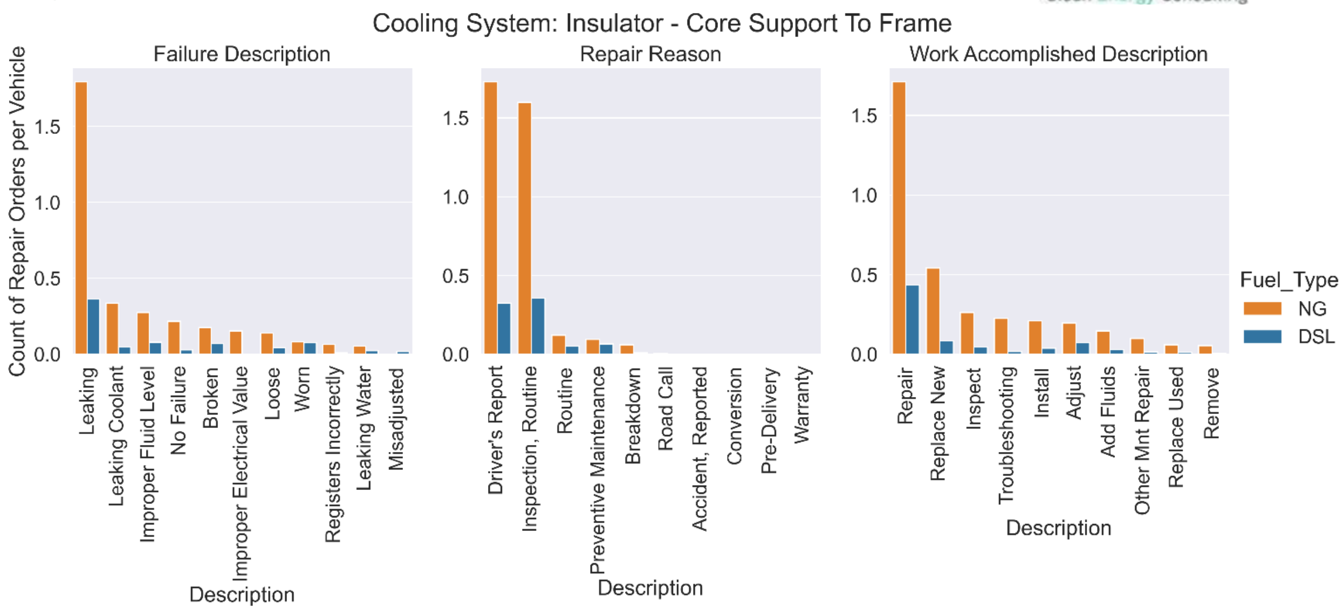
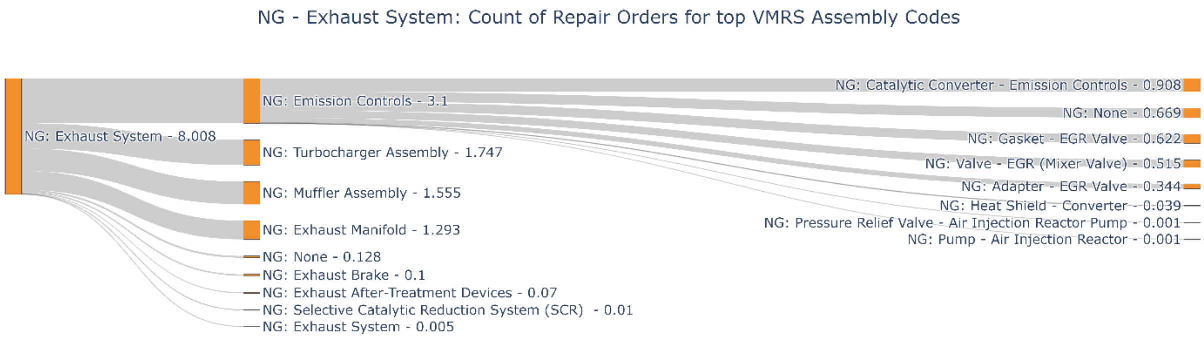


Figure 38: Average Count of Radiator-Core-Component-Related ROs by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

Analyzing the supplemental VMRS codes for this component showed that leaking was the most frequent issue for both fuel types, but NG trucks were five times as likely to experience this issue. This issue was most frequently identified by the drivers or through routine inspections. The component was able to be repaired in most instances.

Exhaust System ROs



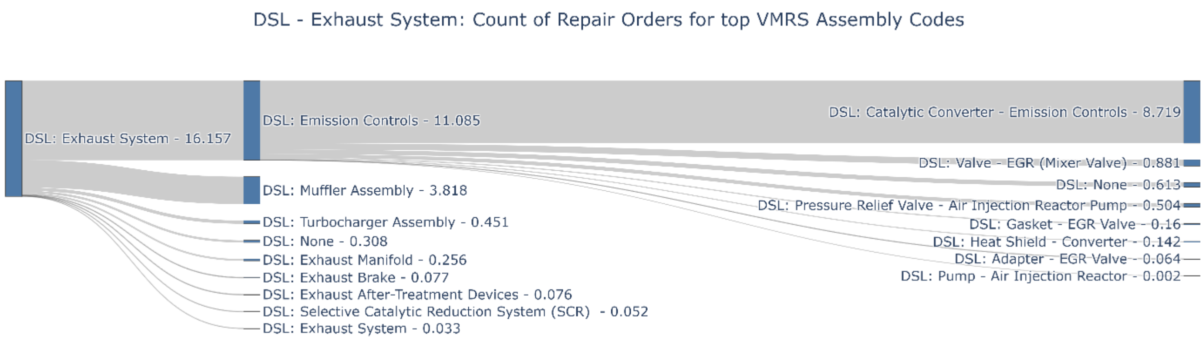


Figure 39: Sankey Plots of Component-Level Differences for Top Assemblies in the Exhaust System
(Note: These plots only include Fleet 1 data.)

Figure 39 shows that the catalytic converter component in the emission controls assembly was the biggest contributor to exhaust system-related maintenance for both fuel types. Diesel trucks required more than three times as much maintenance as the NG vehicles in this dataset. The main reason for this difference is that the exhaust systems on modern diesel trucks are more complex than those on NG-powered trucks.

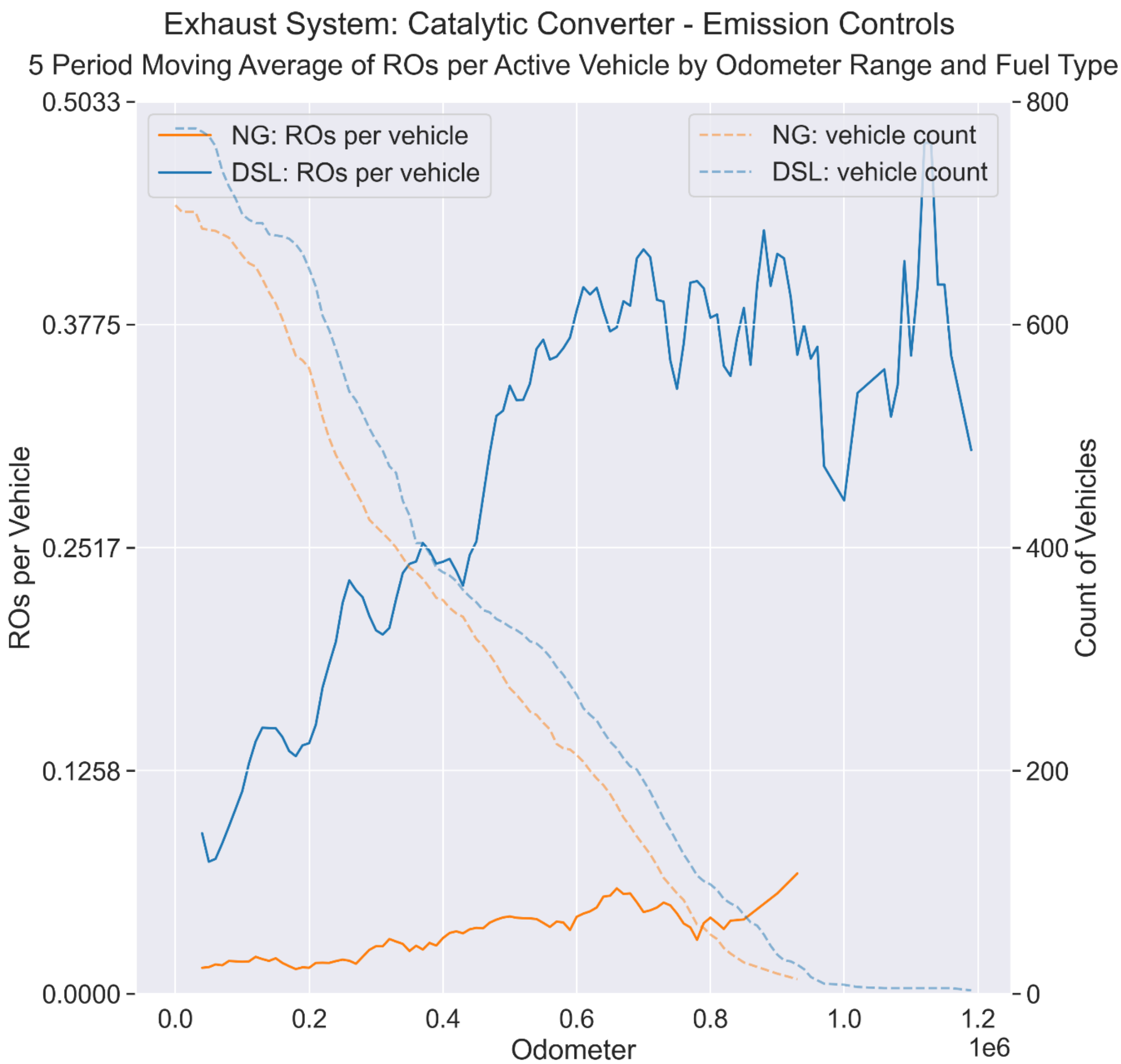


Figure 40: Average ROs per Active Vehicle for the Catalytic Converter Component

Figure 40 shows the trajectory of catalytic-converter-related ROs over a vehicle's lifespan. As expected, diesel vehicles required significantly more catalytic-converter-related maintenance throughout the odometer range. The main reason for this difference is the additional complexity added by components like diesel oxidation catalysts (DOCs) and selective catalytic reduction (SCR) catalysts. In contrast, NG engines only require simple three-way catalysts.

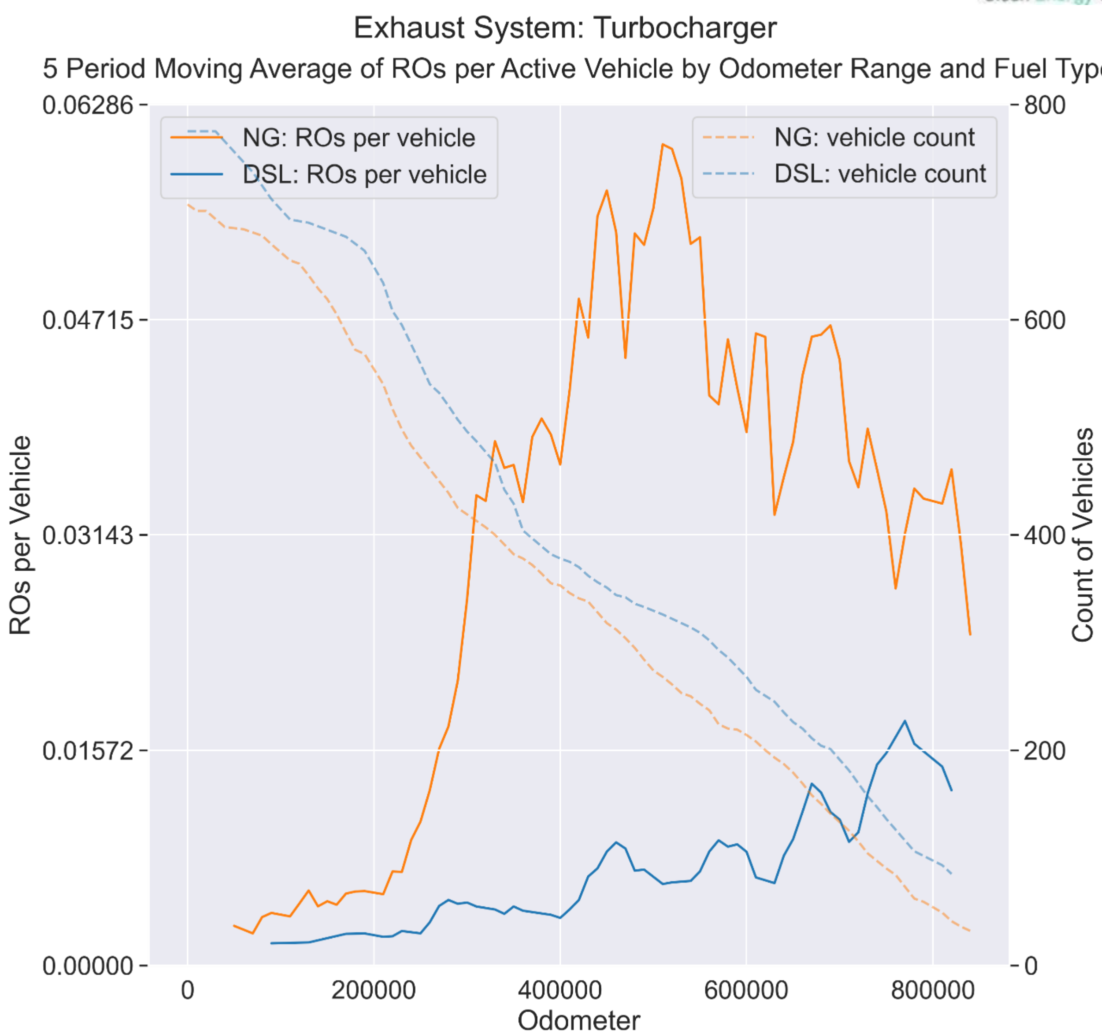


Figure 41: Average ROs per Active Vehicle and Odometer Range for the Turbocharger Component

The turbocharger assembly was the second most common exhaust system-related RO for NG trucks. There were almost four times as many turbocharger-related ROs for NG trucks. Figure 41 shows that there is a sharp increase in turbocharger-related maintenance for NG trucks after the 200,000-mile mark. Diesel trucks show a much more gradual increase. Industry experts speculated that this difference could be due to the increased exhaust temperatures and corrosion that results from NG combustion.

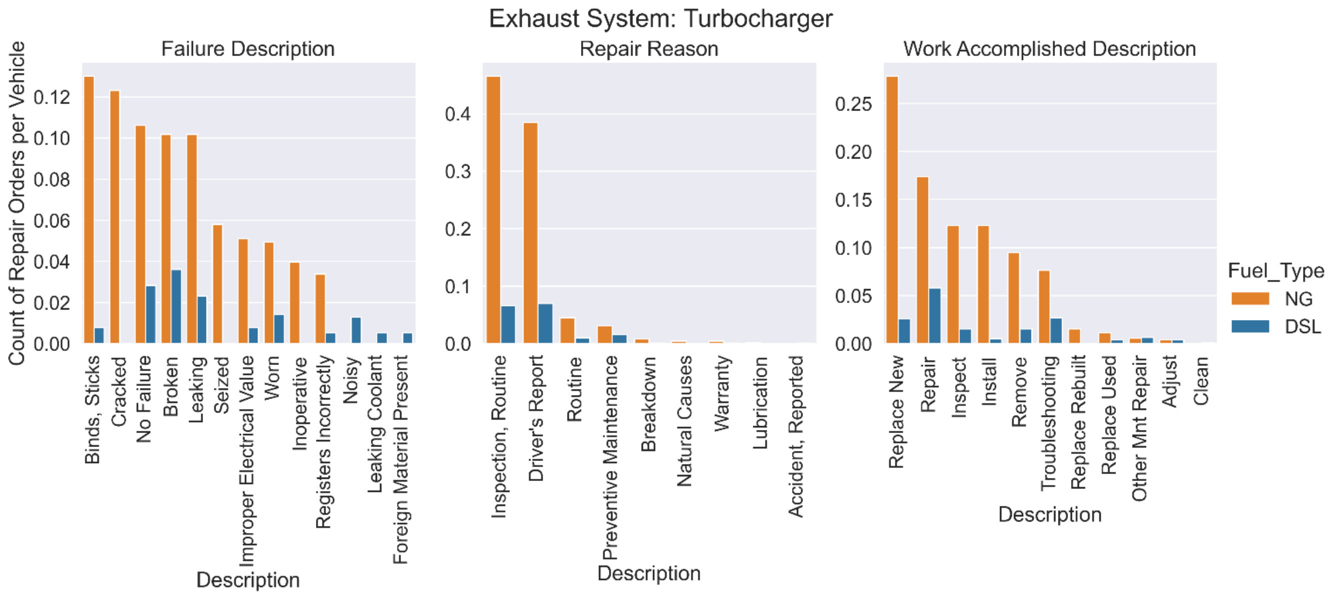


Figure 42: Average Count of Turbocharger-Component-Related ROs by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

The 'Binds, Sticks' failure description was the most frequent for NG trucks. This type of failure likely occurs due to corrosion or buildup of contaminates within the turbocharger. This also corroborates the prediction from industry experts that NG combustion leads to more wear and tear on the turbocharger component. Turbocharger replacement was the most common remedy for correcting these issues.

Powerplant-System ROs

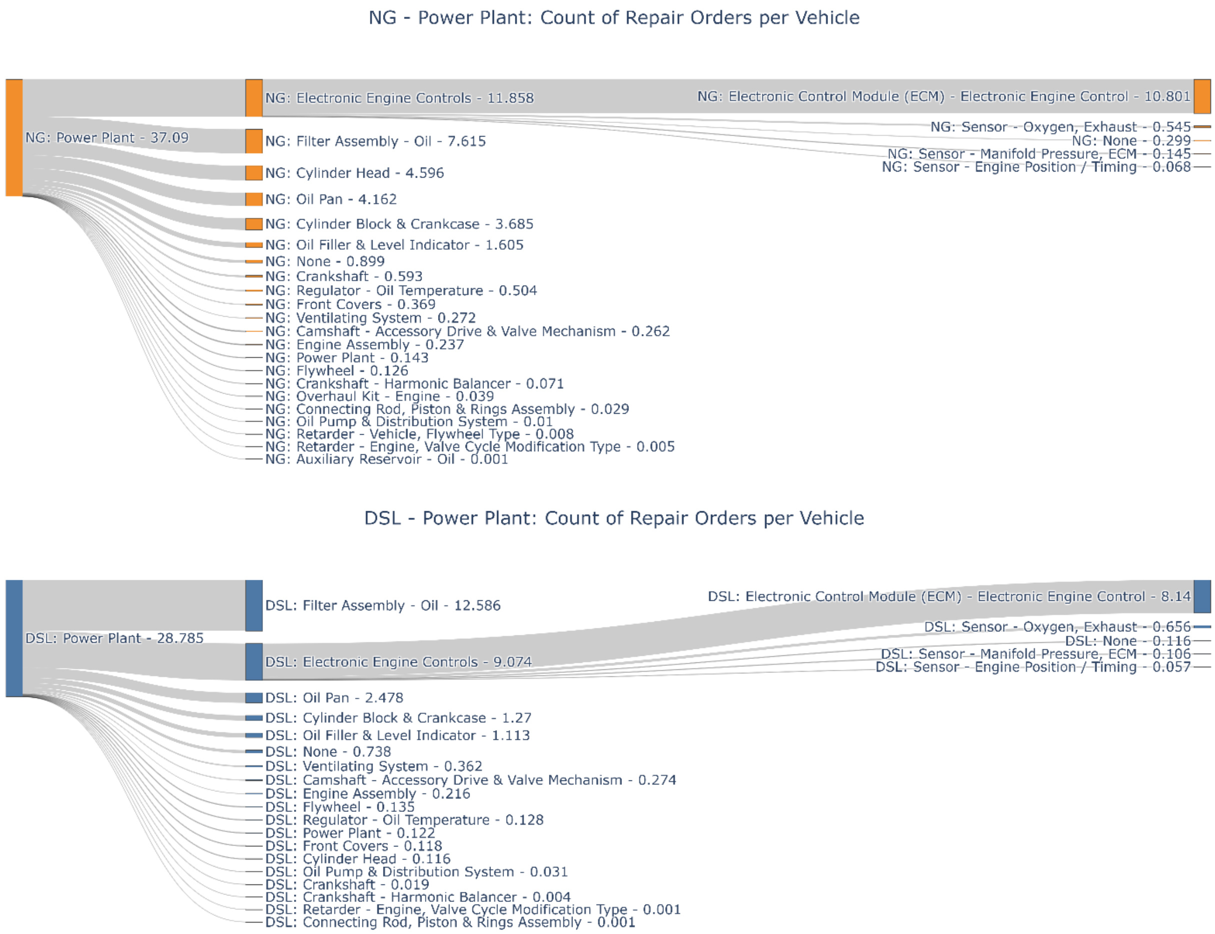


Figure 43: Sankey Plots of Component-Level Differences for Top Assemblies in the Power Plant System
(Note: These plots only include Fleet 1 data.)

Engine electronics and oil filters were the top components in terms for maintenance frequency within the power plant system for both fuel types. Most of the oil filter components likely designate routine oil changes. The diesel trucks in the dataset had slightly more oil changes per vehicle than the NG trucks. This was unexpected because Cummins maintenance schedules require shorter oil change intervals for their NG engines than the typical diesel engines. Another important difference between the two fuel types is that NG-powered trucks had significantly higher cylinder head-related ROs. Cylinder heads were identified as a common point of failure by some of the fleet managers interviewed for this project.

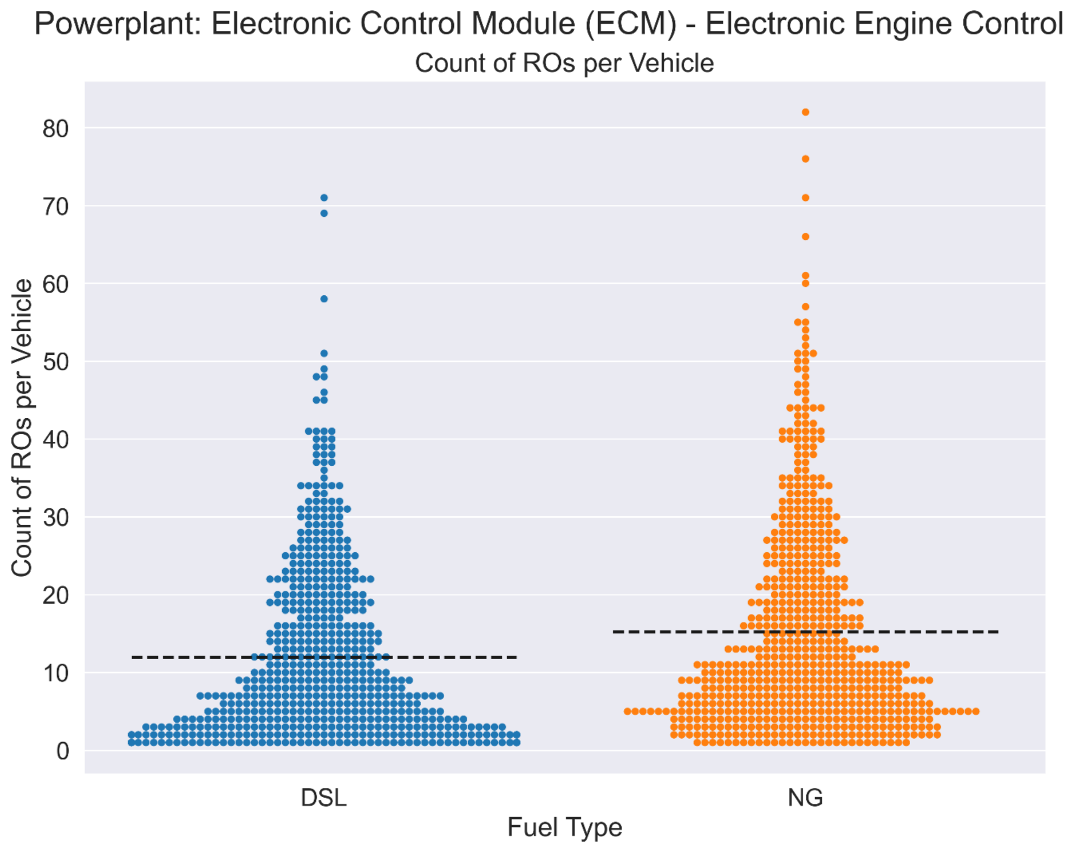


Figure 44: Distribution of Electronic-Engine-Control-Component-Related ROs per Vehicle

T-test:

Electronic Engine Controls: Count of ROs per Vehicle by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-4.725	2.563e-06

The electronic-engine-controls component code covers a broad spectrum of maintenance severity, from simple maintenance reminder resets to critical component failures. The distributions of electronic-control-module- (ECM-)related ROs per vehicle are very similar for both fuel types, but NG-powered trucks had a slightly higher average. The results of the t-test show that there is sufficient evidence to conclude that these averages are statistically different.

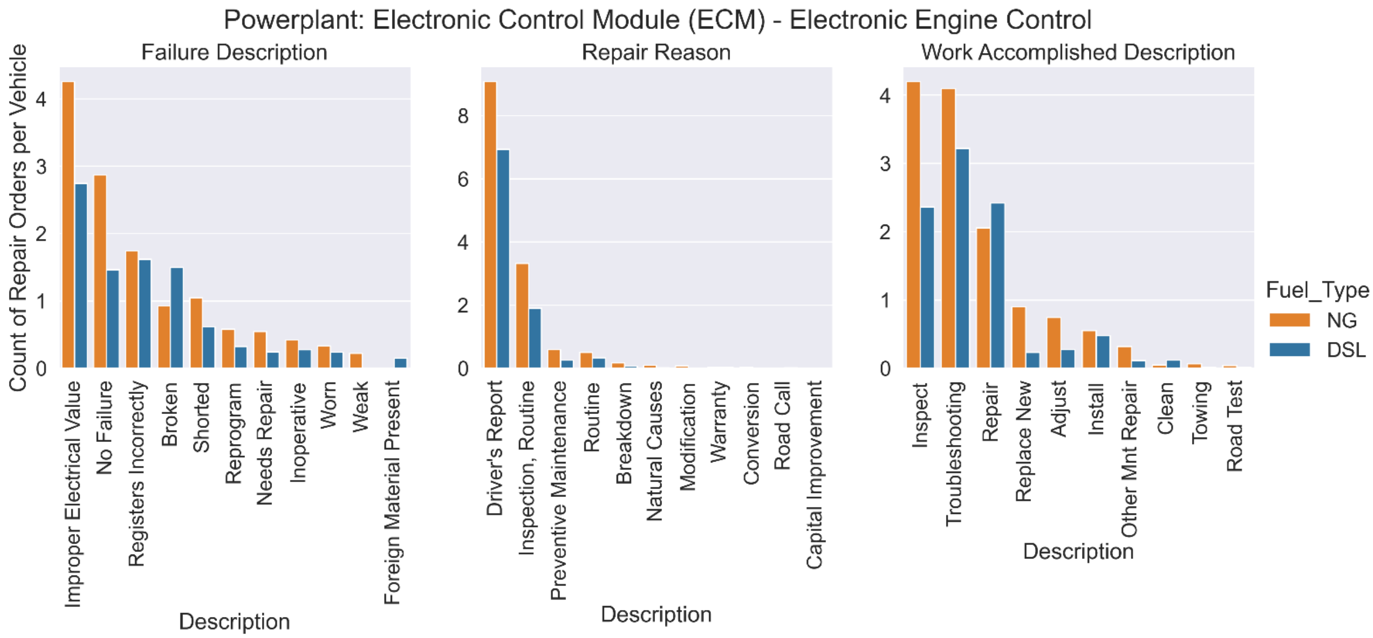


Figure 45: Average Count of ECM-Component-Related ROs
by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

The Work Accomplished codes, shown in figure 45, provide further insights into the reasons for maintenance. 58% of the ECM-related ROs were created for troubleshooting or inspection purposes. Simple maintenance tasks such as reading or clearing check-engine lights are likely captured within these two categories. The 'Repair' and 'Replace New' categories likely indicate component failures. A plausible reason for the differences in repair frequency for this component is that the electronics for NG engines had less development time and experience more bugs than the diesel electronics. Most issues related to this component were identified by drivers. The most common failure type was 'Improper Electrical Value.'

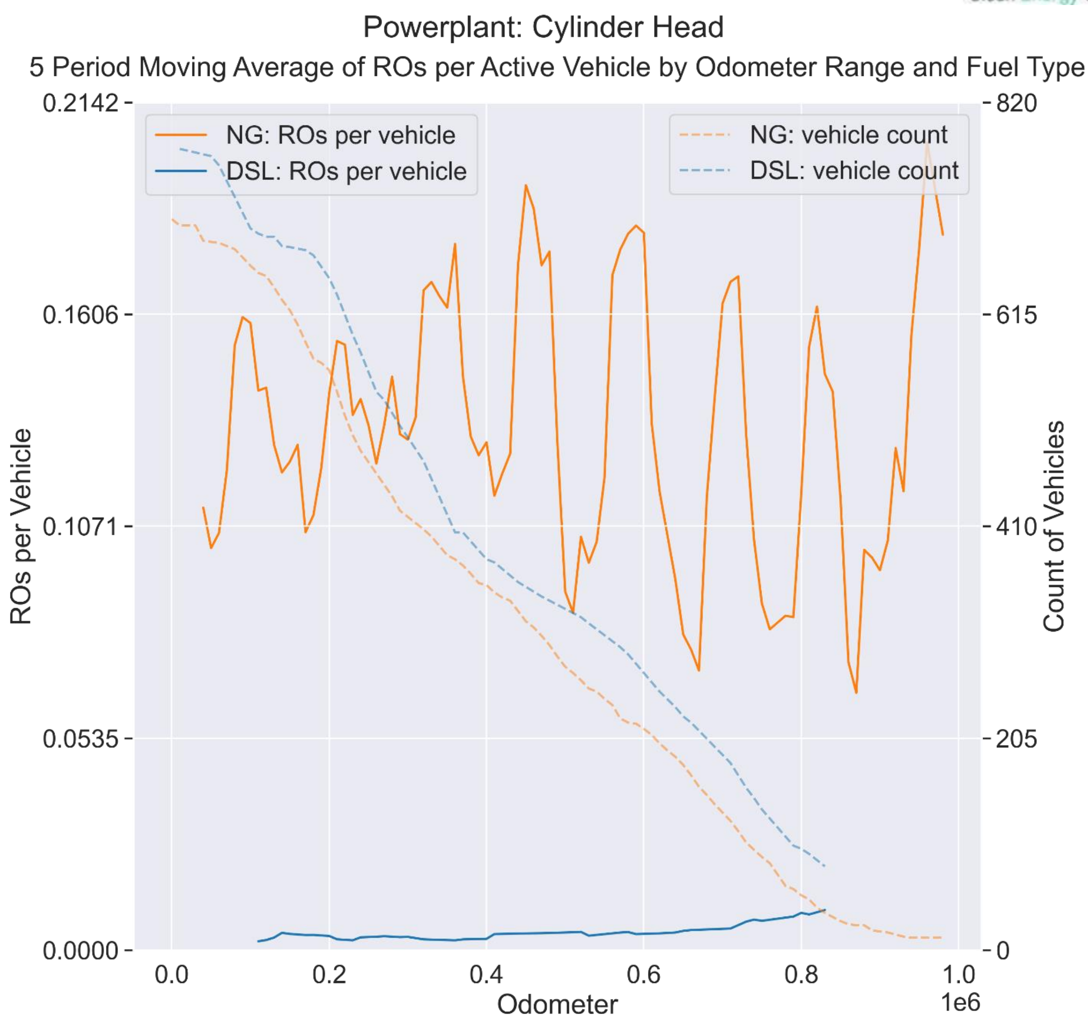


Figure 46: Average ROs per Active Vehicle and Odometer Range for the Cylinder Head Component

Figure 46 shows the frequency of cylinder head-related ROs over the odometer range for each fuel type. The NG trucks required significantly more maintenance for this component throughout the odometer range. The oscillating pattern for the NG trucks suggests that this component required maintenance at regular intervals.

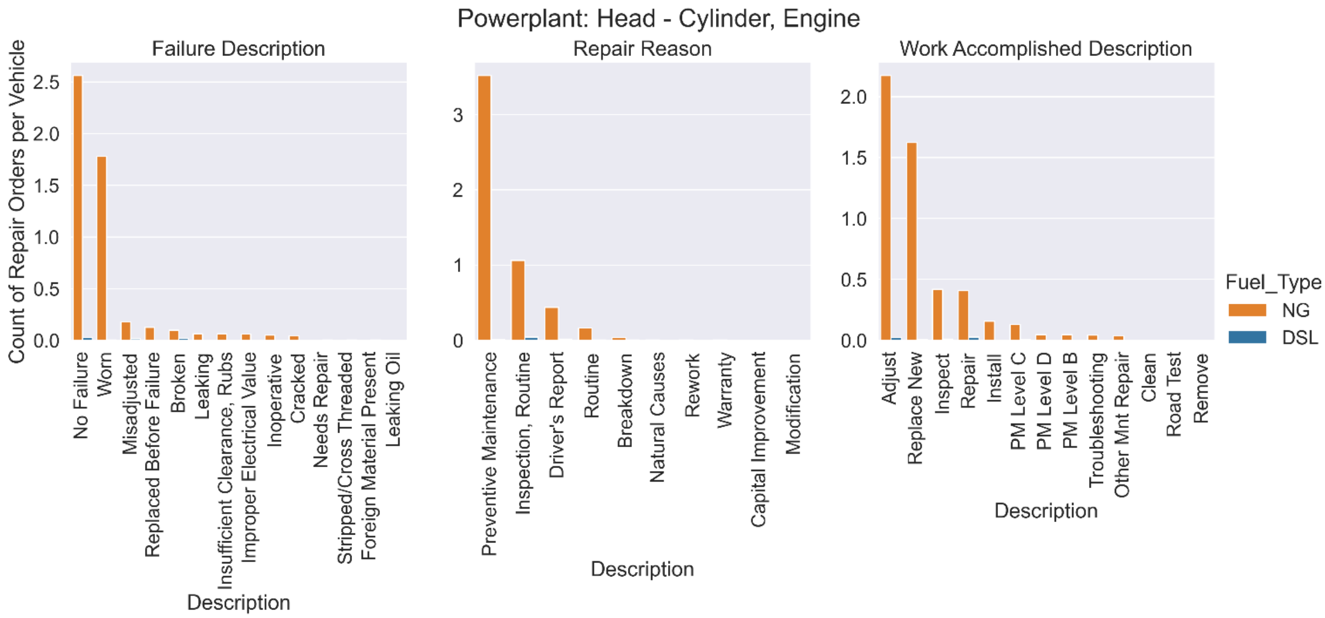
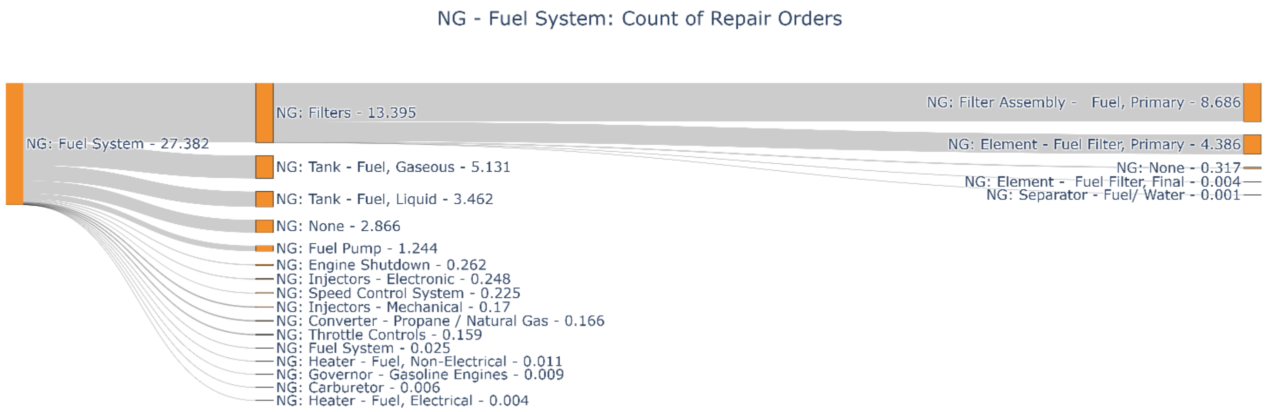


Figure 47: Average Count of Cylinder Head Component-Related ROs
by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

The majority of the cylinder head-related ROs were due to preventative maintenance or routine inspections. 40% of the cylinder head-component-related ROs were coded with the 'Adjust' Work Accomplished description. These ROs likely indicate routine valve clearance adjustments. The 'Worn' designation was the second most common failure type for the cylinder head component after 'No Failure.' More worryingly, 30% of the cylinder head-related ROs had a 'Replace New' Work Accomplished description. The most common parts that could need replacements within the cylinder head are valves, valve seats, or valve springs. It is also possible that the entire cylinder head could have needed replacement if there was severe damage. Components within the cylinder head are often expensive to replace and require extended downtime for the truck.

Fuel-System ROs



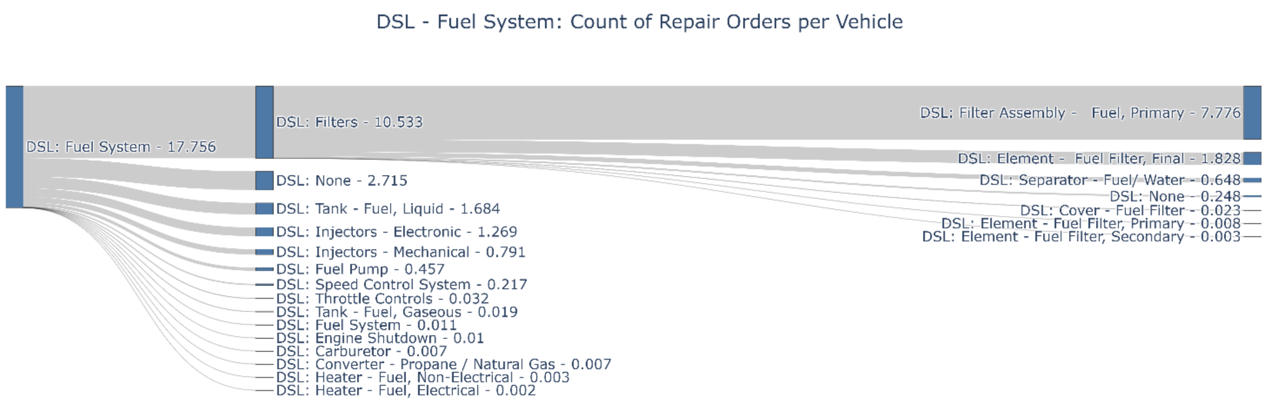


Figure 48: Sankey Plots of Component-Level Differences for Top Assemblies in the Fuel System
(Note: These plots only include Fleet 1 data.)

As shown in Figure 48, fuel-filter-related components were the top contributors to fuel-system maintenance for both fuel types. Fuel filters are generally routine maintenance items that need to be replaced at regular intervals. The NG trucks in the dataset did exhibit more fuel-tank-related maintenance per vehicle than the diesel vehicles.

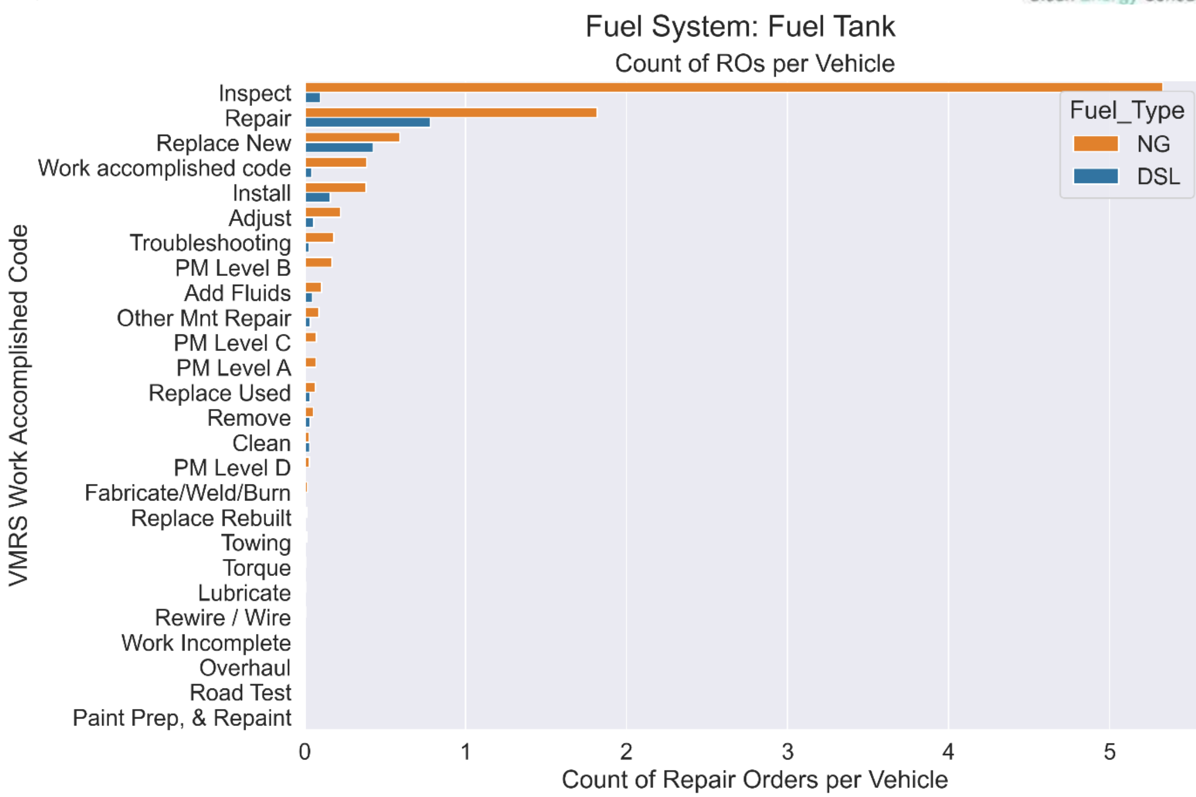


Figure 49: Fuel-Tank-Component-Related ROs per Vehicle by VMRS Work Accomplished Code

Figure 48 shows that the 'Inspect' code was the most frequent work accomplished code. NG trucks have pressurized fuel tanks and require routine inspections to ensure the structural integrity of these tanks. These inspections accounted for most of the differences in fuel-system-related maintenance frequency between diesel and NG trucks.

Component-Level Breakdown Frequency (Fleet 1 Only)

The analysis below focuses on identifying specific component failures that led to breakdowns. Once again, only Fleet 1 was able to provide sufficiently detailed data to distinguish regular maintenance from breakdown-related maintenance.

Breakdowns by VMRS System and Fuel Type

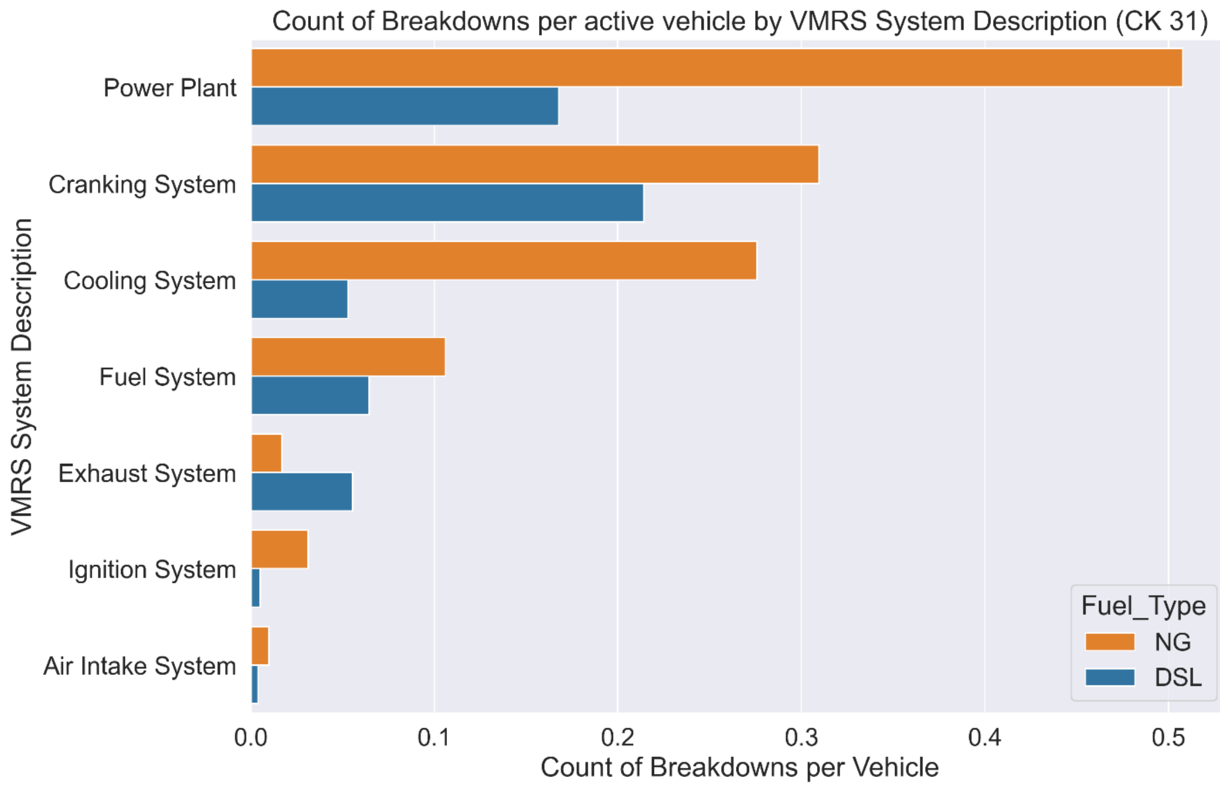


Figure 50: Average Breakdowns per Active Vehicle by VMRS System and Fuel Type

The metrics used in Figure 50 are calculated by first counting the total number of ROs marked as breakdown for the catalogued VMRS systems within each fuel type. These values are then divided by the total number of active vehicles for each fuel type.

The powerplant, cooling, and cranking systems were the top contributors to breakdowns for both fuel types. The powerplant and cooling systems showed the biggest difference in breakdowns between the two fuel types. Failures within the cooling system can have a domino effect on the reliability of other systems (e.g., the power plant or cylinder head). Breakdowns within these components are also usually very expensive to correct due to the cost of parts and the labor hours involved.

Area Chart of Breakdowns by VMRS System and Assembly Codes

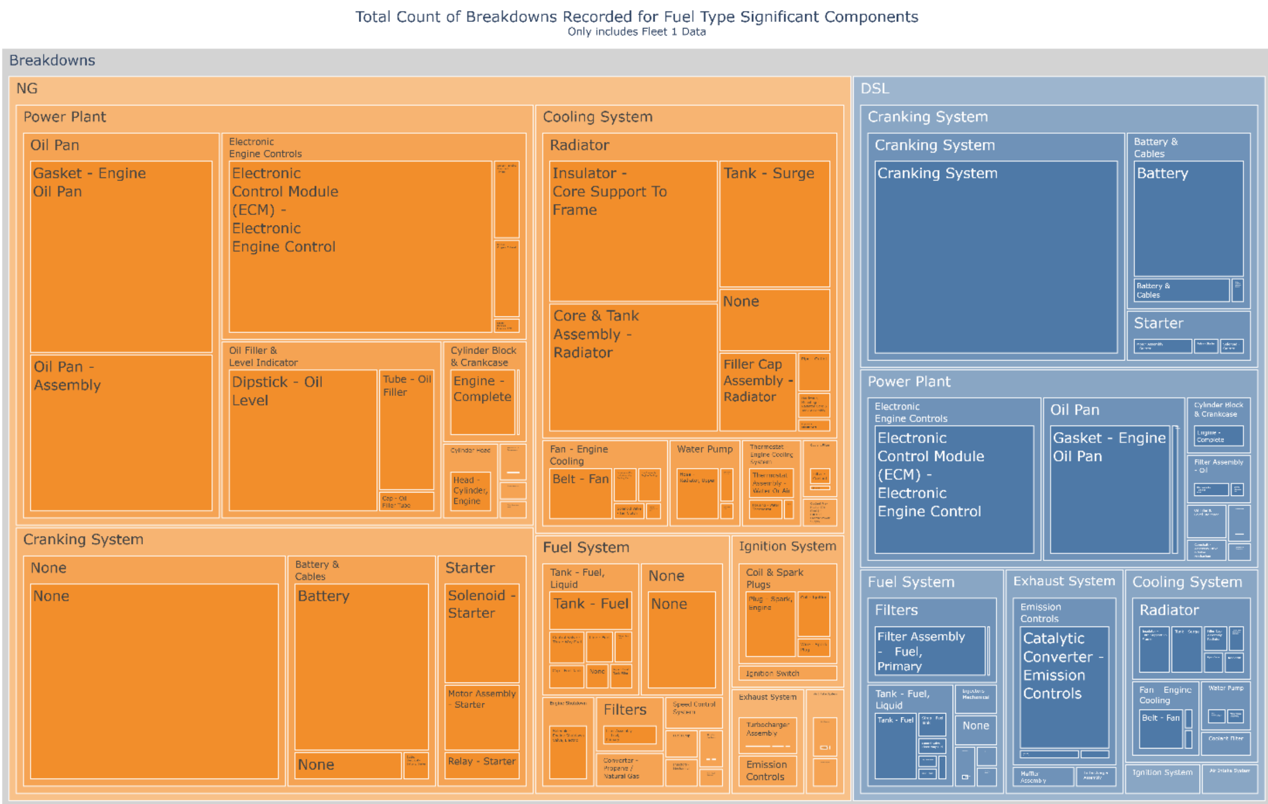


Figure 51: Area Chart of VMRS System and Assembly-Level Breakdown Frequency
(Note: This plot only includes Fleet 1 data.)

Figure 51 above shows that the oil-pan and ECM components made up the largest portion of the powerplant-related breakdowns for NG trucks. It was peculiar that a non-moving component like the oil pan was listed as the failure point for numerous breakdowns. One possible explanation could be that many of the powerplant-related breakdowns involved removing the oil pan to inspect other components, such as the crankshaft or piston rods. Similarly, it is possible that many of the powerplant-related breakdowns involved resetting warnings or re-flashing electronic control units, which would fall within the electronic engine control VMRS component. Most of the cranking-system-related breakdowns likely involved dead batteries or faulty starters.

Average Cumulative Breakdowns per Vehicle by VMRS system

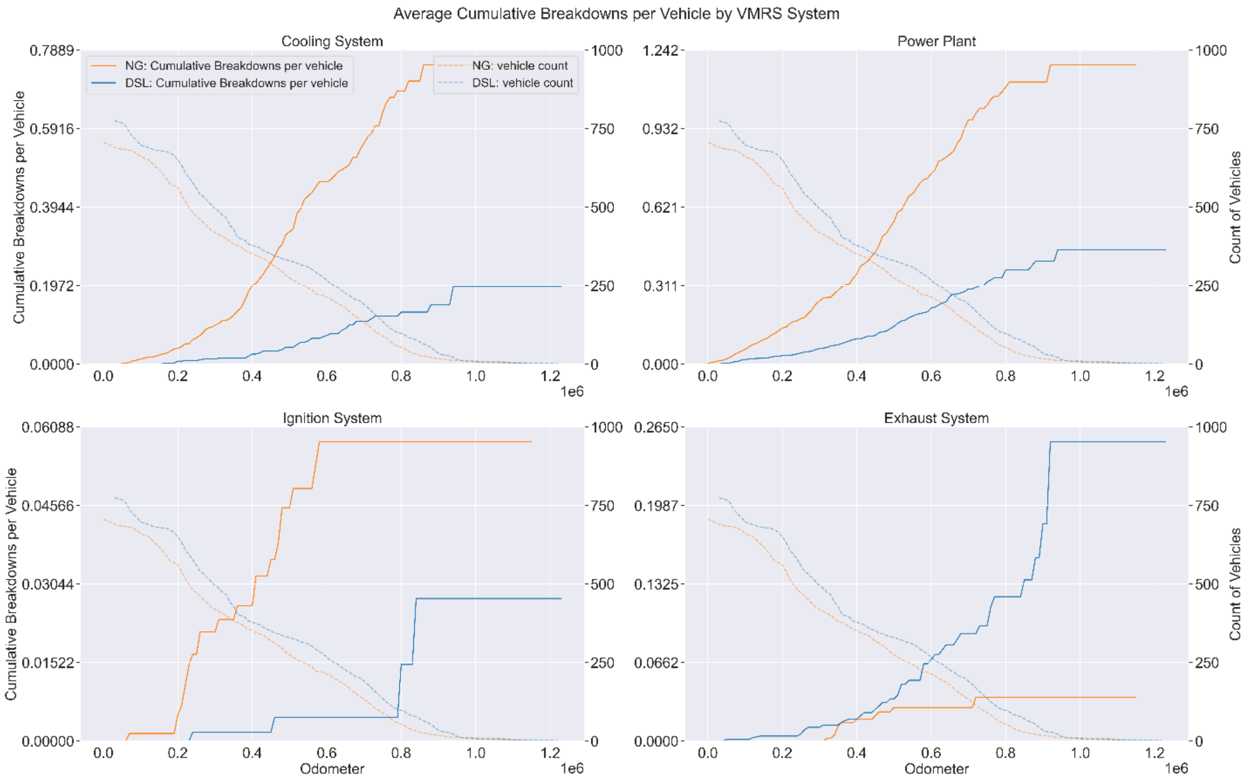


Figure 52: Average Cumulative Breakdowns within the Cooling, Powerplant, Ignition, and Exhaust Systems

Figure 53 shows breakdowns by VMRS system on a cumulative level. The cooling, ignition, exhaust, and powerplant systems showed the largest differences in breakdown frequency between the two fuel types. NG-powered trucks in this dataset started accumulating cooling-, ignition-, and powerplant-related breakdowns early in the odometer range, and the gap between the two fuel types only increased as vehicles accumulated more miles. The exhaust system was the only area where diesel trucks experienced more cumulative breakdowns than the NG trucks. The frequency of exhaust system-related breakdowns starts increasing sharply for diesel trucks at the 400,000-mile mark.

Specific Component-Level Breakdown Frequency Analysis (Fleet 1 Only)

The figures below show the specific component-level differences between diesel and NG trucks that led to breakdowns. Again, this analysis only includes data from Fleet 1.

Ignition-System Breakdowns

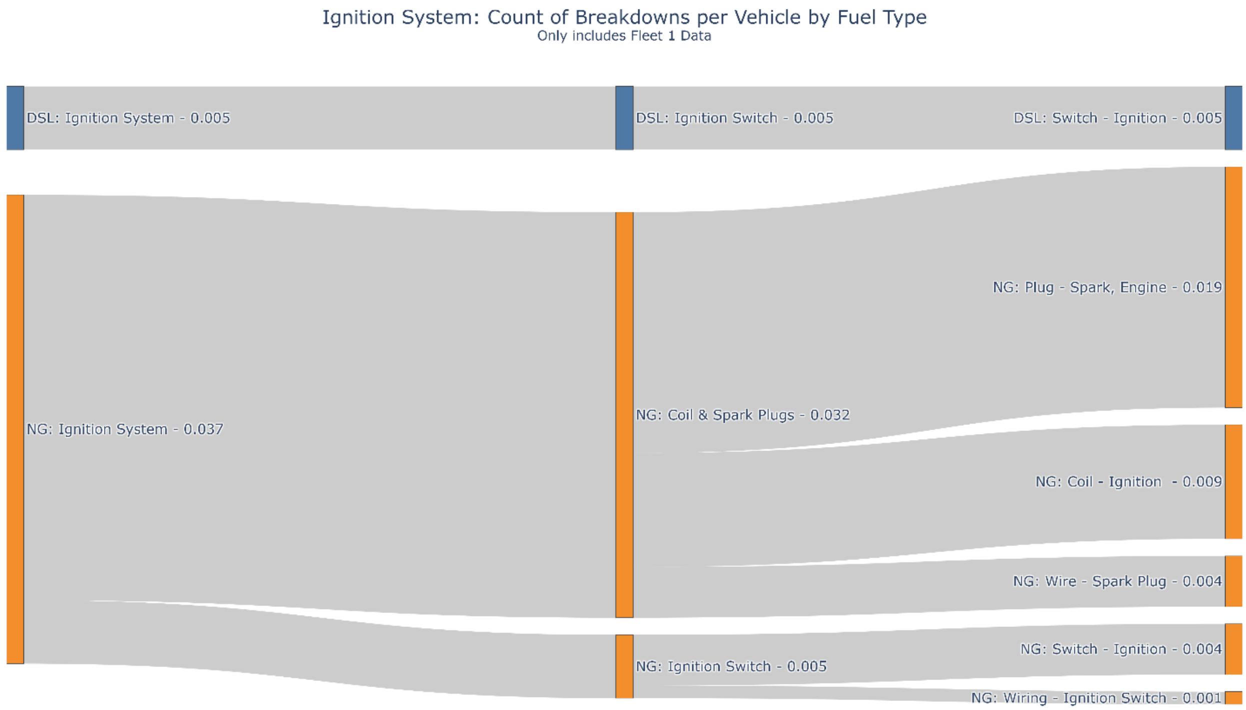


Figure 53: Sankey Plots of Breakdown Frequencies Caused by Components in the Ignition System

Evaluating the ignition-system-related breakdowns on a component level shows that the ignition switch was the only component that failed on diesel vehicles. Spark plugs were the largest cause of ignition-system-related breakdowns for the NG trucks. Industry experts and fleet managers identified spark plug life as a weak point within NG engines. Corrosion caused by impurities in the fuel as well as high combustion temperatures were cited as the primary reasons for shortened spark plug life. Worn out or damaged spark plugs can cause multiple issues, including poor starting and engine misfires, which can lead to breakdowns.

Fuel-System Breakdowns

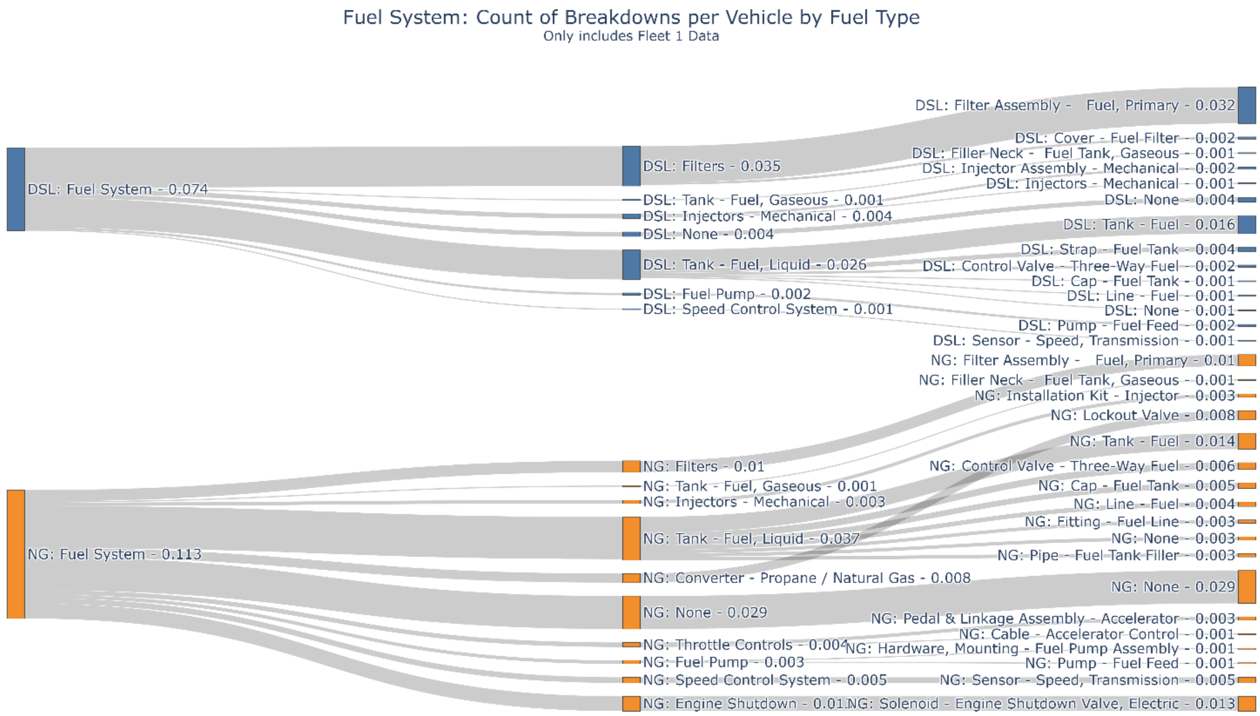


Figure 54: Sankey Plots of Breakdown Frequencies Caused by Components in the Fuel System

Figure 54 shows that the largest contributors to fuel-system-related breakdowns for diesel trucks were fuel filters and fuel tanks. Fuel filters can get clogged and cause fuel starvation and engine shutdowns. Fuel tanks can also leak, making it unsafe to operate the vehicle. Both of these issues are relatively common and easy to remedy. Most of the fuel-tank-related breakdowns for NG trucks were not due to the tanks themselves, but to ancillary components such as fuel lines and control valves.

Exhaust System Breakdowns

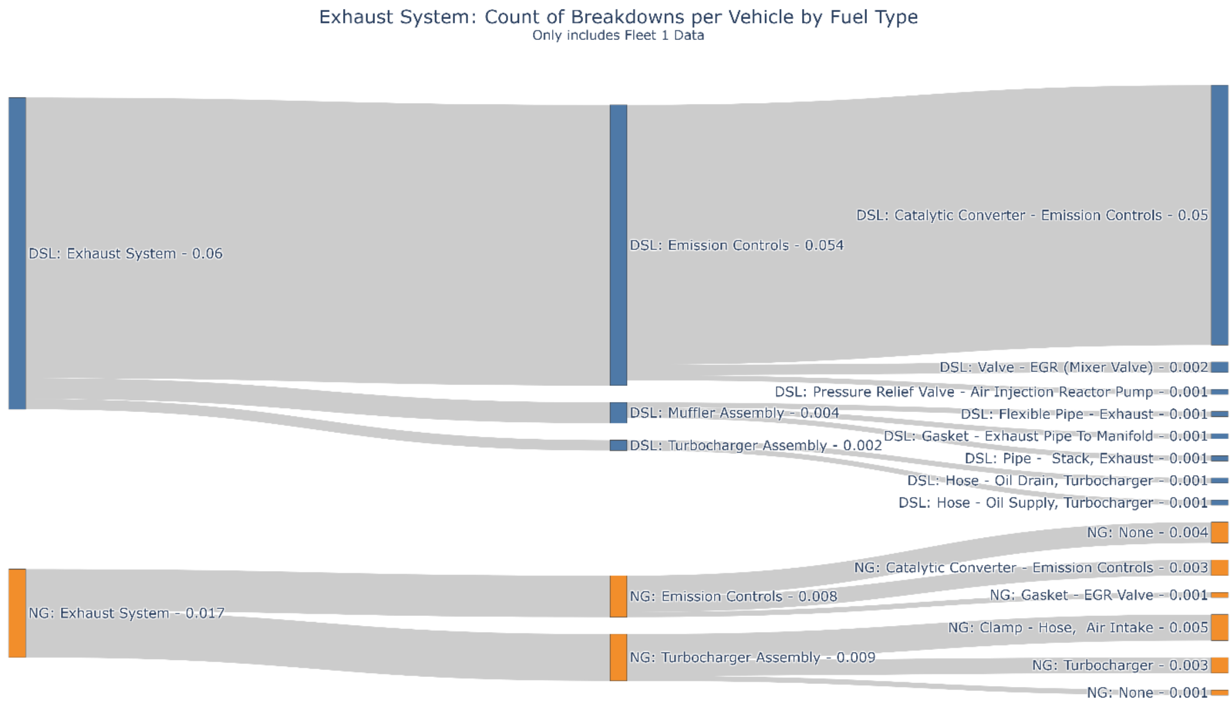


Figure 55: Sankey Plots of Breakdown Frequencies Caused by Components in the Exhaust System

As shown in Figure 55, the diesel trucks experienced more exhaust system-related breakdowns than the NG-powered trucks. The most common failure point was catalytic converters for emission controls. This is similar to the pattern seen in the overall repair frequency analysis for exhaust system-related maintenance. Modern diesel engines require complex emission-controls systems with multiple stages of catalytic converters, and this complexity creates more points of failures in the exhaust system.

Cooling System Breakdowns

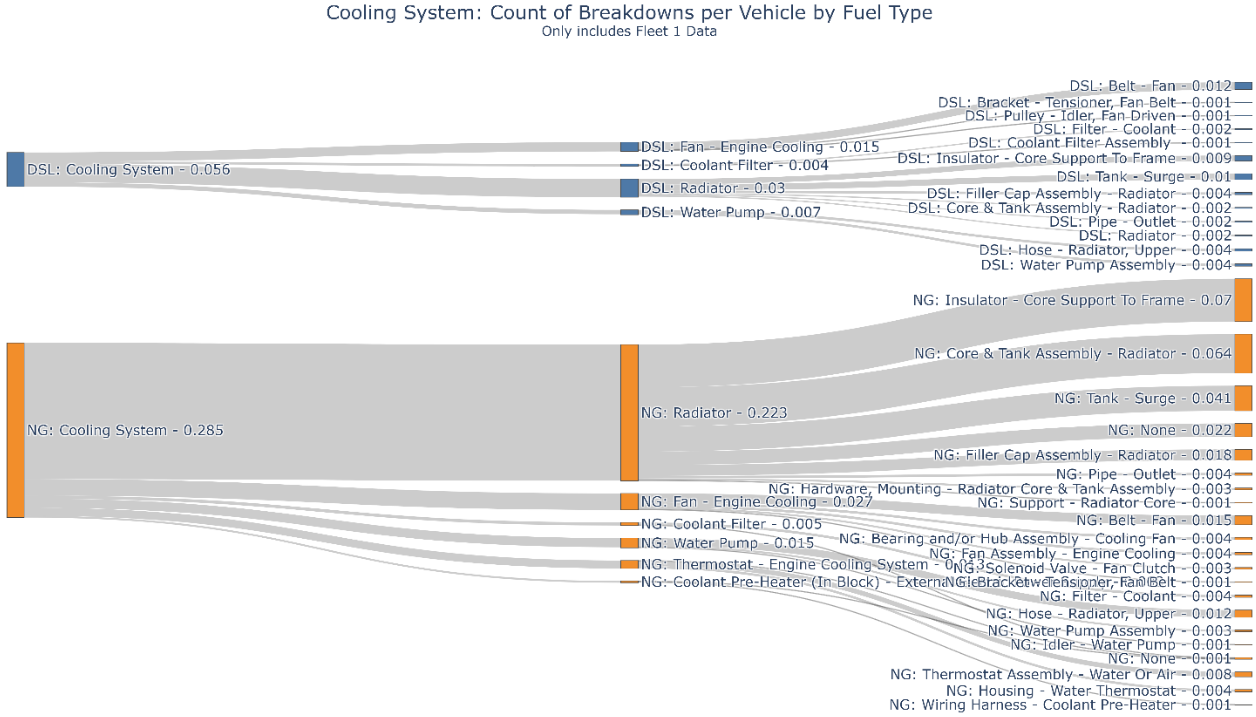


Figure 56: Sankey Plots of Breakdown Frequencies Caused by Components in the Cooling System

The cooling systems for diesel and NG trucks are very similar in terms of components and technology, but they typically have to deal with different thermal ranges. Natural gas combustion generates significantly more heat than diesel combustion. As a result, the cooling systems in NG trucks experience more stress overall, which can lead to more failures. This is reflected in the differences seen in cooling system-related breakdowns between diesel and NG trucks in the dataset. The points of failure were similar between the two fuel types, but NG-powered trucks exhibited a higher number of failures.

Powerplant Breakdowns

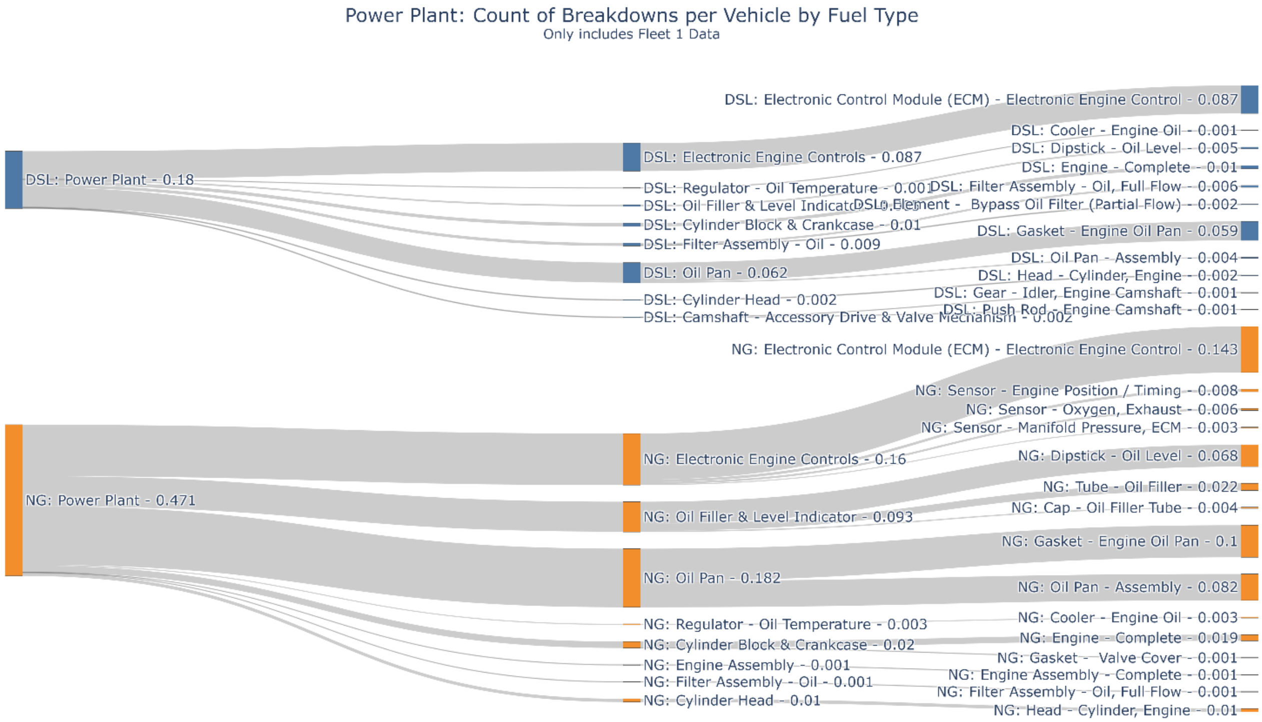


Figure 57: Sankey Plots of Breakdown Frequencies Caused by Components in the Powerplant System

Figure 57 shows that the natural gas trucks in this dataset also experienced more powerplant-related breakdowns than their diesel counterparts. The most common point of failure for both fuel types was electronic engine controls. This is similar to what was seen in the overall and component-level analyses.

Maintenance Cost Analysis

Maintenance costs are an important factor for fleet operators when comparing diesel and NG fuel technologies. The frequency of ROs and uptime/downtime metrics discussed previously can influence important factors in fleet operations, such as the number of vehicles needed in a fleet and the number of technicians and maintenance bays required. However, the costs required to repair vehicles and keep them operating safely also have a direct impact on a company's bottom line, in terms of operating costs per mile traveled. Similar to the maintenance frequency analysis above, the maintenance cost analysis that follows is broken up into overall and component-level analyses. Due to the various nuances in the data provided by the participating fleets, it was not feasible to make comparisons across the fleets for many of the maintenance-cost-related metrics.

Overall Maintenance Costs

This first section of the cost analysis considers all recorded maintenance costs. Similar to the repair frequency analysis, it was not possible to make direct comparisons across fleets due to variations in the ways costs were recorded. Fleet 0 indicated their labor costs include all overhead. The manager from Fleet 1 indicated that their labor costs include most but not all overhead; they also indicated that their hourly rate is likely different from the industry standard. Fleet 2 did not have mechanics or technicians on staff, so the project team was not able to confirm what cost components were included in the labor rates they reported. There are likely also related differences in the reported parts costs of each fleet.

Total Maintenance Cost per Year

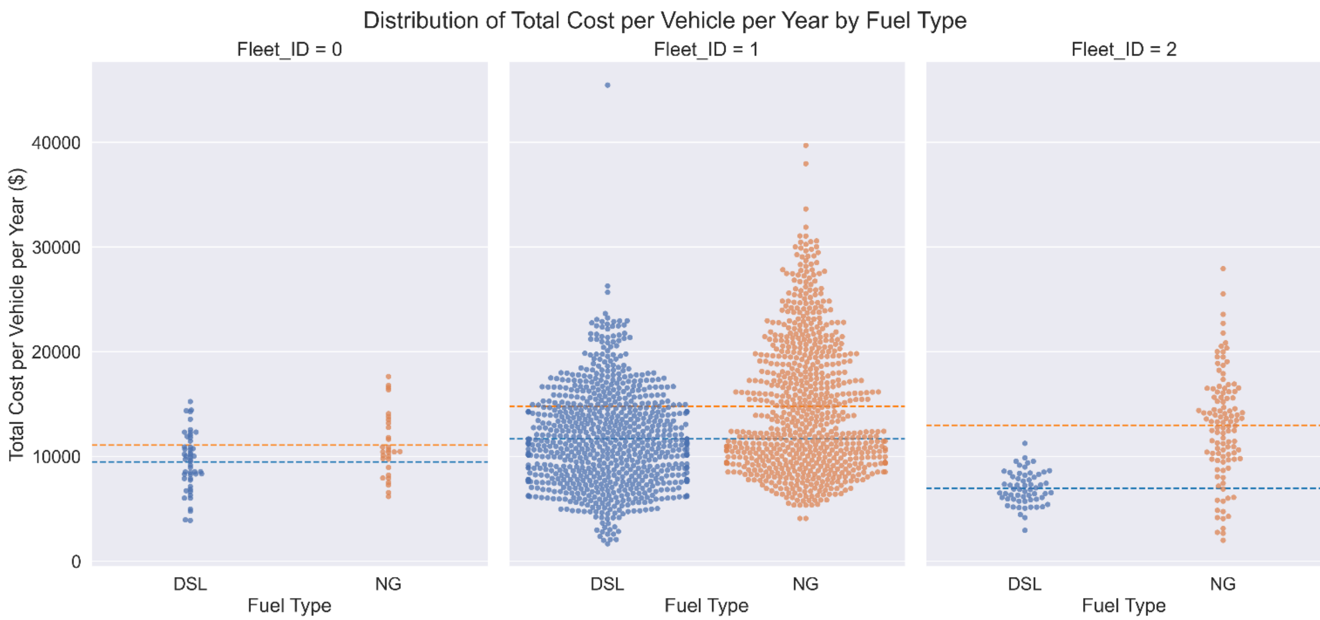


Figure 58: Distribution of Average Yearly Maintenance Costs per Vehicle
(Each point represents a single vehicle.)

Figure 58 shows the differences in yearly maintenance expenditures between diesel- and NG-powered trucks. This metric is calculated by summing the costs for each truck and dividing by the number of years the truck has been active in the fleet. Both parts and labor costs are included in this metric. Each point represents the average yearly expenditure for one vehicle.

All of the fleets included in this study spent more annually on NG vehicle maintenance than on diesel vehicle maintenance. Fleet 0's data showed the smallest difference in average yearly maintenance expenditures between their diesel- and NG-powered vehicles. Fleet 2 showed the largest difference between the two fuel types. Their NG trucks also had a significantly broader distribution for yearly maintenance costs compared to their diesel trucks. This difference is partially explained by variations in truck age ranges. The diesel trucks in Fleet 2 were all the same age, while the model year for their NG trucks ranged from 2014 to 2020.

T-tests:

Maintenance Cost per Year by Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 1 vs. Fleet 0	8.616	4.103e-14
Fleet 1 vs. Fleet 2	5.625	5.605e-08
Fleet 0 vs. Fleet 2	-1.492	0.137

Maintenance Cost per Year by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	-2.330	0.024
Fleet 1: DSL vs. NG	-10.838	2.802e-26
Fleet 2: DSL vs. NG	-11.481	2.609e-22

Results from the t-tests show that the average-cost-per-vehicle-per-year metric for Fleet 1 is statistically different from that of Fleet 0 and Fleet 2. All three fleets had statistically different averages for their NG and diesel trucks. The result for Fleet 0 is only significant to around a 95% confidence level.

Maintenance Cost per Vehicle Miles

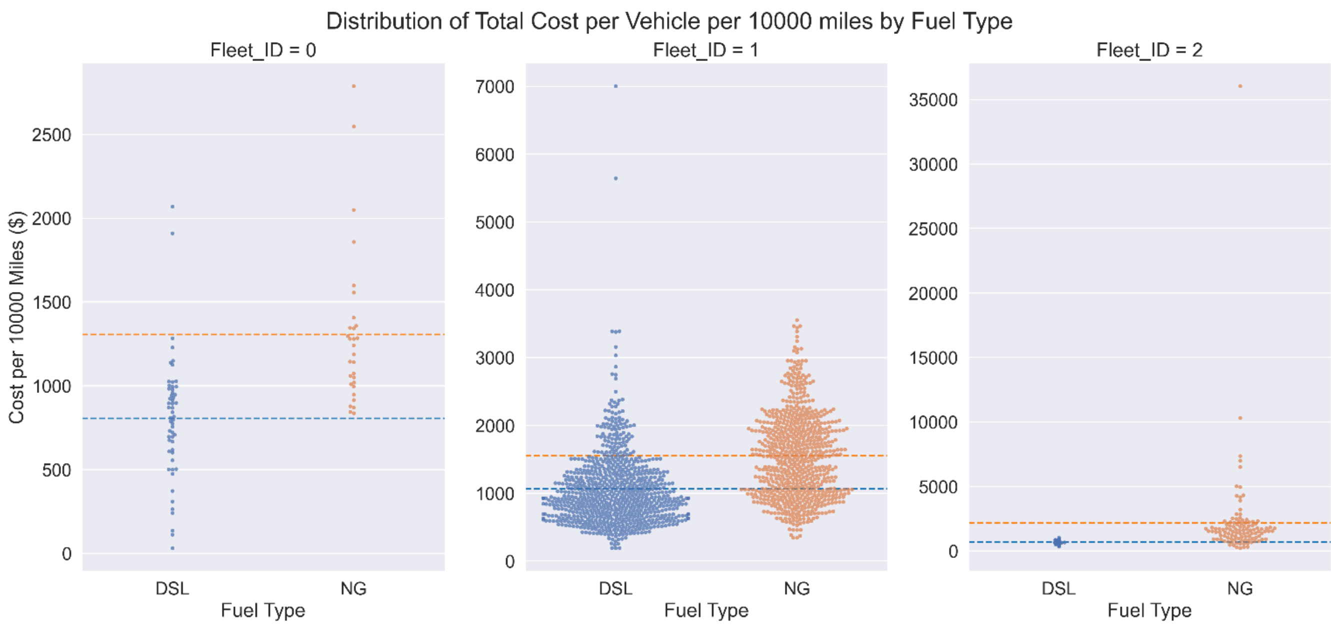


Figure 59: Distribution of Maintenance Costs per 10,000 Vehicle Miles by Fleet and Fuel Type

Figure 59 shows the average maintenance spending per 10,000 vehicle miles. This metric is calculated by summing all parts and labor costs then dividing by total accumulated miles to determine an average cost per mile for each truck. This value is then multiplied by 10,000 to get an average cost per 10,000 miles.

Fleet 0 had the smallest overall range of spending, though there was relatively little overlap between their distributions for diesel and NG maintenance spending. Fleet 1 exhibited more similar distributions between the two fuel types. Their NG trucks averaged $500 of additional maintenance per 10,000 miles compared to their diesel trucks. Fleet 2 showed the largest differences in distribution between the two fuel types. Their diesel trucks were very tightly clustered in the $700 range, but their NG trucks showed the widest distribution of all the fleets in the dataset.

T-tests:

Maintenance Cost per 10,000 Miles by Fleet		
Groups Compared	**T-value**	**P-value**

Fleet 1 vs. Fleet 0	5.939	3.900e-08
Fleet 1 vs. Fleet 2	-1.345	0.180
Fleet 0 vs. Fleet 2	-4.006	8.285e-05

Maintenance Cost per 10,000 miles by Fuel Type for Each Fleet		
Groups Compared	**T-value**	**P-value**
Fleet 0: DSL vs. NG	-5.080	5.963e-06
Fleet 1: DSL vs. NG	-15.328	3.438e-49
Fleet 2: DSL vs. NG	-8.128	6.258e-13

The results of the t-tests show that the averages for Fleet 0 are statistically different from Fleet 1 and Fleet 2, though differences seen between the latter two fleets were not statistically significant. The t-tests also show that the averages between fuel types are statistically different for all three fleets.

Average Maintenance Spending per Vehicle

Figure 60: Average Maintenance Spending per Active Vehicle by Odometer Range

In Figure 60, the average maintenance spending by odometer range shows how maintenance costs change over a vehicle's lifespan. The maintenance costs are first summed for each fuel type and odometer range. These summed cost values are then divided by the number of active vehicles for each fuel type and odometer range. Active vehicles represent the total number of vehicles that crested a certain odometer range within a fleet. The count of active vehicles is indicated by the dashed lines.

Fleet 0 had a relatively small sample size of vehicles and Fleet 2 had a large percentage of incomplete maintenance records—so their results should be interpreted with care. Fleet 1 offers the best point of comparison between the two fuel types because it had the largest number of vehicles and the most complete maintenance records.

Natural gas trucks in all three fleets required more maintenance expenditures throughout most of the odometer range. This pattern is similar to what was seen in the maintenance frequency analysis. The gap in maintenance spending between NG and diesel trucks for Fleet 1 increased significantly after the 180,000-mile mark. Fleet 2 also had higher spending for their NG trucks throughout the odometer range. Their gap in spending between the two fuel types is widest after the 400,000-mile mark.

Another interesting detail is that the average spending per vehicle takes a downward trend in the upper odometer ranges. This is unexpected given that older vehicles with high mileage typically require more maintenance. One explanation could be that only the most reliable vehicles are retained by the fleets beyond a certain mileage range and that these unusually trouble-free vehicles skew the average downwards.

Cumulative Maintenance Costs

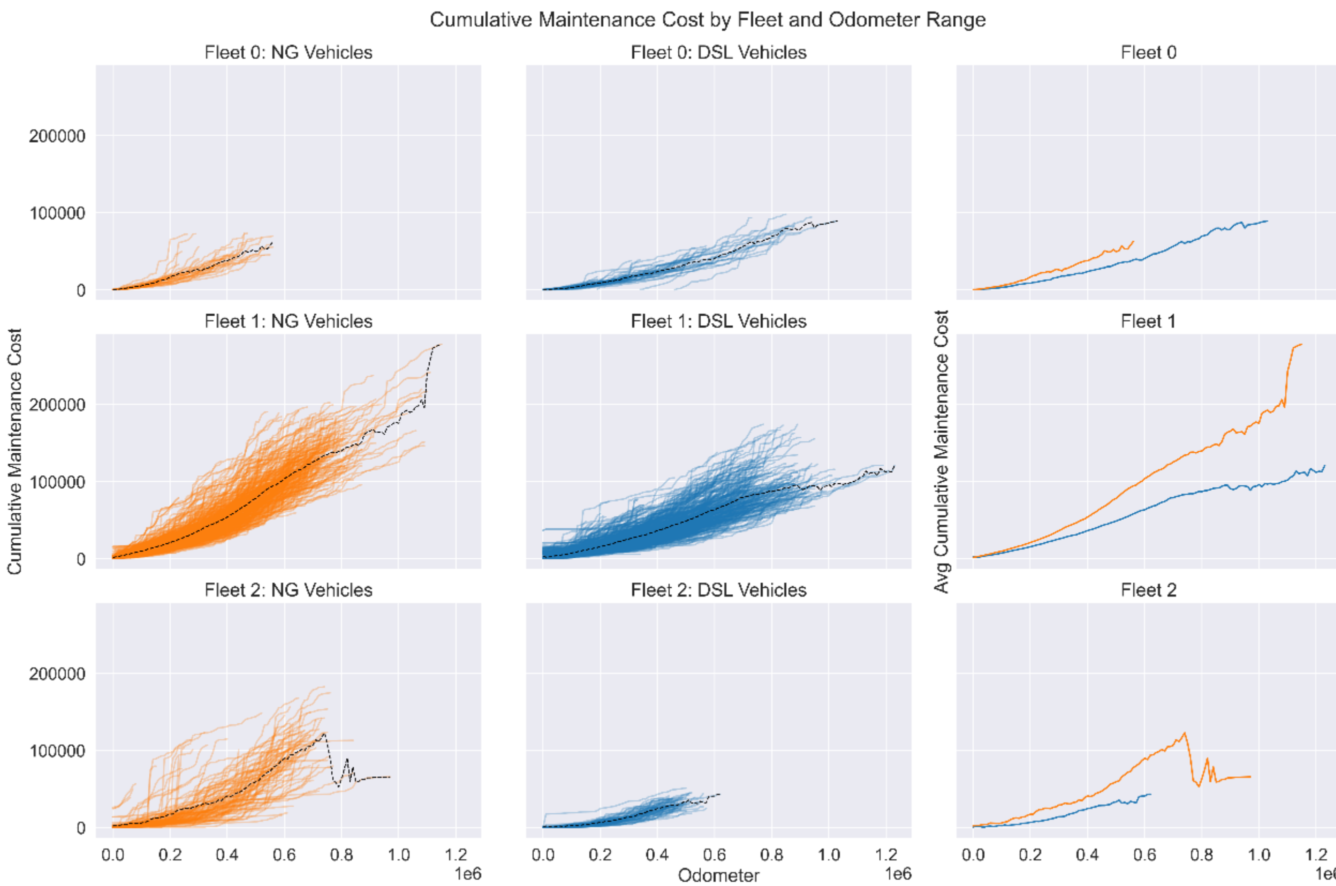


Figure 61: Cumulative Maintenance Cost Trajectories of All Vehicles in the Dataset

Figure 61 shows the cumulative maintenance cost trajectory of each vehicle in the dataset. The data was first grouped by vehicle ID and odometer range, and then the maintenance costs were summed. The cumulative sum of costs was then taken across the full odometer range for each vehicle. The accuracy of this metric is highly dependent on the accuracy of the reported costs and the odometer values for each

RO. Fleet 0 had the most error-free cost and odometer data. Many of the vehicles in Fleet 1 and Fleet 2 had odometer errors, but most of these errors were amenable to the algorithmic correction described above. Vehicles with odometer errors that could not be corrected were excluded from this comparison.

There were similar trends for average cumulative maintenance costs for Fleet 0 and Fleet 1. The maintenance costs for both fuel types stay relatively comparable until the 250,000-mile mark. After this point, the expenditures for NG trucks increase at a faster rate relative to the diesel trucks, and the trend lines start to diverge. The NG trucks in fleet 0 do not accumulate as many miles as the diesel-powered trucks, but it is still possible to see the separation in maintenance spending between the two fuel types. Fleet 1 does not have many vehicles with more than 800,000 miles, so the variability of the average cumulative costs increases after this point. Several NG trucks in Fleet 2 saw a large spike in expenditures around the 200,000-mile mark. These spikes are likely due to erroneous cost data. The diesel vehicles in Fleet 2 have maintenance-cost accumulations very similar to the NG vehicles.

Average Cumulative Maintenance Spending per Active Vehicle

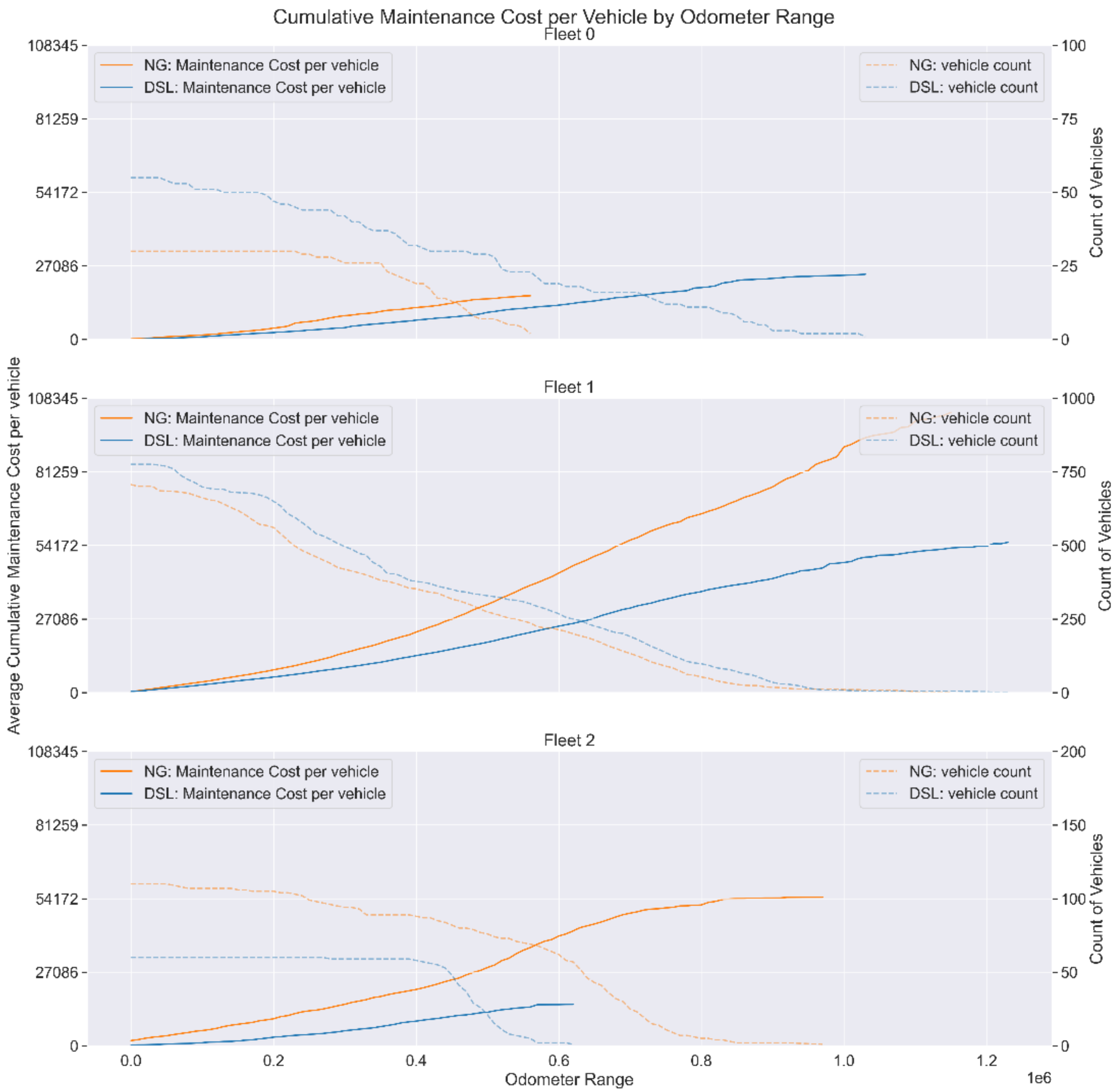


Figure 62: Cumulative Maintenance Spending per Active Vehicle and Odometer Range

The average cumulative maintenance spending by odometer range in Figure 62 shows how maintenance costs accumulated throughout a vehicle's lifespan. This metric is calculated by summing these costs after grouping the data by fleet, fuel type, and odometer range. These values are then divided by the number of active vehicles within each group. Finally, the average-costs-per-vehicle values are sorted by odometer range, and the cumulative sum is taken for each group.

Cumulative maintenance spending is broadly similar for both fuel types at the lower odometer ranges for all three fleets. The point where the spending deviates between the two fuel types is also similar for

Fleet 0 and Fleet 1. Both fuel types in Fleet 0 and Fleet 1 required similar maintenance expenditures until the 200,000-mile mark. After this point, NG trucks for both fleets had higher maintenance costs. The gap in cumulative spending between the two fuel types increased as the vehicles aged within all three fleets.

Overall Breakdown Costs (Fleet 1 Only)

Breakdowns tend to be the most expensive type of maintenance for any vehicle, and minimizing these costs is a key objective for fleets. The analysis below looks at the differences in breakdown-related expenditures between diesel- and NG-powered trucks. The breakdown analysis was only performed on Fleet 1's dataset because it was the only one that distinguished routine maintenance from breakdown maintenance.

Total Breakdown Costs per Year

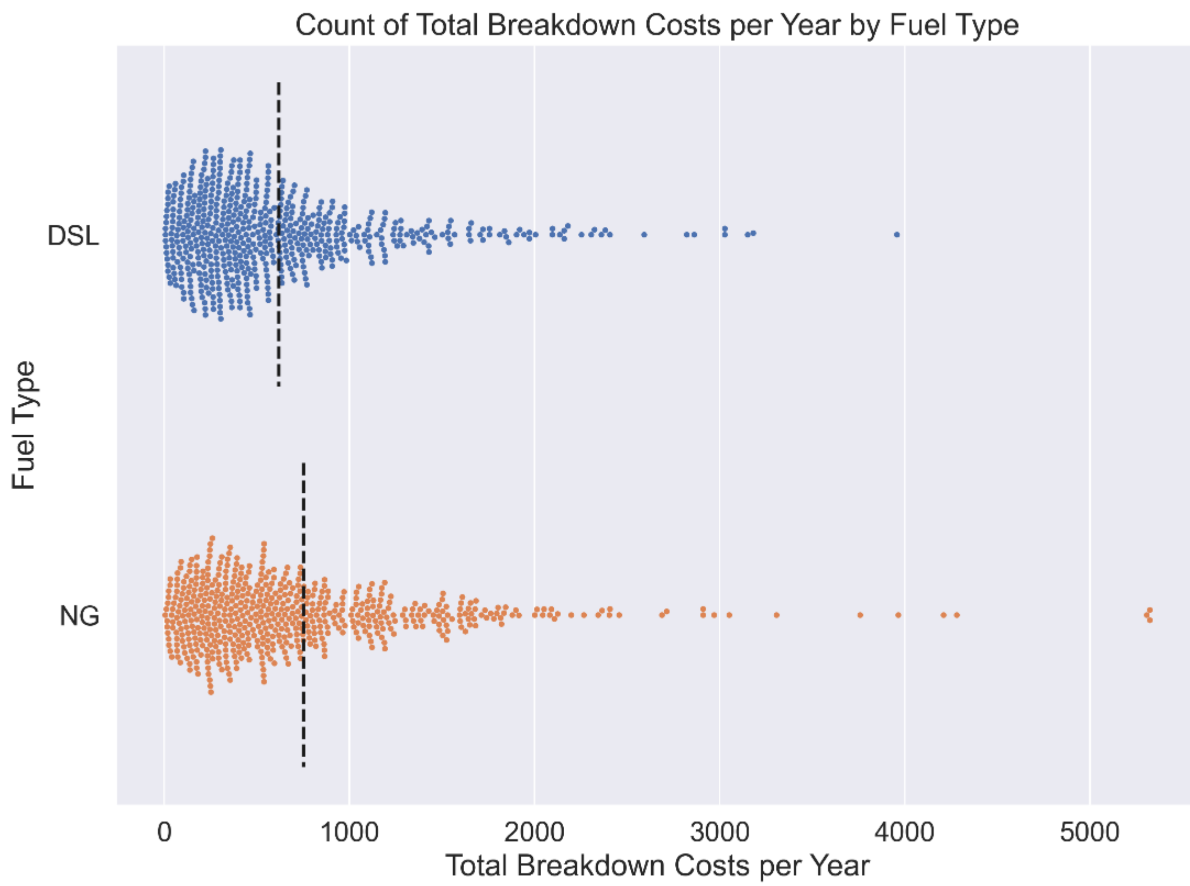


Figure 63: Total Expenditures, Including Parts and Labor, for Breakdown Events per Vehicle
(Each point represents one vehicle.)

Figure 63 shows the average breakdown costs per year for every vehicle operated by Fleet 1. This metric is calculated by grouping the data by unit ID and summing the costs for all rows where the Repair Reason type was listed as breakdown. This value was then divided by the number of years that the truck was in operation. Trucks that were very new (fewer than six operational months) were excluded from this visual. The dashed lines indicate the average for each fuel type.

The distributions are similar for both fuel types, with the majority of the vehicles having less than $700 of breakdown costs per year of service. The averages for both fuel types are also generally similar, but there were more outlier NG trucks that had much higher breakdown costs than the average.

T-test:

Total Breakdown Costs per Year by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-3.527	0.0004

The results of the t-test show that the difference in average breakdown costs between the two fuel types is statistically significant.

Average Cumulative Breakdown Costs

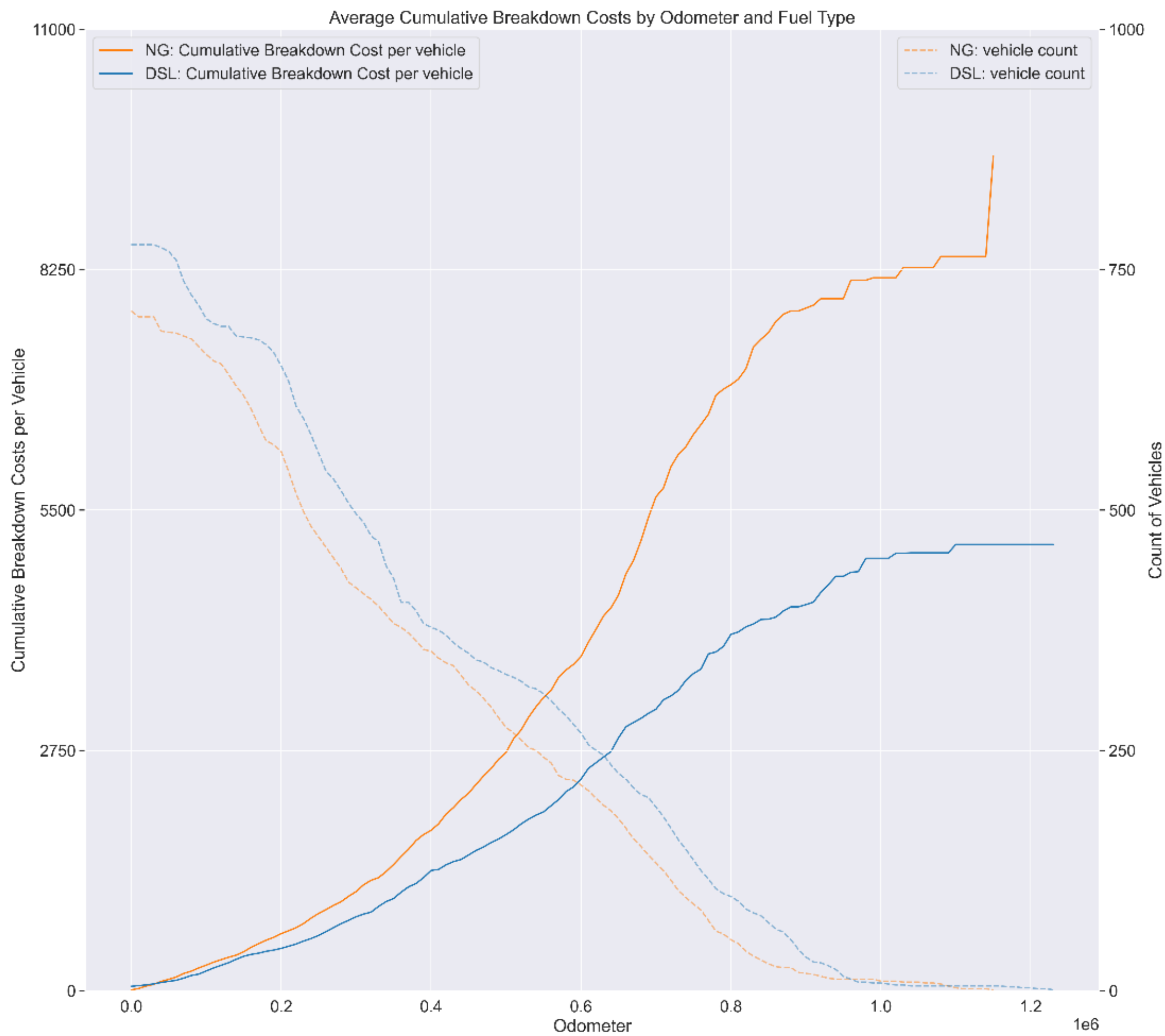


Figure 64: Average Cumulative Breakdown Costs per Active Vehicle
(Only Fleet 1 data is included.)

Figure 64 shows the differences in how trucks for each fuel type accumulated breakdown costs throughout their lifespan. The Repair Reason information was used to subset the data into breakdown-related ROs. This data was then grouped by fuel type and odometer range. The costs were summed within each group and divided by the number of active vehicles to calculate average breakdown costs per vehicle. Finally, the cumulative sum was taken across the odometer range.

The general trends in cumulative breakdown costs are similar between both fuel types, but the NG trucks required higher expenditures across most of the odometer range. The steepest increase in breakdown-related expenditures occurred between 400,000 and 800,000 miles for both fuel types. The gap in spending between the two fuel types also increased within this mileage range.

Total Breakdown Costs by Model Year

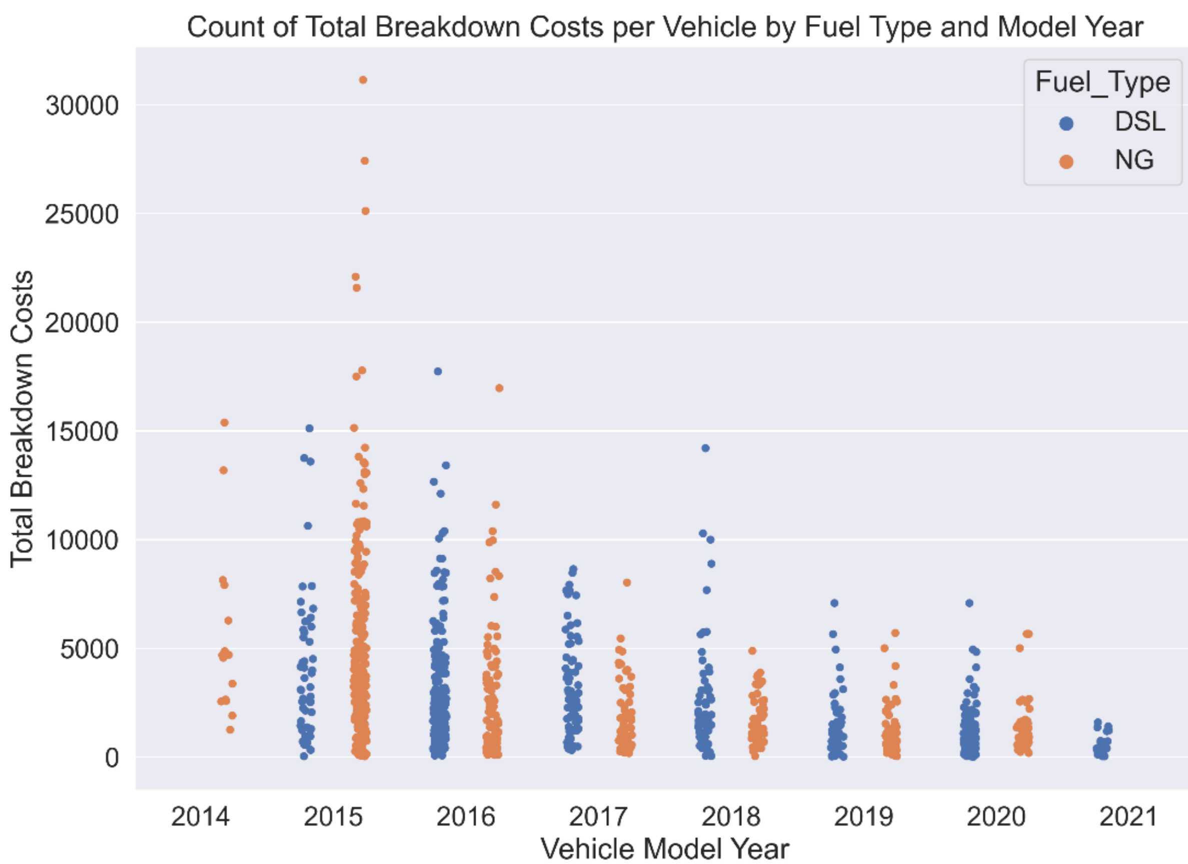


Figure 65: Total Breakdown Costs per Vehicle by Model Year
(Each point represents one vehicle.)

Looking at total breakdown costs by vehicle model year shows that almost all the NG-powered outlier trucks were purchased in 2015. This pattern was also observed for the breakdown-frequency metric. Both diesel and NG trucks showed very similar breakdown costs for the other model years included in this dataset. In fact, the NG vehicles exhibited slightly lower expenditures for all newer model years. As expected, this plot also shows a decreasing trend in breakdown costs for newer vehicles.

Component-Level Maintenance Costs

The goal of this component-level analysis was to identify the key vehicle systems and components causing the biggest differences in maintenance spending between the two fuel types. This analysis was once again focused around the VMRS systems that are affected by fuel type. The system-level comparisons below include data from all three fleets, but component-level comparisons were only possible with Fleet 1's data.

Total Expenditures per Vehicle by VMRS System and Fleet

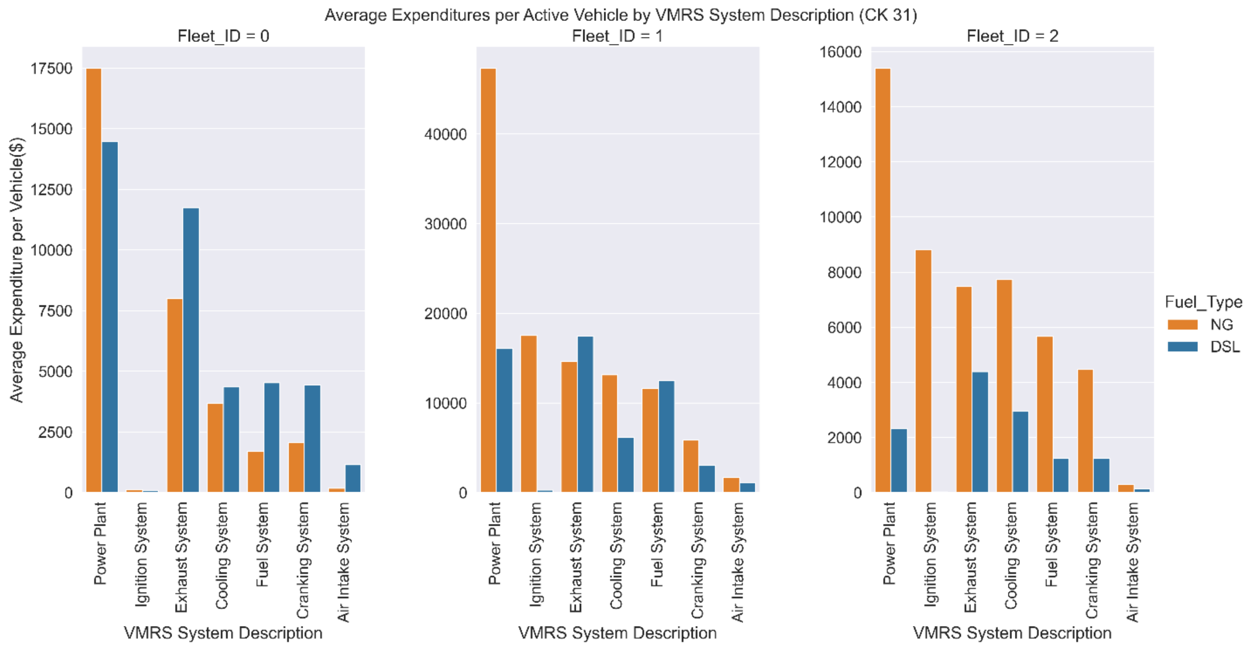


Figure 66: Average Maintenance Expenditures per Active Vehicle
by Fleet, Fuel Type, and Fuel-Type-Significant VMRS System

Figure 66 shows the differences in spending between fuel type for significant VMRS systems. For this figure, the maintenance data was first grouped by fleet, fuel type, odometer range, and VMRS system. The costs were then summed for each group. This value was then divided by the total number of active vehicles within the fleet, fuel type, and odometer groups. The result of this calculation is the average spending per VMRS system normalized by the count and age of vehicles within each fleet.

The powerplant system required the most maintenance expenditures for NG trucks in all three fleets. This system also had the largest gap in spending between diesel and NG trucks. The diesel trucks in Fleet 0 and Fleet 1 had values of powerplant-related spending for NG trucks that were relatively close, while Fleet 2 had significantly lower spending than the other two fleets. Fleet 1 had a much higher average power plant related spending for their NG trucks compared to the other two fleets.

The exhaust system also required significant expenditures for both fuel types in all three fleets. Fleet 1 and Fleet 2 recorded slightly higher average spending on this system for their diesel vehicles, while Fleet 0 had somewhat higher exhaust system-related spending for their NG trucks. One feature of particular note is that Fleet 0 had improbably low ignition-system-related spending for their NG trucks.

Expenditures per Vehicle by VMRS System

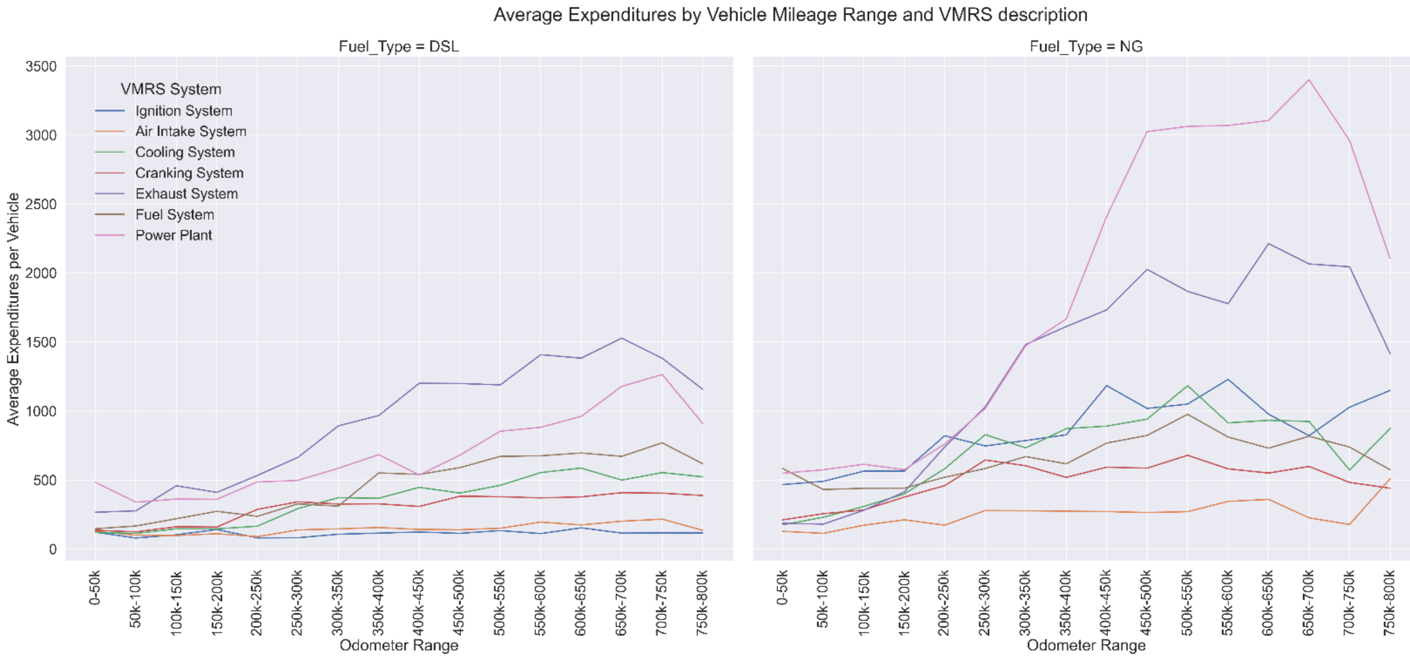


Figure 67: Average Maintenance Expenditures per Vehicle by Fuel-Type-Significant VMRS System

Figure 67 shows the average maintenance spending for each VMRS system over a vehicle's lifespan. The cost data was first summed within each fuel type, VMRS system, and odometer range. This sum of costs was then divided by the number of trucks that generated the ROs.

The ignition, cooling, and powerplant systems showed the biggest differences in maintenance expenditures between NG- and diesel-powered vehicles. All three of these systems also had the biggest differences in repair frequencies. The spending also peaked in the 300,000- to 700,000-mile range for most of these systems for both fuel types. Surprisingly, the NG-powered trucks required the same or higher amounts of spending on exhaust system-related maintenance even though the diesel trucks had more exhaust system-related ROs across all mileage ranges. The air-intake system had similar repair frequencies for both fuel types, but NG-powered vehicles accumulated higher costs.

Average Cumulative Repair Costs by Fuel Type and Cost Category

The following figures are intended to show the trajectory of maintenance spending over a typical vehicle's lifespan. The data is split by cost category to show both parts spending and labor spending. The metric was calculated by categorizing the maintenance data for the relevant VMRS system. This subset of data was then grouped by fleet, fuel type, and odometer range. The sum of costs was taken for each group and these values were then divided by the total number of active vehicles to get the spending per vehicle. Finally, these values were sorted by odometer range and the cumulative sum was taken.

All Fuel-Type-Significant Components Repair Costs

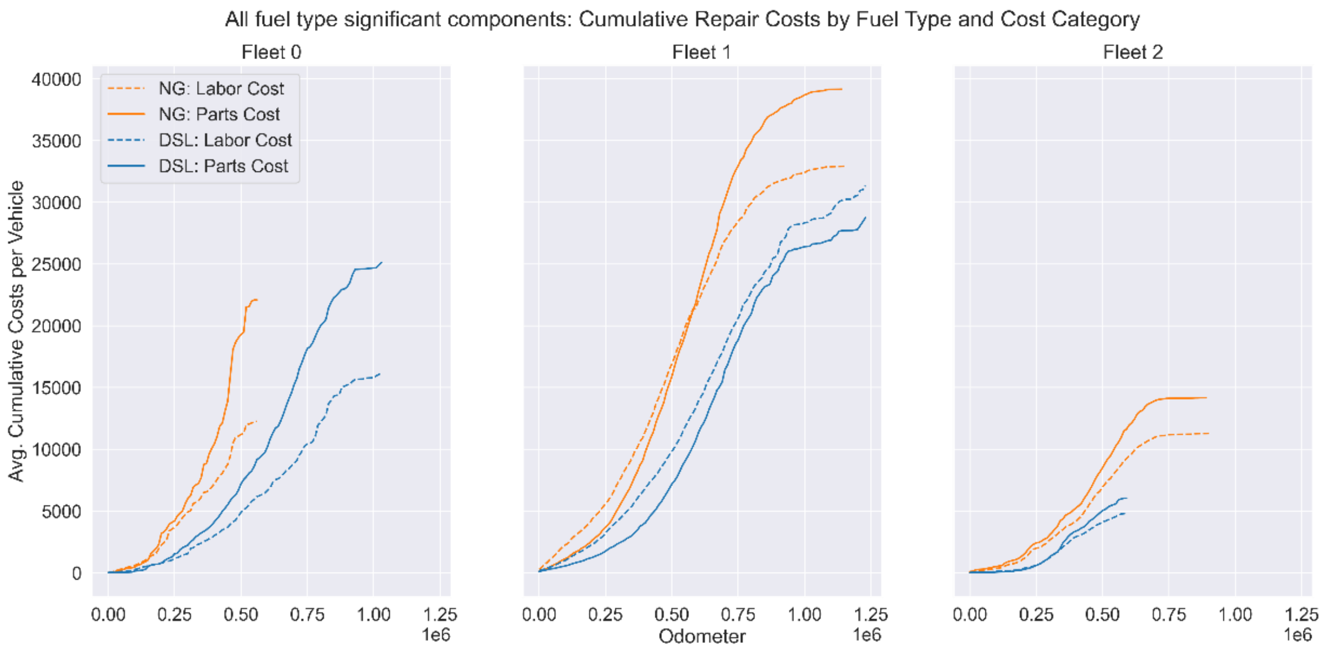


Figure 68: Average Cumulative Maintenance Costs for All Fuel-Type-Significant VMRS Systems

Figure 68 shows that the gap in maintenance expenditures between NG and diesel vehicles is even larger when focusing only on the fuel-type-significant components. All three fleets show significantly higher parts and labor costs for their NG trucks. This difference between the two fuel types is noticeable from as early as 100,000 miles.

Powerplant Repair Costs

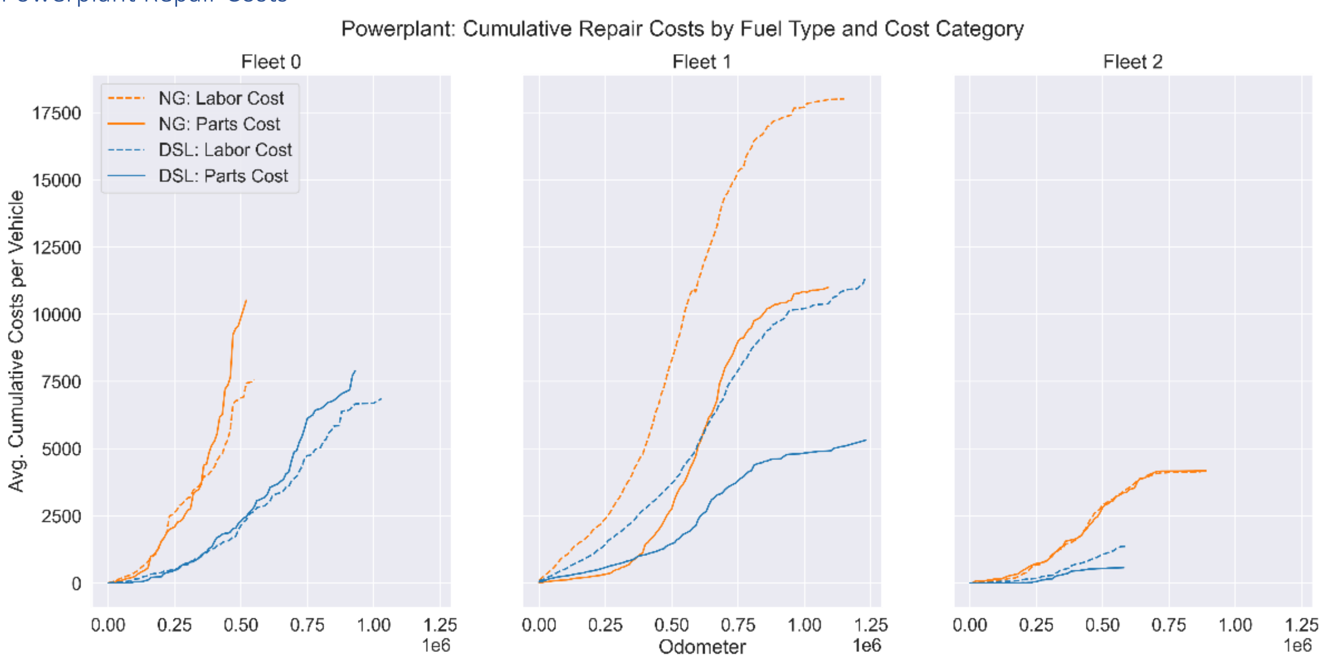


Figure 69: Average Cumulative Costs for Powerplant-Related Maintenance

NG trucks also seem to require more powerplant-system-related spending than their diesel-powered counterparts. As shown in Figure 69, Fleet 0 and Fleet 2 had higher parts and labor costs for their NG trucks across most of the odometer range. Interestingly, there was a large separation between parts costs and labor costs for Fleet 1. Their NG trucks had slightly lower parts costs until the 300,000-mile mark, after which the NG parts costs increased at a significantly higher rate than the parts costs for diesel trucks. The labor costs for Fleet 1 were significantly higher than the parts costs for both fuel types. There was approximately a $6,000 difference between parts and labor costs by the end of a vehicle's lifespan.

Exhaust System Repair Costs

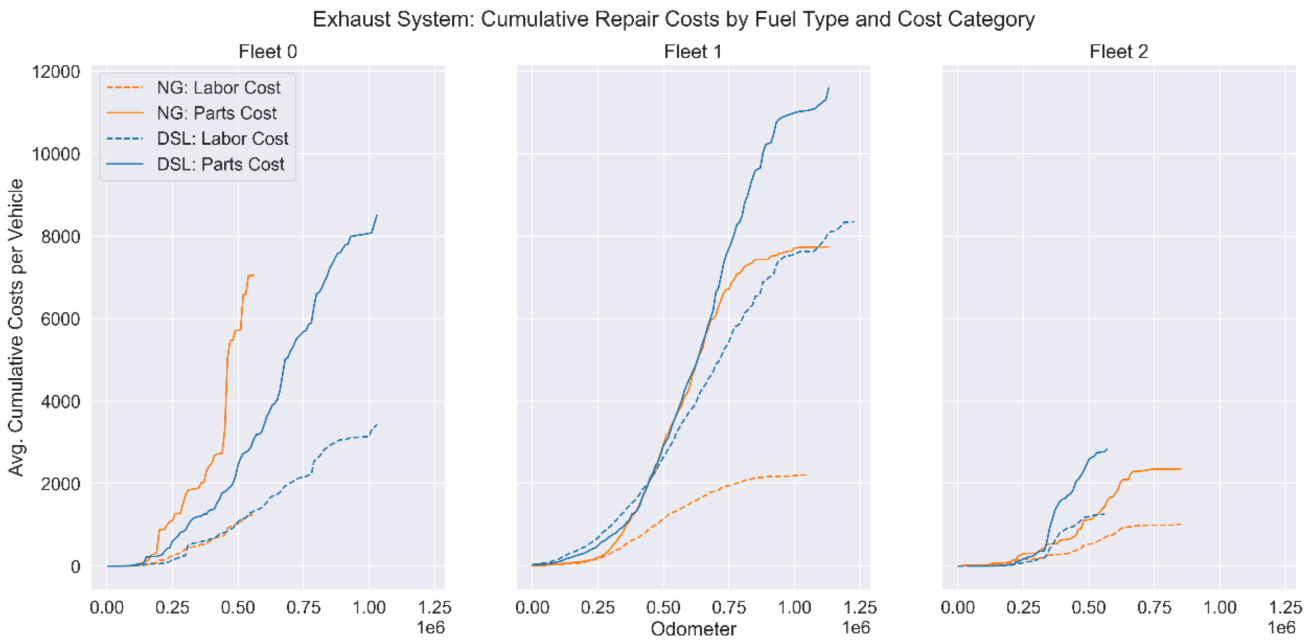


Figure 70: Average Cumulative Costs for Exhaust System-Related Maintenance

The exhaust system was one of the only areas where diesel trucks outpaced NG trucks in the quantity of ROs, but costs were surprisingly close for the two fuel types. Figure 70 shows that Fleet 0 had higher cumulative exhaust system-related parts expenditures for its NG trucks starting at the 200,000-mile mark. Fleet 1 had almost identical parts expenditures for both fuel types until the 700,000-mile mark. The labor costs were much lower for their NG trucks throughout the entire odometer range. These trends suggest that NG vehicles required significantly higher parts spending per exhaust system-related RO than diesel vehicles.

Cooling System Repair Costs

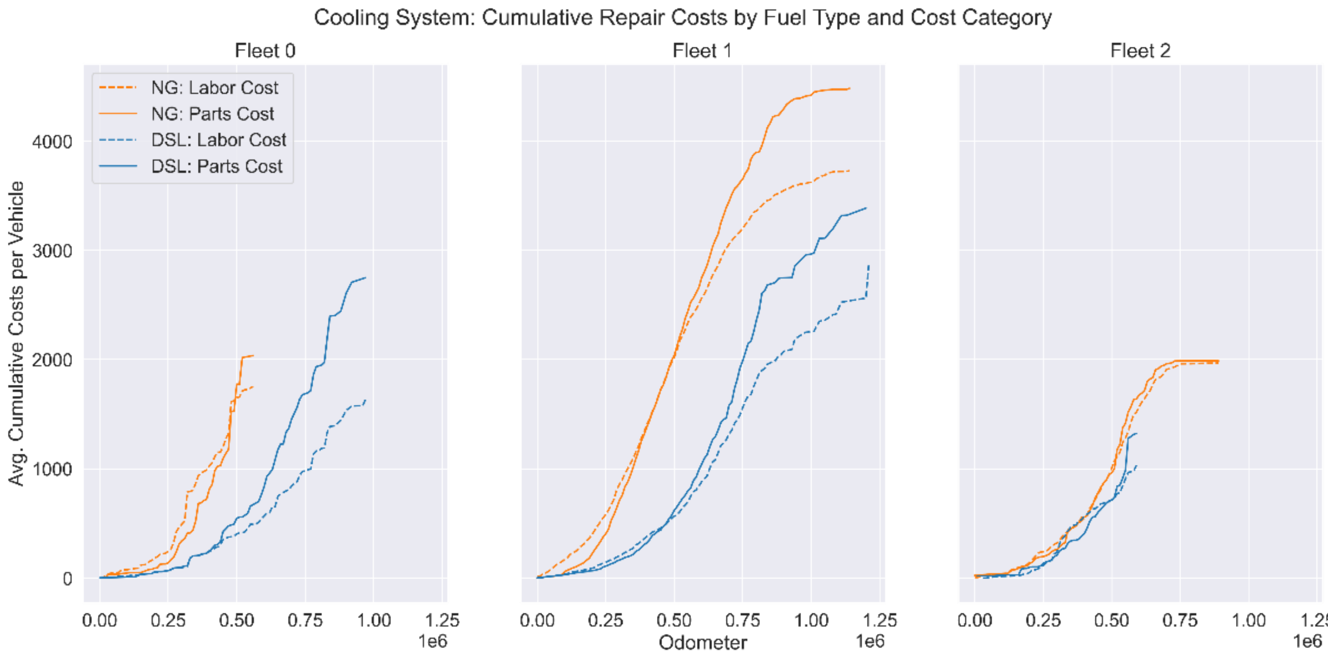


Figure 71: Average Cumulative Costs for Cooling System-Related Maintenance

Figure 71 shows that the NG trucks had significantly higher cooling system parts and labor costs across most of the odometer range for Fleet 0 and Fleet 1. There appear to be some significant deficiencies in the cooling systems specified for NG trucks, as the NG vehicles started experiencing issues very early on in their lifespan. The component-level analysis below helps identify the specific components responsible for these increased costs.

Ignition-System Repair Costs

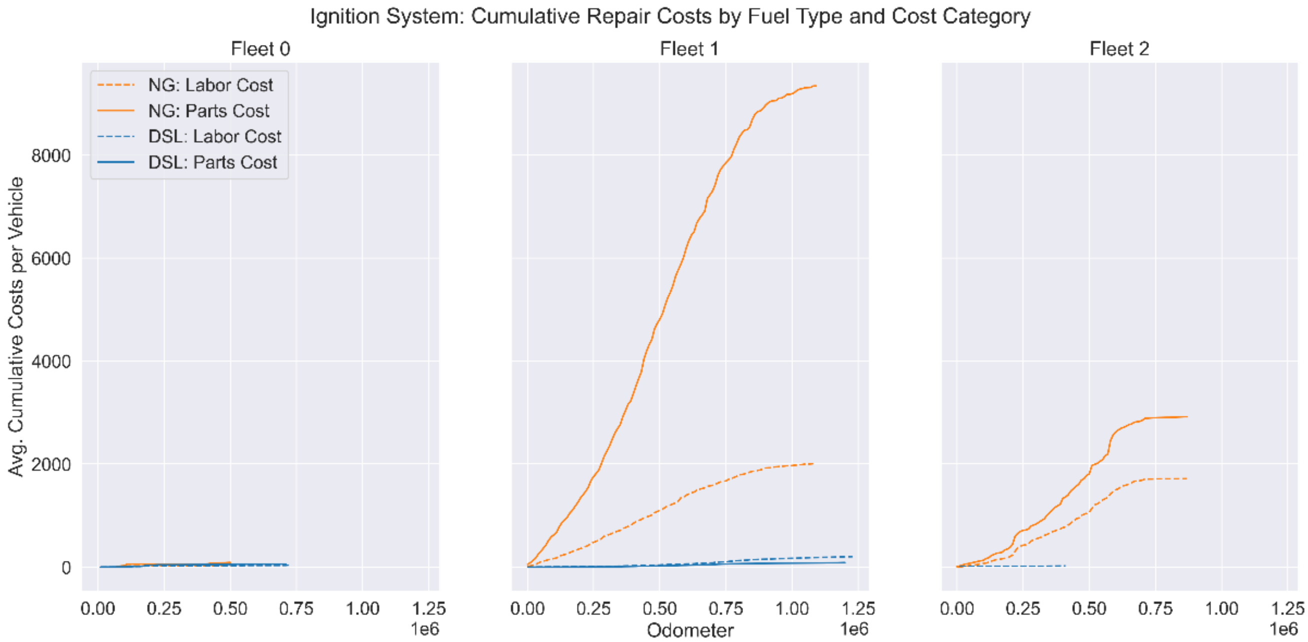


Figure 72: Average Cumulative Costs for Ignition-System-Related Maintenance

Figure 72 plots the ignition system related parts and labor costs for all three fleets. As expected, NG trucks in Fleet 1 and Fleet 2 had considerably higher parts and labor costs for ignition-system-related maintenance. Most of these differences are likely due to routine maintenance-related items like spark plugs and ignition coils. Fleet 0 shows almost no ignition-system-related costs for their NG trucks. This is most likely an error in their maintenance tracking software.

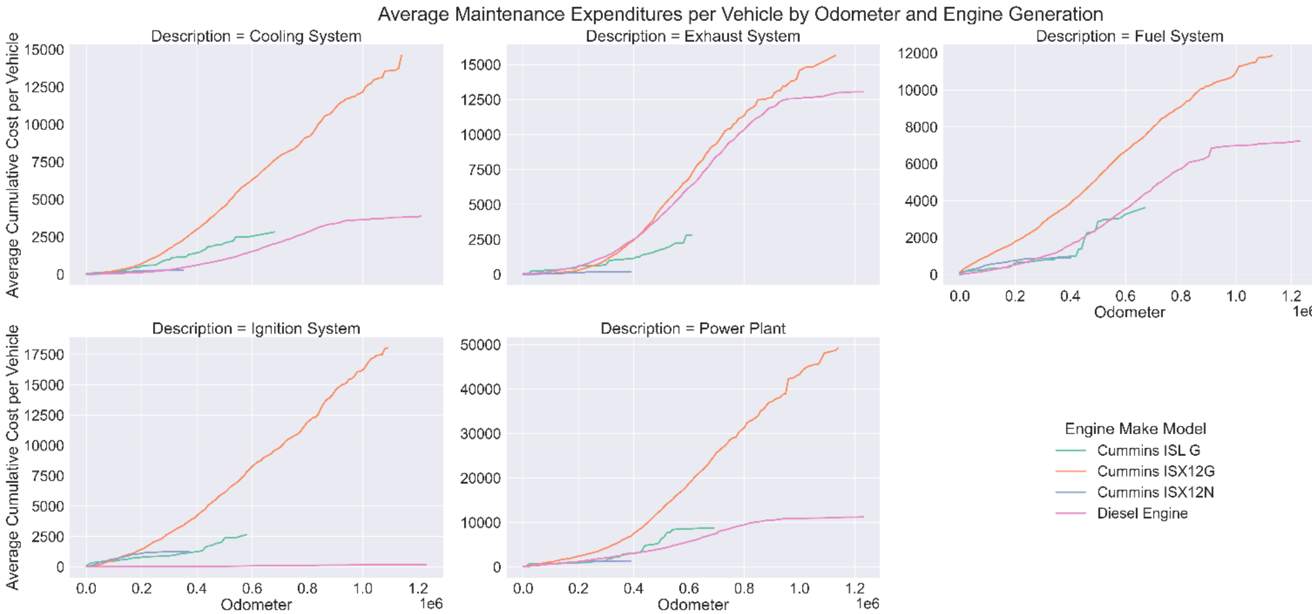


Figure 73: Average Cumulative Maintenance Expenditures by NG Engine Generation
(Note: Diesel engines were assumed to be homogeneous and are included on the plot for reference.)

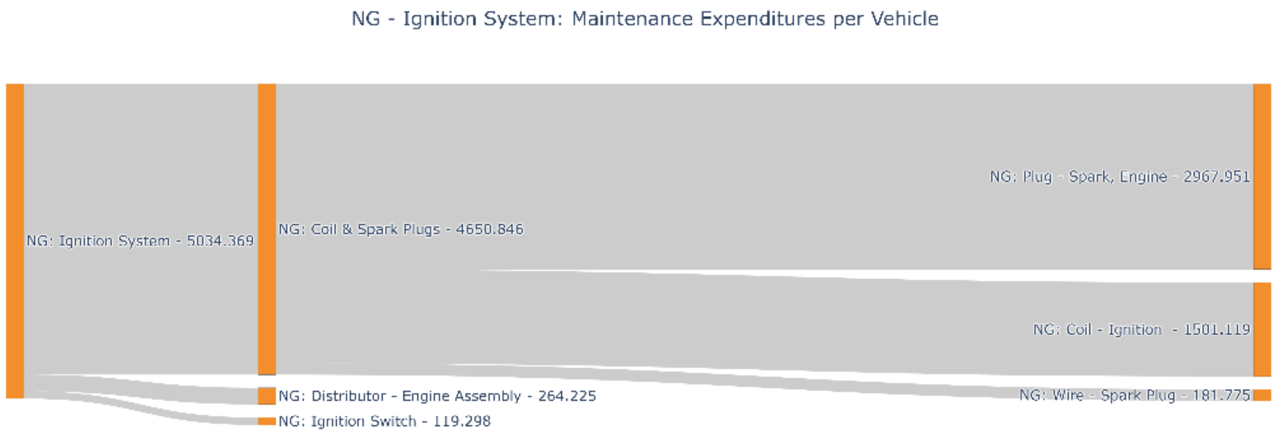
Figure 73 shows the average cumulative expenditures by NG engine generation. The dataset collected for this project is heavily weighted towards the ISX12G engine, which made comparisons between engine generations difficult.

Specific Components Causing Maintenance Cost Differences (Fleet 1 Only)

The following component-level visuals only use data from Fleet 1 because this was the only fleet in this study that coded their maintenance data to the component level on a consistent basis.

The Sankey plots below are used to show the flow of maintenance dollars through an average vehicle's VMRS systems, assemblies, and components. The values at each level are calculated by summing the cost data by a combination of fuel type, VMRS system code, VMRS assembly code, and VMRS component code. These sums are then divided by the total number of vehicles in each fuel type.

Ignition-System Maintenance



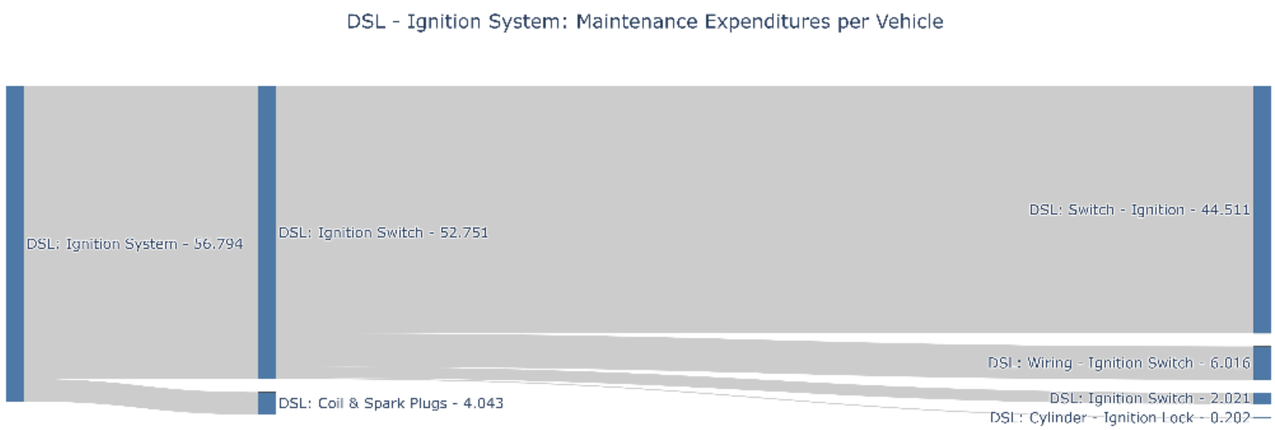
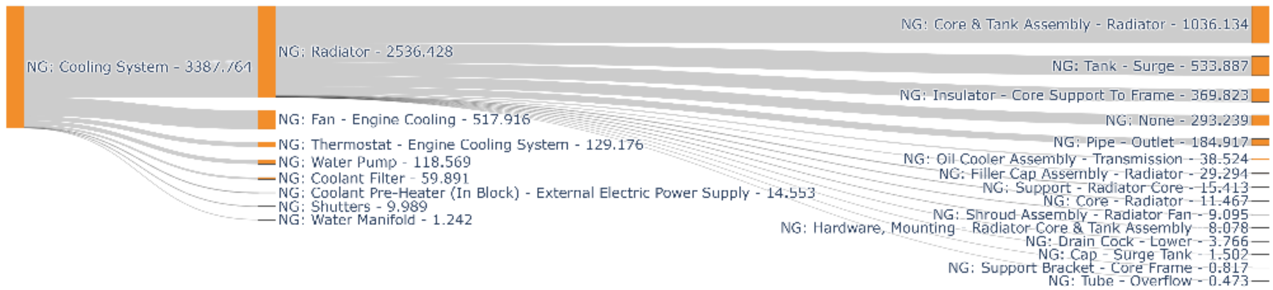


Figure 74: Sankey Plots of Average Maintenance Costs per Active Vehicle for Ignition-System Components
(Note: The plots for NG and diesel trucks are not scaled relative to each other.)

Figure 74 shows that the majority of the ignition-system-related expenditures for NG trucks were due to routine maintenance items, e.g., spark plugs and ignition coils. These costs are unavoidable for maintaining spark-ignited engines.

Cooling System Maintenance

NG - Cooling System: Maintenance Expenditures per Vehicle



DSL - Cooling System: Maintenance Expenditures per Vehicle

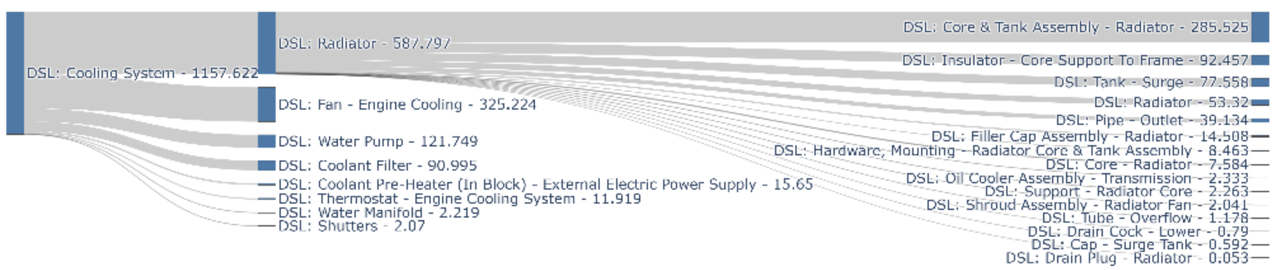


Figure 75: Sankey Plots of Average Maintenance Costs per Active Vehicle for Cooling System Components

As seen in figure 75, the cooling system showed one of the biggest differences in maintenance frequency and cost between the two fuel types. NG trucks had more ROs and costs throughout their lifespan for all three fleets. The radiator and engine-cooling-fan assemblies, as well as the core and tank components, accounted for the majority of cooling system-related costs for both fuel types. The average NG truck in Fleet 1 required more than four times as much spending on the radiator assembly as the typical diesel truck.

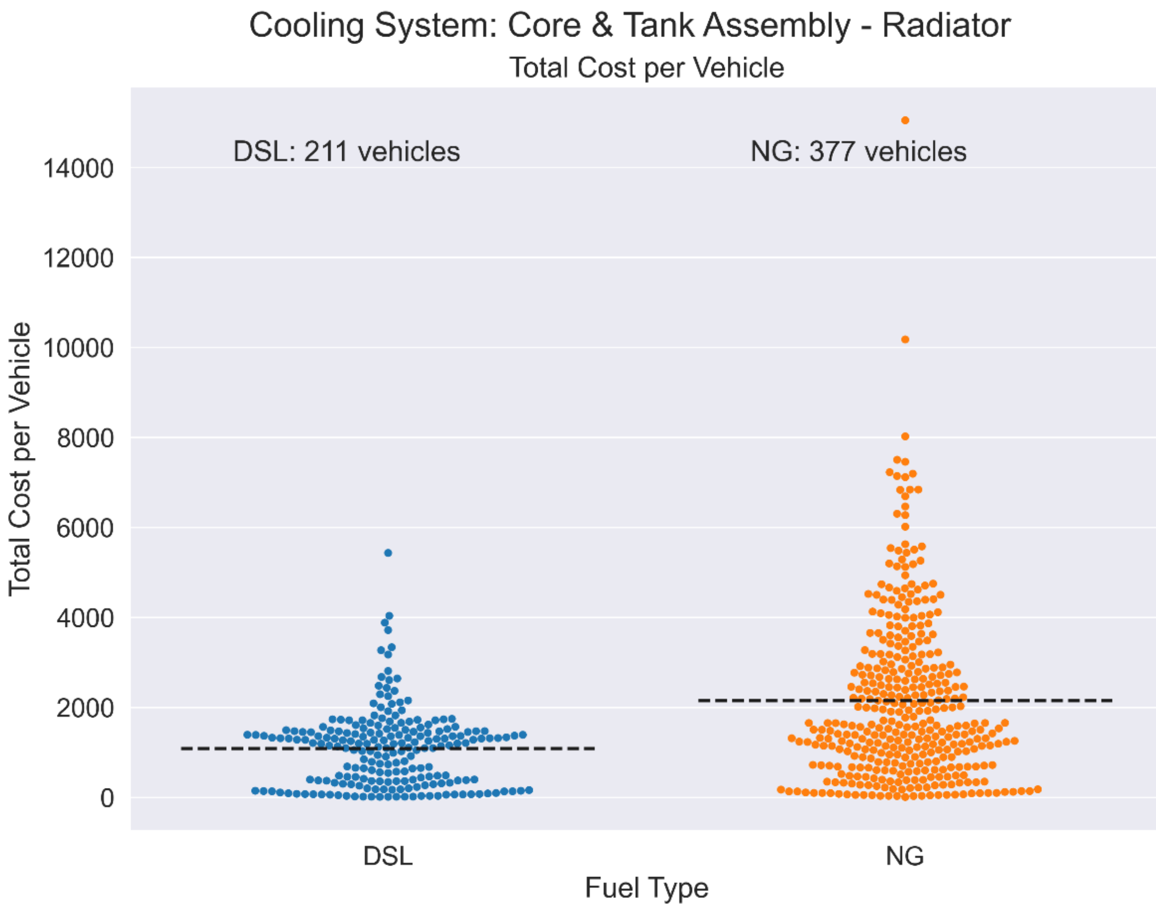


Figure 76: Distribution of Radiator-Core-Component-Related Costs per Vehicle
(Each point represents one vehicle. Only vehicles that generated an RO for this component are included.)

Figure 76 shows the total expenditures per vehicle for the radiator core and tank components. The metric is calculated by first filtering the maintenance data for radiator-core-and-tank-related ROs and then summing the costs for each vehicle. 26% of the diesel trucks and 48% of the NG trucks had at least one radiator-core-and-tank-related expenditure. The NG trucks in Fleet 1 required more spending per vehicle for radiator-core-and-tank-related repairs. The distribution of expenditures also shows that there were many more outlier NG trucks in terms of total expenditures for this component. The number of NG trucks that required more than $5,000 of radiator-core-and-tank maintenance was 16 times larger than the number of diesel vehicles.

T-test:

Radiator Core: Maintenance Costs per Vehicle by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-9.395	1.388e-19

The results of the t-test confirm that the average spending for this component is statistically different between the two fuel types.

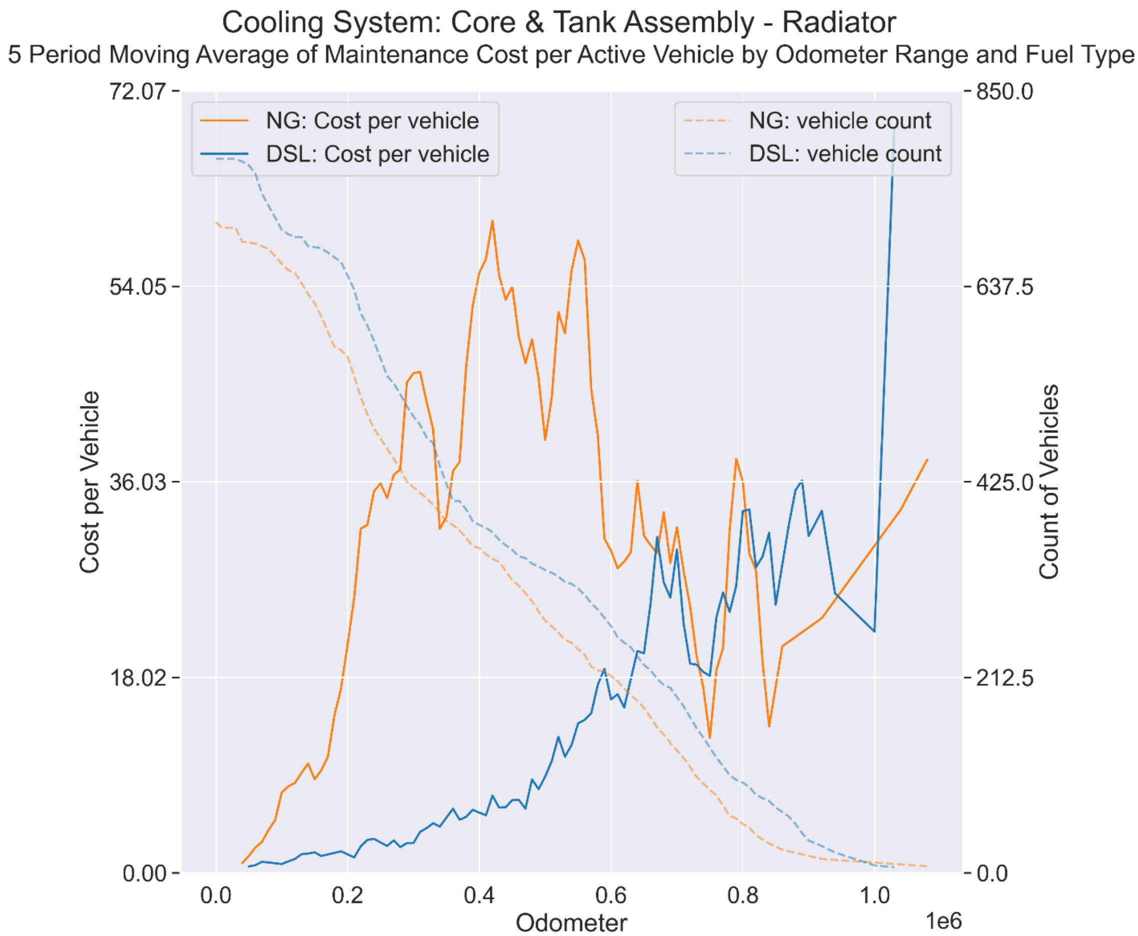


Figure 77: Average Radiator-Core-Component-Related Costs per Active Vehicle over the Odometer Range

Figure 77 shows radiator-core-and-tank-related spending over the odometer range by fuel type. The cost-per-vehicle value is calculated by first filtering the data for radiator-core-and-tank-component ROs. The costs are then summed in the filtered data after grouping by fuel type and odometer range. Finally, this value is divided by the number of active vehicles for each fuel type and odometer range.

The NG trucks experienced issues with this component very early on in their life, and the cost per vehicle peaked at 400,000 miles. In contrast, the cost trajectory for diesel vehicles followed the expected trend that increased much more gradually over the odometer range. The peak value for NG trucks was almost twice that of diesel trucks.

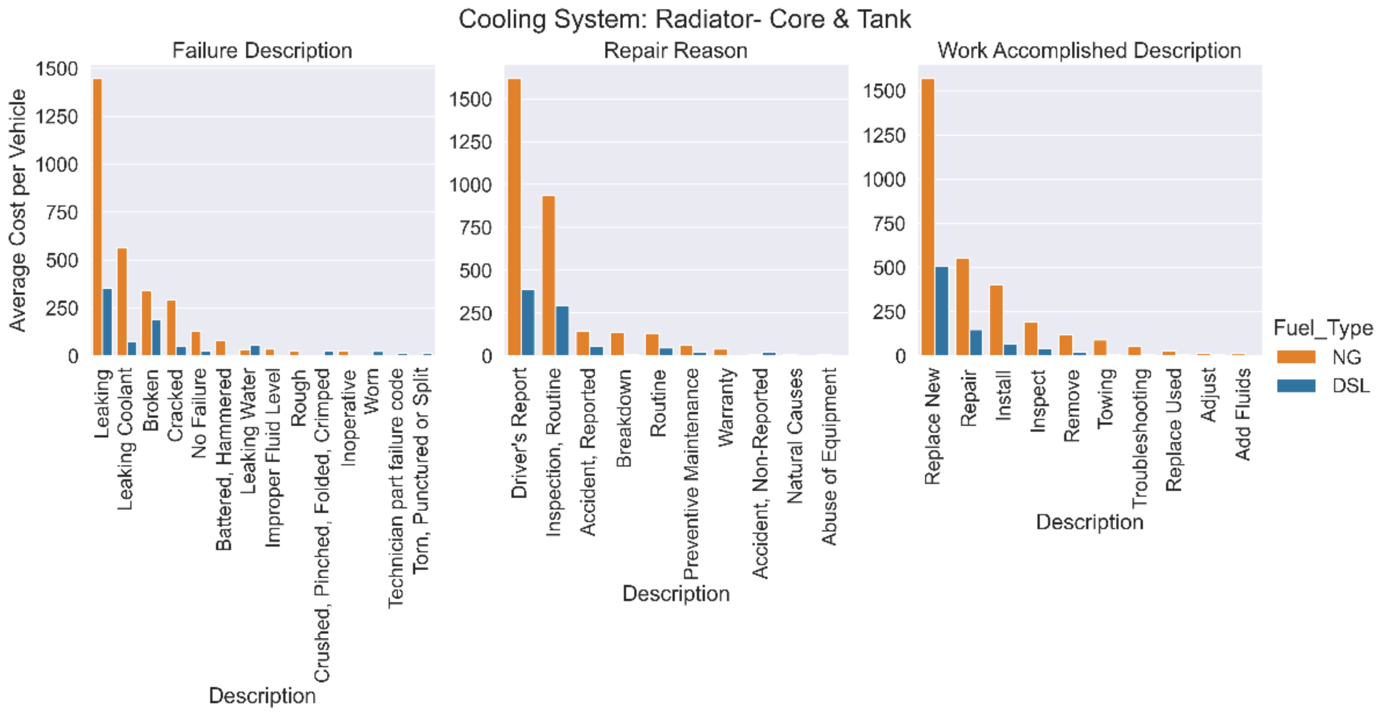
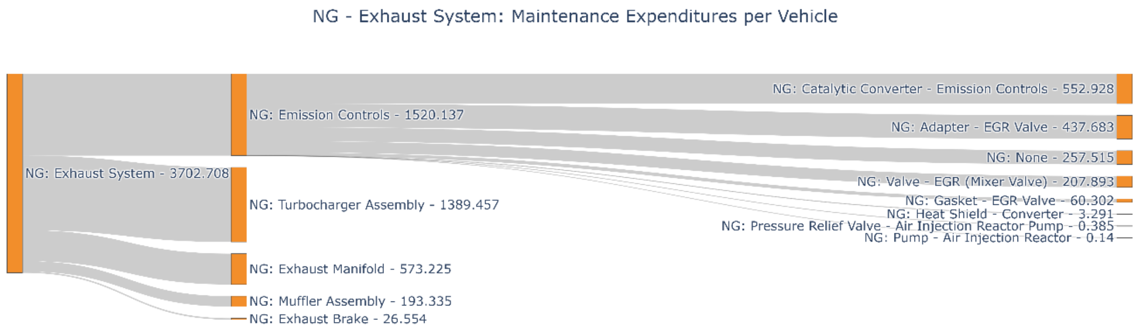


Figure 78: Average Maintenance Expenditures for Radiator-Core-Related ROs
by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

Figure 78 shows the top categories for the Failure Type, Repair Reason, and Work Accomplished descriptions for the radiator core and tank components in terms of costs. The order of the categories is very similar to the order seen in the repair frequency analysis. This indicates that the categories with the highest average ROs also had the highest average costs.

Exhaust System Maintenance



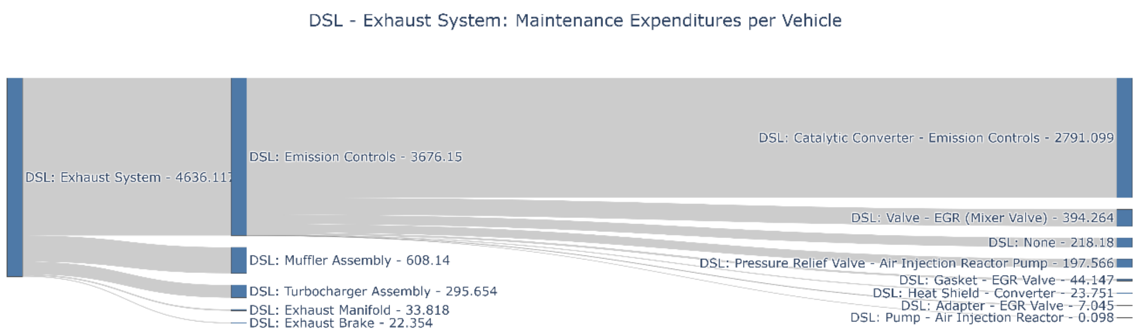


Figure 79: Sankey Plots of Average Maintenance Costs per Active Vehicle for Exhaust System Components (Note: The plots for NG and diesel trucks are not scaled relative to each other.)

As seen in Figure 79, the emission controls assembly required the largest expenditures in the exhaust system for both fuel types. For diesel vehicles, the catalytic converter component accounted for the majority of expenditures within the emission controls assembly and the exhaust system as a whole. 98% of all exhaust system-related costs were due to the catalytic converter component for diesel trucks compared to just 12% for NG trucks.

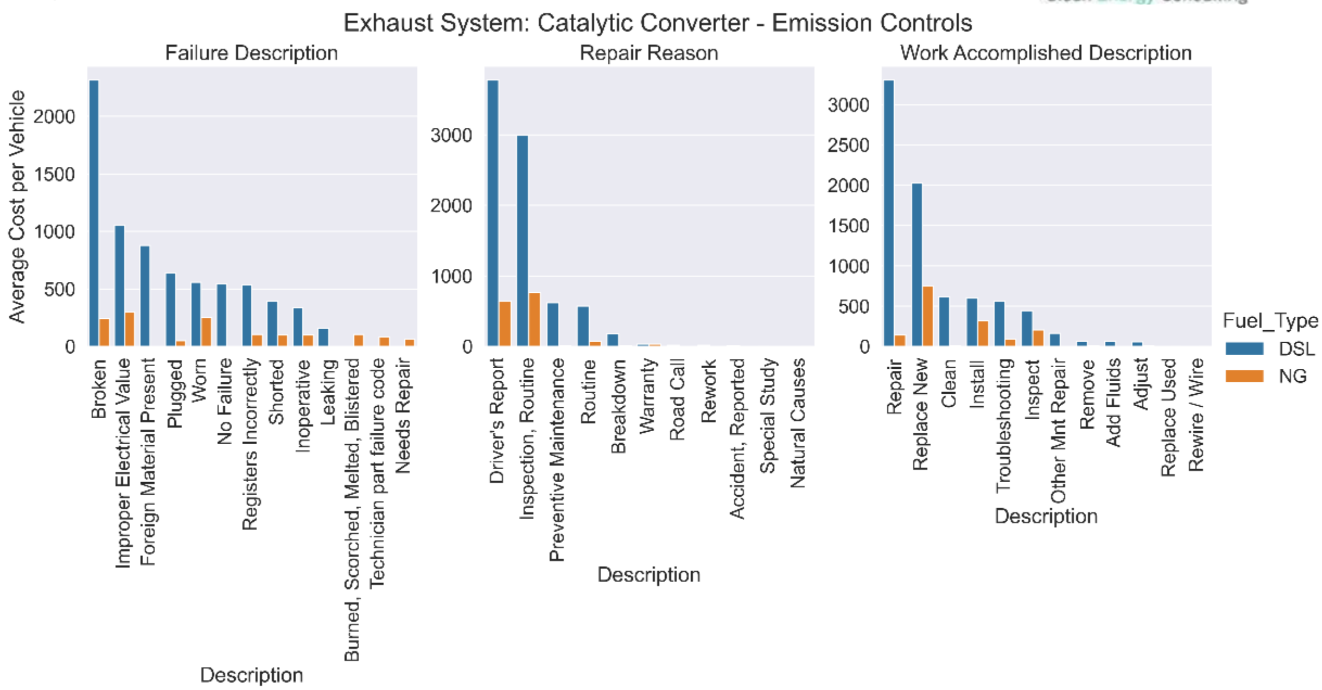


Figure 80: Average Maintenance Expenditures for Catalytic-Converter-Related ROs by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

All of the Failure Type, Repair Reason, and Work Accomplished categories showed much higher expenditure levels for diesel trucks than NG trucks. The 'Broken' failure category had the highest expenditures in the emission controls assembly for diesel vehicles. The 'Driver's Report' repair reason also had the highest expenditures for this component. This could indicate that the majority of the maintenance costs for this component were unexpected.

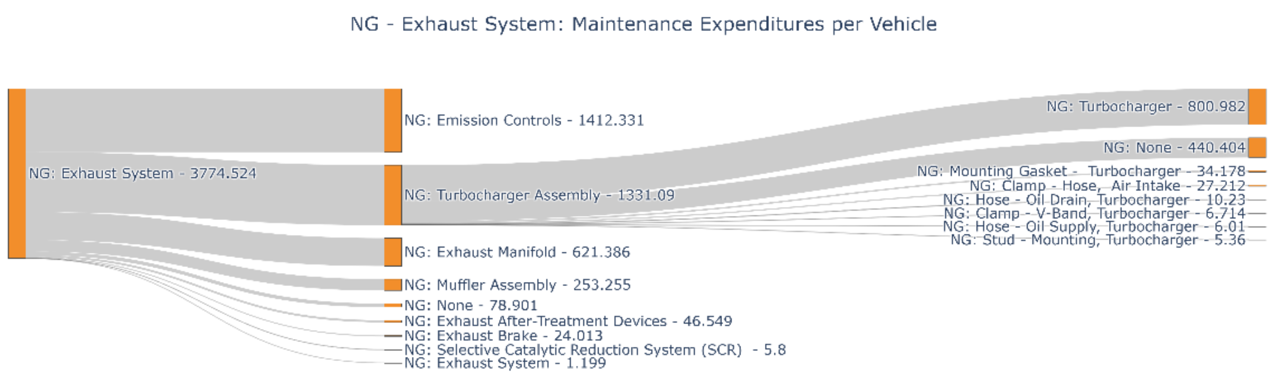


Figure 81: Sankey Plot of Components in the Turbocharger Assembly Requiring the Highest Expenditures

The turbocharger assembly for NG trucks was a close second in terms of expenditures. 35% of exhaust system-related spending for the NG trucks was due to turbocharger-assembly-related maintenance. The turbocharger component itself accounted for 21% of the total exhaust system-related maintenance spending for NG trucks.

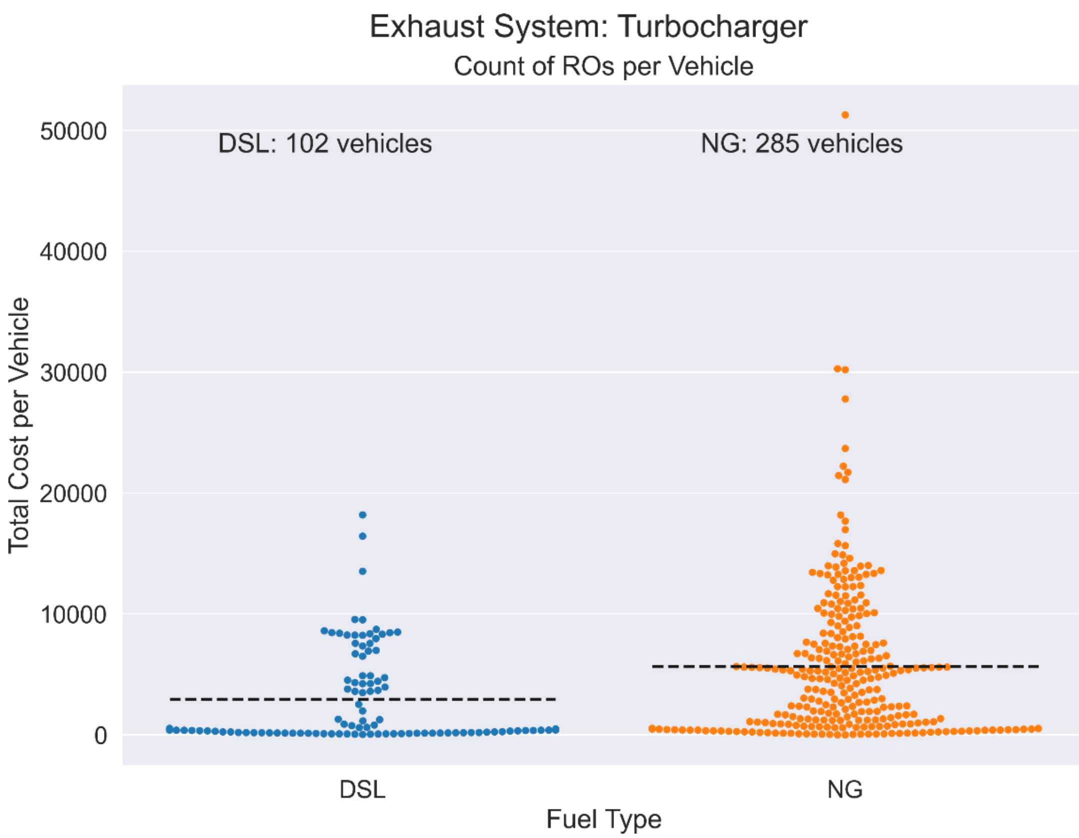


Figure 82: Distribution of Turbocharger-Component-Related Costs per Vehicle
(Each point represents one vehicle. Only vehicles that generated an RO for this component are included.)

Figure 82 shows that the distribution of turbocharger-related expenditures for diesel trucks was heavily right-skewed, and most of them required very little turbocharger maintenance. The distribution for NG trucks is also right-skewed but to a lesser extent. Only 12.7% of the diesel trucks had at least one turbocharger-related maintenance compared to 36.4% of the NG trucks. There was a large clustering of vehicles requiring between $2,000 and $4,000 of turbocharger maintenance. There were also significantly more NG trucks than diesel trucks that required over $5,000 of turbocharger maintenance.

T-test:

Turbocharger: Maintenance Costs per Vehicle by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-3.701	0.0002

The t-test results show that the two fuel types have statistically different average turbocharger-related costs.

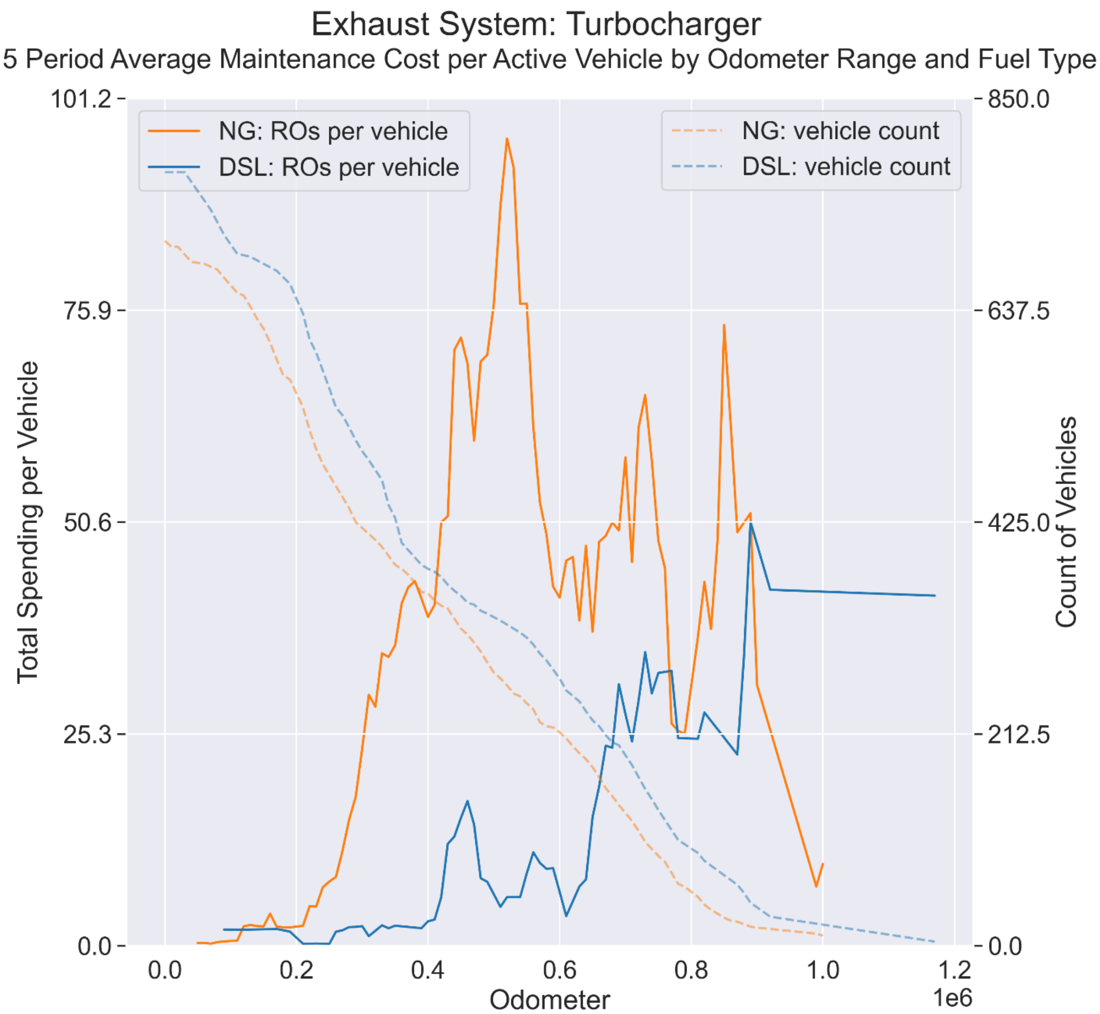


Figure 83: Average Turbocharger-Component-Related Costs per Active Vehicle over the Odometer Range

Figure 83 shows that the NG trucks started requiring turbocharger-related expenditures early on in their lifespan, around the 200,000-mile mark. These expenditures continue increasing until the 500,000-mile mark before tapering off. Diesel trucks showed a much less steep trajectory for turbocharger costs that peaked around the 900,000-mile mark. This peak was also much lower than that of the NG trucks.

Powerplant-System Maintenance

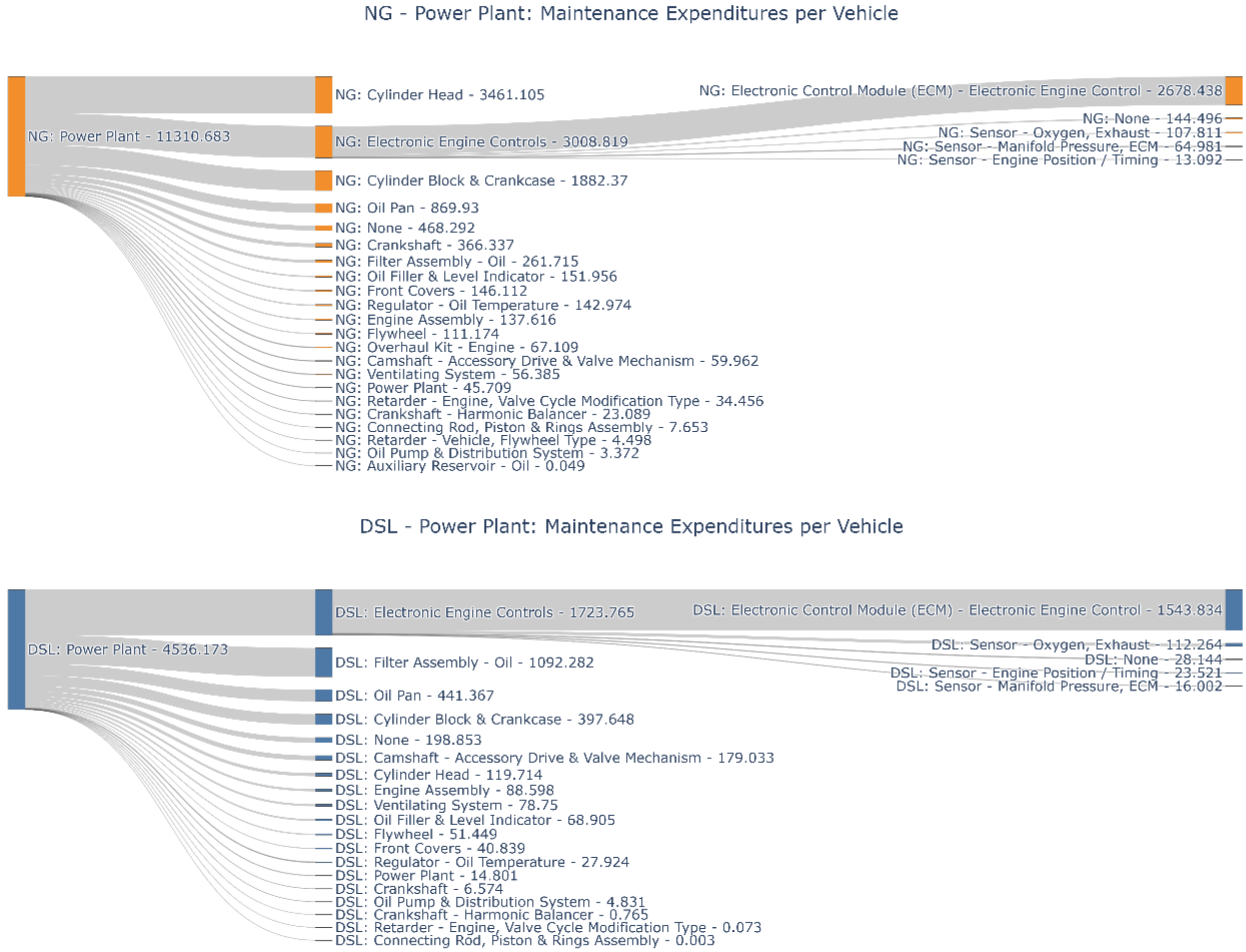


Figure 84: Sankey Plots of the Top Powerplant Components in Terms of Expenditures

Figure 84 shows that the NG trucks also required significantly more expenditures for powerplant-related maintenance. These two systems are closely related because the health of the cooling system can directly affect the health of the power plant. The electronic-engine-controls assembly was one of the top assemblies in terms of maintenance expenditures for both fuel types. This assembly accounted for 38% and 26.5% of powerplant-related expenditures for diesel and NG trucks, respectively. The ECM component accounted for the majority of expenditures within the electronic-engine-controls assembly for both fuel types.

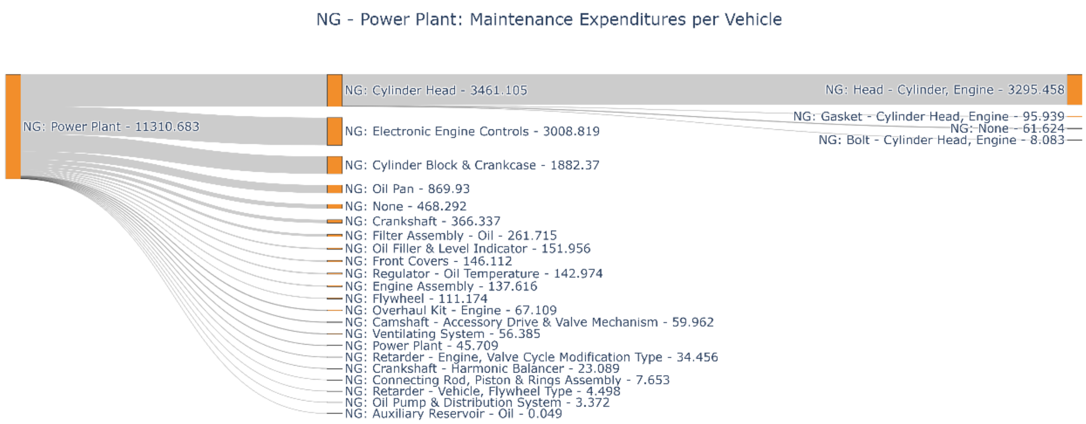


Figure 85: Sankey Plot of the Expenditures within the Cylinder Head Assembly for NG Vehicles

The NG trucks had significantly more expenditures for the cylinder head assembly. 30.6% of all powerplant-related spending was due to the cylinder head assembly for NG trucks compared to just 2.6% for diesel trucks. Within this assembly, the cylinder head component itself accounted for 95% of spending for NG trucks.

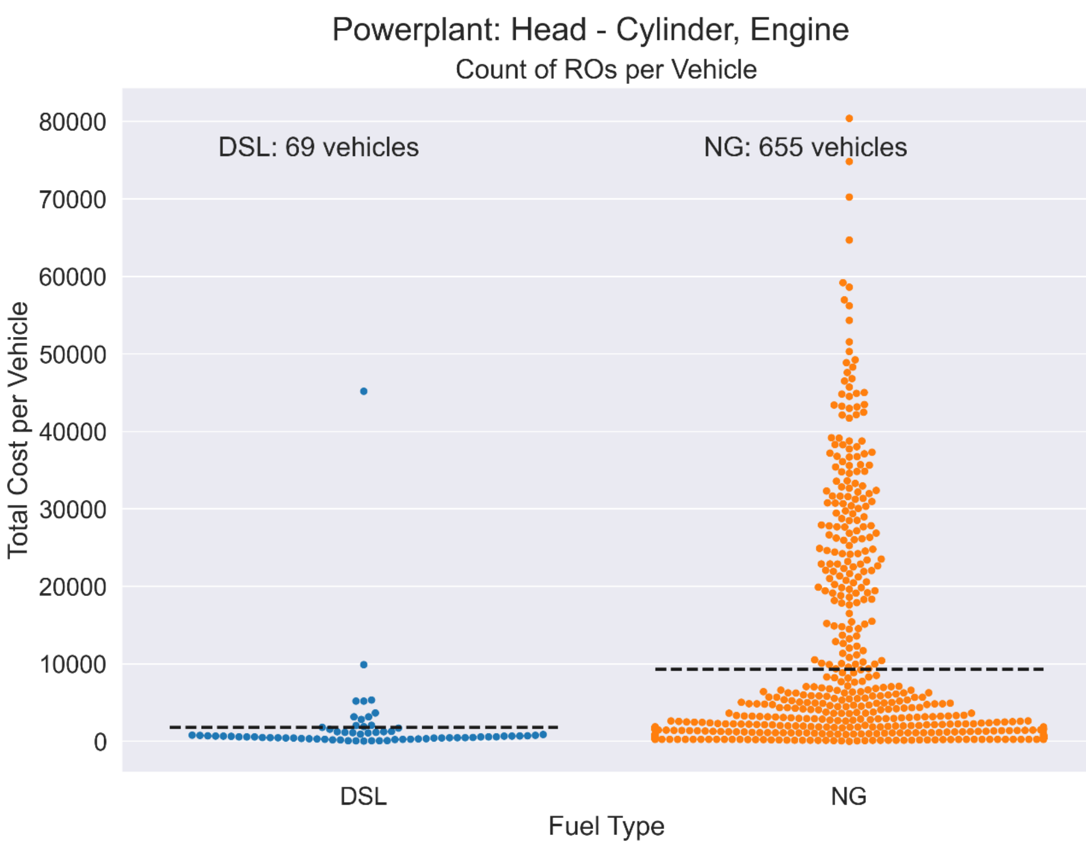


Figure 86: Distribution of Cylinder Head Component-Related Costs per Vehicle
(Each point represents one vehicle. Only vehicles that generated a RO for this component are included.)

The distribution of cylinder head-related expenditures per vehicle showed that the number of NG trucks requiring cylinder head maintenance was almost 10 times larger than the number of diesel vehicles. The NG vehicles also had a much larger range of total expenditures, with a significant number of vehicles requiring more than $10,000 worth of cylinder head maintenance.

T-test:

Cylinder Head: Maintenance Costs per Vehicle by Fuel Type		
Groups Compared	**T-value**	**P-value**
DSL vs. NG	-8.156	9.154e-14

The t-test results show that the average cylinder head-related expenditures were statistically different for diesel and NG trucks.

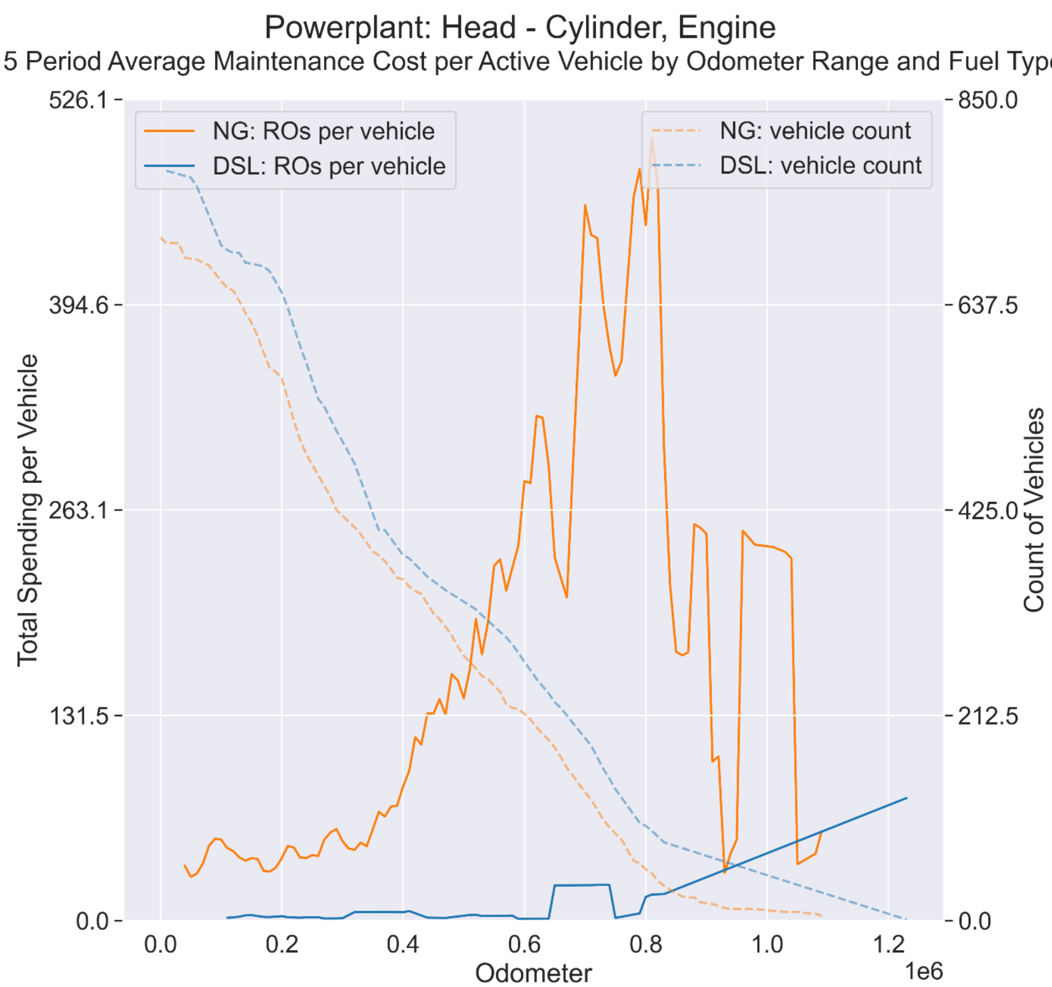


Figure 87: Average Component-Related Costs per Active Vehicle over the Odometer Range

Figure 87 shows the average cylinder head-related spending per vehicle over the odometer range. The NG trucks started experiencing cylinder head issues very early on and peaked around the 700,000-mile mark. In contrast, diesel vehicles did not have any significant cylinder head-related expenditures until 650,000 miles, and, even then, these were much smaller than for the NG vehicles.

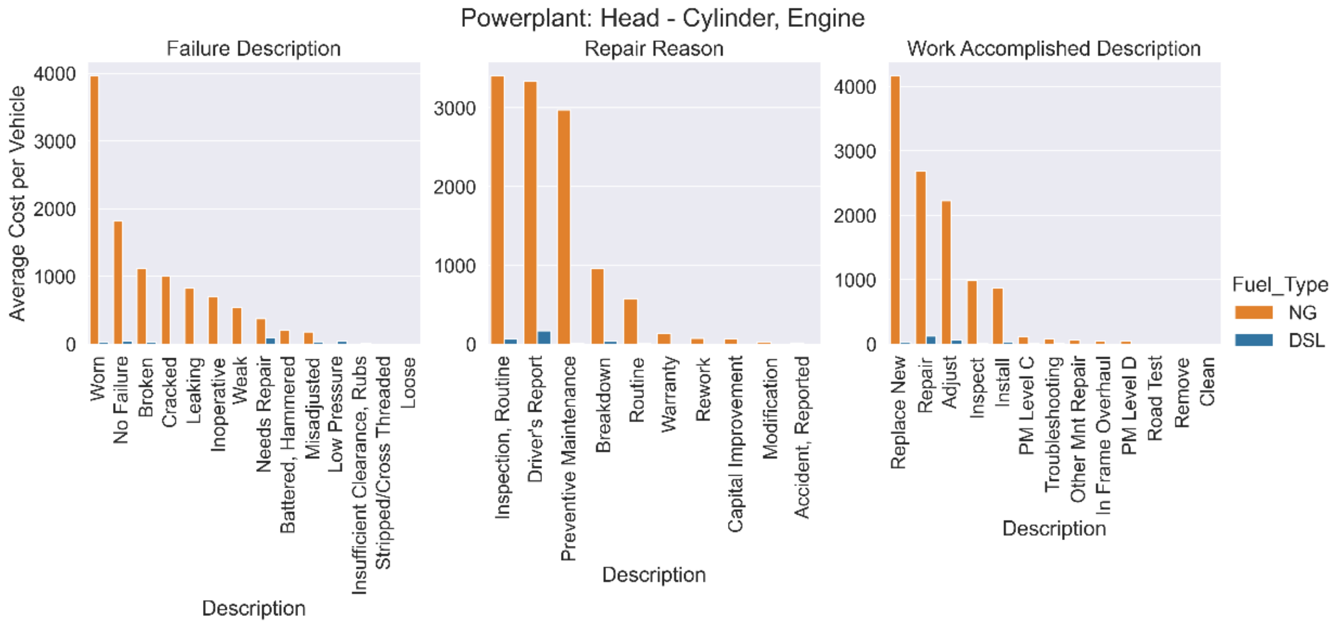


Figure 88: Average Maintenance Expenditures for Cylinder Head Component-Related ROs by Failure Type, Repair Reason, and Work Accomplished VMRS Codes

The 'Routine Inspection' or 'Preventative Maintenance' repair reasons had the highest average expenditures. Valve clearance checks and adjustments likely account for most of these ROs. The 'Replace New' Work Accomplished code had the highest cost per vehicle. Cylinder head components are usually expensive and require a significant amount of labor hours to replace.

Component-Level Breakdown Costs (Fleet 1 Only)

The analysis below attempts to identify the specific components that had the largest differences in breakdown expenditures between diesel and NG vehicles. Only the VMRS systems affected differently by the two fuel types are included in this analysis.

Average Cost per Breakdown by VMRS System Description

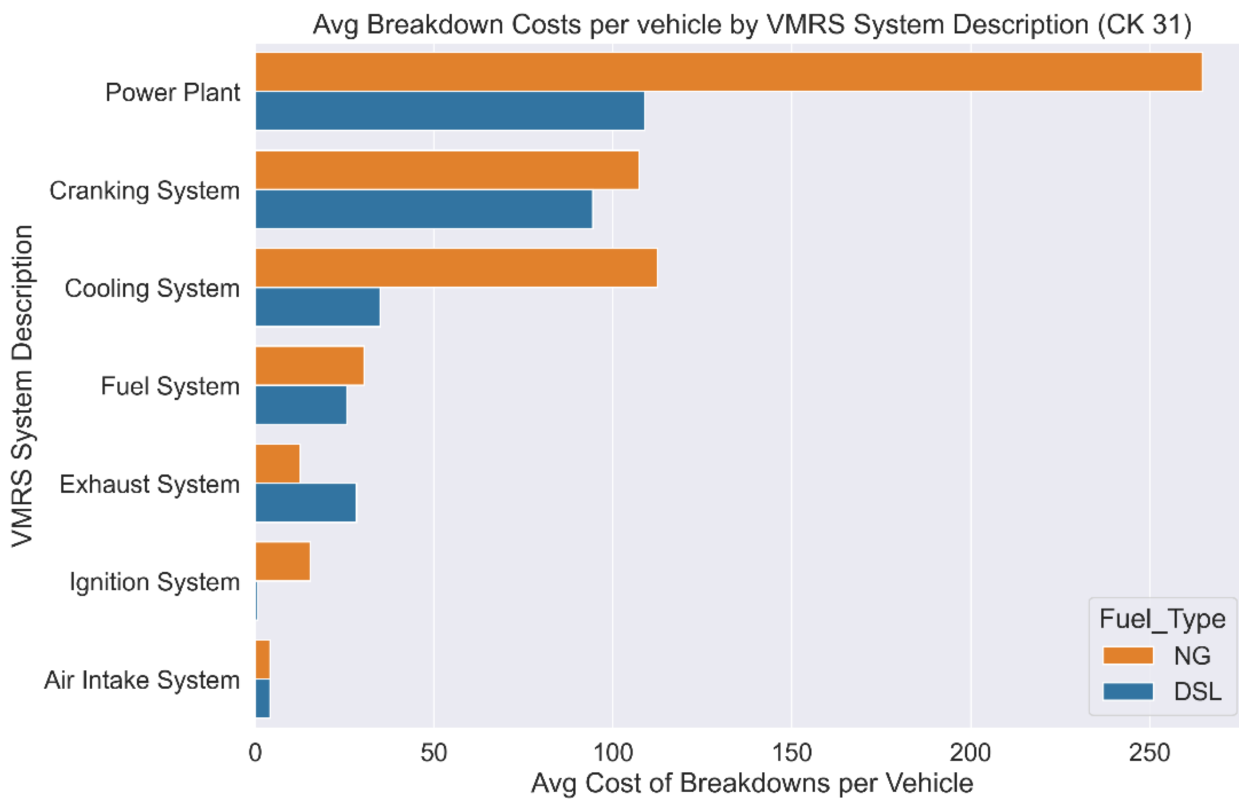


Figure 89: Average Breakdown Costs per Vehicle by Fuel-Type-Significant VMRS System

Looking at the average breakdown costs by VMRS system in Figure 89 shows that the powerplant, cranking, and cooling systems have some of the highest costs per active vehicle for both fuel types. The powerplant and cooling systems had the largest differences in breakdown costs between diesel and NG trucks. These two systems also had the largest cost differences in the regular-maintenance analysis.

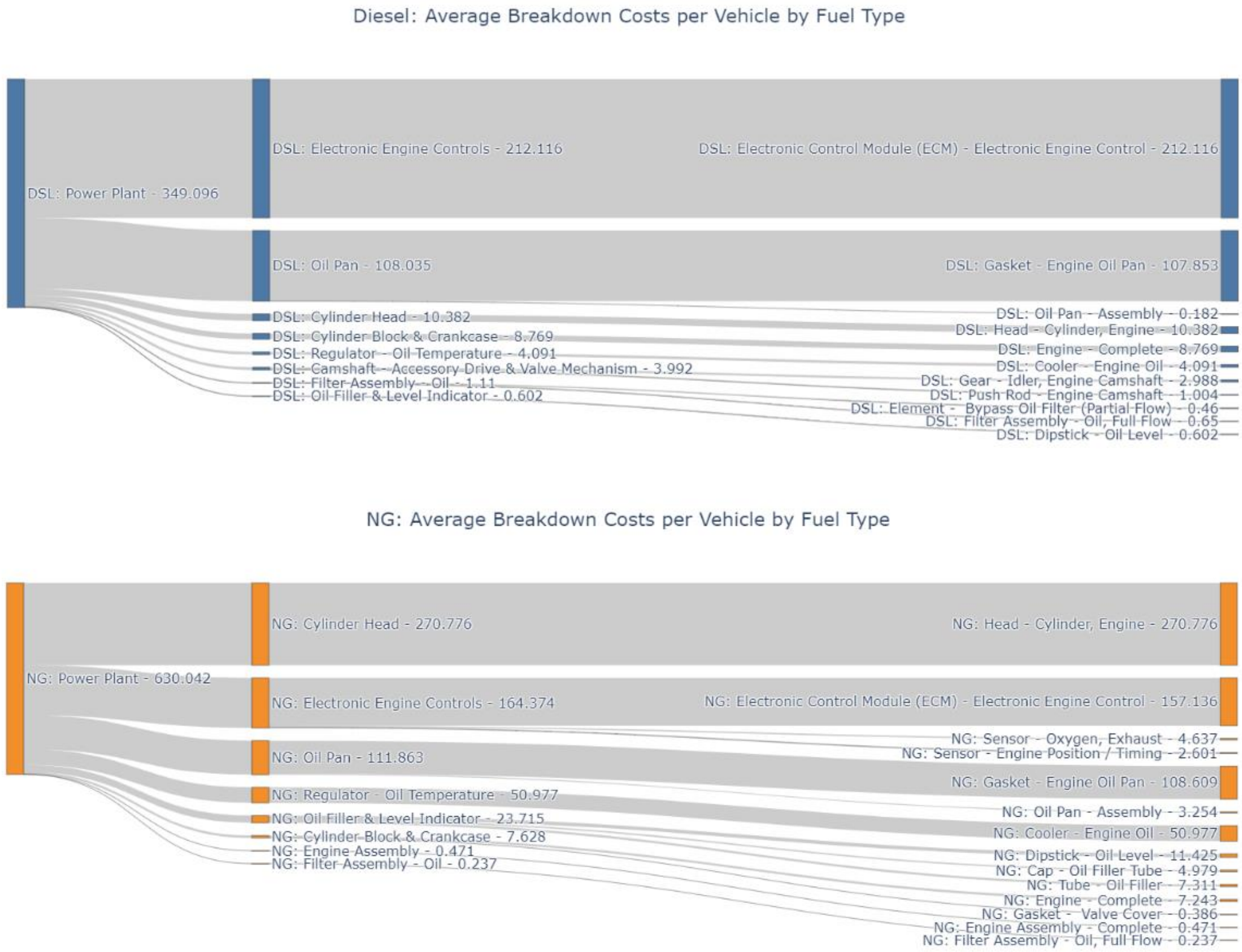
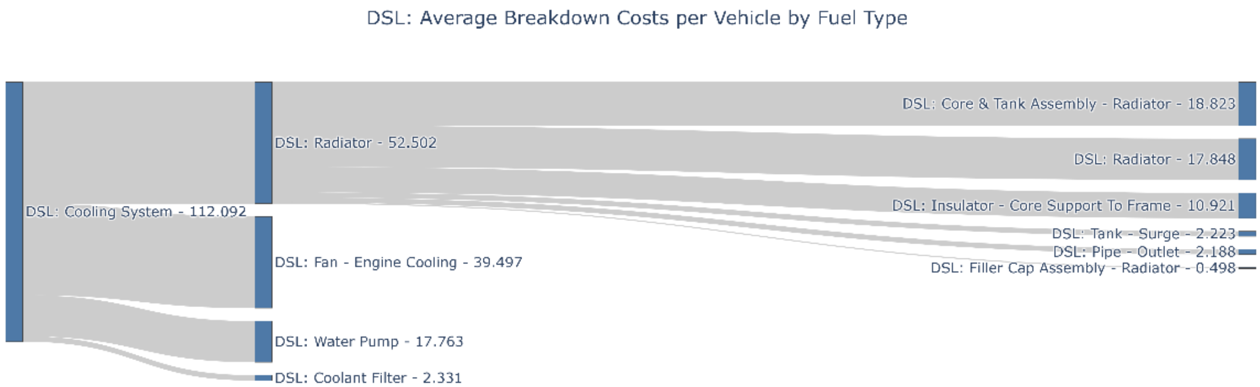


Figure 90: Sankey Plots of Differences in Breakdown Expenditures for Powerplant-System Components

Plotting powerplant related breakdown costs, Figure 90, showed that the same components that required the most general-maintenance expenditures also required the most breakdown expenditures. The electronic-engine-controls module was one of the top components in terms of average breakdown costs for both fuel types. NG trucks had 27 times more costs associated with cylinder head-related breakdowns than diesel trucks.

Cooling System Breakdown Costs



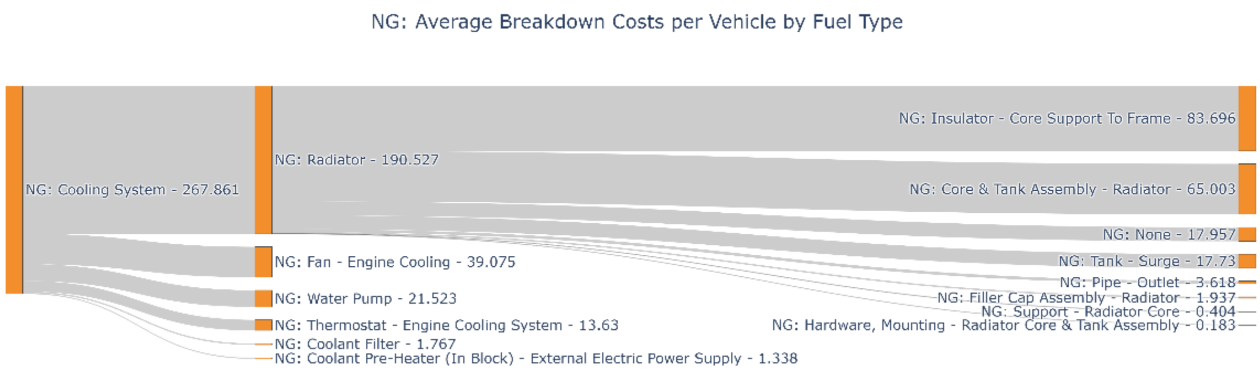


Figure 91: Sankey Plots of Differences in Breakdown Expenditures for Cooling System Components

Similar to the overall maintenance expenditures, Figure 91 shows that the radiator assembly showed the highest average breakdown costs for both fuel types. The radiator core and tank component had one of the higher average breakdown expenditures within the radiator assembly. This component accounted for 16.7% and 24.3% of all cooling system-related breakdown expenditures for diesel and NG trucks, respectively.

Exhaust System Breakdown Costs

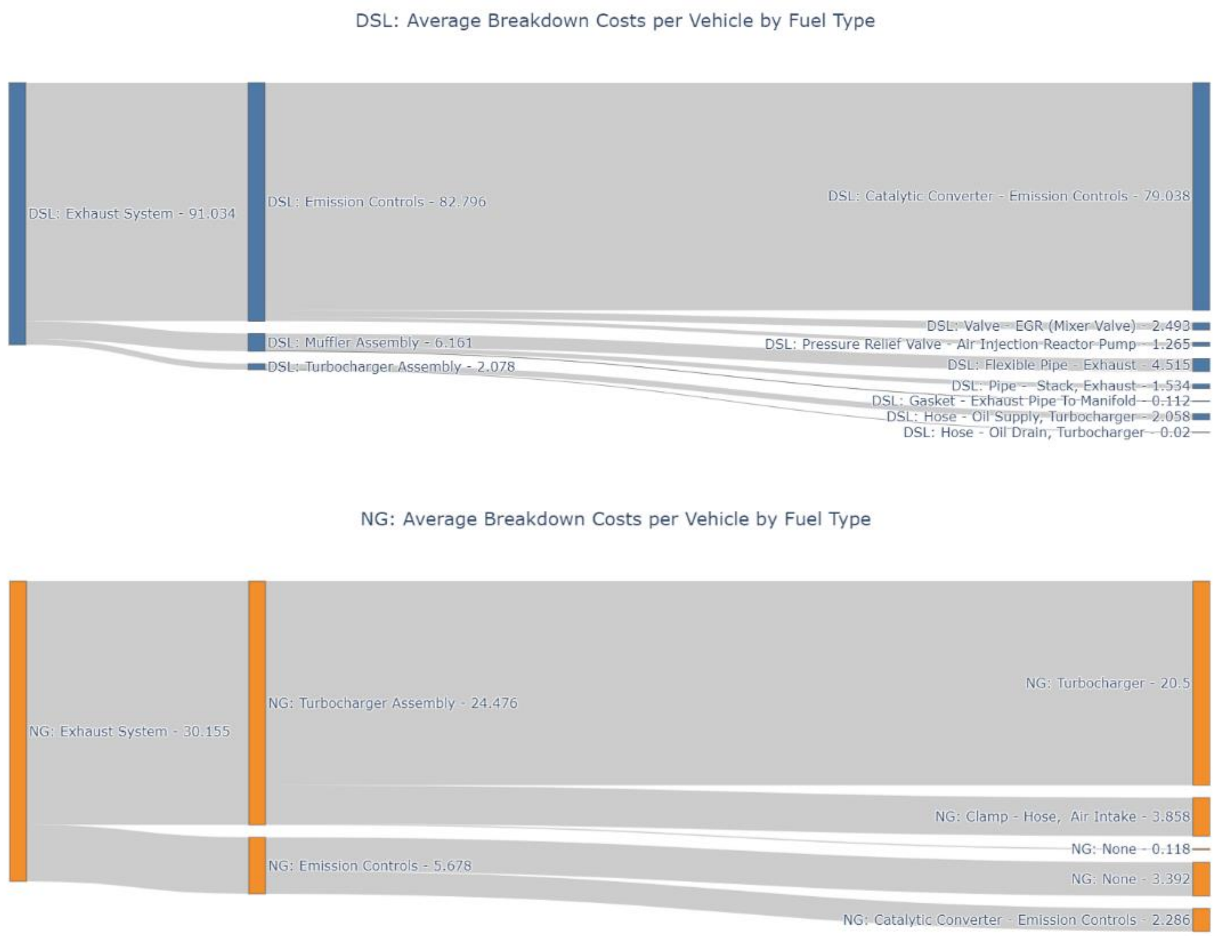


Figure 92: Sankey Plots of Differences in Breakdown Expenditures for Exhaust System Components

As seen in Figure 92, the overall exhaust system-related breakdown costs per vehicle were lower for NG trucks. Similar to what was seen in the regular-maintenance analysis, the emission-controls and turbocharger components were the most common failure points for diesel and NG trucks, respectively.

Overall Data Analysis Findings and Suggestions for Future Study

In many instances, it was also not possible or appropriate to make direct comparisons between the three fleets due to the differences in data completeness. Despite these data issues, the team was still able to make interesting observations from the project's dataset. Our initial expectation was that NG trucks would require higher amounts of maintenance than diesel earlier in their lifespan. This theory was based on the assumption that NG engines have shorter oil change intervals and require more routine maintenance for their ignition and fuel systems. Diesel trucks were expected to require more maintenance than NGVs toward the end of their lifespan due to the complicated exhaust aftertreatment systems required for diesel engines would become more expensive to maintain (and replace) as the trucks age. NG engines, by comparison, have much simpler three-way catalytic converters for exhaust aftertreatment and are typically maintenance-free for the life of the truck.

The results revealed that NG trucks required more maintenance than their diesel counterparts, but the maintenance costs never reached the expected parity between the two fuel types. The NG trucks in this dataset generated more repair orders and required more maintenance expenditures than their diesel counterparts at almost every odometer range. This trend was observed in the maintenance data from all three participating fleets. Further investigation revealed that the **powerplant**, **cooling**, **ignition**, and exhaust systems accounted for most of these observed differences.

Energetics subject matter staff met with PAC member Cummins discussed the project results at the conclusion of the data analysis phase to share the project approach, results, and to discuss questions to learn from additional insights from Cummins' experience.

As detailed in earlier sections, the specific component-level analysis for all of these systems revealed some interesting differences between diesel and NG. The **powerplant system** required the most maintenance for both fuel types, but the NG trucks had significantly more ROs for the cylinder head component than the diesel trucks.

Cummins mentioned that the NG engines require more frequent valve adjustments than diesel engines. This could explain some of the differences in cylinder head-related maintenance. The **cooling system** also had unexpected large differences in maintenance frequency and cost between the two fuel types. Radiator-related failures were the leading repair. The NG trucks in this dataset experienced significantly more cooling system failures than the diesel trucks. Cummins noted that the company provides truck manufacturers with cooling system specifications (diesel and NG) for its engines, but does not provide the cooling system components or review/approve the integrations. Cummins noted that the company provides truck manufacturers with cooling system specifications (diesel and NG) for its engines, but does not provide the cooling system components. Sufficient data to determine the cause of the higher cooling system failure rates with the NG engines was unfortunately not collected in this study.

The NG trucks accumulated three times as many **turbocharger**-related ROs as the diesel trucks. The discussion with Cummins mentioned that the turbochargers may be experiencing pre-mature wear due to the higher NG combustion exhaust gas temperatures, thus causing turbocharger reliability issues. The result was that costs associated with the additional turbocharger maintenance required for NG trucks offset most of the advantages gained from the simpler/less costly exhaust aftertreatment system. The diesel trucks generated three times as many **exhaust-system**-related ROs, but the average exhaust-system-related costs were very similar between the two fuel types.

Cummins staff noted that the NGV UPTIME project findings are similar to internal analyses. Cummins noted that the findings of these internal analyses have been/are being used to guide the development of Cummins' recent and future spark-ignited engine families, with the goal of reducing maintenance costs and improving reliability to be on par with diesel.

This study results quantified the key differences in maintenance frequency and costs between NG and diesel trucks. Data limitations did not allow for performing the planned comprehensive analysis. However, with the established data and analysis framework, gaining access to a larger and broader dataset with more variety and data granularity (i.e., component level) would allow for better analysis results of the reliability improvements across NG engine generations and make it more feasible to pinpoint areas that would benefit from additional development. This information would in turn allow NG engine OEMs to make the improvements necessary to better align the maintenance requirements for diesel and NG engines. Eliminating this maintenance disparity between the two fuel types would remove one of the biggest hurdles and consumer adoption barrier for NGV adoption.

Appendices

NGV UP-TIME Data Partner Fact Sheet

The NGV UP-TIME Project Team is Seeking fleet data partners in the freight and goods movement sector with medium-/heavy-duty trucking applications to contribute natural gas vehicle and diesel vehicle maintenance costs & data for a study funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office. Led by Clean Fuels Ohio and Energetics, the NGV UP-TIME project will create a nationwide database of NGV maintenance & operations information resulting in a comprehensive study documenting maintenance costs, technology solutions, and best practices capable of reducing maintenance or other related ongoing costs for medium- and heavy-duty NGVs used in freight and goods movement, relative to equivalent base diesel models, including emissions after-treatment systems. *See Project One Pager for more information.*

An NGV UP-TIME Data Partner has rights to data from natural gas and diesel vehicles and is willing to share that data with the Project Team. These data partners may only include fleets with both natural gas and diesel vehicles in the freight and goods movement sector with medium-/heavy-duty trucking applications. *See Data Sharing Agreement for more details on the proposed arrangement.*

Energetics' Data Management and Analysis work will collect, validate, collate, analyze, summarize, and publicly release anonymized real-world datasets from natural gas and diesel truck vehicle maintenance data. Energetics will use a secure process for transferring and storing the raw data from the vehicles while removing any Personally, Identifiable Information (PII) and anonymizing data entries. Energetics will develop summary data reports to showcase trends and findings and will share the cleaned dataset with DOE for further analysis. *See Data Analysis Samples as model project outcomes that anonymize the data and results shared publicly.*

NGV UP-TIME Data Partner Benefits include receiving an individualized fleet maintenance data analysis report with results that can be compared to other project data sets. By contributing to an aggregated national database used by the natural gas vehicle industry, freight and trucking industry, and research community, data partners will play a key role in advancing natural gas vehicle efforts.

Become an NGV UP-TIME Data Partner by:

- ✓ Verifying the quantity of available natural gas vehicle and diesel vehicle data that can be shared
- ✓ Notifying the NGV UP-TIME Project Team of your interest
- ✓ Asking questions about the data collection or analysis process, if needed
- ✓ Review, sign, and return the Data Sharing Agreement

Learn more at www.NGV-UPTIME.org

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Updated Performance Tracking Integrating Maintenance Expenses

Appendix B – NGV UPTIME Data Partner Two-Pager

CLEAN FUELS OHIO
OHIO'S CLEAN TRANSPORTATION ADVOCATE

energetics
Clean Energy Consulting

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

NGV ◆ UP-TIME

Clean Fuels Ohio

NGV U.P.-T.I.M.E. Analysis:

Updated Performance Tracking Integrating Maintenance Expenses

Led by Clean Fuels Ohio, this project will provide fleets, natural gas vehicle (NGV) industry stakeholders, and other end-users relevant, real-world information through a proven, multi-data set analysis approach detailing NGV maintenance costs to improve total cost of ownership calculations and to determine the maintenance cost differences between NGV technology generations (current state-of-the-art) and current advanced clean diesel engines (post-2010 and post-2017) for relevant medium-/ heavy-duty **freight and good movement applications**. There is little publicly available data that clearly compares the relative maintenance costs of NGVs and diesel trucks using modern exhaust after-treatment systems to validate claims of NGVs' lower TCO and their potential to improve energy security and cost-effectiveness nationwide. Our team will conduct a comprehensive study quantifying the difference in maintenance costs between diesel and CNG vehicles resulting in individualized fleet reports.

Delivering Real Results from Real Data

The project will implement a proven, multi-data set analysis approach to clearly determine the maintenance cost differences between compressed natural gas (CNG) generations (current state-of-the-art and previous) and current advanced clean diesel engines (post-2010 and post-2017).

The study will strive to capture the impacts of different technology solutions and/or best practices used by project partner fleets capable of impacting/reducing maintenance costs. The results will also showcase the analysis findings by end-use application, engine/fuel system manufacturer, vehicle chassis manufacturer, among others to determine specific research and development and/or outreach needs by application.

What Clean Cities Coalitions Need from Fleet Data Partners

1. **Signed Data Sharing Agreement** guaranteeing that the fleet will that the fleet receives data protection and anonymity by providing data to project team and US DOE.
2. **Preliminary fleet data:** Total # of NGVs, Total # of Diesel Vehicles, Vehicle Class(es), Duty Type(s)/Application(s), and if fleet uses VMRS
3. **Natural Gas Vehicle (NGV) and Diesel Vehicle Maintenance Data**
   - *Via a one-time data upload, spanning data from Jan 2007 and later*

Type of Data	Vehicle Maintenance Data Specifics	
Vehicle Data	• Number • Year/Make/Model • Vehicle Type	• Current Mileage • Fueling Data • Vehicle End-Use Application
Repair Data	• Repair Order Number • Open Date/Time • Close Date/Time • Days in Service	• Length of Repair Order • System/subsystem/ parts repaired
Repair Costs	• Parts • Labor	• Vendor • Repair Total • Warranty Costs

Project Timeline (Oct 1, 2019 – Sep 31, 2022)

<u>Year 1 (Oct 2019 – Sep 2020):</u>
- Gather signed Data Sharing Agreements, collect data

<u>Year 2 (Oct 2020 – Sep 2021):</u>
- Collect data, conduct initial data quality review, develop maintenance & repair code decoder, ensure dataset consistency,

<u>Year 3 (Oct 2021 – Sep 2022):</u>
- Combine and finalize datasets, perform combined dataset analysis, generate and distribute fleet-specific reports and final project report

Why Fleet Data Partners Should Join/Benefits of Project

1. **Individual Fleet Maintenance Analysis Data Report**
   a. Graphical assessment of major parameters by vehicle powertrain, year and model: repair cost per mile, repair frequency, and vehicle utilization
   b. Data to help fleets answer operational questions comparing natural gas and diesel vehicles
   c. Data to help fleets assess cost reduction strategies
2. **Secured Fleet Partnership Agreement**
   a. Agreement will guarantee fleet receives data protection, anonymity, and a fleet specific analysis report of their NGV vs. Diesel maintenance costs.
3. **Access to Full Report with Key Recommendations on Best Practices & Technology Solutions to Reduce NGV Maintenance Costs**
   a. Highlighting cost differences between CNG (both old & new) and current advanced clean diesel engines
   b. Capturing the impacts of different technology solutions and/or best practices used by project partner fleets capable of reducing maintenance costs

Join us and other committed fleet partners to work together to improve the NGV industry!

Project Prime

Clean Fuels Ohio

Project Data Analysis Lead

ENERGETICS
A Division of Akimeka, LLC

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Learn more at www.NGV-UPTIME.org

CLEAN FUELS OHIO

OHIO'S CLEAN TRANSPORTATION ADVOCATE

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Clean Energy Consulting

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES OFFICE

NGV ◆ UP-TIME

Clean Fuels Ohio

Individualized Fleet Maintenance Analysis Data Report

As a result of this project, project facilitators will provide a report to each committed fleet stakeholder who provides data to this NGV maintenance study. The individualized fleet maintenance analysis data report will include real-world, relevant information and data with the following (see below):

CNG RNG LNG

From the report, fleet data partners will receive:

**Fleets should be aware that the level of detail in the individual fleet maintenance analysis report strongly depends on the fleet data inputs and the quality and type of data provided by the fleet.*

1. Complete cleaned dataset including all vehicle and repair order records

2. Graphical assessment of major parameters by vehicle powertrain, year, and model

- Repair cost per mile, both total and by sub-system
- Repair frequency (e.g., repairs per 100 miles, days in ship per 1,000 miles)
- Vehicle utilization (e.g., miles per day, percent uptime)

3. Answers to important operational questions from the assessment such as:

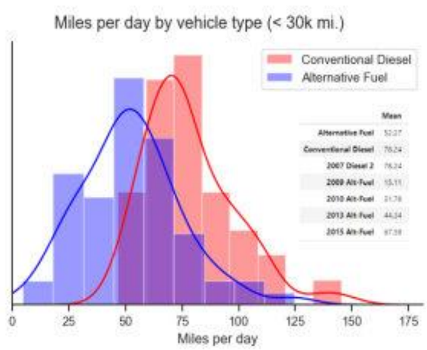
- Has NGV technology improved operational costs? Are older models more expensive to maintain?
- Are NGV's in the shop more or less expensive to repair than conventional diesel/gasoline vehicles?
- Are the models that have the least cost to operate per mile being driven the most to minimize fleet maintenance costs?
- Where are most of the maintenance costs coming from? (e.g. engine repair, tires, wear-and-tear, unscheduled component failure, etc.) Is this different for conventional diesel vehicles versus NGV's?
- Which vehicles spend the most time in the shop? What portions of these repairs are covered by warranty?

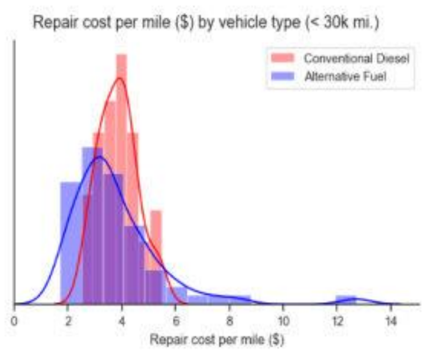
Final outputs may include tables and graphics similar to those below:

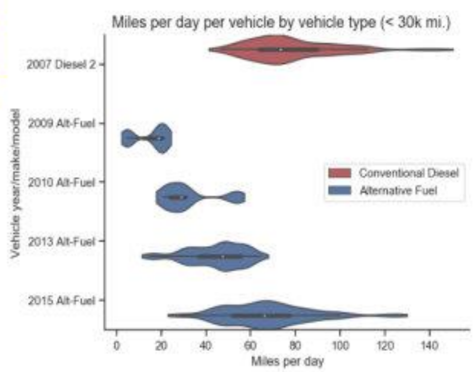
**The sample tables and graphics below were produced as examples and do not represent conclusions for any given fleet or technology.*

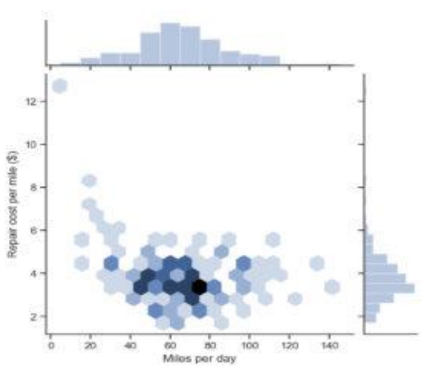
Vehicle Component & Conventional		Pre-2015 Alt-Fuel	2015 Alt-Fuel
Fuel	1.32	0.89	0.89
Tires	1.07	1.55	1.28
Brakes	0.3	0.04	0.07
Engine	0.13	0.07	0.02
Cooling	0.06	0.01	0
Other	0	0.01	0
PM	0.14	0.25	0.13
Body	*1.21*	*1.21*	*0.31*
HVAC	*0.03*	*0.01*	*0.01*
Suspension	*0.02*	*0.01*	*0.01*
Instruments	*0.02*	*0.01*	*0.01*
DEF	*0*	*0.04*	*0.01*
Overall	5.18	5.13	3.68

- Miles driven per day by vehicle type
- Repair cost per mile ($) by vehicle type
- Repair orders per 100 mi by vehicle type
- Average repair order length (days) by vehicle type









Appendix C – NGV UPTIME Data Partner Step by Step Process

NGV UP-TIME Data Partner Step By Step Process

The Natural Gas Vehicle (NGV) UP-TIME project team (Clean Fuels Ohio and Energetics) will work with Fleet Data Partners to collect NGV and diesel vehicle data. Data Partners interested in sharing data can anticipate completing the following three-step process from first contact to sharing data in approximately 3-4 weeks.

First Contact Between Project Team and Fleet Data Partner: The project team will first meet (via email/phone) with the Fleet Data Partner to provide a project overview, answer questions, and confirm fleet preliminary information [e.g., point of contact, email, phone, number of NGV and diesel trucks, vehicle class(es), and duty type(s)/application(s)]. Once Fleet Data Partner expresses interest in becoming a data provider to the project, Clean Fuels Ohio will share the *Data Sharing Agreement template document for Fleet Data Partner to review*.

1. Fleet Data Partner Reviews & Signs Data Sharing Agreement

- Clean Fuels Ohio sends draft agreement (in MS Word) to Fleet Data Partner.
- Fleet Data Partner reviews 3-page agreement and provides feedback/redlines to project team, if any.
- After changes are made, if any, and agreement review is finalized, Fleet Data Partner signs the agreement and sends signed *Data Sharing Agreement* to project team.
- Clean Fuels Ohio and Energetics co-sign *Data Sharing Agreement*.
    - Clean Fuels Ohio shares version of fully executed agreement back to Fleet Data Partner to finalize agreement process.
- **Goal:** Project team fully executes Data Sharing Agreement with Fleet Data Partner
- **Anticipated Time to Complete:** 2 weeks

2. Project Team Works with Fleet Data Partner on Data Sharing Process

- After the Data Sharing Agreement is executed, the Project Team will set up an initial phone call with the fleet data partner point(s) of contact to discuss the data sharing process via the steps below:
    - **Energetics and Fleet Data Partner will discuss the following:** maintenance and fuel use tracking software, maintenance job coding (VMRS), maintenance labor, common natural gas truck failures, warranty, operations, and other available raw data points from fleet data partner.
    - Review, complete, and return *Fleet Inventory and Route Data Questionnaire*
    - Review, complete, and return *Fleet Inventory-Route Data Spreadsheet*
- **Goal:** Fleet Data Partner confirms raw data available to share and provides completed fleet documents
- **Anticipated Time to Complete:** 1-2 weeks

3. Fleet Data Partner Uploads CSV File to Energetics Secure Online SharePoint Site

- Project team is asking for a ONE-TIME dataset upload in order to ensure less work for the fleet partner.
- Energetics will send an email with instructions for fleet data partner to receive a unique log-in for fleet data partner to access the secure online SharePoint site to upload fleet data. The data will only be visible to fleet data partner and Energetics.
- **Goal:** Fleet Data Partner completes a one-time data share/upload to Energetics SharePoint data collection site
- **Anticipated Time to Complete:** 1 day