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16. ABSTRACT

The objective of this research effort was to evaluate the hybrid electric street sweeper powered by hydrogen fuel cell (HFC) technology as a suitable zero-emission alternative to the street sweeper technologies currently implemented by Caltrans. To make this determination, a research study was conducted to compare various aspects of diesel, compressed natural gas (CNG), and HFC street sweepers.

The research results show that HFC street sweepers are a viable alternative to current street sweeper technologies, with certain advantages and caveats. This research generated a variety of metrics and results relating to the diesel, CNG, and HFC street sweepers. Some of the key metrics are estimates of emission reductions associated with replacing CNG and diesel with HFC street sweepers, regenerative braking energy captured by the HFC street sweeper, operator and mechanic impressions ofHFC performance and reliability relative to conventional technologies, observed operating range of the street sweepers, and Impact of cold start on diesel and CNG emissions.\

In addition to activity and emission data that was collected to help with this evaluation, two surveys were developed and administered. One survey targeted street sweeper operators and was administered to four Caltrans operators, and the other targeted mechanics and was administered to four Caltrans mechanics. The surveys covered various aspects of the sweeper technologies including performance, reliability, ease of use and comfort.

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Evaluation of Hybrid Electric Street Sweepers

FINAL REPORT

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Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Department of Transportation (Caltrans). The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

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Acronyms and Abbreviations

AC........alternating current
ATS........after treatment system
CARB........California Air Resources Board
CE-CERT........College of Engineering - Center for Environmental Research and Technology
CFR........Code of Federal Regulations
CNG........compressed natural gas
CO........carbon monoxide
CO_2........carbon dioxide
CSV........comma-separated values
DOC........diesel oxidation-catalyst
DOE........division of equipment
DOM........division of maintenance
ECM........engine control module
ECU........engine control unit
EGR........engine gas recirculation
EPA........United States Environmental Protection Agency
GPS........global positioning system
HFC........hydrogen fuel cell
HP........horsepower
HSD…........high-side dump
HFID…........heated flame ionization detector
HVAC........heating, ventilation, and air conditioning
LAX........Los Angeles international airport
NDIR........non-dispersive infrared
NO_x........nitrogen oxides
OEM........Original Equipment Manufacturer
PEMS........portable emissions measurement systems
PM10........particulate matter 10 micrometers and smaller
PTO........power take-off
RPM........revolutions per minute
SAFD…........speed-acceleration frequency distribution
SCAQMD…........South Coast Air Quality Management District
SCR........selective catalytic reduction
THC........total hydrocarbons
UCR........University of California at Riverside
UV........ultraviolet
ZEV........zero emission vehicle

Executive Summary

California has enacted several policies to transition state owned vehicles from traditional fuels to Zero Emission Vehicle (ZEV) platforms. The South Coast Air Quality Management District also does not allow the use of diesel street sweepers, which has led Caltrans to deploy compressed natural gas (CNG) sweepers. CNG sweepers have traditionally been less reliable and have lower production rates relative to diesel sweepers. Caltrans' Divisions of Equipment (DOE) and Division of Maintenance (DOM) are exploring alternatives to using CNG and diesel powered sweepers.

The objective of this research effort was to evaluate the hybrid electric street sweeper powered by hydrogen fuel cell (HFC) technology as a suitable zero-emission alternative to the street sweeper technologies currently implemented by Caltrans. To make this determination, a research study was conducted to compare various aspects of diesel, CNG, and HFC street sweepers. This final report summarizes multiple research tasks that were performed by the research team at the University of California Riverside (UCR) in coordination with Caltrans to meet the goals of this project.

Literature Review

A literature review was performed to identify relevant information concerning street sweepers and street sweeper testing. The South Coast Air Quality Management District (SCAQMD) has certification criteria for sweepers relative to entrained PM10 and a rule to move toward alternative-energy powered sweepers. There are very few studies on the emission and performance of street sweepers. A few studies characterize ambient air quality concentrations during street sweeping, but there were no studies found that characterize tail-pipe emissions from street sweepers with respect to their operating cycles. In addition to characterizing street sweeper activity in the Caltrans fleet, a major focus of this project was evaluating emissions during sweeper operation.

Activity Data Collection

A number of Caltrans' street sweeper activity datasets from several sources were collected and analyzed for this project. Seven street sweepers, 3 CNG and 4 diesel, where instrumented with engine data loggers and several months of data were collected for each sweeper. More than 400 hours of general activity data for the HFC sweeper was collected from US Hybrid, the developer of the HFC powertrain. US Hybrid also provided 23 days of detailed activity data, including the power consumption of various HFC sweeper systems. Daily summary activity data by vehicle was obtained from the Caltrans fleet management system database for all sweepers.

Emission Measurements

For this project, street sweeper emissions were measured using two different emission measurement setups, namely field testing using the Portable Emissions Measurement System (PEMS) and chassis dynamometer testing with PEMS. PEMS field testing was conducted to measure emissions under real-world activity in actual usage. For field testing, a custom bracket was fabricated and four sweepers were tested, two CNG and two diesel, for two days each. Time-lapse cameras with time stamps and set at one picture frame per second

were used to monitor activity including broom activity and hopper movement. Chassis dynamometer testing using the PEMS system was performed on prescribed cycles, developed in part from real-world activity, for the purpose of comparing sweeper emissions and performance on the same activity.

Survey Work

The primary objective of this research has been to evaluate the hybrid electric HFC sweeper technology as an alternative to the diesel and CNG sweepers that are currently used in the Caltrans fleet. In addition to activity and emission data that was collected to help with this evaluation, two surveys were developed and administered. One survey targeted street sweeper operators and was administered to four Caltrans operators, and the other targeted mechanics and was administered to four Caltrans mechanics. The surveys covered various aspects of the sweeper technologies including performance, reliability, ease of use and comfort.

Work Order Evaluation

As part of Caltrans' fleet management system, equipment maintenance and repair work order information is retained. This information, which included individual work orders, work order durations, and reasons for delay, was analyzed to help characterize the reliability and downtime of the various sweeper technologies across the Caltrans vehicle fleet.

Results

Evaluation of the datasets collected under this research project generated a variety of metrics and some of the key results are presented here in a list of "Pros and Cons" relative to the objective of this research project, which was to evaluate the hybrid electric HFC as an alternative to the conventional diesel and CNG street sweepers that are currently used in the Caltrans fleet.

Pros:

- *Emission Reductions* -The HFC street sweeper uses compressed hydrogen gas as fuel and produces only water and warm air. It is a zero-emission technology at the point of use. The average reduction in emissions of replacing a diesel sweeper is 9.82 tones CO_2/year, 4.88 kg/year, 0.21 kg/year THC, and 5.1 kg/year NO_x. The average reduction in emissions of replacing a CNG sweeper is 10.59 tones CO_2/year, 171.77 kg CO/year, 10.24 kg/year THC and 1.26 kg NO_x/year.
- *Cold-Start Emission Non-Issue* -In addition to running emissions, the HFC street sweeper is also not impacted by cold-start emissions. Cold-start NO_x g/mile emissions, for example, were shown to be 46 times higher in diesel relative to hot-stabilized emissions for moderate activity. For the HFC street sweeper, there is no emission related warm-up consideration.
- *Regenerative Braking* -The energy recapture rate for regenerative braking on the HFC street sweeper was found to be in the range of 7.36 to 13.38% with a median value of 10.81% in the in the real-world activity dataset that was analyzed. Regenerative braking was in the range of 0.36% to 6.77% in the mode specific chassis dynamometer testing. Arterial driving showed the highest recovered energy and

freeway and low speed sweeping showed the least. The diesel and CNG sweepers have no mechanism to recapture braking energy.

- *Broom Performance* - Broom performance of the HFC street sweeper is independent of the drivetrain and can be adjusted independently. In the diesel and CNG street sweepers, broom performance is tied to the engine speed. Caltrans street sweeper operators generally much preferred the operation of the HFC broom system and indicated it had better performance relative to the other sweepers.
- *Driving Performance* - The HFC street sweeper propulsion is by direct electric drive motor, which, by the nature of electric motors, provides instant maximum torque at the start. This produces better low end acceleration and power relative to combustion engine based platforms that produce their maximum torque only once their engine speed rev up to the proper engine speed. Most Caltrans street sweeper operators indicated that the HFC had better driving performance.

Cons:

- *Operating Range* - The stated range of the HFC is 180 miles per tank of hydrogen. Analysis of operating distances and refueling indicate that under normal mixed operation (driving and at least 20% of time sweeping), the HFC range is roughly between 51 to 66 miles, depending on the percentage of sweeping, idling, and to what fuel level the HFC is refueled. From the fleet management database, the median of the daily trip lengths for all diesel, CNG and HFC are 25.5, 19.2, and 16.6 miles. The median of the maximum trip lengths for each diesel, CNG and HFC are 64.9, 57.5 and 62.2 miles. Based on the results of the fleet management data, the average of all the daily diesel and CNG sweeper trips are well within the lower end of the typical HFC daily range (51 miles), however, the maximum daily distances for all diesel and CNG sweepers exceed the lower daily HFC threshold. Only 28.6% of CNG had maximum daily distance traveled within the upper HFC range of 66 miles, the remainder were outside this range and the HFC would likely not comfortably achieve the maximum trip distance of many of these vehicles with mixed activity including sweeping. It is unknown what percentage of sweeping the maximum daily trips consisted of.
- *Refueling Locations*- One of the difficulties with hydrogen technology is that the infrastructure to support refueling is not readily available and hydrogen refueling locations are limited. This is even more so the case with larger heavy duty hydrogen applications relative to light duty hydrogen vehicles. Larger heavy-duty applications are not well suited to passenger refueling infrastructure which are not designed to dispense the larger amounts of hydrogen required for larger applications. There is also an issue with hydrogen station reliability and downtime which may impact refueling.
- *Reliability* - The hybrid electric HFC street sweeper from US Hybrid is the first of it's kind. It is in the early stages of implementation and the longer term reliability is not known, although HFC transit bus applications have shown good results. During the course of this project, the HFC sweeper was converted from a two high-capacity battery system to a one high-capacity battery system to address technical issues. Maintenance survey respondents rated the HFC as having high frequency of in cab

component and powertrain repair. To inform on the issue of reliability, work order data for all sweepers was evaluated to determine the number of offline hours from work order repairs. Work order data showed that diesels had the least median offline hours and that offline hours for both the CNG and HFC were significantly higher. The offline hours for the HFC were comparable to the CNG sweepers, however, the work order count for the HFC was about 30% higher than for the CNG and 142% higher than for diesel. This may indicate that issues with the HFC were being addressed more quickly. On the other hand, a HFC has no moving parts, unlike a combustion engine, and in theory, could potentially be more reliable than its conventional counterparts in the future.

- *Perceived Safety Concerns* – At least one operator survey respondent expressed safety concerns associated with the refueling, repair and maintenance, and accident safety relative to the 5000 psi hydrogen fuel tanks that are utilized in the HFC street sweeper. This study did not address potential risks associated with the HFC street sweeper's high pressure hydrogen fuel system.

Recommendations:

The following recommendations are suggested:

- The HFC street sweeper tested for this project is a viable alternative to current street-sweeper technologies in the typical use case, provided that the hydrogen refueling infrastructure is there to support it. In areas of limited hydrogen refueling service, deployment of a hydrogen refueling infrastructure should coincide with or precede acquisition of the HFC street sweeper.

- Ensure the availability of local repair facility in the area of deployment.

- Educate operators and maintenance staff on the risks and safety concerns related to high pressure hydrogen systems as well as high capacity battery systems. This is important, not only to increase safety, but also to dispel any myths that users of the system may have.

- Hydrogen can be produced from renewable energy. Ensure that hydrogen is sourced from renewable based hydrogen.

1. Introduction

California has enacted several policies to transition state owned vehicles from traditional fuels to Zero Emission Vehicle (ZEV) platforms. Additionally, the South Coast Air Quality Management District does not allow the use of diesel street sweepers, which has led Caltrans to deploy compressed natural gas (CNG) sweepers. CNG sweepers have traditionally been less reliable and have lower production rates relative to diesel sweepers. The Divisions of Equipment (DOE) and Maintenance are exploring alternatives to using CNG and diesel powered sweepers.

1.1. Project Objectives and Report Organization

The objective of this research effort was to determine if a hybrid electric street sweeper powered by a hydrogen fuel cell is a suitable alternative to using CNG or diesel powered sweepers. To make this determination, a research study comparing various aspects of diesel, CNG, and hydrogen fuel cell street sweepers was conducted. This research will evaluate equipment and methods to be identified to meet sweeping needs while minimizing costs and satisfying all regulatory mandates and laws.

To achieve the project objectives, the research team at the University of California Riverside (UCR) performed multiple research tasks including collection of real-world street sweeper activity using data loggers, collection of on-road emissions data using PEMS, chassis dynamometer energy and emission testing, evaluation of Caltrans' fleet management data, and surveying of Caltrans street sweeper mechanics and operators. The research activities and results are presented in this report, which is organized as follows:

- Chapter 2: Literature review of existing research relative to street sweeper performance and emissions.
- Chapter 3: Description of Caltrans fleet composition, sweeper technologies and vehicle test matrix.
- Chapter 4: Presentation of the various street sweeper activity data collection efforts in this project, the analysis of the activity data analysis and results. Sources for activity data include data loggers, the fuel cell manufacturer, and fleet maintenance software.
- Chapter 5: Presentation of the PEMS on road data collection effort, PEMS data analysis and results.
- Chapter 6: Presentation of the chassis dynamometer street sweeper testing, test data analysis and results.
- Chapter 7: Presentation of the operator and mechanic surveying effort and summary of survey results.
- Chapter 8: Provides additional analysis and discussion of various research results
- Chapter 9: Presents research conclusions

- Chapter 10: Provides recommendations for future research.
-

2. Literature Review

In 1997, South Coast Air Quality Management District (SCAQMD) in California was the first government entity to introduce a certification procedure for testing the efficacy of road sweepers in removing PM_{10}. The agency's 'Rule 1186 - PM_{10} Emissions from Paved and Unpaved Roads, and Livestock Operations', required testing of road sweepers' ability to remove more than 80% of the typical urban street dust loadings and limits the amount of PM_{10} entrained during the sweeping process to less than 200 mg/m [1]. In 2000, SCAQMD has adopted 'Rule 1186.1 - Less Polluting Sweepers', that requires municipal agencies to use alternative-energy-powered sweepers [2]. Similarly, Canada and Germany have their sweeper testing protocols [3].

There are limited numbers of existing studies about emission and performance evaluation for street sweepers. So far none of the studies have characterized tail-pipe emissions from sweepers in respect to the operating cycles, which is the goal of this project. A few studies measured ambient air quality concentrations during street sweeping and before/after street sweeper to examine air quality benefits. Some of the studies also evaluated the dust-removal efficiency. A few of the studies evaluated the sweeping performance of the street sweepers. The following sections will summarize the existing papers and reports.

2.1 Existing Evaluation of Air Quality Benefits

Fitz and Bumiller *et al.* [4] applied an artificial tunnel and quantified the emission rates for several street sweepers (four vacuum-type and one broom sweeper) under operating conditions. PM_{10} concentrations were measured at the inlet and outlet while a sweeper removed sand deposited along the road. They observed a large difference in emission rates between vacuum-type sweepers, with rates varying from 5 to 100 mg/meter swept. The authors believed that the background PM_{10} was primarily from the diesel engine exhaust. They found that PM10 emission factors from sweeping sand on a paved road were comparable with emissions from driving on an unpaved road constructed of the same type of sand. The conclusion is that emissions, during the operation of street sweepers to remove heavy deposits of sand from a paved road, are not significant compared with the benefit in reduced emissions provided by a cleaned road [4].

Amato *et al*. [5] reviewed more than 100 sweeper related studies and policies to evaluate the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. The authors found there were very few studies on air quality benefit induced by street sweeping. Depending on the measurement setup, local dust composition, and weather condition, the effects could be anything - no discernible difference or observing reduced/increased curbside PM_{10} level [5]. The challenges lie in the determination of background concentration and uncertainties of ambient measurement.

A European report reviewed a number of studies in Europe, they found that there were a relatively small number of studies of the impact of street sweeping and washing on ambient PM_{10} concentrations in Europe. Most studies have been limited spatially and temporally. The road sweeping studies have generally shown no effect when the uncertainties of the measurements are considered [5].

Bogacki *et al*. [6] studied the impact of the cleaning of a dual carriageway located in a street canyon in Krakow (Southern Poland) on the levels of the PM_{10} and $PM_{2.5}$ air concentrations. For this purpose, representative dust samples from the analyzed street were collected corresponding to the street cleaning situation, the re-entrained road dust PM_{10} and $PM_{2.5}$ emissions were estimated in accordance with the U.S. EPA guidelines, and the particulate matter atmospheric dispersion modelling was carried out using the CALINE4 model for a selected episode of street cleaning. The modelling results were compared with the measurement results of the PM_{10} and $PM_{2.5}$ air concentrations obtained from the air quality monitoring station (traffic type) located in the middle of this street canyon. The results of the air dispersion modelling in the canyon zone confirmed the strong impact of street cleaning on the temporary (1-hour) PM_{10} concentrations in the direct vicinity of the cleaned section depending on meteorological conditions. During the cleaning episode, no significant increase in the $PM_{2.5}$ concentration in the air was observed. The authors concluded that intensive street cleaning process may contribute to a short-term, lasting-up-to-3-hour increase in the air concentrations of PM_{10} and, to a lesser degree, those of $PM_{2.5}$ due to the re-entraining process of the dust deposited on the road by the sweeper [6].

2.2 Existing Performance Evaluation

Dessouky *et al*. [7] studied the sweeping performance of CNG sweepers in LA County. They found that switching to CNG sweepers has resulted in a reduction in the productivity of sweeping operations due to sweeping operations due to sweeper design issues and far refueling locations. They found no significant difference between the maintenance costs of the diesel and CNG sweepers. To offset this loss in productivity with CNG sweepers, the authors developed mathematical optimization models to make specific recommendations regarding (a) the locations where Caltrans should promote the use of CNG fueling stations, and (b) the rebalancing of the routes. [7].

2.3 Alternative-Powered Sweepers Available on the Market

According to several online media articles, New York City is the first city in the world to adopt a hybrid street sweeper in year 2010. The Allianz 4000 hybrid sweeper features a 6.7-liter Cummins diesel in addition to two 12-volt lithium-ion batteries and an electric-traction drive system. With the setup, it is estimated that 40 to 45 percent fuel can be saved over a diesel-only sweeper [8], [9].

Table 2-1 Sweepers available on the market [10]

Manufacturer	Model	Fuel	Heavy-Duty Power System
Autocar	ACMD-Xpert	CNG - Compressed Natural Gas, LNG - Liquefied Natural Gas	Cummins Westport L9N 8.9L Near Zero
Autocar	ACX-Xpeditor	LNG - Liquefied Natural Gas, CNG - Compressed Natural Gas	Cummins Westport ISX12N 11.9L Near Zero, Cummins Westport L9N 8.9L Near Zero
Elgin	Broom Bear	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
Elgin	Crosswind1	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
Global	M3 CNG	CNG - Compressed Natural Gas	GMC 5.7L V8
Global	M3 SUPERCHARGED	Electric	US Hybrid AC Induction with Integrated Gear Reduction 120kW electric motor
Global	M4 CNG	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
Global	M4 Hybrid	Hybrid - Diesel Electric	Cummins ISB6.7
Global	M4 SUPERCHARGED	Electric	US Hybrid AC Induction with Integrated Gear Reduction 120kW electric motor
Nitehawk	Osprey II sweeper	Propane - Bi-fuel	GMC 6.0L V8
Nitehawk	Osprey II sweeper	Ethanol (E85)	Ford 6.2L V8
Nitehawk	Raptor II sweeper	CNG - Compressed Natural Gas, Propane - Bi-fuel	GMC 6.0L V8
Schwarze Industries	A7 Tornado sweeper	CNG - Compressed Natural Gas	
Schwarze Industries	A7 Zephyr sweeper	CNG - Compressed Natural Gas	
Schwarze Industries	M6 Avalanche	CNG - Compressed Natural Gas	
TYMCO	500x	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
TYMCO	600	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
TYMCO	HSP	CNG - Compressed Natural Gas	Cummins Westport L9N 8.9L Near Zero
US Hybrid	HySweep sweeper	Hybrid - Diesel Electric	Cummins ISB6.7

3. Caltrans Street Sweeper Fleet Composition

The focus of this project was on street sweepers utilized in the Caltrans vehicle fleet. The Caltrans fleet consists of street sweepers from three different powertrain technologies namely diesel, compressed natural gas (CNG), and hydrogen fuel cell hybrid electric street sweeper. The Caltrans fleet consists primarily of street sweepers manufactured by Global Environmental Products, Allianz Johnston and Freightliner, with the majority of the newer street-sweepers being the M4 and M4HSD line from Global Environmental Products. The Allianz Johnston street sweepers are primarily the 4000 model, which was one of the Allianz Johnston sweeper product lines purchased by Global Environmental Products in 2011 [11] and is the predecessor to the Global M4. The Johnston street sweepers are model year 2009 and older, while the newer street sweepers are by Global Environmental Products and Freightliner. The Caltrans street sweeper fleet composition by fuel type, make and model is presented in Figure 3-1. A breakdown of street-sweeper powertrain technology by model year is presented in Figure 3-2.

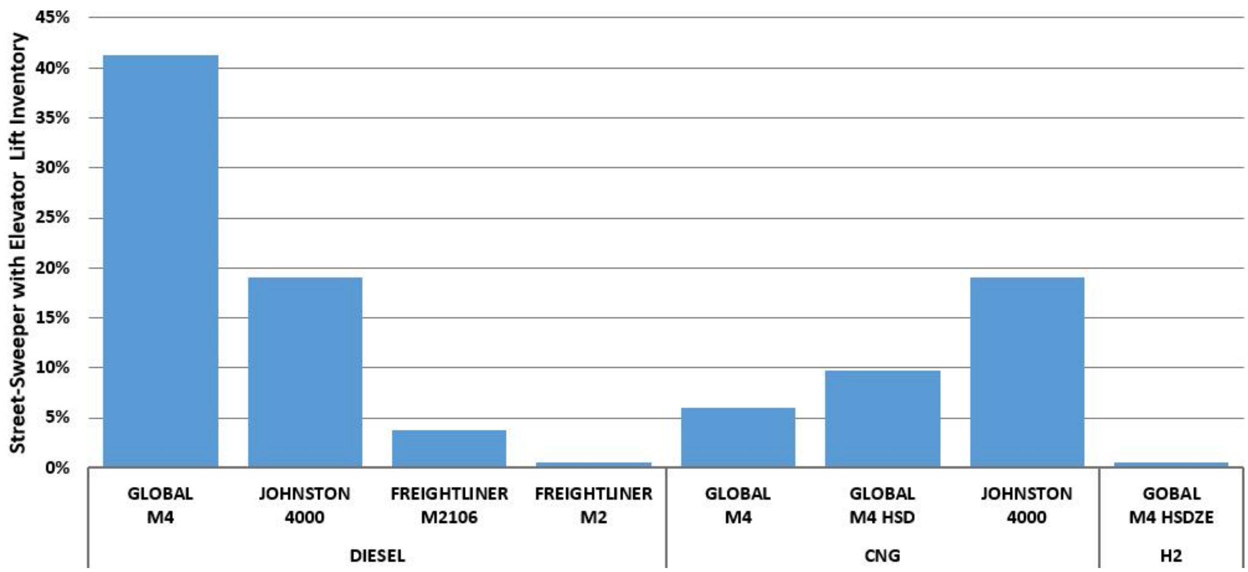

Figure 3-1 Caltrans Inventory of Street-Sweepers with Elevator Lift by Model Type

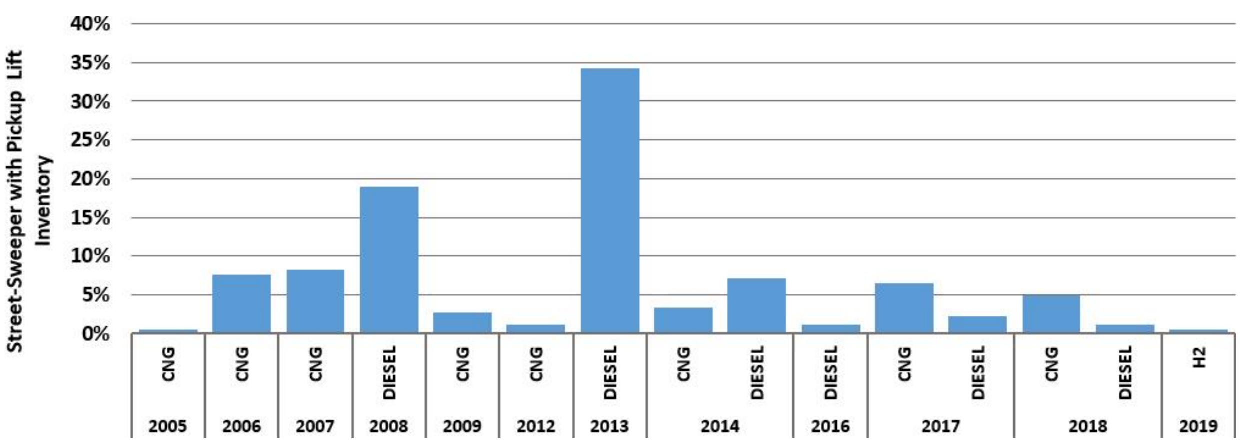

Figure 3-2 Caltrans Inventory of Street-Sweepers with Elevator Lift by Model Year

The majority of newer street sweepers in the Caltrans fleet are the Global M4 and Global M4 HSD models from Global Environmental Products. These two models are distinguished by the hopper dumping method. The Global M4 is a rear dumping street sweeper, shown in Figure 3-3, and the Global M4 HSD is a high side dumping street sweeper, shown in Figure 3-4. Both, the Global M4 and Global M4 HSD, are available as diesel and CNG, however the Global M4s in the Caltrans fleet are typically diesel and the Global M4 HSDs in the Caltrans fleet are typically CNG.

Figure 3-3 Global M4 rear dump street sweeper

Figure 3-4 Global M4 HSD high side dump street sweeper.

3.1. Fuel Cell Electric Street Sweeper

Caltrans' new fuel cell electric street sweeper is a zero emission hybrid electric street sweeper manufactured by Global Environmental Products and powered by a hydrogen fuel cell system from U.S. Hybrid. This is the world's first zero emission sweeper with this powertrain. The fuel cell system uses a thermo-chemical process to produce electricity and H_2O from compressed hydrogen gas. The H_2O is a byproduct of the electricity production by the hydrogen fuel cell and is diverted to the sweeper's water tank system for dust suppression. Electricity generated from the fuel cell system is fed to an inverter and powers a direct electric drive AC motor for the sweeper's drive wheels. Electricity from the inverter also powers a set of hydraulic pumps to run hydraulic functions such as brooms. Electricity generated by the fuel cell system also charges high voltage batteries which supplement energy to the inverter during high load events. The fuel cell street sweeper uses the Global M4 HSD design and is shown in Figure 3-5.

Figure 3-5 Hydrogen fuel cell electric street sweeper

3.2. Vehicle Test Matrix

For this project, a number of street sweepers were monitored for activity, four were tested with PEMS, and three were tested on the chassis dynamometer. Table 3-1 lists the street sweepers that were involved in this research and their particular characteristics. Some of these sweepers overlapped two or more activities. The activities that each of the street sweepers were involved with are presented in Table 3-2.

Table 3-1 Description of street sweepers involved in this research

Label	Model Year	Fuel Type	Model	Powertrain	Power Rating	Transmission	Tare Weight	Hopper Capacity (cu yd)	Dump Position
7011371	2019	H_2	Global M4HSD	US Hybrid Fuel Cell	Fuel Cell 80 kw Battery 160 kw peak Drive Motor 200kw Hydraulic Motor 40kw	Electric Drive	22860	5.2	Scissor-lift with hopper tilt
7012818	2018	CNG	Global M4HSD	Cummins BG-230 8.9L	250 hp	Hydrostatic Drive	23760	5.2	Scissor-lift with hopper tilt
7011373	2017	CNG	Global M4HSD	Cummins BG-230 8.9L	250 hp	Hydrostatic Drive	23240	5.2	Scissor-lift with hopper tilt
7011374	2017	CNG	Global M4HSD	Cummins BG-230 8.9L	250 hp	Hydrostatic Drive	23240	5.2	Scissor-lift with hopper tilt
7008055	2013	Diesel	Global M4	Cummins ISB-280 6.7L	280 hp	Hydrostatic Drive	19680	5.6	Rear dump
7005947	2013	Diesel	Global M4	Cummins ISB-280 6.7L	280 hp	Hydrostatic Drive	19680	5.6	Rear dump
7011098	2017	Diesel	Schwarze M6 Avalanche Freightliner M2 106 Chassis	Cummins ISL 8.9L	310 hp	Automatic Gear Shift	24400	5.0	Scissor-lift with hopper tilt
7011099	2017	Diesel	Schwarze M6 Avalanche Freightliner M2 106 Chassis	Cummins ISL 8.9L	310 hp	Automatic Gear Shift	24400	5.0	Scissor-lift with hopper tilt

Table 3-2 Identification of street sweepers and associated research activities

Label	Model Year	Fuel Type	Model	Install Location	PAMS	PEMS	Chassis Dyno
7011371	2019	H_2	Global M4HSD	Westdale	X		X
7012818	2018	CNG	Global M4HSD	Westdale	X		X
7011373	2017	CNG	Global M4HSD	Bloomington	X	X	
7011374	2017	CNG	Global M4HSD	Bloomington	X	X	
7008055	2013	Diesel	Global M4	Yucca Valley		X	
7005947	2013	Diesel	Global M4	Victorville	X	X	X
7011098	2017	Diesel	Schwarze M6 Avalanche Freightliner M2 106 Chassis	Sylmar	X		
7011099	2017	Diesel	Schwarze M6 Avalanche Freightliner M2 106 Chassis	Sylmar	X		

4. Activity Data Collection

Data was collected from seven street sweepers across three different powertrain technologies, consisting of three diesel, three compressed natural gas (CNG), and one hydrogen fuel cell hybrid electric street sweeper. The powertrain technologies were limited to those available in the Caltrans street sweeper fleet. All street sweepers from which data was collected were located in the Southern California Caltrans fleet. Table 4-1 summarizes the vehicles tested and data collected.

Table 4-1 Activity Data Collection Test Matrix

Fuel Type	Install Location	Model Year	Model	Label	Logger Info		Install Date	Last Collected Activity	Data Collected (hours)
H_2	Westdale	2018	Global M4HSD	7011371	US Hybrid	Online	GPS 4/26/2019	12/5/2020	484.52
CNG	Westdale	2018	Global M4HSD	7012818	2724	Cellular	11/14/2019	12/8/2020	472.26
CNG	Bloomington	2017	Global M4HSD	7011373	2728	Cellular	1/31/2020	12/7/2020	134.13
CNG	Bloomington	2017	Global M4HSD	7011374	2735	Cellular	1/31/2020	11/12/2020	581.18
Diesel	Victorville	2014	Global M4	7005947	2716	Cellular	1/23/2020	12/4/2020	555.68
Diesel	Sylmar	2017	Freightliner M2106	7011098	1200	In Field SD	11/21/2019	8/31/2020	316.25
Diesel	Sylmar	2017	Freightliner M2106	7011099	1514	In Field SD	11/21/2019	8/31/2020	559.51

[a] Missing 37 active days of GPS data between 12/16/2019 and 4/21/2020. Includes engine stopped data.

4.1. Diesel and CNG Street Sweeper Activity Data Logging

Activity data was collected from the diesel and CNG street sweepers using the J1939 Mini Logger™, which is a GPS enabled engine data loggers produced by HEM Data Corporation. The data loggers are configured to collect upwards of 200 ECM parameters at a frequency of 1 Hz. A subset of the type of data that are collected is provided in Table 4-2. The data loggers communicate with the engine's ECM/OBD through industry standard communication protocols. The data loggers are also equipped to collect GPS data on a second-by-second basis. The GPS is capable of measuring the truck's location (latitude and longitude) and altitude, from which speed can also be derived. The HEM data loggers are a small unit that can be attached quickly to a vehicle's J1939 CAN port in the cab on the driver's side. Figure 4-1. HEM data logger shows a Y-cable splitter was used to retain the 9-pin service port in the vehicle while the logger was installed. The HEM data loggers are self-triggering to start automatically when the test vehicle engine is started and stop automatically when the test vehicle engine is stopped and can store data for up to 6 months. Several of the data loggers had the ability to transfer data via cellular transmission and for these sweepers, data was uploaded automatically to the CE-CERT data server.

Table 4-2 Key ECU/GPS Parameters

ECU Data	GPS Data
Engine Hours	Velocity
Engine Load Percentage	Latitude
Engine Actual Torque Percentage	Longitude
Engine Frictional Torque Percentage	Altitude
Engine Reference Torque	Date and Time
Engine RPM	Number of Satellites Fixed
Fuel Rate	Fix Quality
Exhaust Temperature	Position Dilution of Precision
DPF Aftertreatment Temperature	
Equipment Speed	

Figure 4-1. HEM data logger and installation

4.1.1. Data Logger Data Processing

There were several data processing steps that were performed in order to analyze the data collected from the HEM loggers. The main data processing steps are described here.

1. ***Data Conversion***: The J1939 Mini Logger™ creates two files for each trip: a .GPS file that logs the GPS data and a binary .IOS file that logs the ECM data. The DawnEdit™ software from the HEM Data Corporation, with the appropriate conversion database, was used to convert and align a binary .IOS data file with its accompanying .GPS file into a single comma-separated value (CSV) data file.

2. ***Data Aggregation***: HEM data loggers that were set up to transmit via cellular were set up to transfer every 15 minutes. This was done in order to avoid losing larger data files in the event that an all battery power shut off was performed at the end of the day via a master battery disconnect switch. This complete shut off of power would interrupt the cellular file transmission process and that data file would potentially be lost. This process created numerous individual data files for each sweeper. During the

processing step, these data files were concatenated in chronological order into a single data file for each vehicle.

3. ***Data Cleaning***: The CSV data files produced by the DawnEdit software went through several data cleaning procedures. One main focus was on vehicle speed. There are two sources of vehicle speed data: 1) vehicle speed provided by the GPS and 2) wheel based speed from the ECM. The speed data reported by GPS is based on the distance of travel in a given time determined from the satellite positioning data, and for this reason the accuracy of GPS based speed depends on the accuracy and quality of the satellite signal. The GPS based speed is subject to zero-speed drift when the vehicle is stopped. This is a result of small fluctuations in the GPS signal that are recorded as low speeds when the vehicle is stopped. The GPS speed for a stopped vehicle is not exactly zero as one would expect, as shown in Figure 4-2. Absolute errors in positioning data have a larger impact at slower speeds where the distance covered at each time step is less and the absolute error is a larger percentage of the distance traveled value.

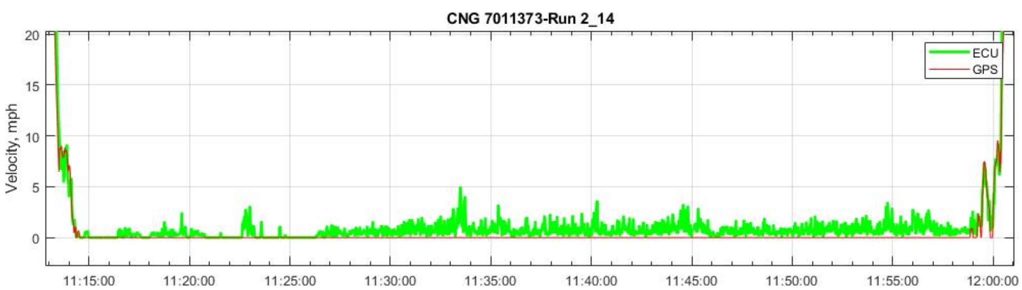

Figure 4-2 Comparison of zero-speed GPS drift.

The speed data reported by the ECM is based on the rotational speed of the wheels and can be affected by general tire wear, changing wheel size, and manufacturer's settings. ECM based speed is also subject to errors in signal transmission and may show maxed out default values, data drops, or other anomalies. In general, the GPS speed data was found to be more accurate, and therefore, was used as the primary source of vehicle speed in this research. The ECM speed data was used to supplement or replace the GPS speed data as needed, especially at low speed.

4. ***Power Calculation***: Engine break power was calculated using ECM broadcast J1939 standardized information. These signals are the same signals used for in-use compliance testing for the not-to-exceed standards in the 40 CFR Part 1065. A brief description is provided to describe the calculation and the results from the calculation. Equations 1 and 2 show the formula to calculate torque and brake power.

$$T_{eng} = \frac{(T_{actual} - T_{friction}) \times T_{reference}}{100} \qquad \text{Eq. 1}$$

Where:

TT_{nnnnnn} = net torque (N·m)
$TT_{aaaannaaaaaa}$ = ECM broadcast actual torque in (%)
$TT_{ffffffaannffffnn}$ = ECM broadcast friction torque in (%)
$TT_{ffnnffnnffnnnaann}$ = ECM broadcast reference torque in (ft-lb)

$$bbhpp = \frac{RRRRRR \times TT_{ffnnaa}}{5252} \qquad \text{Eq. 2}$$

Where:

$bbhpp$ = brake power in units of (hp)
$RRRRRR$ = engine speed in revolutions per minute (rpm)
TT_{nnnnnn} = net torque (ft-lb)

The engine speed, actual torque, and friction torque are real time second by second signals. The reference torque is a constant value and is fixed for each engine. Sometimes the reference torques is provided from the OEM and other times they can be downloaded from the ECM.

5. ***ECM Fueling:*** Real-time ECM fuel rate are important to understand the real-time energy consumption of heavy-duty engines. The fuel-rate broadcast from diesel engines is well understood, and the parameters have been successfully logged in previous projects. In the case of natural gas engines, these parameters are not fully understood, and the data broadcasted on the fuel-rate PGN may be questionable.

4.1.2. Identification of Operating Modes in Activity Data

The modes of operation for the collected activity data from the HEM data loggers was determined based on vehicle speed, engine speed and a number of thresholds that were observed in the data. The model that was set up evaluated continuous blocks of activity that fell within a vehicle speed range and exceeded the normal operating engine speed at those speeds. The blocks of activity were also required to meet a minimum distance and time threshold to reduce transient data and exclude hoper lifting events from the sweeping mode. An example of the modeled sweeping mode is presented in Figure 4-3. In this example the percent sweeping time was determined to be 23.14%. This case was validated against PEMS testing for the same day in which the modes were determined visually from video data. PEMS testing is discussed in Chapter 5. The PEMS comparison plot is presented in Figure 4-4, and shows a sweeping time of 22.92%. This methodology was used to generate the modal analysis of the activity data. The idle time is calculated as periods of idle longer than 60 seconds. The short 60 second threshold was added to avoid including shorter zero speed events, such as transient events and stop and go traffic.

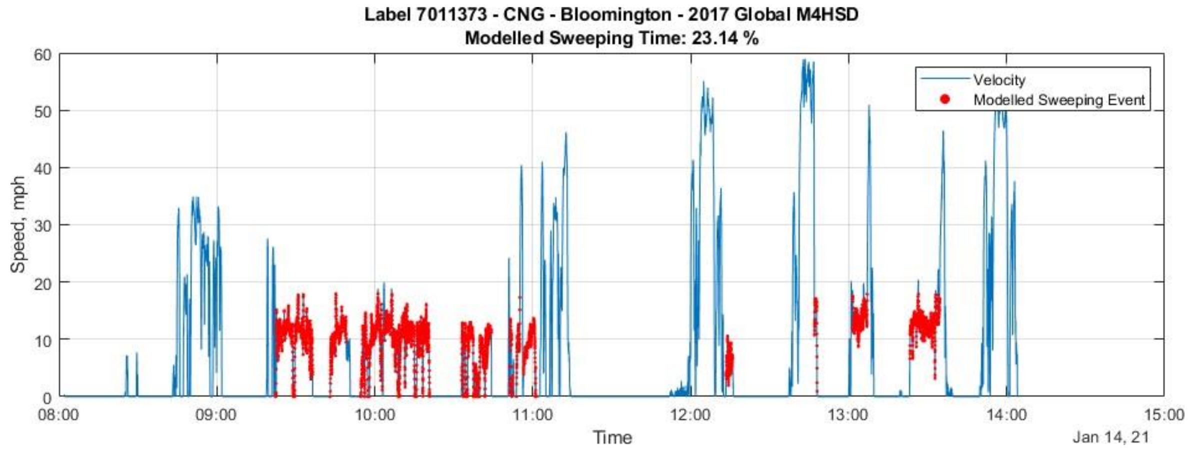

Figure 4-3 Activity data for 1/14/2021 with modeled "sweeper mode"

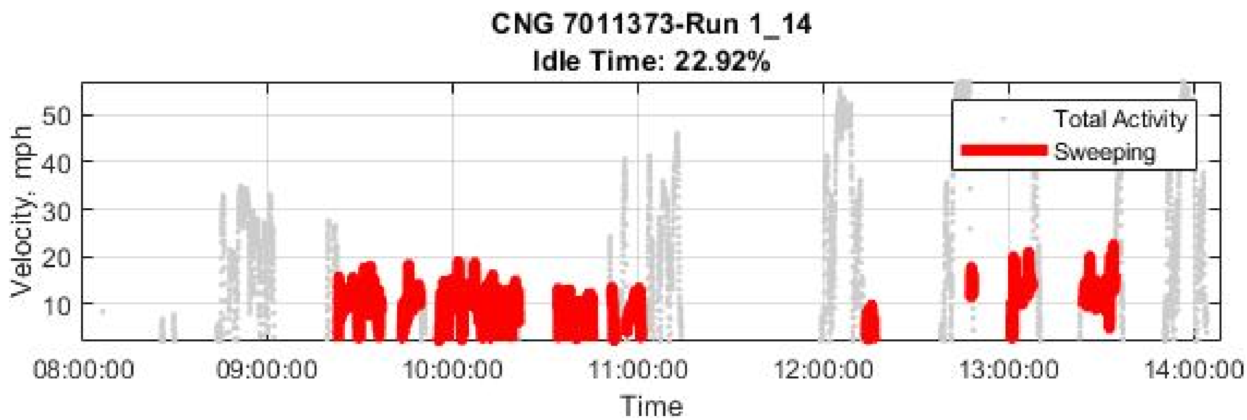

Figure 4-4 PEMS test on 1/14/2021 with video based mode identification

4.2. Fuel Cell Street Sweeper Activity Data Collection

Data for the fuel cell street sweeper was not collected directly, since the conversion database necessary to process raw ECM data was not provided. The conversion database contains proprietary information and was therefore not readily available. Two sets of activity data for the fuel cell street sweeper were provided by US Hybrid. The first set of data was accessed through US Hybrid's website and downloaded manually for every day where it was available. This dataset contained GPS data and select parameters including power consumption and wheel based speed. This set of data contained over 480 hours of operating data. The second set of data was provided by US Hybrid directly and contained more detailed information such as motor power, hydraulic power, H_2 consumption and SOC data, in addition to GPS and wheel speed data. This second set of data was available for 23 days of operation.

4.2.1. Identifying Operating Modes – Fuel Cell Hybrid

ECM data provided by US Hybrid for the fuel cell hybrid included various parameters such as hydraulic load, motor speed, vehicle speed, and shift position. Since the drivetrain on the fuel cell hybrid is electric, the hydraulic power is primarily used for running hydraulic sweeper functions and operating the hopper. On the fuel cell sweeper, the tractive power requirement does not directly impact the sweeper's hydraulic power functions as in it does on the diesel and CNG sweeper platforms. The diesel and CNG sweepers both use a hydrostatic transmission and the tractive and sweeping functions are both powered by the hydraulic power system. Figure 4-5 shows an example of some of the parameters that were useful in determining sweeping mode for this subset of fuel cell sweeper data. In Figure 4-5, the red portions are sweeping events that are defined as high load events with velocity under 20 mph with a non-zero average speed. High hydraulic load events with a zero average vehicle speed and duration of more than a few seconds are indicative of hopper dumping or load leveling events. These events are excluded as being part of the sweeping mode. From examining the data, it was determined that the sweeping activity for the fuel cell sweeper correlated with shift position value of 8 as can be seen in Figure 4-5. This information along with the other sweeping criteria made determining sweeping modes on this subset of fuel cell data straightforward.

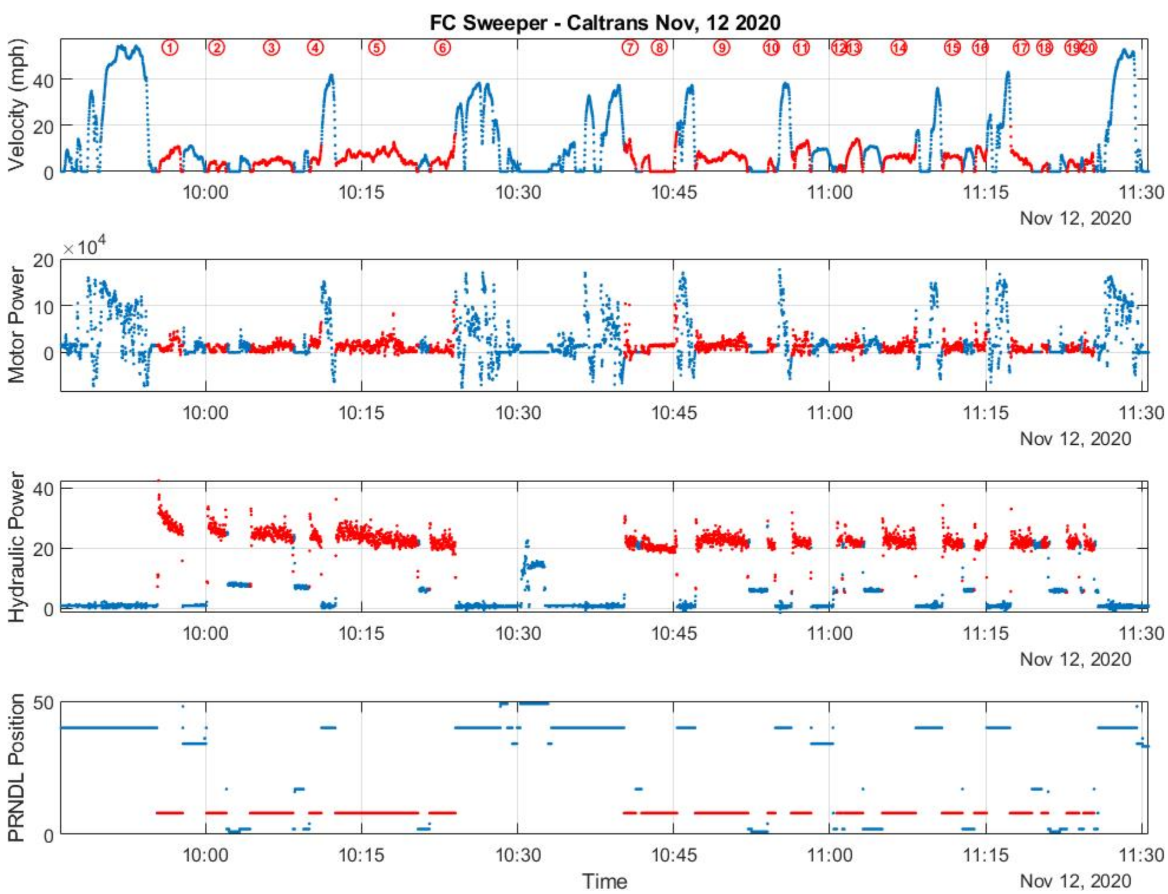

Figure 4-5 Fuel cell activity, motor power, hydraulic power and shift position.

4.2.2. Fuel Cell Energy Usage and Regeneration

Power consumption analysis was performed on the detailed ECM data provided by US Hybrid for 23 days of hydrogen fuel cell operation. The basic fuel sweeper architecture is provided in Figure 4-6. The hydrogen fuel cell provides energy for the drive motor and hydraulic motor. The high voltage batteries store electrical energy and their voltage can vary between 300 and 410 volts. The batteries are used to supplement the hydrogen fuel cell energy during high load events such as heavy acceleration or for additional hydraulic loads. The battery only range, according to US Hybrid training material, is stated as 3-8 miles. Through regenerative braking, the drive motor converts braking energy to electrical energy which is stored in the sweeper's high voltage batteries. At the time corresponding to the provided ECM data set, the hydrogen fuel cell sweeper was configured with two high voltage batteries. The fuel cell sweeper has since been configured to operate on one high voltage battery, which should reduce the battery only range.

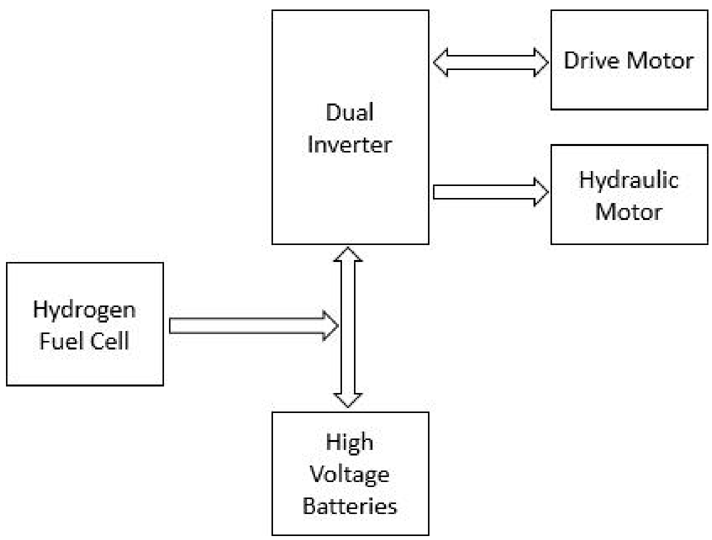

Figure 4-6 Fuel cell sweeper architecture

Data from the main power systems of the fuel cell sweeper were compared and evaluated. The battery voltages and currents were used to determine energy flow out of and into both high voltage batteries. The power consumed by the drive motor and hydraulic motor was compared to the power from the fuel cell and high voltage batteries as shown in Figure 4-7. The top subplot in the figure presents the velocity data for activity file and the second plot shows the main energy components. In the figure, the components that produce power are shown as positive values and the components that consume power are shown as negative values.

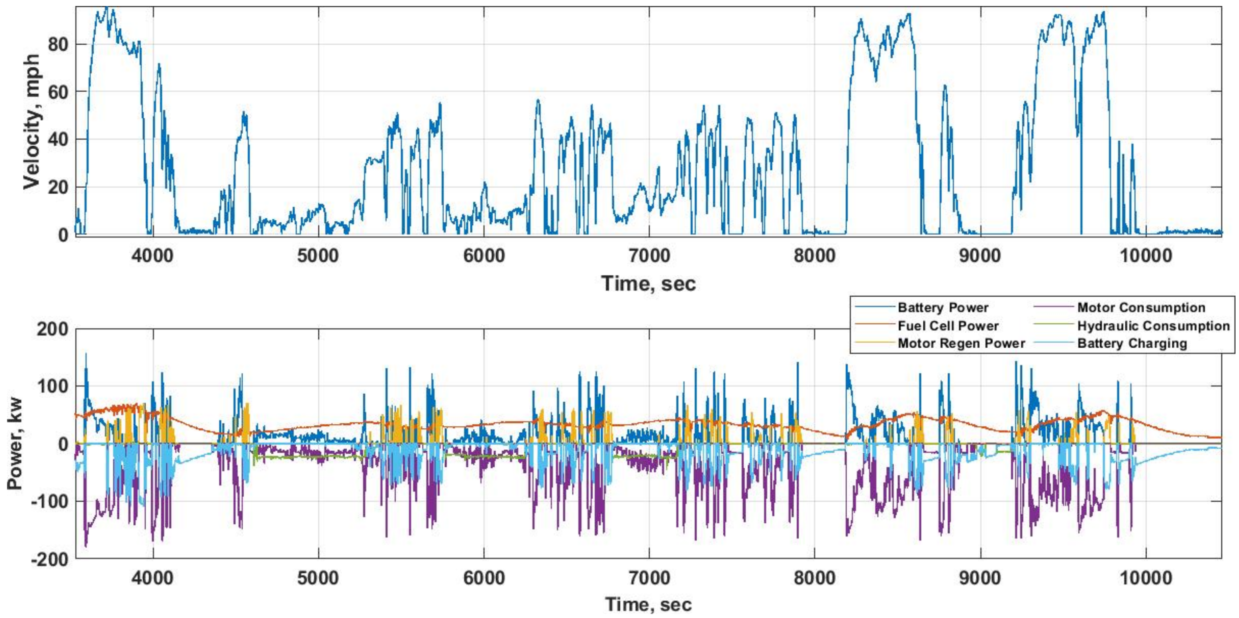

Figure 4-7 Hydrogen fuel cell power usage

During regenerative braking, the motor generates power that is transferred back to the batteries. Figure 4-8 provides a closer look of a velocity snippet and the power of the associated regenerative braking motor event, and shows how braking energy is recaptured during deceleration events. To quantify the recaptured energy from regenerative braking, the cumulative regenerated energy for each test was calculated and compared to the cumulative energy consumed by the motor. The results are presented in Figure 4-9.

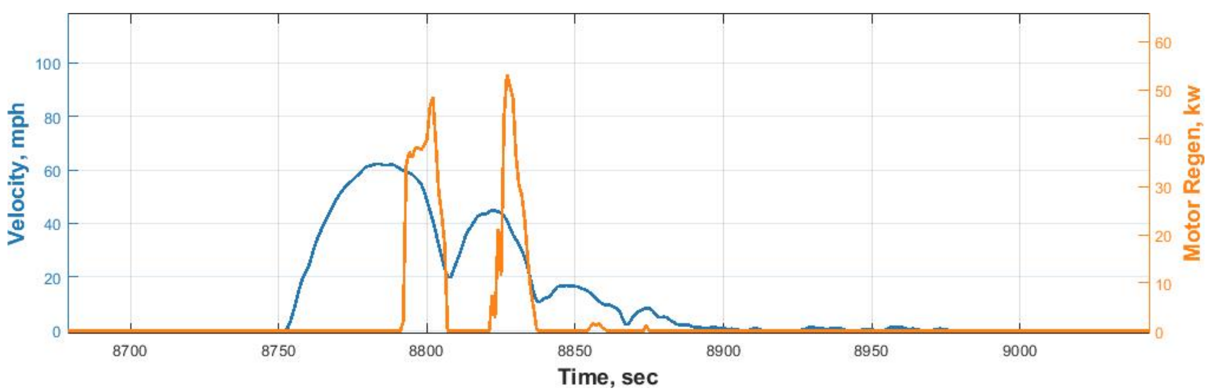

Figure 4-8 Velocity snippet from hydrogen fuel cell showing motor regeneration

The energy saved across all 22 tests was determined using this method and the summary of the results are provided in Figure 4-9, which shows the median electrical motor energy recovered of 10.81 with a range between 7.36% to 13.38%.

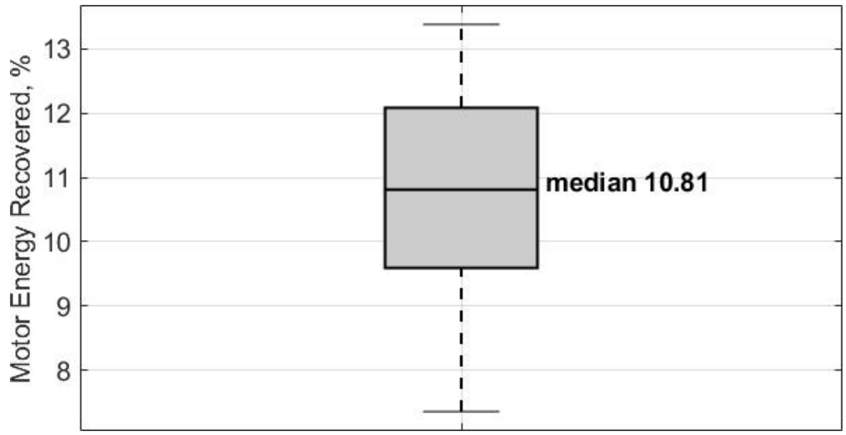

Figure 4-9 Portion of electrical motor energy recovered

4.2.3. Hybrid Electric Fuel Cell Range

The range of the hybrid electric HFC street sweeper is an important consideration when evaluating its suitability as an alternative to diesel or CNG powered street sweepers. To determine the typical range of the street sweeper, the detailed ECM data for 23 non-consecutive days of hydrogen fuel cell operation was evaluated. This data set contained the date, time, velocity and the hydrogen fuel tank pressure. The weight of hydrogen is not known and will depend on the temperature. For this analysis, we did not adjust for temperature. The hydrogen fuel tank pressure ranged from 457 psi to 5133 psi. The rated pressure for the hydrogen fuel tanks is 350 bars or 5076 psi. The activity was split into trips by refueling events based on the increase in hydrogen tank pressure. Two examples of daily activity data divided into trips are provided in Figure 4-10 and Figure 4-11. In Figure 4-10, one refueling event occurred and the activity is divided into two trips. The refueling event also provides the refueling pressures at the beginning and the end of the refueling event. In Figure 4-11, no refueling events occurred and the entire day's activity is one identified as one trip.

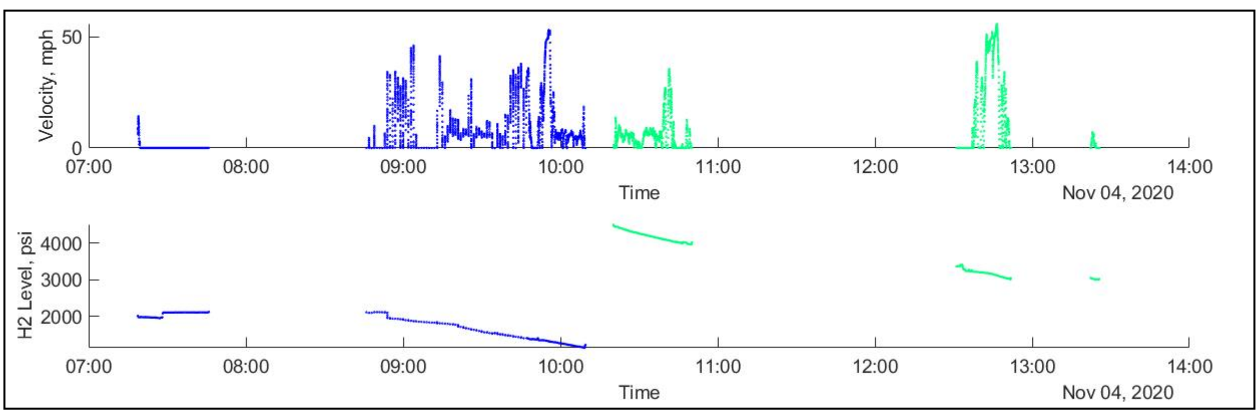

Figure 4-10 Example 1 of activity data divided by refueling events.

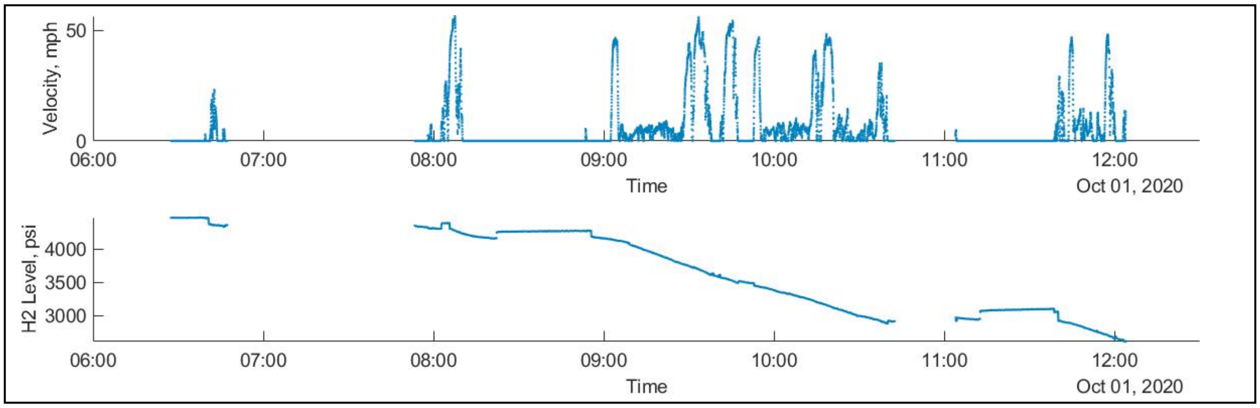

Figure 4-11 Example 2 of activity data divided by refueling events.

The distance traveled and the fuel consumed for each trip were calculated and a regression between the two variables is plotted in Figure 4-12. The regression equation is provided in the figure and has an adjusted R^2 of 0.66. Since the data set consists of non-consecutive days, the trips in the dataset may not represent the full distance traveled between refueling events. The data does provide the distance traveled per unit fuel consumption. The noise in the distance traveled versus fuel consumption relationship is heavily dependent on activity. To account for this, the ratio of distance traveled by fuel use for trips was evaluated relative to the percentage of time spent sweeping and is presented in Figure 4-13. This figure only includes trips that consumed at least 500 psi of fuel. As expected, this figure shows that the higher distance to fuel consumption ratios correlate with lower percent time sweeping. There are also low distance to fuel consumption ratios at low sweeping percentages and these correlate with higher idling times. From the activity dataset, the average sweeping time ranged roughly from 30-45%. As an approximation, the average distance to fuel consumption ratio of 20-40% is 0.0143 mi/psi and between 30-45% is 0.013 mi/psi. These ratios were used to estimate the range of the sweeper on a full tank for activity with typical percent sweeping time.

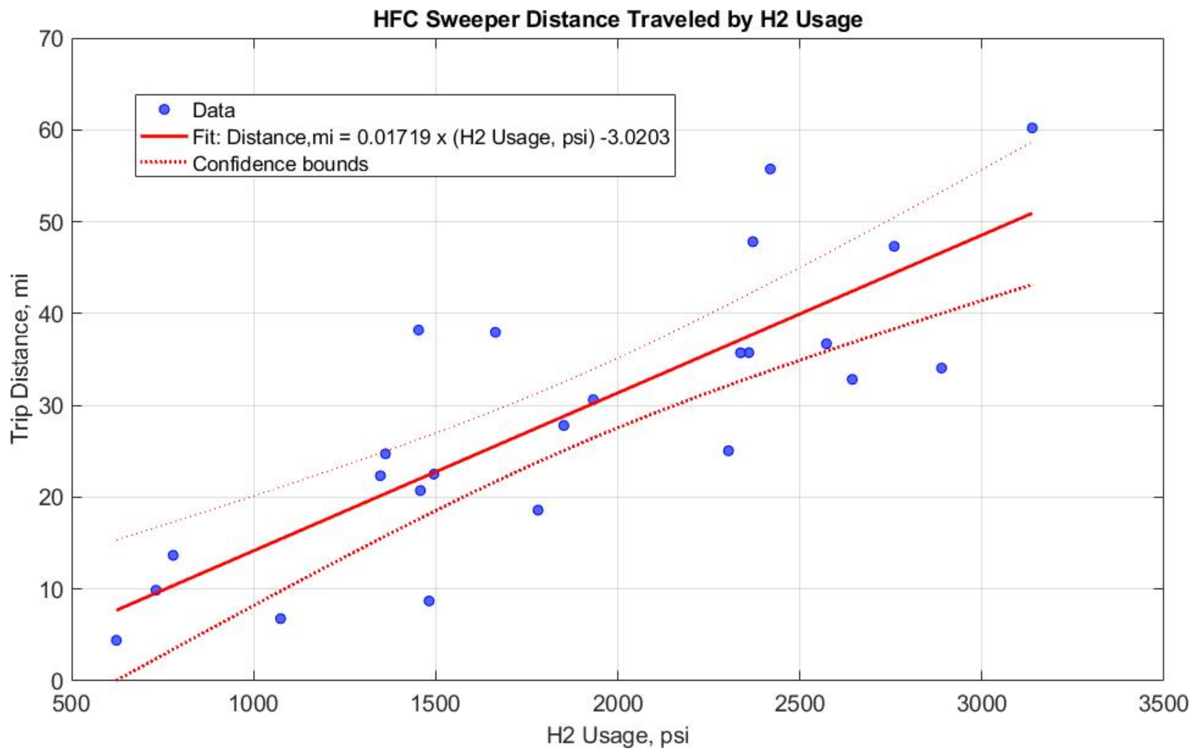

Figure 4-12 HFC distance traveled vs fuel consumption

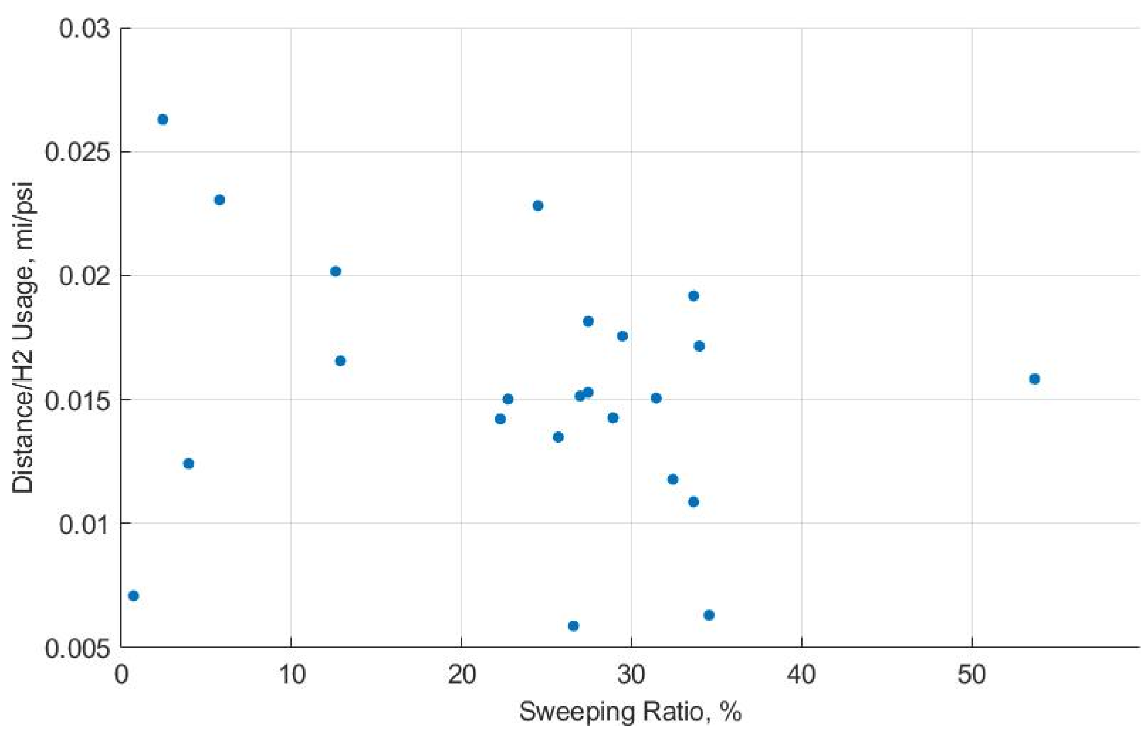

Figure 4-13 Distance/H2 Usage vs sweeping frequency

A full tank of hydrogen was based on the refuel levels that were observed in the data. Refuel levels, in terms of pressure, are presented in Figure 4-14. This figure shows the hydrogen levels before the refueling events and the hydrogen levels after, and gives an indication of what the upper and lower limits are. The range between the highest and lowest pressure in this data subset is 4676 psi (5133 psi – 457 psi). At that level of fuel consumption and typical activity, the estimated range using the average distance to fuel consumption ratios for sweeping between 20-40% and 30-45%, is 60.78 and 65.46 miles. At the highest rate in Figure 4-13, which is 0.02629 mi/psi and correlates with 2.4% sweeping, the range estimate reaches 122.9 miles. Traveling at an optimal speed with no idle or sweeping, the range of the sweeper may be somewhat higher. It is also worthy to note that the typical level at which users refuel the sweeper is likely much higher than the lowest level observed in this data set. Figure 4-14 shows that the sweeper was typically refueled at a hydrogen tank level closer to 1200 psi. Using this criteria, the amount of hydrogen used would be closer to 3922 psi and the range, following the same calculation above, would be 50.99 miles and 54.90 miles.

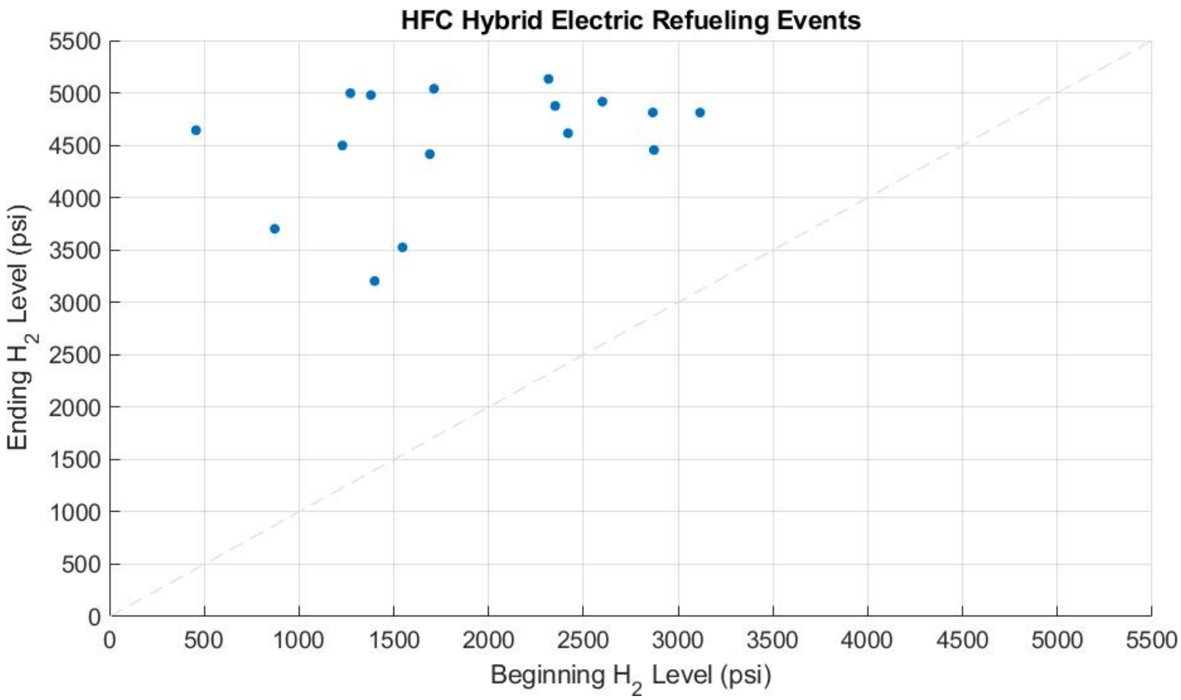

Figure 4-14 Refuel levels for HFC sweeper.

4.3. Activity Results

Results from the activity analysis are provided in the following section. The activity data consists of data from three CNG sweepers, three diesel sweepers and one hydrogen fuel cell sweeper. Table 4-3 provides various parameters describing the total activity from each of the test sweepers in terms of operating time, distance traveled, sweeping time, idling time and average velocities. This data in addition to other parameters were used to generate various activity rates in Table 4-4 in Table 4-5.

Table 4-3 Activity logger data collection summary

Label	7012818	7011374	7011373	7011098	7011099	7005947	7011371
Fuel	CNG	CNG	CNG	Diesel	Diesel	Diesel	Hydrogen
Make	Global M4HSD	Global M4HSD	Global M4HSD	Schwarze Avalanche	Schwarze Avalanche	Global M4	Global M4HSD
Model Year	2018	2017	2017	2017	2017	2013	2018
Number of Days	247	174	173	59	117	242	23
Number of Days over 1/4 mile	172	151	154	31	88	193	23
Time (hrs)	738.9	735.48	699.52	104.79	485.34	877.53	99.16
Sweeping (hrs)	251.78	240.65	230.94	33.48	217.83	267.99	30.52
Idle (hrs)	188.83	237.41	206.99	39.8	176.2	224.13	41.1
Distance (mi)	2491.41	7553.67	8267.69	1194.76	3721.32	7927.79	858.84
Sweeping (mi)	710.34	1958.69	1801.64	180.83	943.89	1360.16	118.19
Avg. Moving Velocity (mph)	8.51	16.91	18.6	21.67	14.32	14.25	16.37
Max Velocity (mph)	74.71	70.36	74.59	61.16	73.43	72.7	63.86
Avg. Sweeping Velocity (mph)	2.82	8.14	7.8	5.4	4.33	5.08	3.87

Table 4-4 provides daily activity rates for each test vehicle divided by idle mode, sweeping mode, and combined activity. The percent idle time and sweeping time for each test vehicle are provided and as well as the breakdown of % sweeping time

Table 4-4 Activity logger data collection activity rates

Label	7012818	7011374	7011373	7011098	7011099	7005947	7011371
Fuel	CNG	CNG	CNG	Diesel	Diesel	Diesel	Hydrogen
Make	Global M4HSD	Global M4HSD	Global M4HSD	Schwarze Avalanche	Schwarze Avalanche	Global M4	Global M4HSD
Model Year	2018	2017	2017	2017	2017	2013	2018
All (hrs/day)	2.99	4.23	4.04	1.78	4.15	3.63	4.31
Sweeping (hrs/day)	1.02	1.38	1.33	0.57	1.86	1.11	1.33
Idle (hrs/day)	0.76	1.36	1.2	0.67	1.51	0.93	1.79
Sweeping Total (hrs/day moving)	1.46	1.59	1.5	1.08	2.48	1.39	1.33
Operating Distance (mi/day)	10.09	43.41	47.79	20.25	31.81	32.76	37.34
Operating Distance (mi/day moving)	14.48	50.02	53.69	38.54	42.29	41.08	37.34
Sweeping (mi/day)	2.88	11.26	10.41	3.06	8.07	5.62	5.14
Sweeping(mi/day moving)	4.13	12.97	11.70	5.83	10.73	7.05	5.14
Idle Time (%)	25.56	32.28	29.59	37.98	36.31	25.54	41.45
Sweeping Time (%)	34.07	32.72	33.01	31.95	44.88	30.54	30.79
Idle Work (%)	6.68	6.90	6.74	12.91	8.37	2.22	5.36
Sweeping Work (%)	44.75	44.39	41.76	32.74	54.70	36.73	41.02

Table 4-5 Activity logger data collection work

Label	7012818	7011374	7011373	7011098	7011099	7005947	7011371
Fuel	CNG	CNG	CNG	Diesel	Diesel	Diesel	Hydrogen
Make	Global M4HSD	Global M4HSD	Global M4HSD	Schwarze Avalanche	Schwarze Avalanche	Global M4	Global M4HSD
Model Year	2018	2017	2017	2017	2017	2013	2018
All (kwh/day)	102.75	193.24	185.9	54.88	122.92	112.47	103.49
Idle (kwh/day)	6.86	13.33	12.52	7.09	10.29	2.49	5.54
Sweeping (kwh/day)	45.98	85.77	77.64	17.97	67.24	41.31	42.45
Miles/hours	3.37	10.27	11.82	11.4	7.67	9.03	8.66
All (kw/day moving)	147.55	222.67	208.83	104.44	163.42	141.03	103.49
Sweeping (kw/day moving)	66.02	98.84	87.22	34.2	89.4	51.79	42.45
All (kwh/mi)	10.19	4.45	3.89	2.71	3.86	3.43	2.77
Sweeping (kwh/mi)	15.99	7.62	7.46	5.86	8.33	7.35	8.26
All (kwh/hr)	34.35	45.72	45.97	30.9	29.63	31.02	24.01
Idle (kwh/hr)	60.14	62.86	64.89	26.64	44.65	44.6	3.1
Sweeping (kwh/hr)	45.1	62.02	58.16	31.66	36.12	37.3	31.98

4.3.1. Results Summarized by Fuel Type

The activity data in this section is summarized based on daily statistics and fuel type. Daily statistics are calculated for all street sweepers and days with activity greater than 1 mile. This was to exclude days that consist only of non-representative activity such as re-parking or moving the street sweeper around in the Caltrans yard for maintenance or cleaning. Daily statistics across all sweepers were grouped by fuel type and summarized for each fuel group. Statistics for individual sweepers are presented in Appendix B.

Summarized results of activity data is this section are presented in box-whisker plots. The box-whisker plots show the median value line (top of the 2nd quartile or 50%) which divides the box and the median value in text. The box shows the 2nd and 3rd quartiles. The height of the box is the interquartile range and represents 50% of the data around the median value. The whiskers are set at the maximum and minimum values provided they are less than 1.5 times the interquartile range distance from the top or bottom of the box. If they are beyond those points, the whiskers are set at 1.5 times the interquartile range from the box end and the data points are shown as outliers.

Mixed Activity Statistics

Mixed activity includes all data from days with activity greater than 1 mile and not filtered by operating mode. The mixed activity statistics are the overall statistics as observed in the real-world data set. Figure 4-15 through Figure 4-17 provide the daily operating time, distance, and distance based work for all sweeper fuel types. The final boxplot in each figure provides the general value for all street sweepers. The data shows that there is a wide range of values for all three of these metrics, but the central tendency of the data sets do not seem to differ substantially.

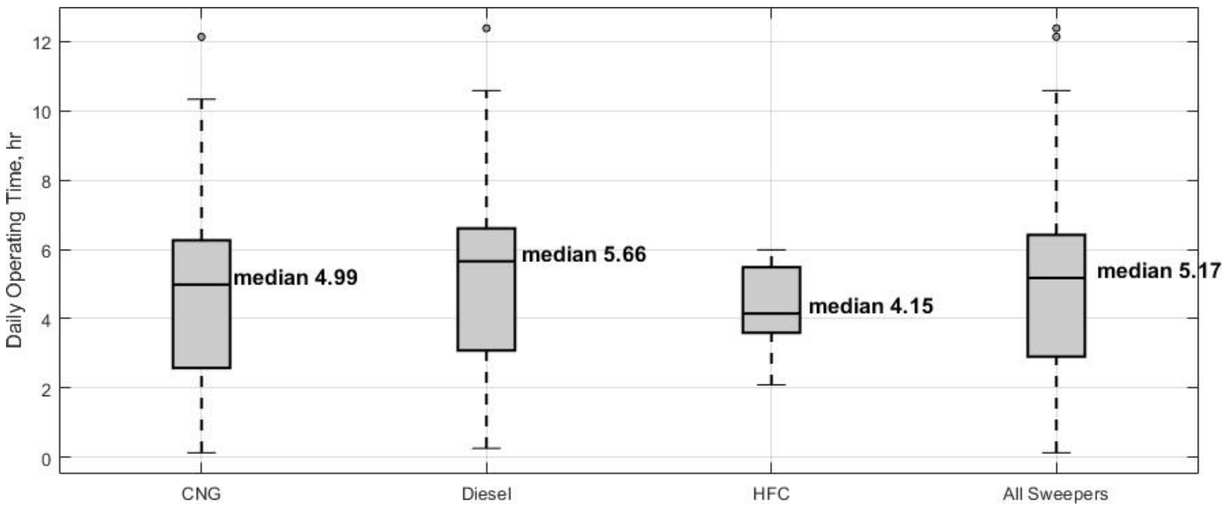

Figure 4-15 Daily operating time by fuel type

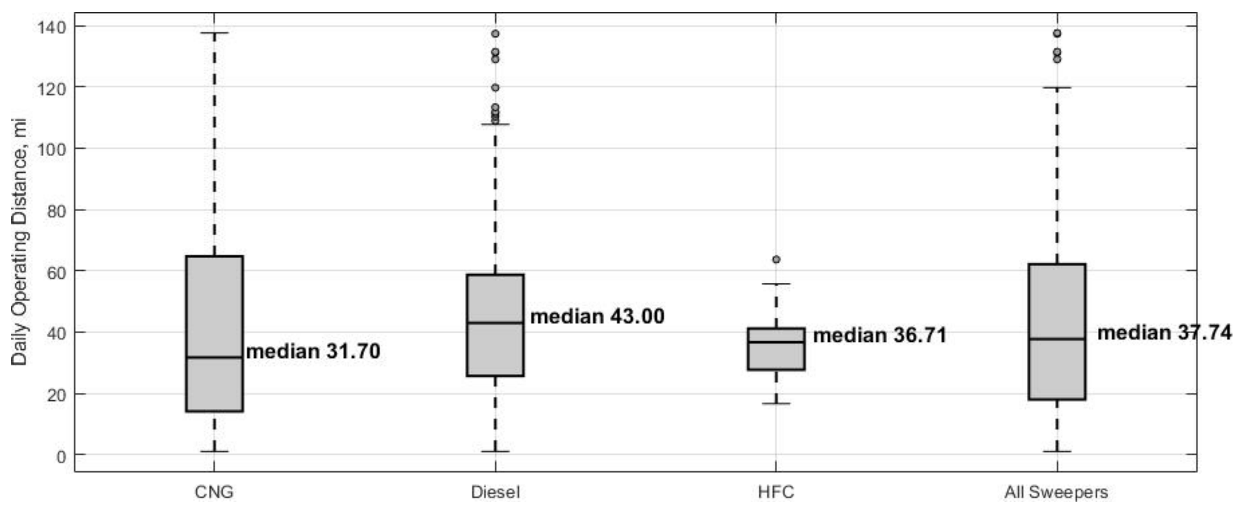

Figure 4-16 Daily operating distance by fuel type

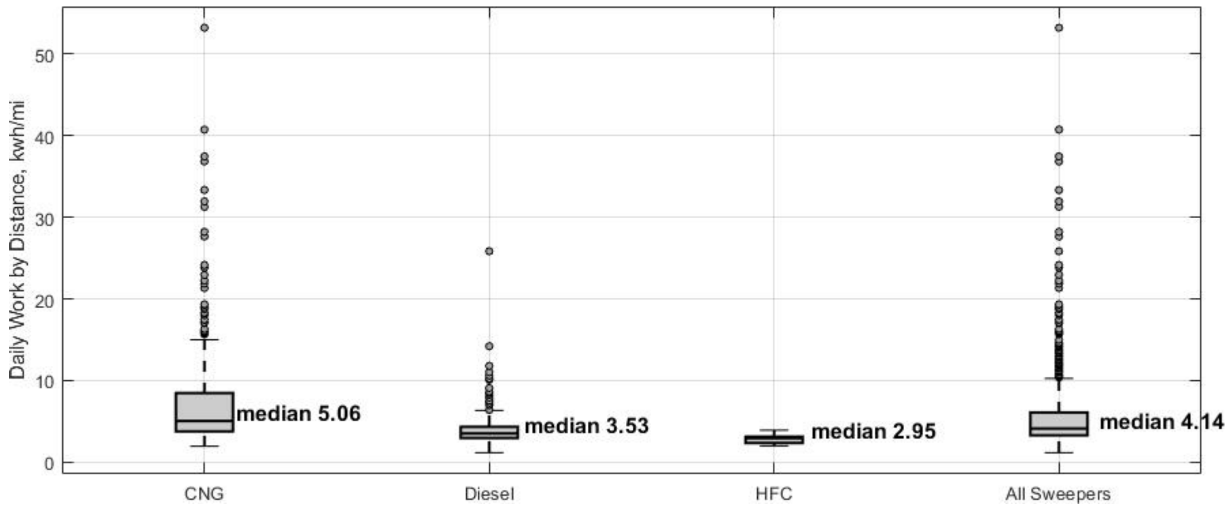

Figure 4-17 Daily distance based work by fuel type

Sweeping Activity Statistics

Figure 4-18 through Figure 4-20 provide summary statistics by fuel type for the street sweepers in the activity data set. The figures show sweeping activity by distance per day, by percent time and by percent of work. The daily distance is based only on days in which the sweeper moved more than a quarter mile. This was intended to exclude days in which the sweeper may have only been turned on and not moved or had minimal movement such relocating the sweeper in the maintenance yard.

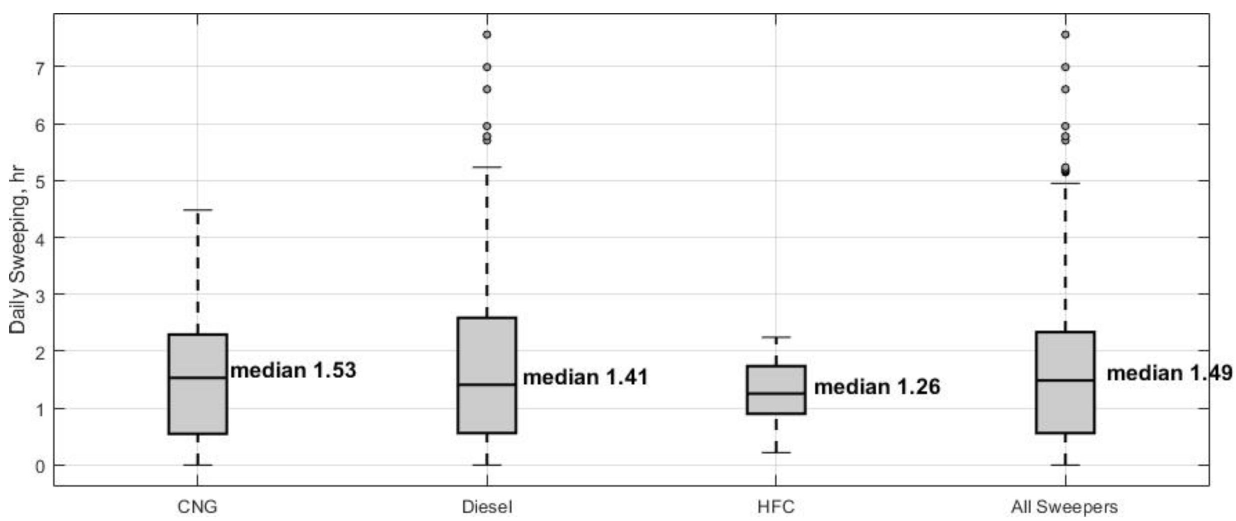

Figure 4-18 Daily sweeping time by fuel type

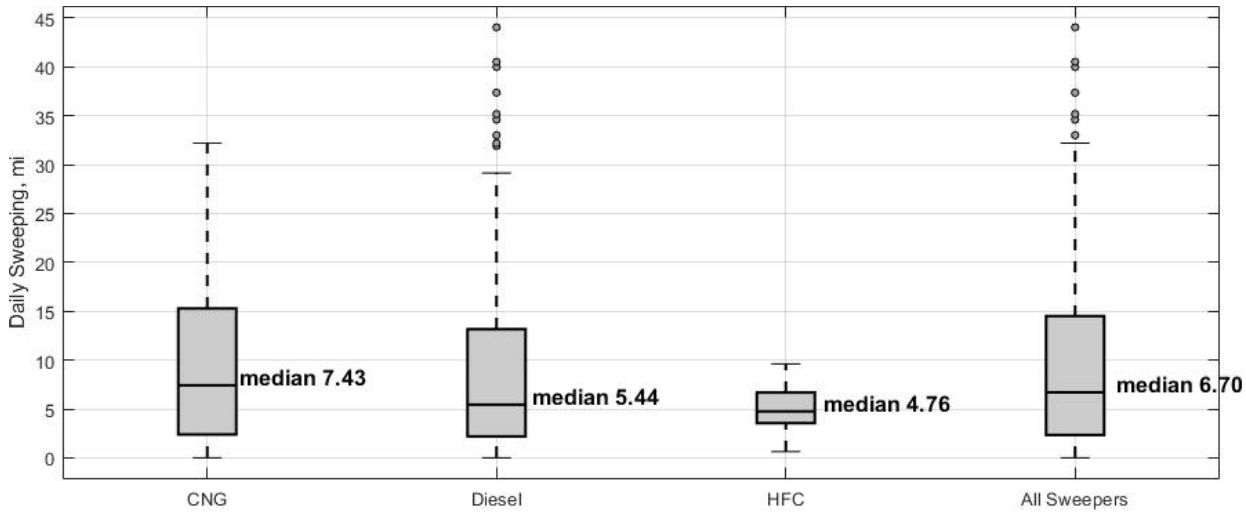

Figure 4-19 Daily sweeping distance by fuel type

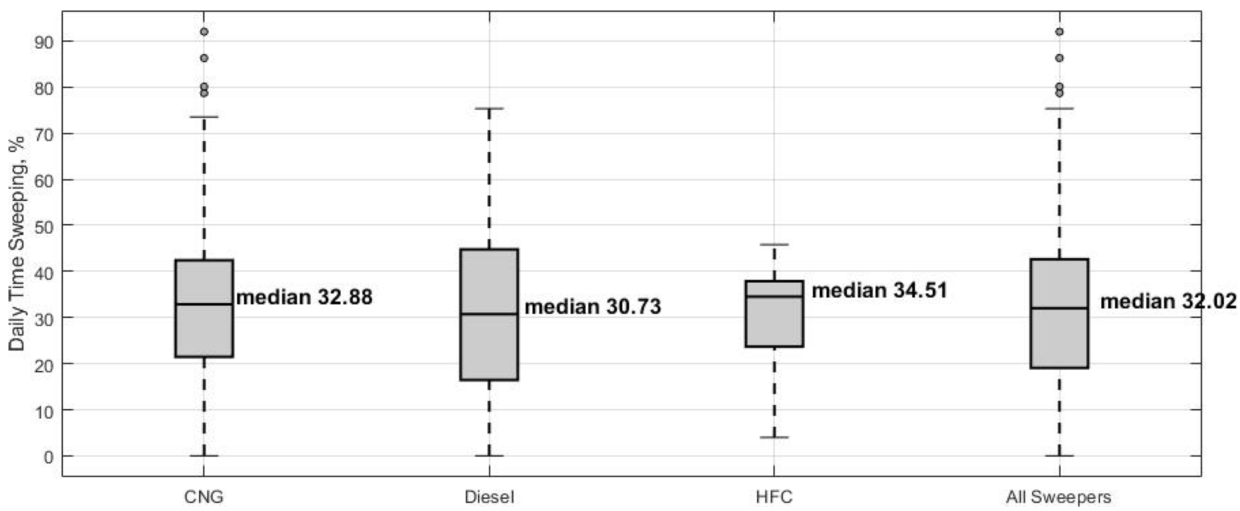

Figure 4-20 Percent sweeping time by fuel type in activity data

Idle Activity Statistics

Figure 4-21 and Figure 4-22 provide idle summary statistics for the street sweepers. The idle time for the fuel cell sweeper is based on zero-speed key-on events with duration longer than 60 seconds.

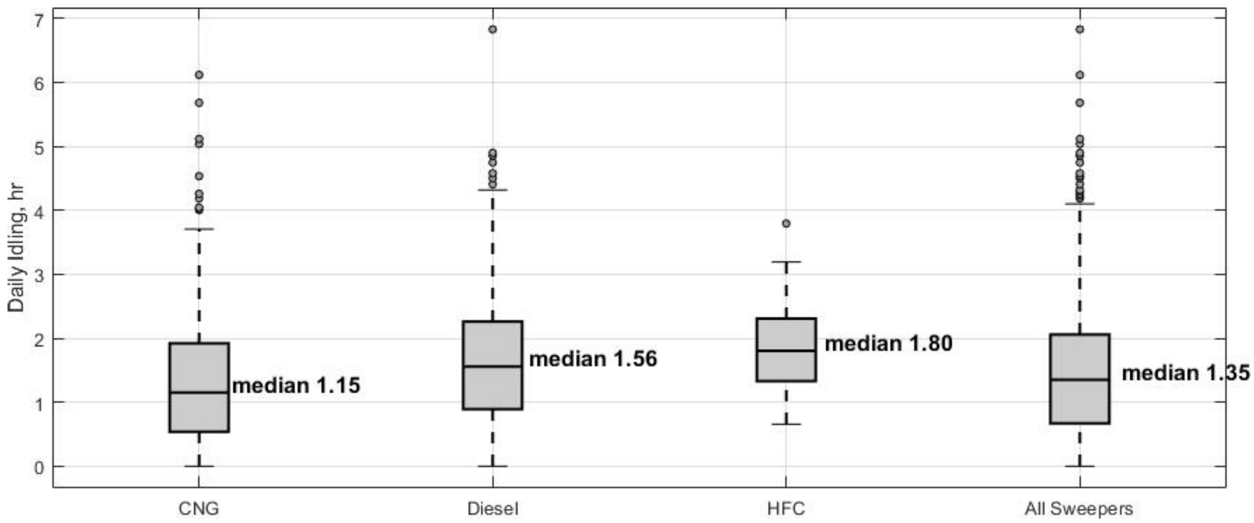

Figure 4-21 Daily idle time by fuel type

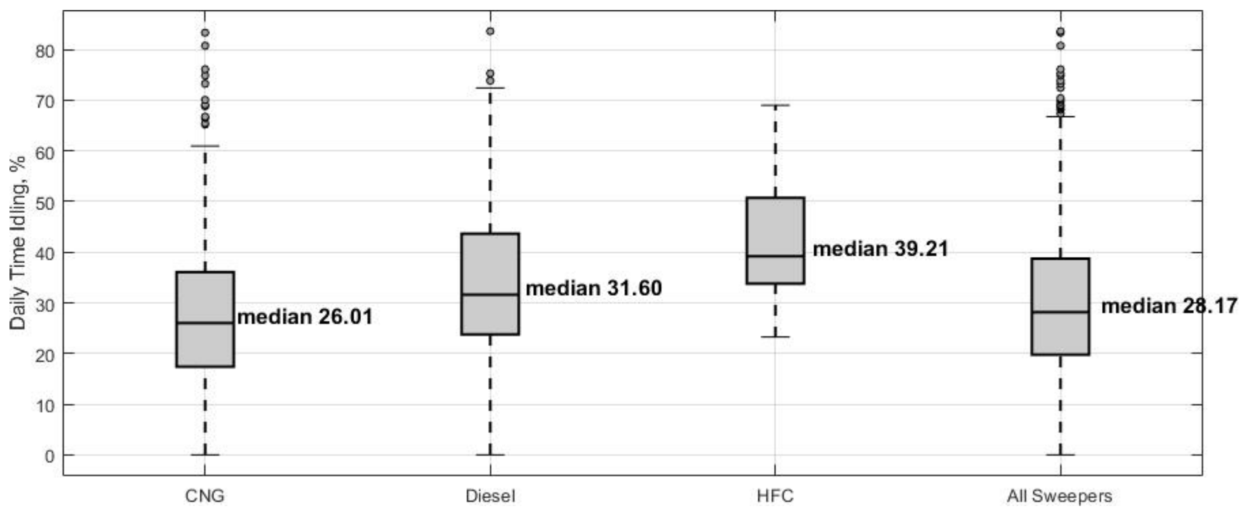

Figure 4-22 Percent daily idle time by fuel type in activity data

Travel Mode Activity Statistics

The traveling activity represents activity that is not part of idle activity or sweeping activity. This activity is essentially the activity associated with the street sweeper traveling on arterials or freeways and not engaged in sweeping. Since this activity covers a wide range of speeds and accelerations, the range of activity is very large.

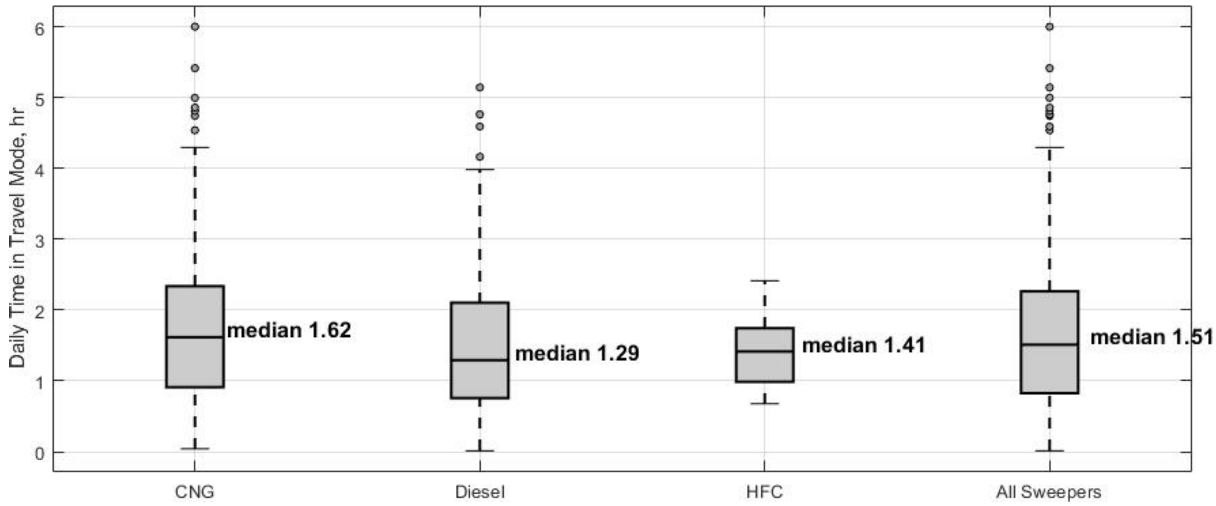

Figure 4-23 Daily time spent in travel mode by fuel type

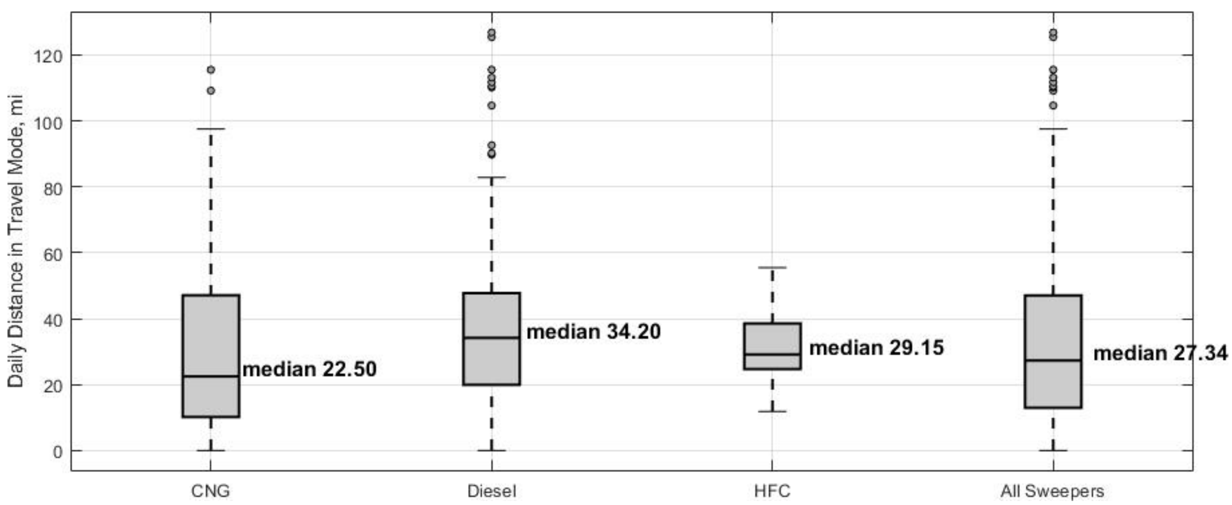

Figure 4-24 Daily distance traveled in moving mode by fuel type

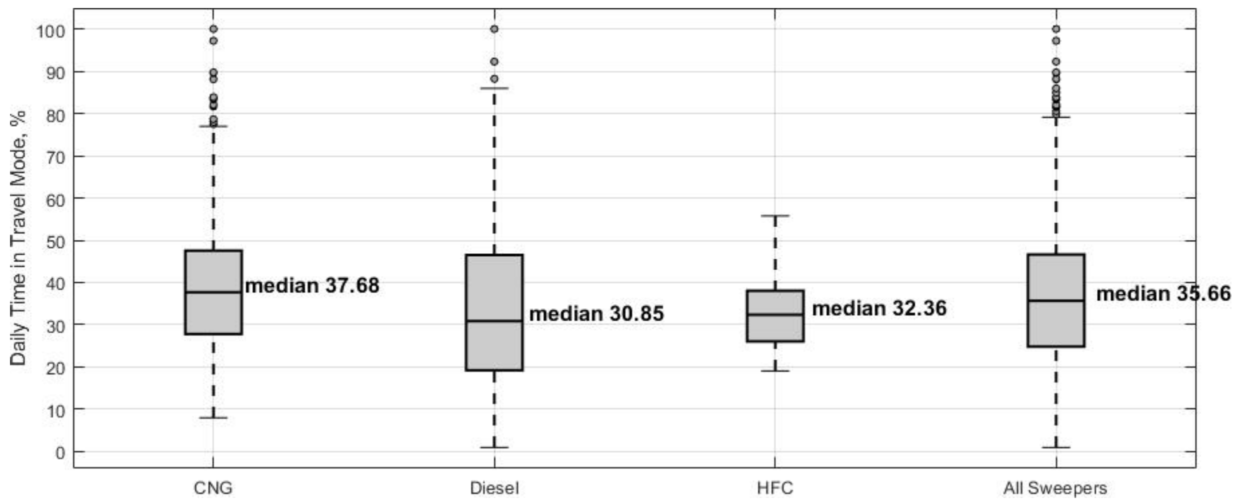

Figure 4-25 Percent daily time traveled in moving mode by fuel type

4.4. Fleet Management System Data

One of the sources of activity data that the research team has access to is from the Caltrans fleet management system. Caltrans fleet data was stored and managed using AssetWorks Fleet Focus (FA) fleet management software, however, at the time of this project, Caltrans was in the process of migrating their fleet to the Geotab fleet management system. For this analysis, the research team looked at AssetWorks Fleet Focus data from the 2020 calendar year for Caltrans district 7 and/or 8 as indicated. The hydrogen fuel cell sweeper was located in district 7. Various parameters were available for individual pieces of Caltrans equipment including the following: total miles traveled in the 2020 calendar year, average trip distance, maximum trip distance, average daily miles, and maximum daily miles traveled. From this data, trip times were divided into idle trips, and non-idle trips. An idle trip is a key-on/key-off event, where the vehicle did not move based on the speed data. A non-idle trip is a trip where vehicle movement was observed. Idle trip hours are a sum of the idle trip times. Idle trip hours do not include all idle time. Non-idle trips may also include idle activity, however, this information could not be determined from the AssetWorks Fleet Focus data.

4.4.1. Trip statistics

Activity statistics are presented in Figure 4-26 through Figure 4-28. Results in Figure 4-26 show that although the median of the maximum trip distances was similar between the three fuel types, the diesel sweepers maximum trip distances had a much higher range and included significantly longer trips. The maximum diesel trip was 132.6 miles and the maximum CNG trip was 83.5 miles.

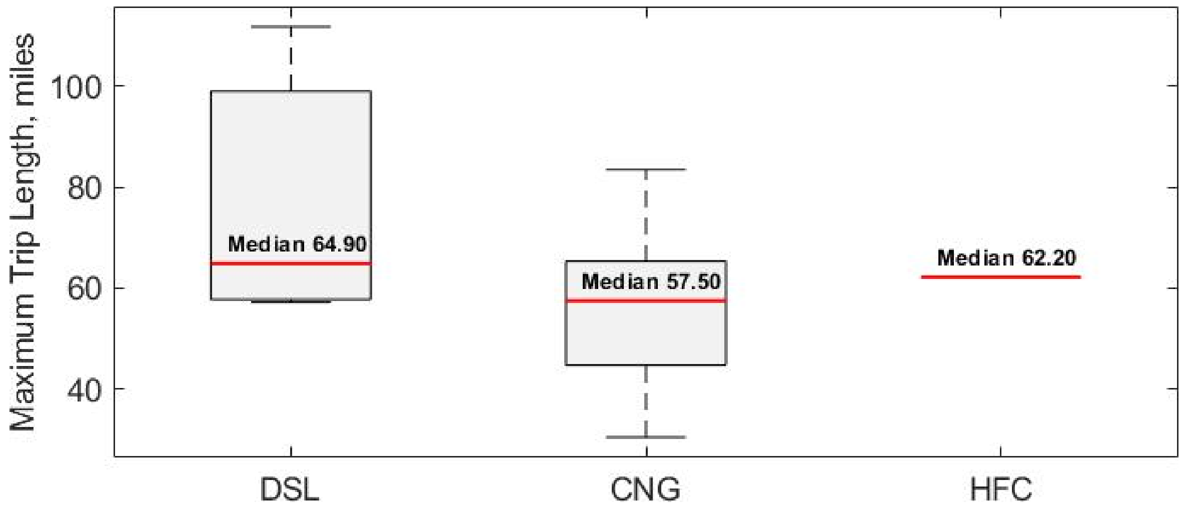

Figure 4-26 Maximum trip distance, D7 + D8-Caledar year 2020.

Figure 4-27 shows the distribution of average daily distances traveled for different sweeper fuel types. Again, the diesel sweeper show the highest average daily trip distances, followed by the CNG sweeper and the fuel cell. This is expected due to the available range of each of the sweeper platforms and the availability of refueling.

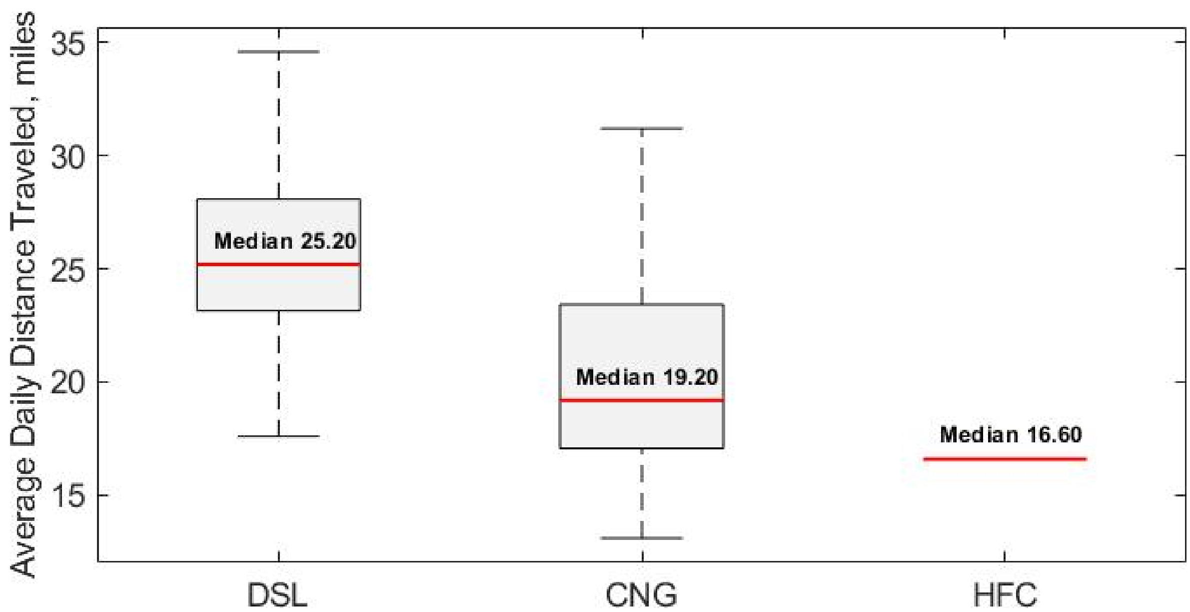

Figure 4-27 Average daily distance traveled, D7+ D8-Calader year 2020.

Figure 4-28 shows the cumulative idle trip hours per vehicle for the 2020 calendar year in Caltrans district 7 and 8. An idle trip is defined as a key on to key off event with no vehicle movement. Idle trip hours do not include idle hours that occur during a trip that includes vehicle movement. Total idle hours are not provided by the fleet management activity dataset.

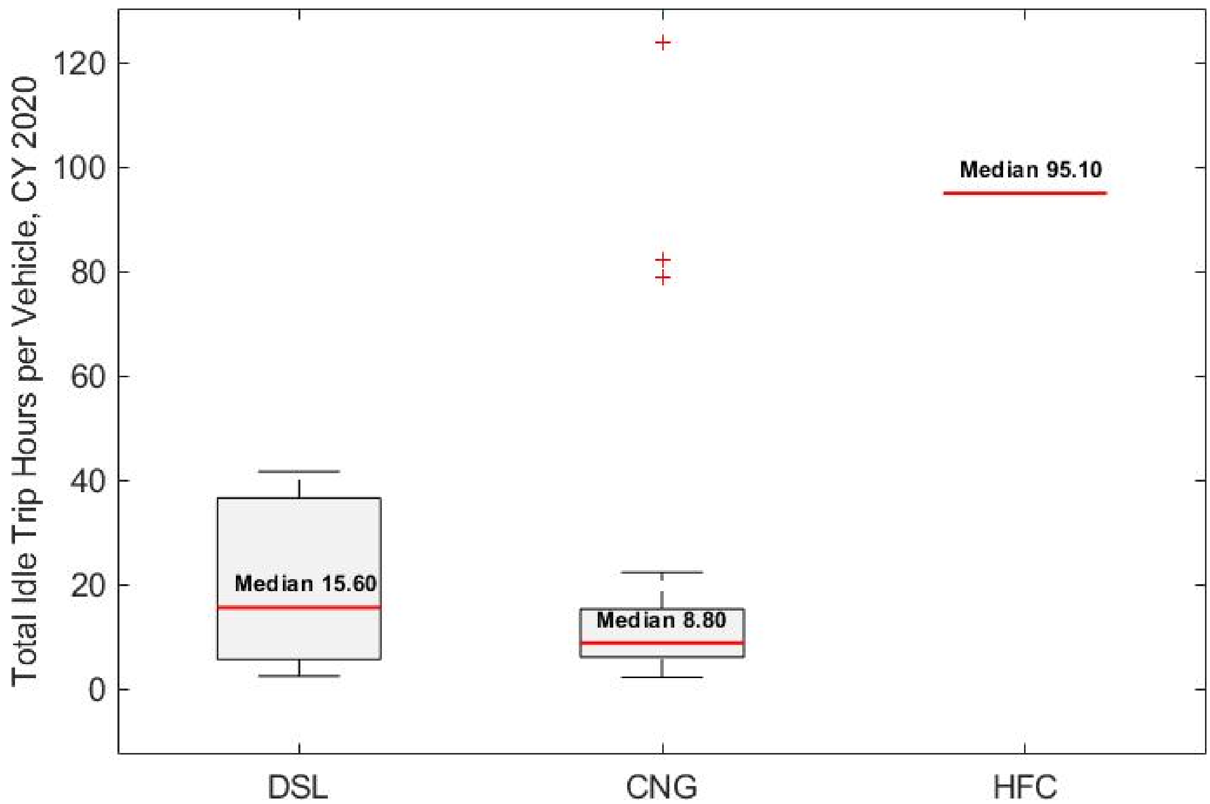

Figure 4-28 Cumulative idle trip hours per vehicle, D7+D8 -Calendar year 2020

Figure 4-29 and Figure 4-30 show cumulative distribution functions (CDF) of daily operating distance and trip distance. The CDF plot are useful in determining the percentage of activity that falls below a certain value in the dataset. For example, the maximum trip distance observed in the dataset for the HFC is 62.2 miles. Figure 4-30 indicates that the percent of maximum trip distances that are less than or equal to the HFC value of 62.2 miles is 40% for diesel and 71% for CNG.

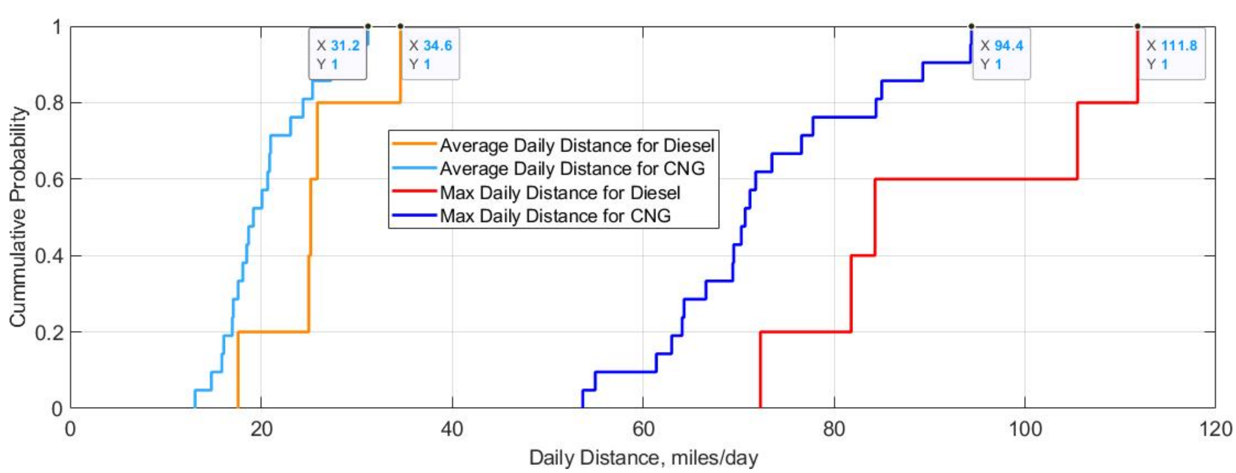

Figure 4-29 Cumulative distribution of daily operating distance. D7+D8, CY 2020

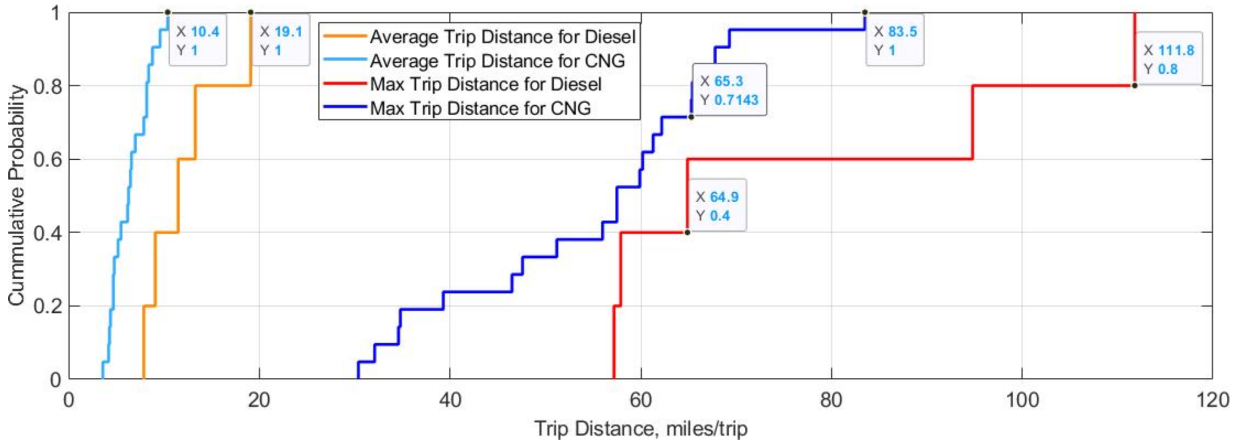

Figure 4-30 Cumulative distribution of trip distance. D7+D8, CY 2020

4.4.2. Annual Operating Time

Figure 4-31 and Figure 4-32 show annual operating hours and annual operating days for calendar year 2020 and Caltrans district 7. Operating days are considered days with activity greater than 0.25 miles. The median values for operating days range from 75.5 for the diesel sweeper to 116 for the HFC. The maximum operating days are as high as 290 days per year for the Diesel sweeper.

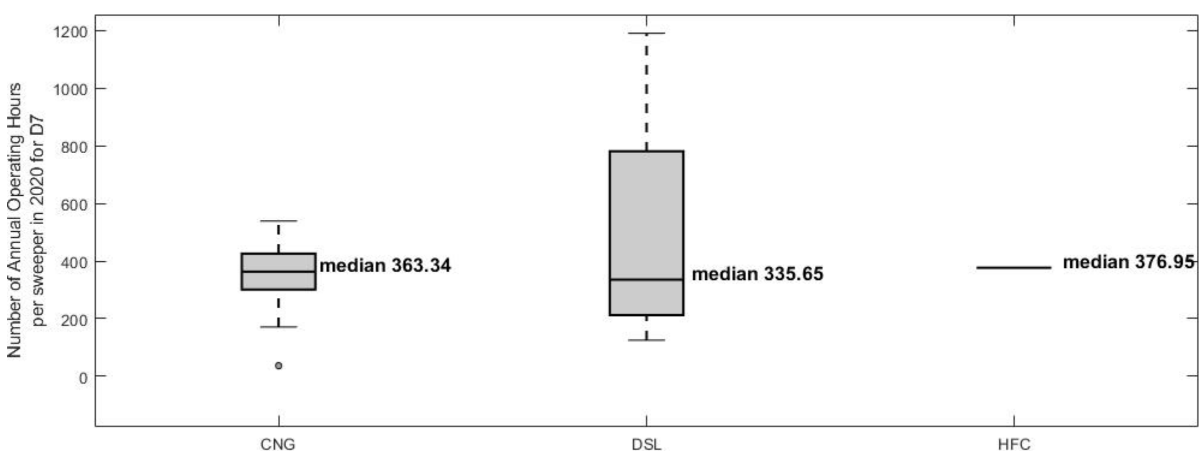

Figure 4-31 Annual operating hours per vehicle CY 2020 in D7

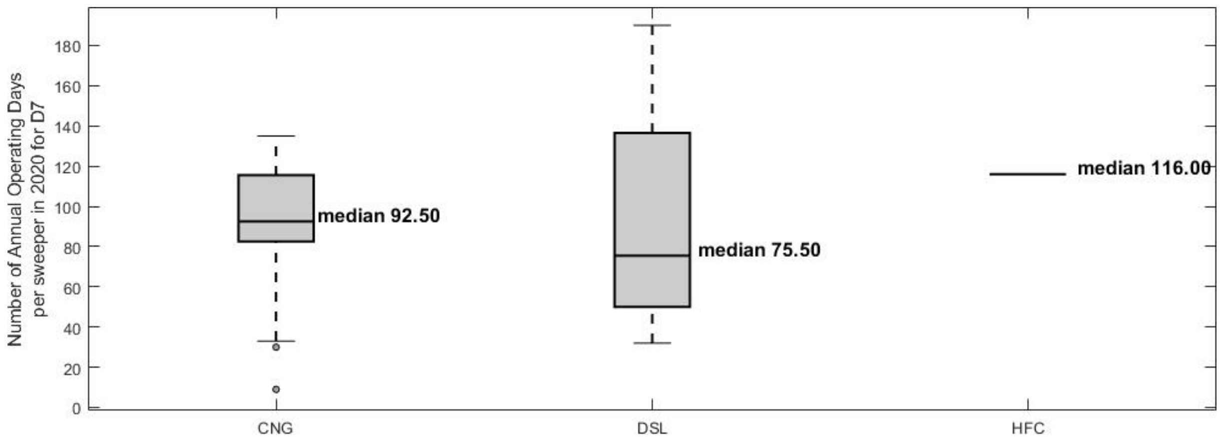

Figure 4-32 Annual operating days per vehicle CY 2020 and D7

4.4.3. Offline Hours and Work Order Counts

The Caltrans Assetworks fleet management data base also contains work order history. Work orders are a record of service work that was performed on any equipment in the Caltrans fleet and include start times, end times, and delay codes describing the nature of the work order delay. Table 4-6 shows the delay codes that were observed and that delay codes starting with "W" indicate that the vehicle was in-service during the work order period.

Table 4-6 Work order delay codes

Delay Code	Description
03	LABOR - NOT AVAILABLE
04	SPACE - NOT AVAILABLE
05	SPECIAL TOOLS REQUIRED
06	APPROVAL PENDING
07	PART DELAY UNIT DOWN
15	VENDOR - NOT AVAILABLE
16	UNIT AT VENDOR
T	WAITING TOW
TS	TRANSFER SHOP RESPONSIBILITY
TU	TRANSFER USER RESPONSIBILITY
WA	INSERVICE- AWAITING APPROVAL
WB	INSERVICE-SPACE NOT AVAILABLE
WC	INSERVICE-COMPONENT REPAIRS
WE	INSERVICE-WAITING FOR EQUIP
WL	INSERVICE-LABOR NOT AVAILABLE
WP	INSERVICE PART DELAY
WR	INSERVICE-REQUESTED BY USER
WT	INSERVICE-WAITING FOR TOOLS
WV	AVAILABLE

The research team evaluated work order hours associated with delay codes other than "W" to estimate offline hours by sweeper fuel type. Work order hours were cumulated based on each work order time and date range, and overlapping periods were removed to avoid counting the same offline period more than once. The information is presented in Figure 4-33 and Figure 4-34.

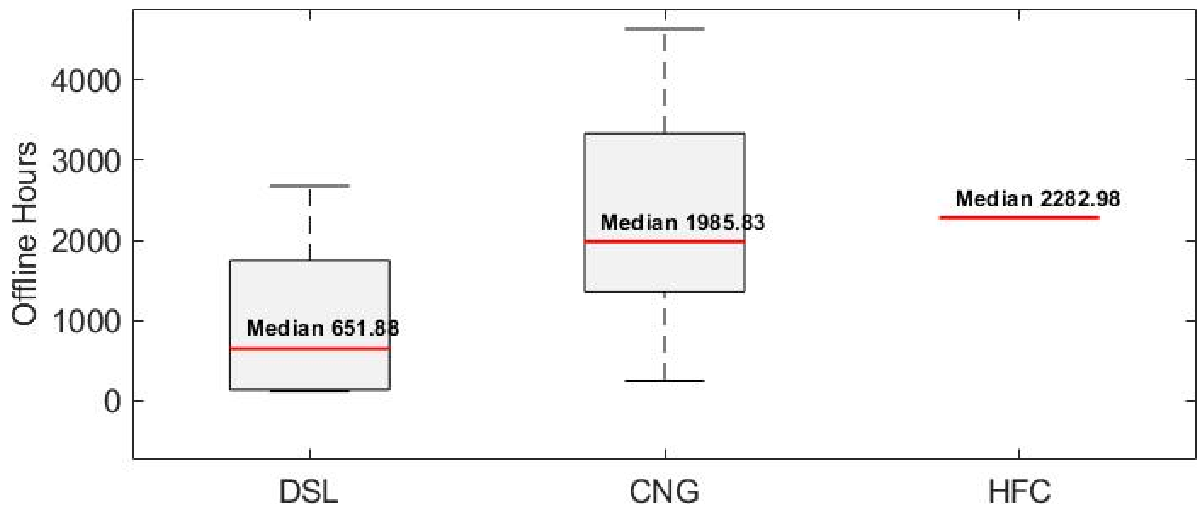

Figure 4-33 Sweeper per Unit Offline Hours –D7 -2020

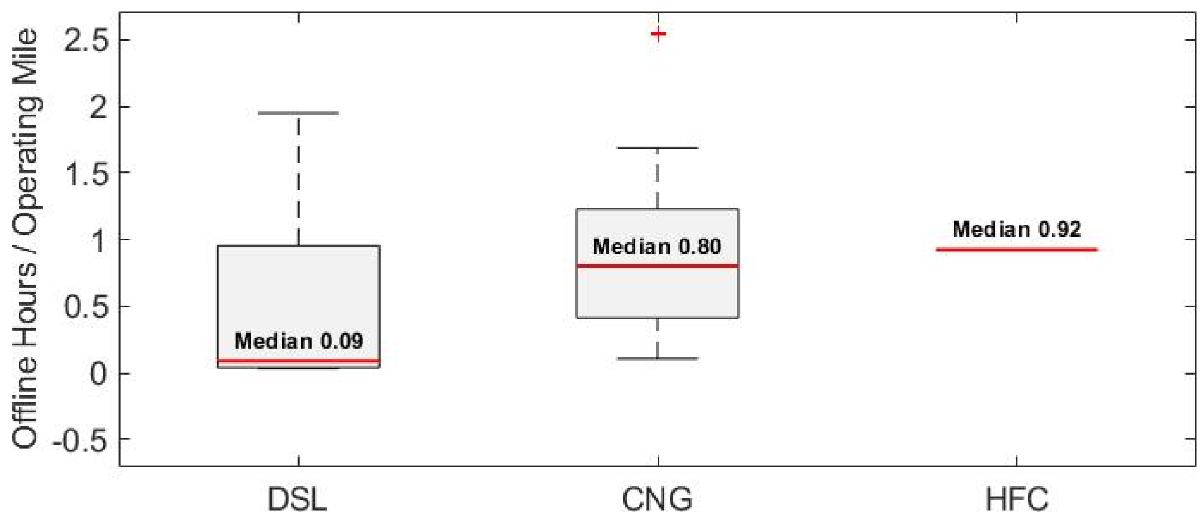

Figure 4-34 Sweeper per Unit Offline Hours / Operating Mile –D7 -2020

In addition to offline hours, the research team looked at the number of "non-W" work order counts for individual sweepers as shown in Figure 4-35. The "non-W" work order counts are work orders that are associated offline hours.

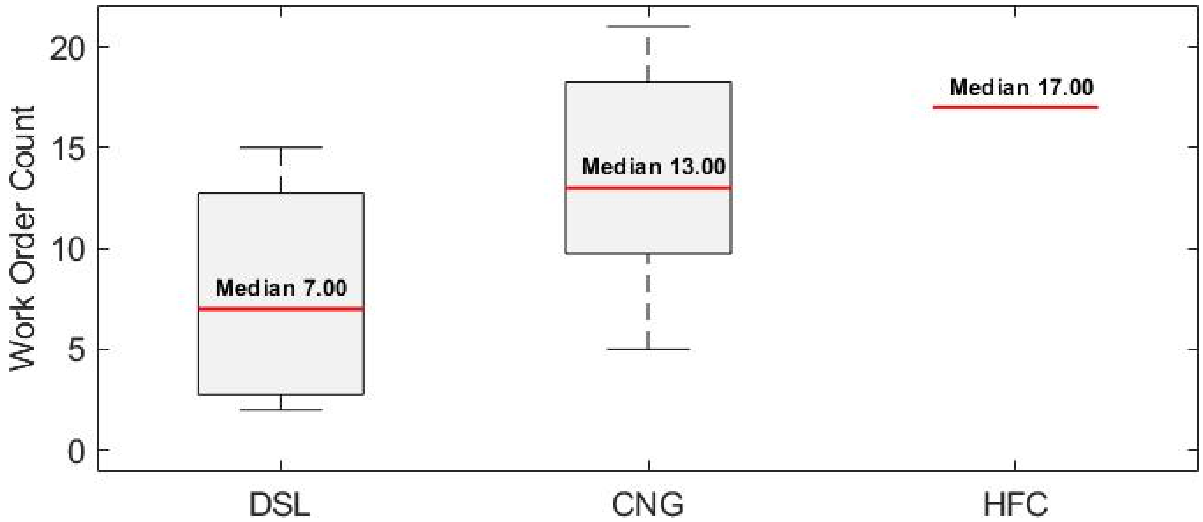

Figure 4-35 Caltrans district 7 per vehicle work order count for calendar year 2020

Work order data showed that diesels had lower offline hours and lower work order counts. The data also shows that HFC had comparable offline hours to the median CNG sweeper, but the HFC had higher work order counts. This may indicate that the work orders for the HFC were being resolved quicker than for the median CNG sweeper.

5. Portable Emissions Measurement Testing

This chapter describes the real-world emission testing that was performed on four street sweepers using a Portable Emission Measurement System (PEMS) and provides analysis and discussion of the data that was collected.

5.1. Equipment Tested

Four street sweepers were selected for PEMS testing based on their fuel type, age in the fleet, and their feasibility for testing. A summary of the equipment tested is provided in Table 5-1 along with the test distance and duration. The tested street sweepers consisted of two CNG fuel sweepers and two diesel fuel sweepers manufactured by Global Environmental Products. More information on the vehicles that were tested can be found in Section 3.2.

All of the street-sweepers selected for PEMS testing were Global Environmental Products street sweepers for the following reasons: 1) a majority of the newer Caltrans street-sweepers are the Global M4 and M4HSD line, 2) they were readily available for testing, and 3) the test procedure that UC Riverside developed was specific to the US Global platform.

Table 5-1 List of street sweepers selected for PEMS testing

Fuel Type	Location	Model Year	Model	Label	Test Date	Distance (miles)	Duration (hrs)
CNG	Bloomington	2017	Global M4HSD	7011373	1/13/2021	42.05	5.11
					1/14/2021	48.18	5.66
CNG	Bloomington	2017	Global M4HSD	7011374	1/20/2021	56.55	3.83
					1/21/2021	85.52	7.59
Diesel	Victorville	2013	Global M4	7005947	4/23/2021	89.85	5.99
					6/24/2021	24.61	3.98
Diesel	Yucca Valley	2013	Global M4	7005955	7/29/2021	33.91	5.04
					7/30/2021	39.75	4.28

The PEMS testing for each street sweeper consisted of a setup day in which the PEMS unit and accompanying test equipment was installed, followed by two days of testing under real-world operating conditions and normal daily activity.

5.2. PEMS Equipment and Installation

Gaseous emissions were measured with a Semtech-DS emission analyzer [12]. This system measures NO_x using a UV analyzer, total hydrocarbons (THC) using a heated flame ionization detector (HFID), and carbon monoxide (CO) and carbon dioxide (CO_2) using a non-dispersive

infrared (NDIR) analyzer. THC emissions are collected through a line heated to 190°C consistent with the conditions for regulatory measurements. The analyzers provide measurements of the concentration levels in the raw exhaust. The Semtech-DS also records information broadcast by the ECM which is needed to calculate emissions in g/bhp-hr.
The PEMS units employed in this work to measure gaseous are compliant with federal test methods (CFR 1065) for on-road testing and installed following manufacturers recommendations. Prior the on-road testing, a calibration procedure including leak checks and zero-span calibration was performed.

The PEMS unit used for this work is roughly 300 lbs. and locating it on the street sweeper was challenging. It was determined that the best mounting location for the PEMS unit was at the rear of the street sweeper using the bolts that attach the rear tow hooks. This required fabrication of a specialized rack to fit the mounting location. Figure 5-1 shows the PEMS unit installed at the rear of a Global street sweeper using the custom bracket fabricated.

Figure 5-1 PEMS unit mounted to rear of HSD street sweeper

Although all the PEMS tested street sweepers were Global, they consisted of two models, the Global M4HSD and the Global M4, which differed in the way the hopper functioned. The Global M4HSD, as the model name indicates, is a high-side dump sweeper, while the Global M4 is a rear dumping street sweeper. Figure 5-2 shows the PEMS unit installed on the rear of a rear-dumping street sweeper. Figure 5-3 shows both of these sweeper designs and the dumping action.

Figure 5-2 PEMS unit mounted to rear of rear-dumping street sweeper

Figure 5-3 a) Global M4HSD high-side dump sweeper and, b) Global M4 rear dump sweeper

The fact that the Global M4 dumps to the rear has implications for the PEMS test, since it puts the rear mounted PEMS unit in the line of the debris during hopper operation. The rear mounted PEMS also prevents the street sweeper from backing up to a debris container in the normal fashion and dumping in the container. The decision was made to dump protect the PEMS unit as much as possible with plywood and a tarp, and dump across the PEMS unit and directly onto the ground. In this manner, exhaust emissions from the dumping event could be collected. Figure 5-4 shows the rear hopper dumping event with a rear installed PEMS unit.

Figure 5-4 Rear dumping event with PEMS equipment installed.

5.3. Engine and Video Data Collection

Engine activity data from the ECM and video data was collected as part of PEMS testing. ECM data was collected using a GPS equipped HEM data logger as discussed in Section 4.1. Video data was collected using time lapse cameras set to collect data a 1 Hz frequency. The video data was used to associate sweeper activity (e.g. broom engagement, dumping of the hopper, and road type) with time stamps so those events could be isolated in the data analysis. In order to accomplish this, two time-lapse cameras were mounted facing towards the rear of the sweeper from the side mirror support. Figure 5-5 shows the installation of the time-lapse cameras.

Figure 5-5 Time-lapse cameras mounted for PEMS testing

The time-lapse cameras were angled to capture side broom activation and the hopper lifting event from both sides of the street-sweeper. From the video, freeway and arterial activity could also be separated. Both the time-lapse cameras were time synced and the video was time stamped. The views from the driver side and passenger side rear mounted time-lapse cameras are shown in Figure 5-6 and Figure 5-7.

Figure 5-6 View from driver side rear-mounted time-lapse camera.

Figure 5-7 View from passenger side rear-mounted time-lapse camera.

5.4. Data Processing and Analysis

PEMS testing produced the following data sets: 1) measured emissions from the PEMS, 2) engine and GPS data from the ECM data logger, and 3) time-stamped video data from the time-lapse cameras. Various aspects of processing and integration of these data sets, as well as data analysis are discussed in this section. The ECM/GPS data was collected using the same type of HEM data loggers that were used in the activity data collection portion of this work. Additional information on processing the HEM ECM/GPS logger data can be found in Section 4.1.1.

5.4.1. Time Alignment

The PEMS, ECM, GPS, and video data sets each contains time data that was adjusted as necessary in order to align the data sets with each other. The ECM and GPS data are aligned by the HEM data logger data post-processing software. The GPS time from the ECM data set was used as the reference time to which the PEMS and time lapse video data was aligned. The PEMS data was aligned based on the CO_2 emissions in the PEMS data set, and the fuel rate and vehicle speed in the ECM data set. The time lapse video data was aligned based on vehicle movement starting and stopping events, which were easily identifiable in the video and the vehicle speed data, as well as the CO_2 emission data. Once all of the time parameters were aligned, reference to a particular time range in each dataset would reference the appropriate data.

5.4.2. Defining Activity Modes

Time-lapse video from each camera records a time-stamped image at each second. The time-lapse video was reviewed and time stamps were manually recorded for the following key events: broom off, broom on, hopper up, hopper down, arterial roadway, ramp roadway, and freeway roadway. Time stamps indicating when the vehicle was stopped and when the vehicle was moving were added programmatically based on vehicle speed and engine speed from the ECM. Test time was based on engine on status. Engine-off time during the test period was not included in the test time, even though the PEMS equipment would remain on. Time stamps were recorded only when a change in states occurred and continuous status flags for various modes were created programmatically. An example of the status flags created is shown in Figure 5-8. Note that a hopper raising event could be a hopper dumping event or a hopper load leveling event in which the hopper is raised and lowered to redistribute the hopper contents. Hopper events would necessarily occur during idle on events when the vehicle was not moving.

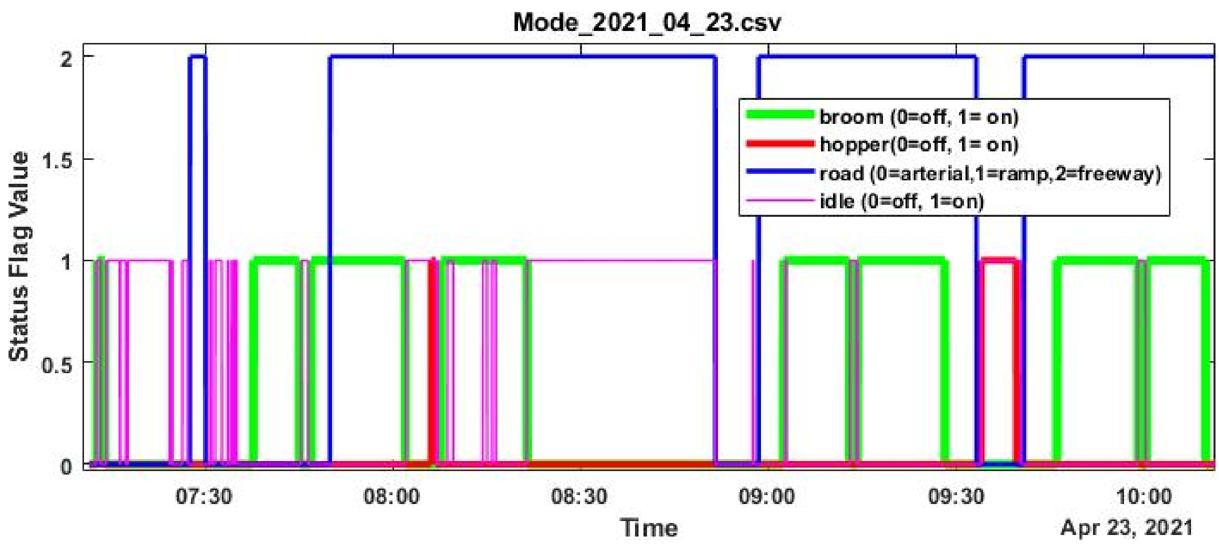

Figure 5-8 Example of continuous status flag values generated from time-lapse data.

Status flags defined various aspects of operation such as sweeping, not sweeping, hopper activation and road types traveled. The status flags could be combined to define various combined modes of operation such as stopped broom off, stopped broom on, arterial broom off, arterial broom on, freeway broom off, freeway broom on, and a hopper lift event. An example of velocity data colored by modal events is shown in Figure 5-9. A summary of modal results from this analysis are presented in the following section.

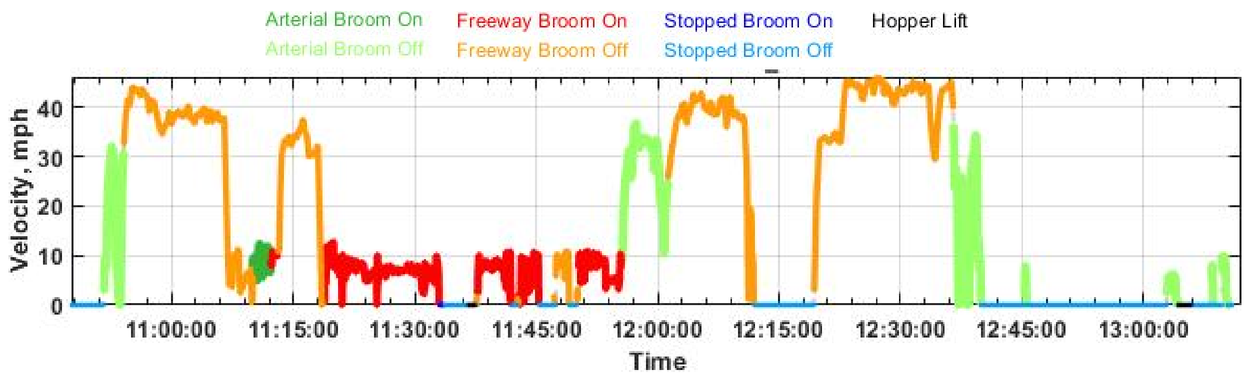

Figure 5-9 Example of velocity colored by modal events

5.5. PEMS Testing Results

The emissions results for the PEMS testing are presented in the following section. Emission rates in units of grams/hour, grams/mile and grams/kwh generated from each of the test scenarios can be found in

The box plots for each pollutant show the results for each sweeper type based on the average of tests conducted on that particular test combination. In the boxplot, the top of the box represents the 75th percentile, the line inside the box represents the median value whose number is provided in text next to the median line, the bottom of the boxplot represents the 25th percentile, the whiskers represent maximum and minimum values and points beyond the whiskers are outliers.

General statistics for the PEMS tests are presented in Table 5-2. On three test days, colored in gray, a portion of the testing was lost due to equipment failure. For these days, only statistics for the valid period of data are recorded. This means that some of the statistics, such as percent idle time, may not be representative of a real-world work shift. This is observed, for example, on the diesel sweeper test on 6/24/2021, which shows the sweeping time to be unusually high at 87%.

Table 5-2 General statistics for PEMs tests

Vehicle Label	7005947	7005947	7005955	7005955	7011373	7011373	7011374	7011374
Fuel Type	Diesel	Diesel	Diesel	Diesel	CNG	CNG	CNG	CNG
Test Date	4/23/2021	6/24/2021	7/29/2021	7/30/2021	1/13/2021	1/14/2021	1/20/2021	1/21/2021
Test Location	Victorville		Yucca Valley		Bloomington		Bloomington	
Test Identifier	Diesel 1 - Test 1	Diesel 1 - Test 2	Diesel 2 - Test 1	Diesel 2 - Test 2	CNG 1 - Test 1	CNG 1 - Test 2	CNG 2 - Test 1	CNG 2 - Test 2
Test Dur (hrs)	5.99	3.98	5.04	4.28	5.11	5.66	3.83	7.59
Test Distance (mi)	89.85	24.61	33.91	39.75	42.05	48.18	56.55	85.52
Test Avg. Velocity (mph)	15.01	6.18	6.72	9.29	8.22	8.52	14.75	11.27
Test Max Velocity (mph)	61.19	44.18	69.12	69.65	57.86	60.01	63.35	66.86
Test Avg. Sweeping Velocity (mph)	9.29	4.93	4.62	4.08	10.49	10.11	13.29	10.63
Test Max Sweeping Velocity (mph)	18.69	14.83	22.86	13.31	22.67	22.63	20.59	20.61
Test Idle (hrs)	2.02	0.11	1.46	0.93	1.71	2.64	0.84	2.78
Test Sweeping (hrs)	1.88	3.46	1.64	0.94	2.39	1.39	2	2.41
Test Sweeping (mi)	17.46	17.09	7.58	3.82	25.02	14.01	26.56	25.59
Test Percent Time Idle	33.7	2.77	28.97	21.84	33.41	46.65	22.03	36.65
Test Percent Time Sweeping	31.39	87.01	32.57	21.88	46.65	24.49	52.11	31.74

5.5.1. Diesel Idle Emission

Idling emissions for diesel sweepers shows a substantially greater range of values across all metrics and emissions than for the CNG sweeper. Diesel idle emissions normalized by work also show a much larger variation than the work normalized emissions for the sweeping and traveling mode. This is not the case for the CNG sweeper and seems counterintuitive since the idling mode is not impacted by variations in tractive power demand. Examining the idling data for diesel vehicles shows that there is a mode during idle in which the fuel rate is increased and the EGR flow rate is shut off, as depicted in Figure 5-10. This causes a step in emissions, as shown in Figure 5-10, that adds variation to the idle emission rates. This EGR shutoff event coincides with a drop in aftertreatment temperature and may be a tactic to keep the aftertreatment system at optimal temperature.

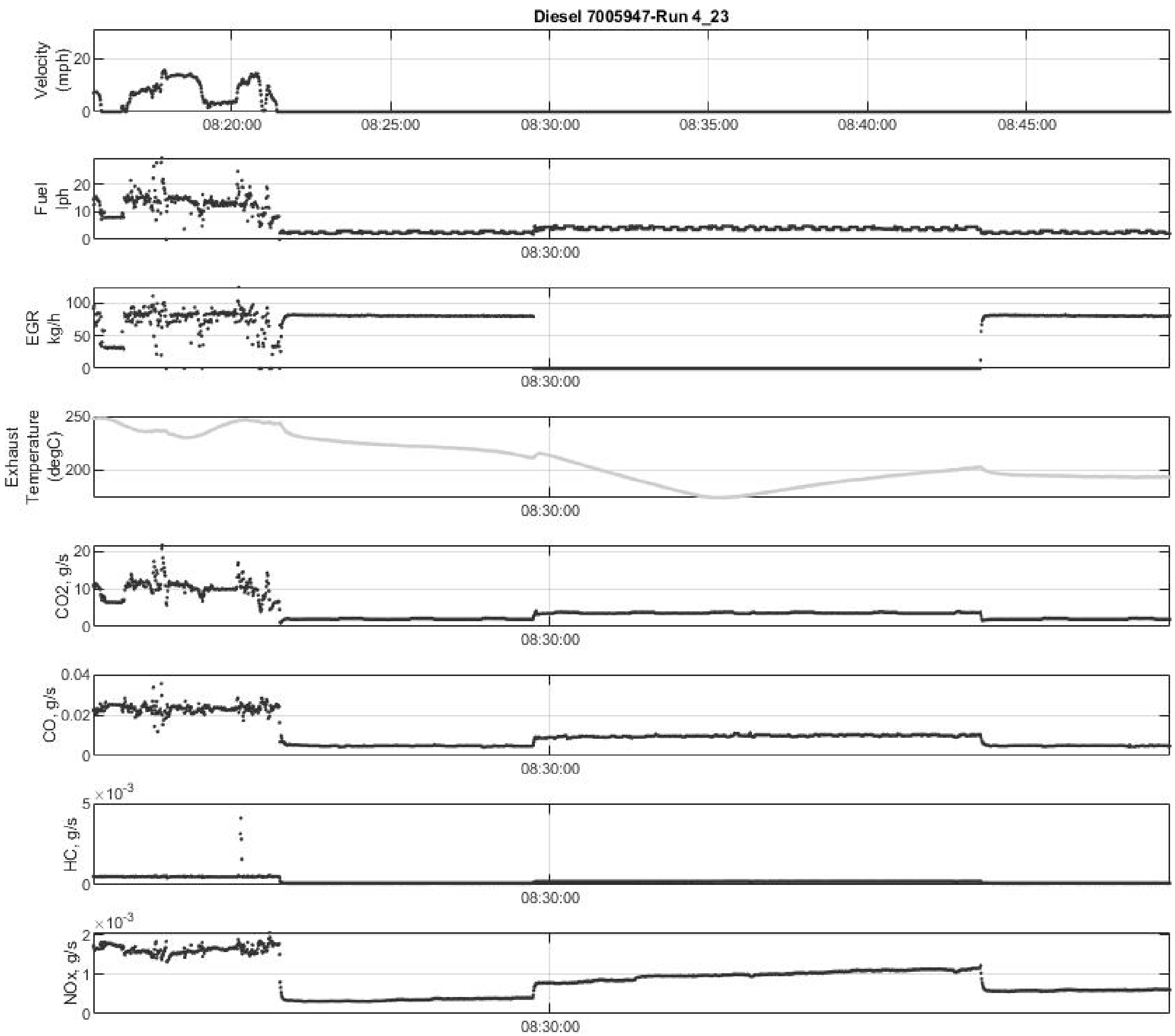

Figure 5-10 Diesel EGR shutoff mode and impact on idle emission

5.5.2. CO_2 Emissions

CO_2 emissions are presented in Figure 5-11 through Figure 5-13. Emissions are provided by fuel type for the combined activity, for the sweeping mode and for idling. The time and distance based activities reflect the work the amount of work performed. Higher work activity will result in higher time or distance based emission rates, even between vehicles with the same work based emission rate. The CO_2 kg/kwh work based emission rates are presented in Figure 5-13, and indicate that the work based overall and sweeping rates are similar, while the work based idle emission rate is higher. The results show that the diesel CO_2 kg/kwh emissions are greater than for the CNG across the three activity categories.

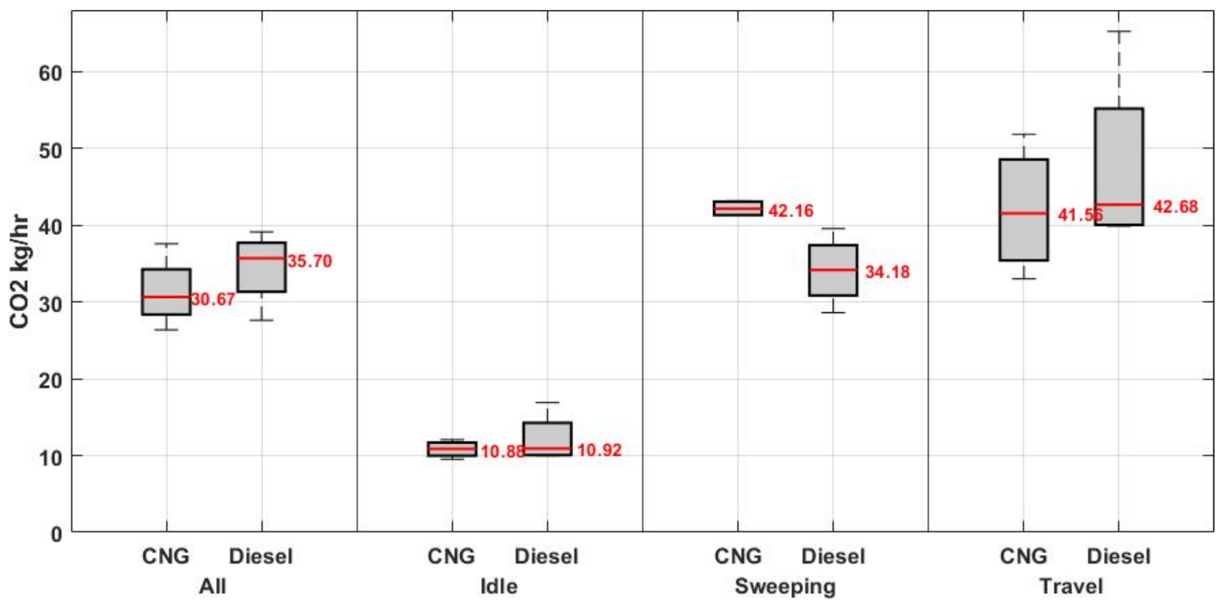

Figure 5-11 CO_2 kg/hr PEMS emission results

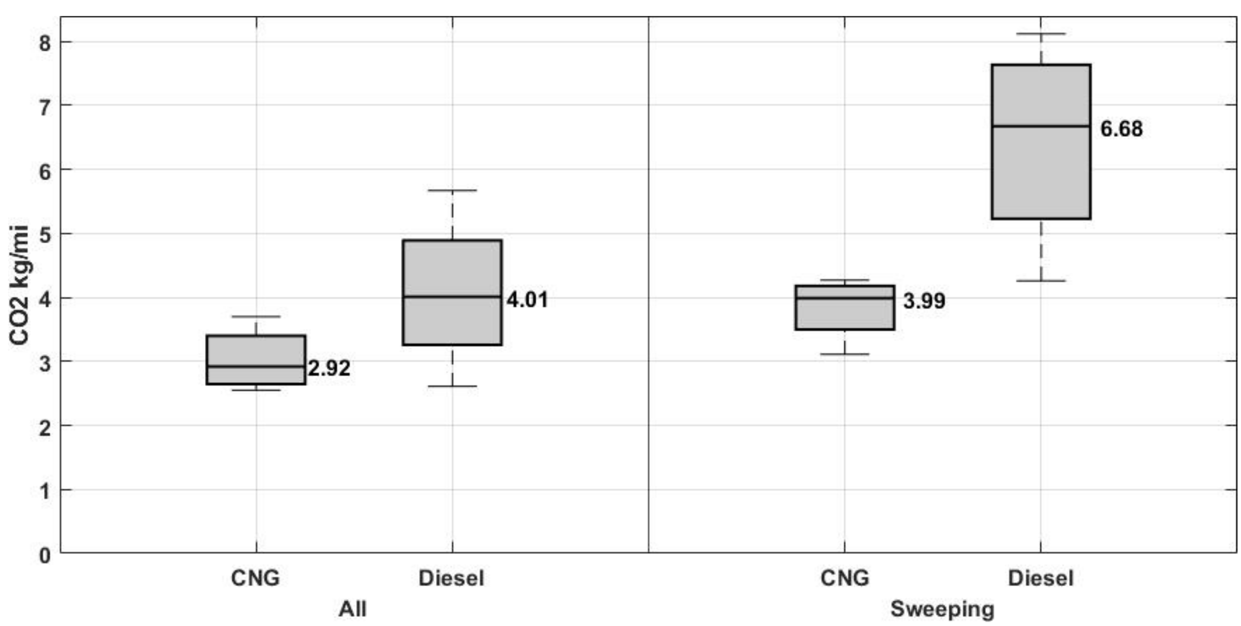

Figure 5-12 CO_2 kg/mile PEMS emission results

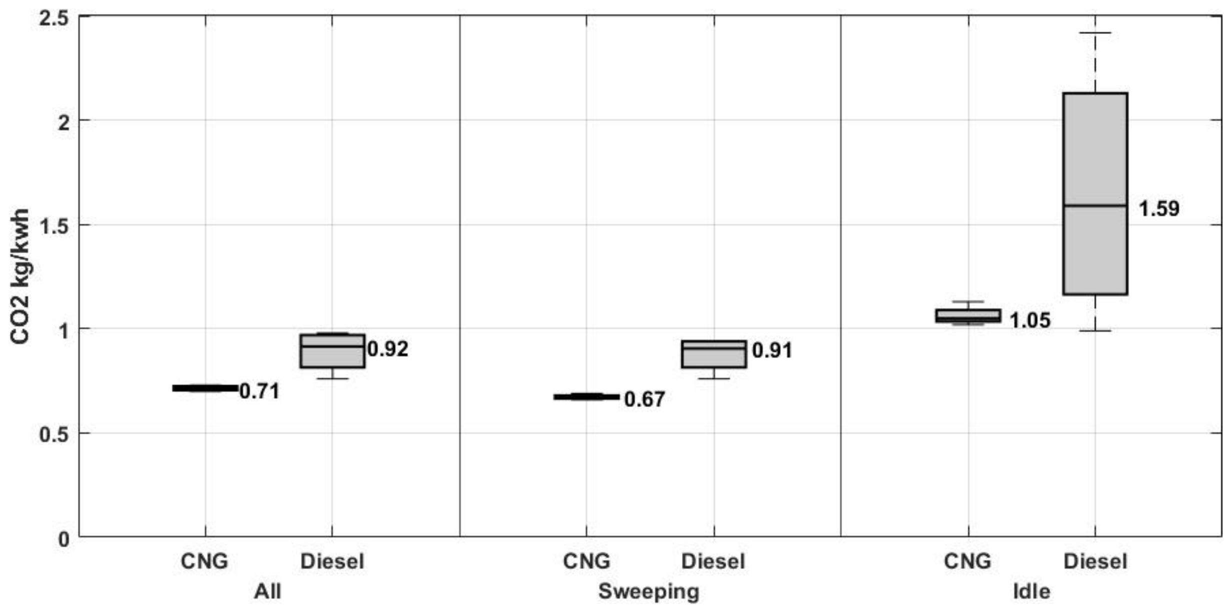

Figure 5-13 CO_2 kg/kwh PEMS emission results

5.5.3. CO Emission

Summary results for CO emissions from the PEMS test are presented in Figure 5-14 through Figure 5-16. The results show that the CNG sweeper produces significantly more CO emissions across all activity categories. Emission rates are roughly 6 to 36 times higher for the CNG sweeper, depending on the activity mode and units of measure.

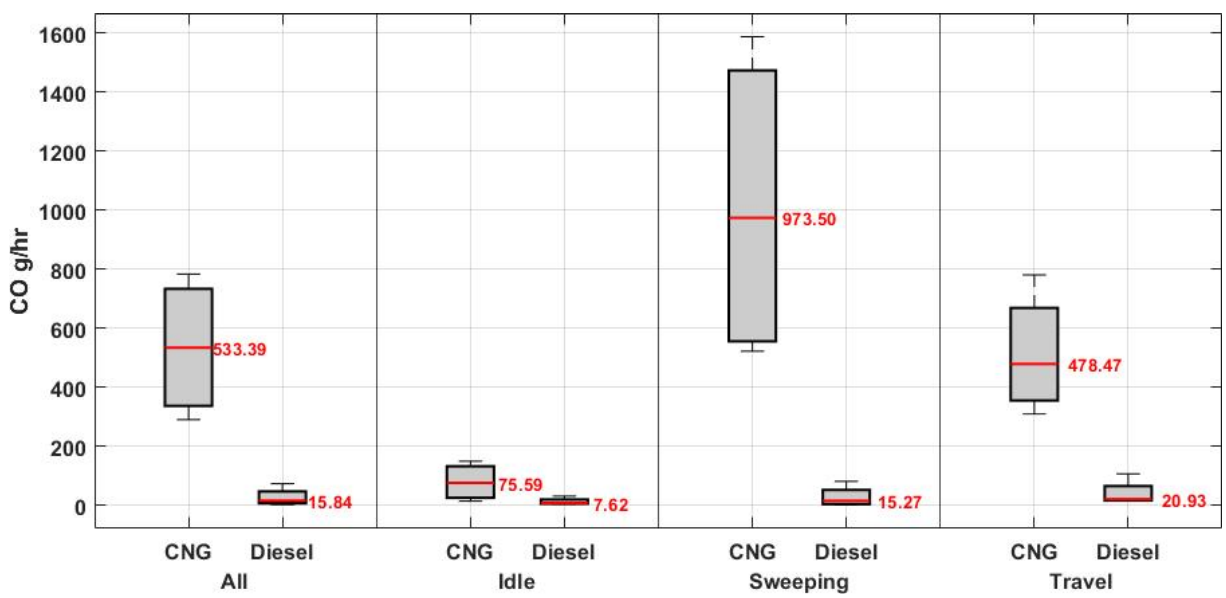

Figure 5-14 CO g/hr PEMS emission results

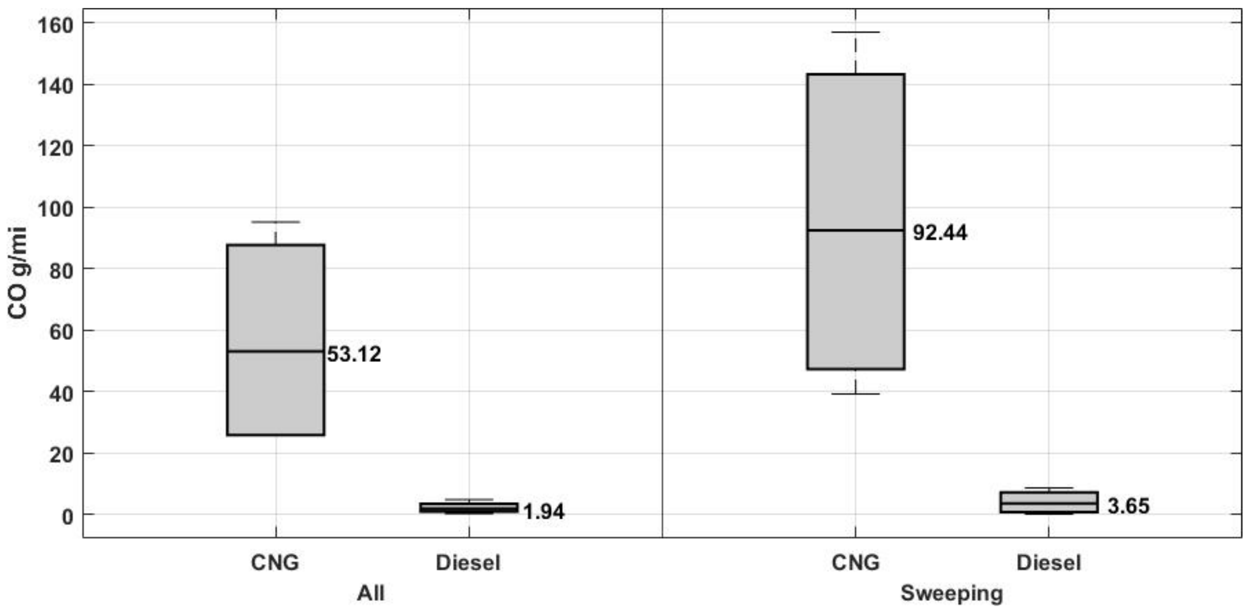

Figure 5-15 CO g/mile PEMS emission results

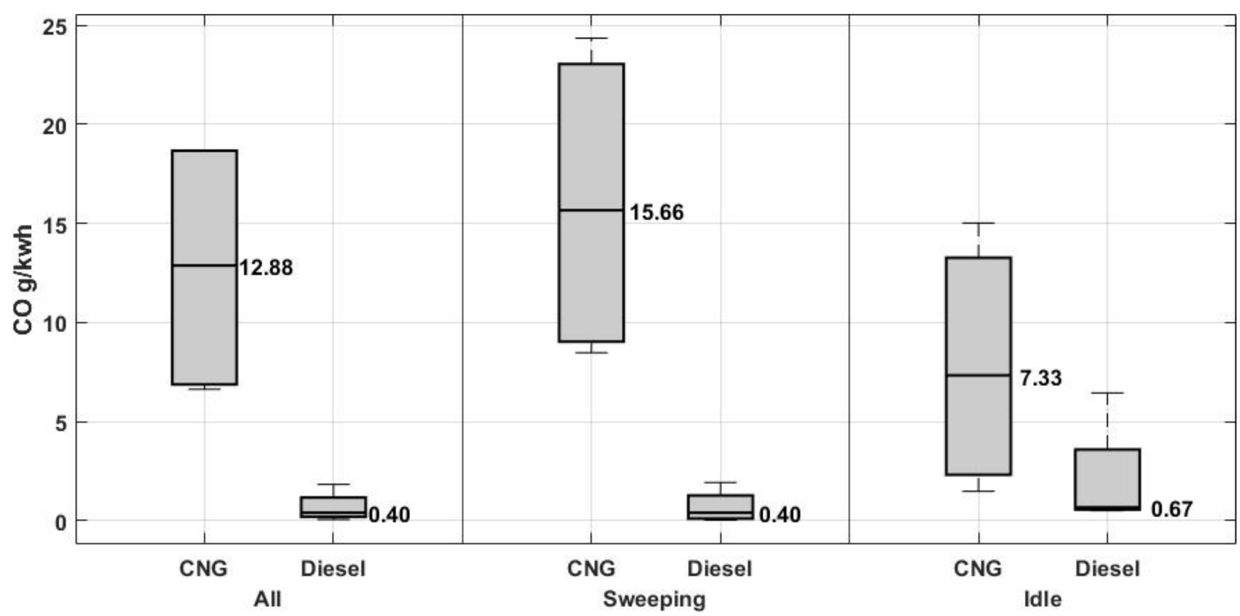

Figure 5-16 CO g/kwh PEMS emission results

5.5.4. THC Emission

Summary results for THC emissions from the PEMS test are presented in Figure 5-17 to Figure 5-19. The results show that the CNG sweeper produces significantly more THC emissions across all activity categories. THC emissions for the CNG sweeper are up to 88 times higher than the diesel sweeper, depending on the activity mode and units of measure.

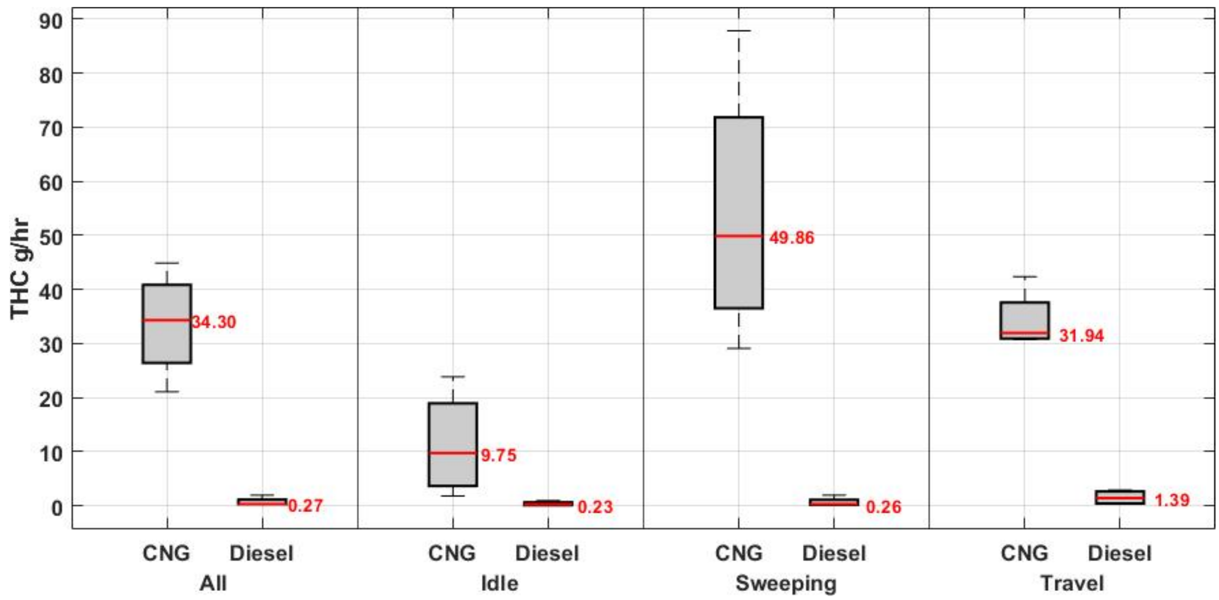

Figure 5-17 THC g/hr PEMS emission results

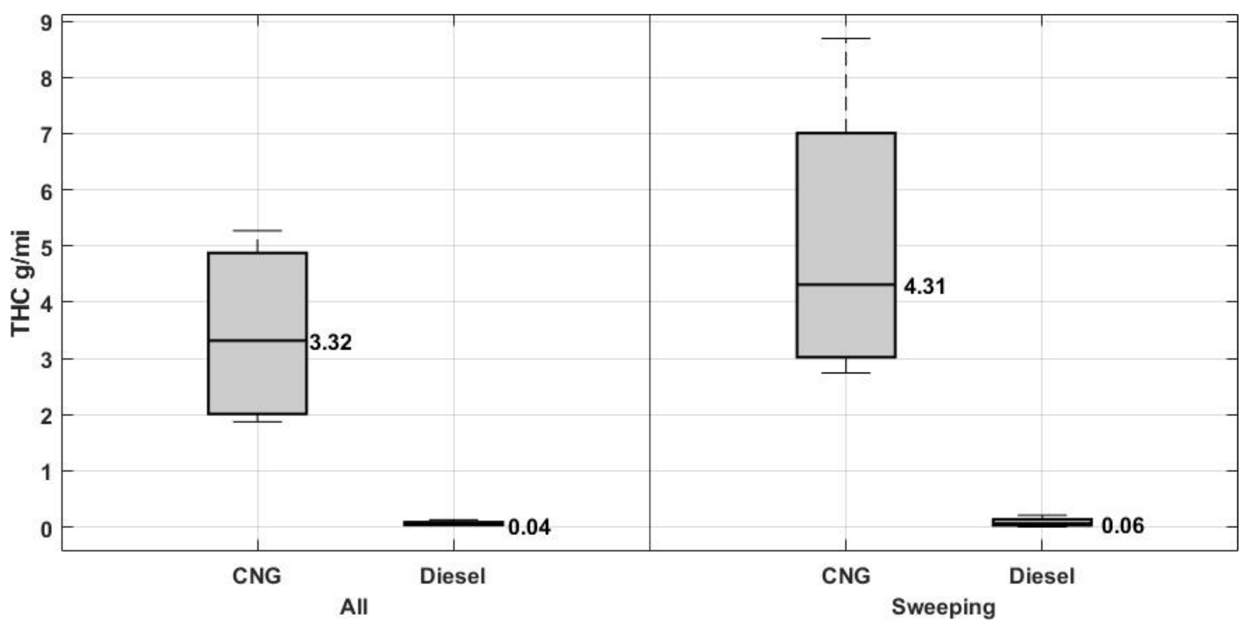

Figure 5-18 THC g/mile PEMS emission results

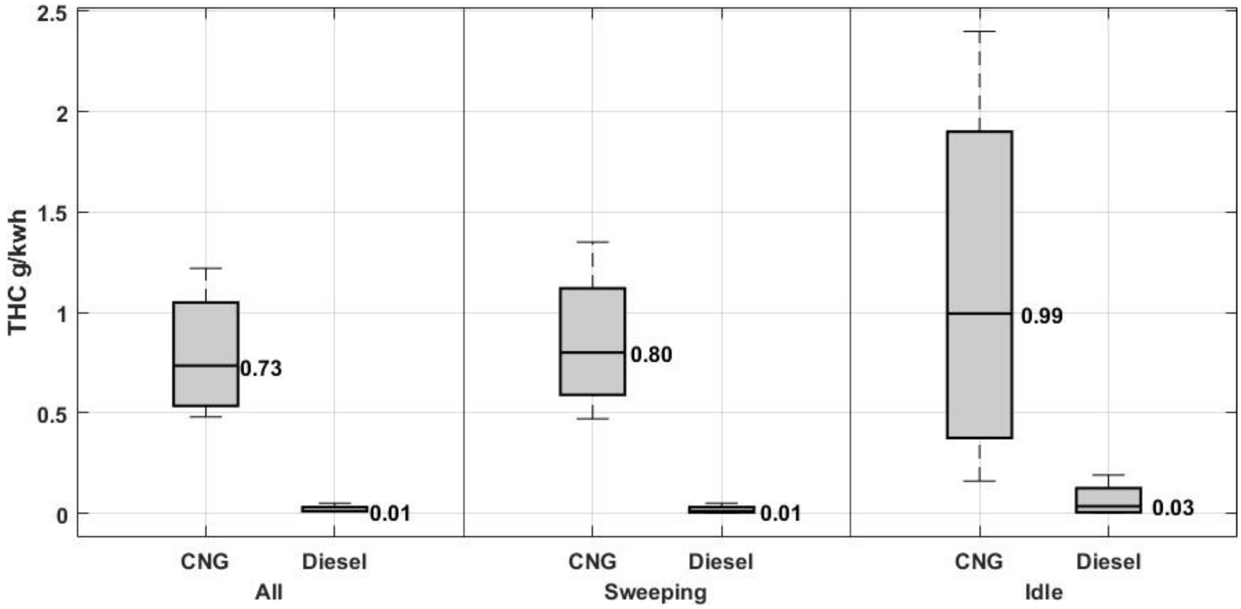

Figure 5-19 THC g/kwh PEMS emission results

5.5.5. NO_x Emission

Summary results for NO_x emissions from the PEMS test are presented in Figure 5-20 to Figure 5-22. The results show that the diesel sweeper produces significantly more NO_x emissions than the CNG sweeper across all activity categories. NO_x emissions for the diesel sweeper are up to 9.8 times higher than for the CNG sweeper, depending on the activity mode and units of measure.

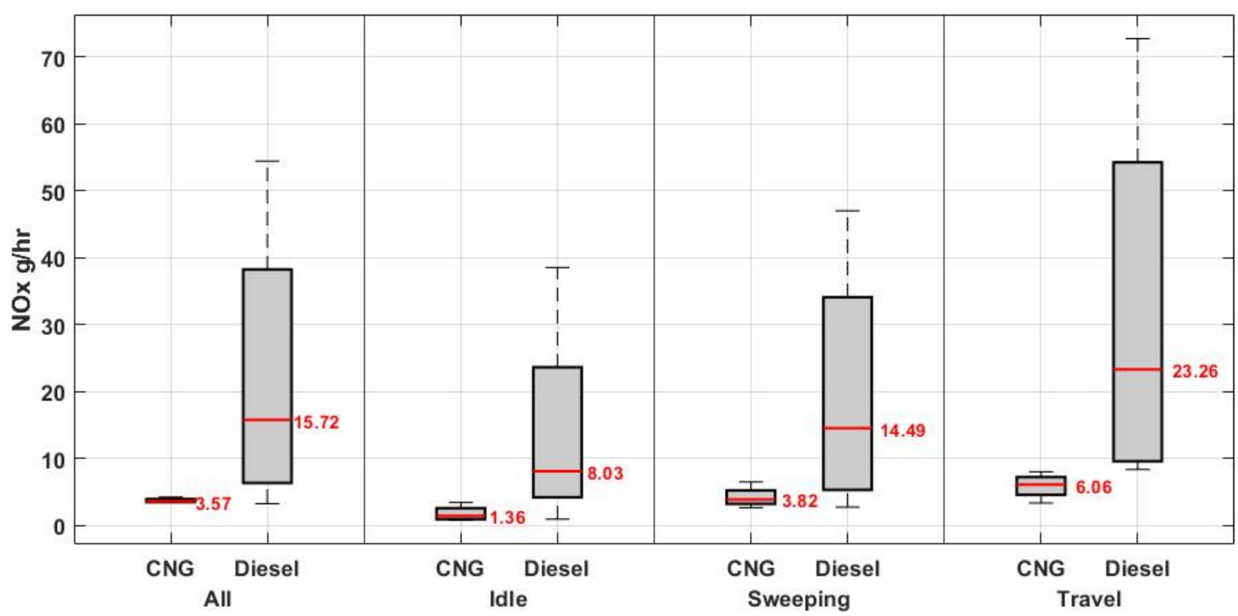

Figure 5-20 NO_x g/hr PEMS emission results

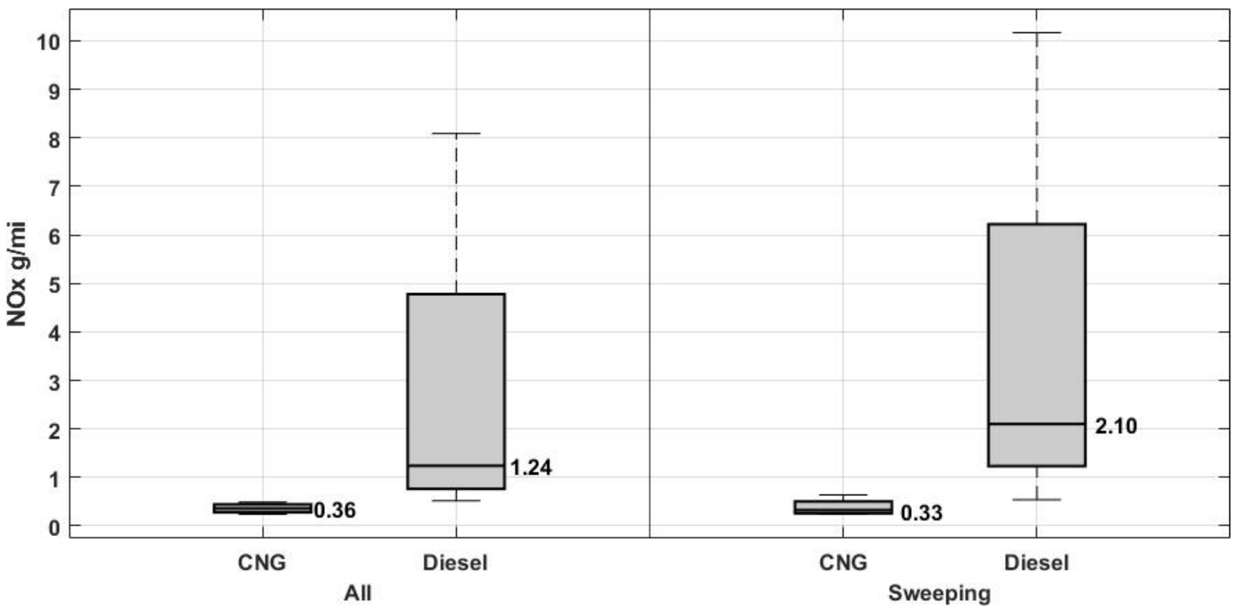

Figure 5-21 NO_x g/mile PEMS emission results

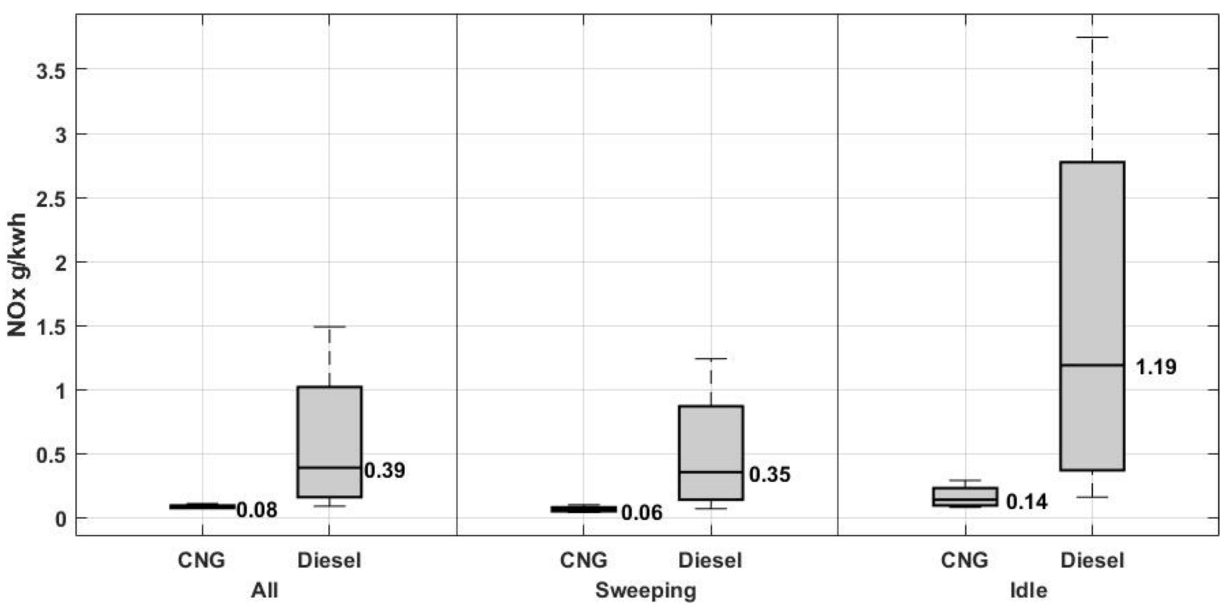

Figure 5-22 NO_x g/kwh PEMS emission results

6. Chassis Dynamometer Testing

One of the main objectives of this work was to compare emissions and performance of the selected street sweeper powertrain technologies. This is addressed by the real-world data collection in Chapter 5. The advantage of the PEMS data is that it captures the effects of real-world conditions such as varying road surfaces, road grades, winds, and any other external forces that are difficult to capture in a laboratory setting. The disadvantage of the PEMS testing is that, although the conditions represent the real word, they vary between testing locations, testing conditions, driver, etc., which introduces some unaccountable variably in the resulting comparisons. The advantage of the chassis dynamometer testing is that the operating conditions between street-sweepers can be managed to make them more directly comparable. This chapter discusses the chassis dynamometer testing effort, including chassis dynamometer setup, test schedule development, and testing results.

6.1. Chassis Dynamometer

CE-CERT's Heavy-Duty Engine Dynamometer Test Facility is designed for a variety of applications including verification of diesel ATS devices, certification of alternative diesel fuels, and fundamental research in diesel emissions and advanced diesel technologies. UCR's chassis dynamometer is a 48" electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles. The dynamometer includes dual, direct connected, 300 horsepower motors attached to each roll set that apply loads at the vehicle tires to simulate factors such as the friction of the roadway and wind resistance, as would be experienced under typical driving conditions. The dynamometer has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horsepower at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common. The dynamometer is capable of performing a wide range of driving conditions and test schedules.

Figure 6-1 Chassis dynamometer test set up

During the chassis testing portion of this work, the regular chassis dynamometer emission testing hardware and software underwent maintenance and upgrades. As an alternative, the emission measurement for the chassis dynamometer testing utilized the PEMS equipment. Figure 6-1 shows the setup of the PEMS unit attached and the diesel sweeper strapped to the chassis dynamometer for testing.

6.2. Vehicle Selection

Testing was performed on one diesel, one CNG and one HFC street sweeper. Emissions were collected from the diesel and CNG sweepers and ECU parameters were collected from all three sweepers. The diesel sweeper that was tested on the chassis dynamometer was from the Caltrans Yard in Victorville and had been part of the ECU activity data collection effort and the PEMS emissions testing portion of this project. Both the CNG and HFC sweeper were from the Caltrans Westdale yard and were part of the activity data collection portion of this project. Additional information on the equipment tested on the chassis dynamometer is provided in Table 3-1.

6.3. Drive Cycles

Drive cycles were developed for the chassis dynamometer testing of street sweepers for this project. The drive cycles were designed to represent real-world activity, including various modes of operation, and were created from on-road data collected as part of the PEMS testing discussed in Section 5. The following three street sweeper drive cycles were created and are presented below: 1) a cold-start test, 2) an engine soak and idle test, and 3) the main drive cycle consisting of various activity modes.

The cold-start test, presented in Figure 6-2, was designed to capture emissions associated with a cold engine and aftertreatment system. The cycle consists of 90 seconds of idle followed by more than ten minutes of low load activity.

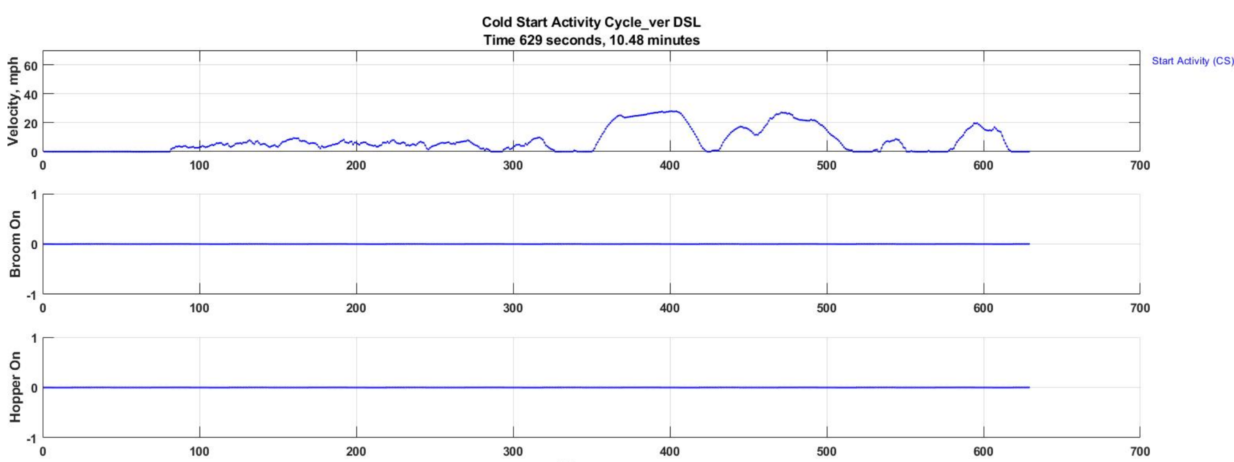

Figure 6-2 Cold start activity

In addition to cold start, another issue of interest is the cooling of the aftertreatment system due to reduced load such as idling or even shutting the engine off. To examine this issue, a 10 minute engine off time (engine soak time), followed by the cold start activity was created as seen in Figure 6-3. The cycle also contains a 10 minute idle followed by cold start activity. The start-activity prep section ensures that the sweeper is at normal operating temperature. This same low load activity from the cold-start test is used in the engine soak and idle test for comparison purposes. Cold-start and warm-start emissions are discussed in Section 6.4.2.

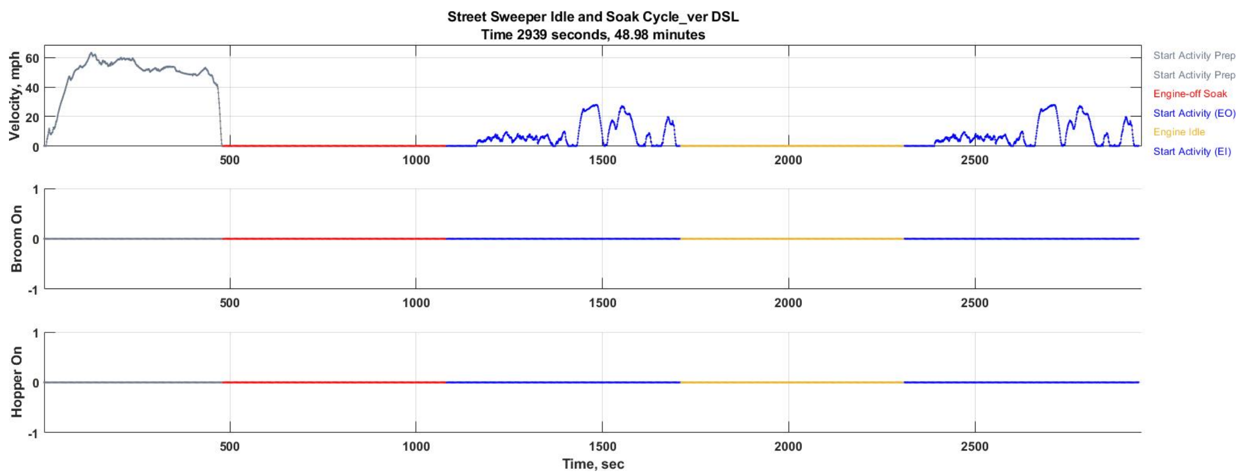

Figure 6-3 Engine soak and engine idle test

The main cycle is presented in Figure 6-4 and consists of various sections that represent different modes of operation. The top subplot in the figures presents the velocity trace, the middle subplot shows the broom activation state (0 = broom not active and 1 = broom active), and the bottom subplot shows the hopper activation state (0 = hopper lift inactive, 1 = hopper lift active). The first 500 seconds include high speed activity to ensure that the test vehicles are warmed up to operating temperature. The following sections include arterial or low speed moving, freeway travel, moving sweeping, stationary sweeping, and idle event. The mode "moving sweeping" is sweeping while moving, which is the typical mode of sweeping. The mode "stationary sweeping" is sweeping while stationary. This mode occurred very infrequently and briefly in the field and is only included for reference.

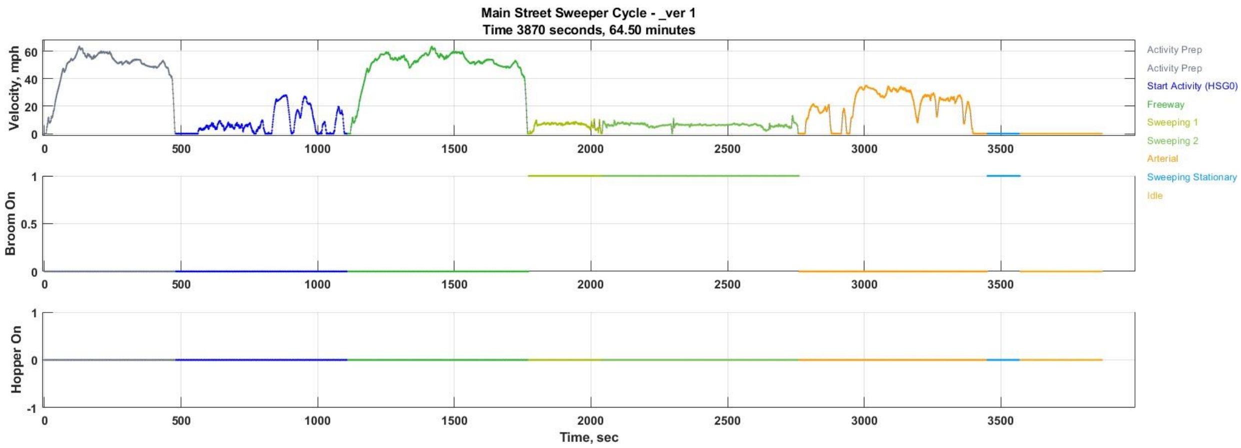

Figure 6-4 Main drive schedule with activity mode sections

6.4. Test Results

The CNG, diesel, and H2 sweepers were tested on the chassis dynamometer. Tailpipe emissions were measured from the CNG and diesel sweepers, and ECU data was collected from all three sweepers. Energy consumption for all testing was based on ECU reported power in order to include energy not measured at the dynamometer rollers, such as the energy to power the brooms, debris elevator, hopper, etc. Engine brake power was calculated using ECM broadcast J1939 standardized data as found in the CFR and described in Eq. 1 and Eq. 2 in Section 4.1.1.

6.4.1. Drive Cycle Compliance and Testing Issues

Drive cycle compliance was an issue for the freeway mode and the moving sweeping mode in some scenarios. The average speed of the driving modes presented for each fuel type are presented in Figure 6-5.

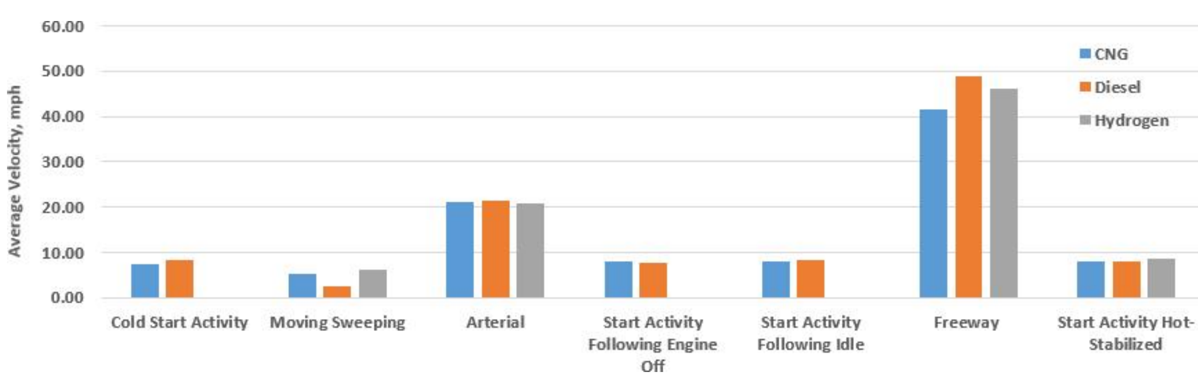

Figure 6-5 Average speed during select chassis dynamometer test modes

The CNG sweeper ran hot during the freeway mode, so the freeway speed was not maintained by the test team. The CNG sweeper may have been impacted by insufficient cooling, since the equipment is stationary on the chassis dynamometer. Cooling fans are used during testing to replicate air flow, but some platforms, are more sensitive to heat buildup, as was observed with the CNG sweeper. Since system temperature dramatically impacts emissions, the high speed testing was removed from the emission analysis. There were also issues with the diesel sweeper performance on the chassis dynamometer relative to sweeping. For an unknown reason, the diesel sweeper was not able to achieve the proper sweeping speed while on the chassis dynamometer and the average sweeping speed was 48% of the prescribed average speed as is shown in Figure 6-5. At some point during testing, the diesel sweeper would no longer engage in the sweeping mode until the unit was removed from the chassis dynamometer. It is unknown if this is related to the fact that only the drive wheels are in motion during the chassis dynamometer test.

For the CNG and diesel sweepers, energy based emission rates in units of g/kwh were calculated for individual operating modes using ECU reported power. In order to minimize the impact of variations in following the drive traces between tests and any loading issues related to the dynamometer setup for each sweeper, distance and time based emission rates for CNG and diesel were calculated from energy based emission rates and a common load for each section, as presented in Table 6-1.

Table 6-1 Selected Chassis Dynamometer Test Mode Information

Activity	Time, sec	Dis, mile	Energy, kwh	Power, kw
Cold Start Activity	539	1.13	6.36	42.48
Start Activity Following Engine Off	539	1.18	5.36	35.82
Start Activity Following Idle	539	1.21	5.47	36.57
Start Activity Hot-Stabilized	539	1.20	5.75	38.39
Arterial	634	3.69	9.66	54.85
Idle	599	-	1.23	7.39
Stationary Sweeping	114	-	1.27	40.23
Moving Sweeping	949	1.41	12.92	49.01

6.4.2. Cold-start and Warm-start Emissions

The first test that the diesel and CNG sweepers performed on test day was a cold start test. In order to insure that the test sweepers were cold, they were set up on the day prior to testing. The cold start was designed to capture emission events that were associated with a cold engine and aftertreatment system. Aftertreatment systems with a catalytic component such as dual oxidation catalyst (DOC) and selective catalytic reduction (SCR) require elevated temperatures for the catalytic components to operate properly. At lower aftertreatment temperatures, the aftertreatment emission conversion efficiency is poor and a larger proportion of the engine emissions pass through the tailpipe unconverted. The emission impact of this warm up period with reduced conversion efficiency will depend on the activity that the sweeper is engaged in during this period. If the sweeper engages in high load/high engine out emission activity during the warm up period, the associated emission events will be more significant than if the aftertreatment is allowed to warm up at low load/low engine out emissions. The duration of the cold-start effect will depend on the activity load. A higher activity load will reach proper operating temperatures quicker, but produce much greater emissions. To minimize the cold-start emission effect, the system should be allowed to come to operating temperature under minimum load. In the chassis dynamometer testing, the cold-start effect lasted about 3.5 minutes in the diesel street sweeper and roughly 3 minutes in the CNG sweeper. With increased air flow in a real-world scenario, they aftertreatment system may take longer to reach proper operating temperature.

Once the aftertreatment system has achieved the minimum operating temperature for proper operation, it is important that it stays above this minimum temperature for the continued proper operation. It is expected that moderate to high activity loads will produce enough heat to keep the aftertreatment system above the minimum operating temperature, however, this may not be the case for low load activity. To examine the impact of cold-start and reduced load, the start-activity was measured and compared following a cold start, following a 10 minute engine off period, following a 10 minute idle period, and under hot-stabilized running conditions. The resulting CO, THC, and NO_x emissions from this testing are presented in Figure 6-6, Figure 6-7, and Figure 6-8.

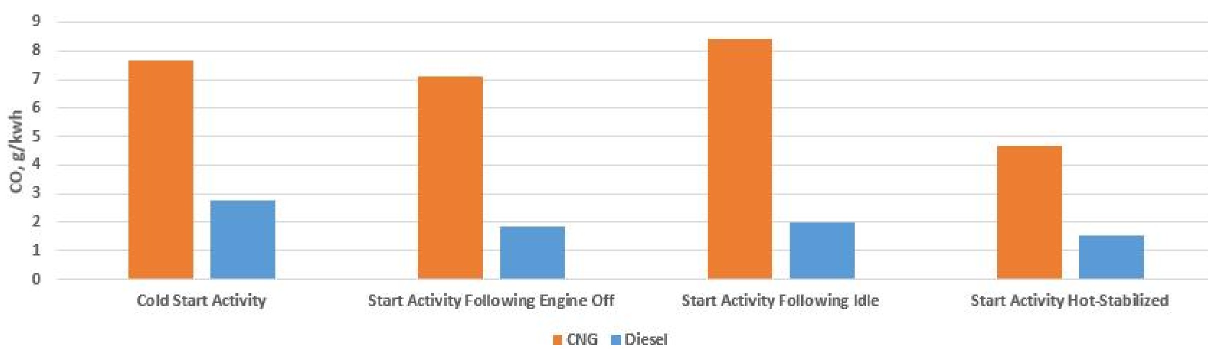

Figure 6-6 Start activity CO emissions following cold-start, engine off, idle, and under hot stabilized conditions.

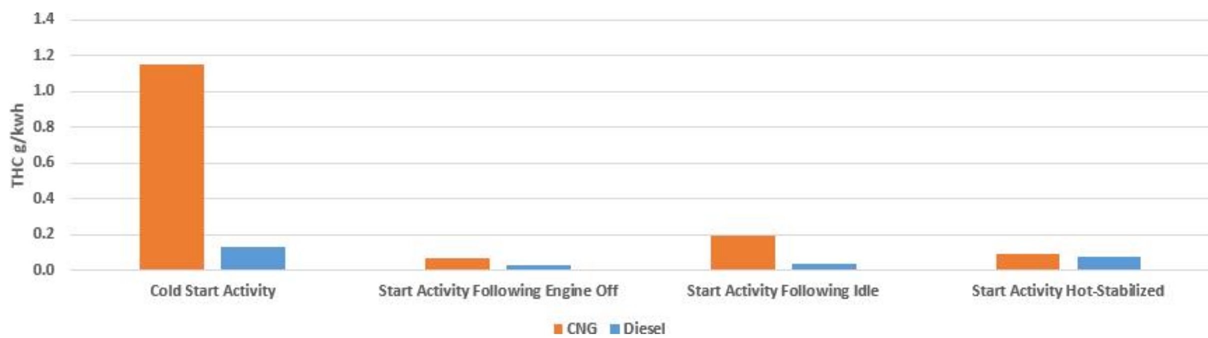

Figure 6-7 Start activity THC emissions following cold-start, engine off, idle, and under hot stabilized conditions.

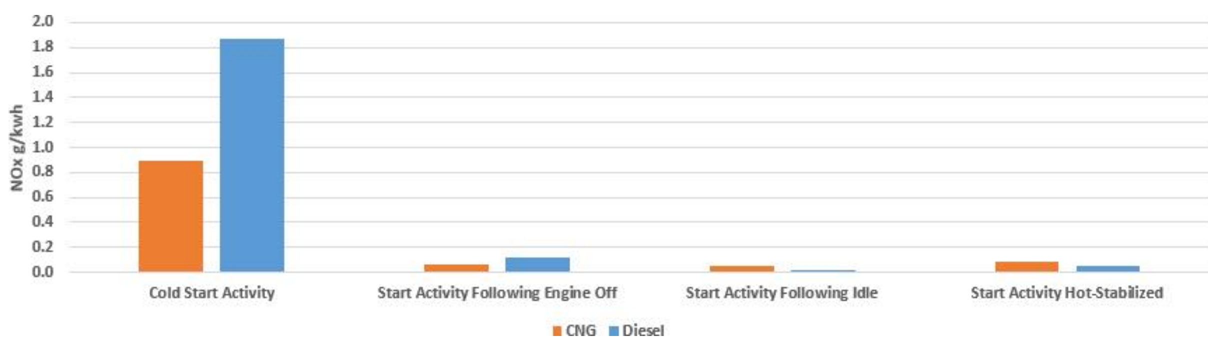

Figure 6-8 Start activity NO_x emissions following cold-start, engine off, idle, and under hot stabilized conditions.

The ratios of energy based mass emission rates (g/kwh) for cold-start start activity to hot-stabilized start activity are presented in Table 6-2 and show that NO_x g/kwh cold start emissions are ~39 times higher than hot stabilized for the diesel and ~10.6 times higher for CNG. The data shows that the THC cold-start emissions for the CNG sweeper are also significantly higher than hot-stabilized emissions at a ratio of 12.4. Time based and distance based emission results shows similar cold/hot activity ratios. The results also show that a 10 minute engine off increased the NO_x energy based mass emission rate for diesel about 2.5 times relative to the hot-stabilized emission rate.

Table 6-2 Cold-Start (g/kwh)/Hot-Stabilized (g/kwh) ratio

Fuel	CO2	CO	THC	NOx
CNG	1.0	1.6	12.4	10.6
Diesel	1.2	1.8	1.8	39.3

Table 6-3 Cold-Start (g/hr)/Hot-Stabilized (g/hr) ratio

Fuel	CO2	CO	THC	NOx
CNG	1.1	1.8	13.7	11.7
Diesel	1.4	2.0	2.0	43.4

Table 6-4 Cold-Start (g/mi)/Hot-Stabilized (g/mi) ratio

Fuel	CO2	CO	THC	NOx
CNG	1.1	1.9	14.6	12.4
Diesel	1.4	2.1	2.1	46.1

6.4.3. Regenerative Braking

One of the benefits of a battery-based platform is the ability to recapture a portion of the kinetic energy from a moving vehicle during the braking process known as regenerative braking. Regenerative braking relative to the hybrid electric fuel cell sweeper, is discussed in Section 4.2.2. The hybrid electric fuel cell sweeper was tested on the chassis dynamometer over the main test cycle and regenerative braking energy was calculated for several modes of operation. A portion of chassis dynamometer testing and the recaptured energy related to regenerative braking is shown in Figure 6-9.

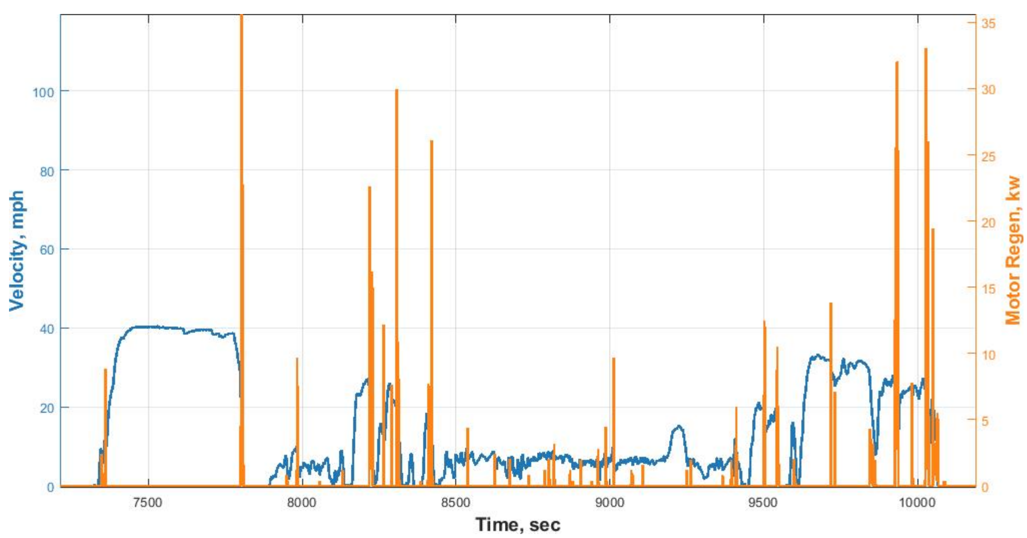

Figure 6-9 Drive cycle snippet showing regenerative braking during chassis dynamometer testing

The amount of energy recaptured from regenerative braking is highly dependent on the driving activity and the frequency of braking. The percentage of the motor force that is recaptured by regenerative braking for various modes of operation is presented in Figure

6-10. This figure shows a significant difference in the percent of braking energy recovered between different modes of operation. The start-activity and arterial modes are both moderate speed modes with significantly more braking activity than the freeway and moving sweeping modes, and therefore have higher regeneration rates. Although the freeway mode is a higher speed mode with more kinetic energy than the other tested modes, there is not much braking and little opportunity for regenerative braking. The ratio between the percent of motor energy recaptured during the sweeping mode and the arterial activity is roughly 19 times.

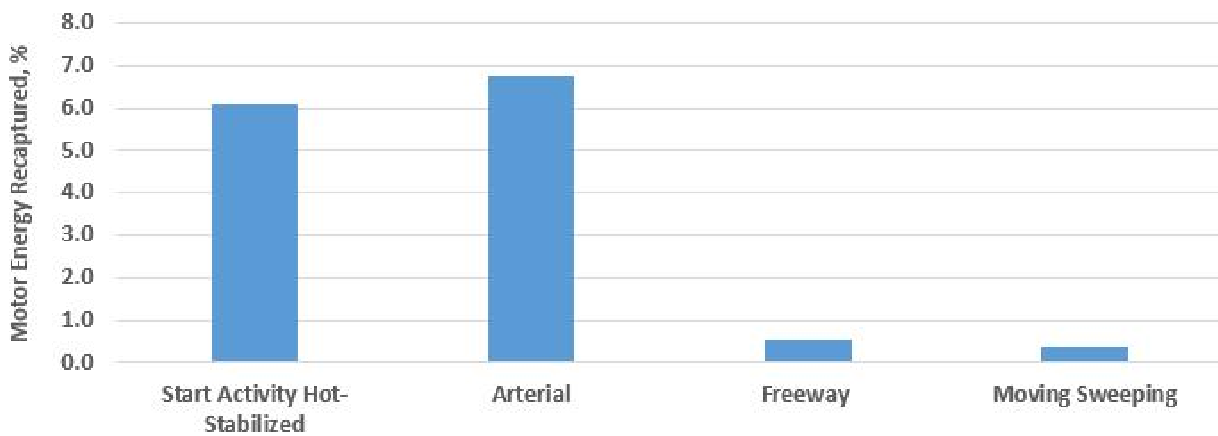

Figure 6-10 Regenerative braking energy by mode of operation

6.4.4. CO_2 Emissions

Emissions were measured from the diesel and CNG sweepers. CO_2 emission results for various modes of operation are presented in Table 6-5 in a kg/kwh, kg/hr, and kg/mi basis, and in Figure 6-11 in a kg/kwh basis. For diesel the CO_2 energy based mass emissions were generally in the range from 0.90 kg/kwh to 1.20 kg/kwh, with the exception of the idle CO_2 rate at 2.9 kg/kwh. For CNG, the CO_2 emissions range from 0.75 kg/kwh to 0.96 kg/kwh, with the exception of the idle CO_2 rate at 1.42 kg/kwh. The last column in Table 6-5 shows the ratio of CNG kg/kwh emission rate to diesel kg/kwh emission rates and shows that this ratio is between 0.49 and 0.95.

The CO_2 time based mass emission rates for diesel range from 21.42 to 51.03 kg/hr and for CNG from 10.48 to 42.74 kg/hr. The CO_2 distance based emission rates for diesel range from 2.35 to 8.27 kg/mi and for CNG they range from 2.04 to 6.84 kg/mi. For both fuels the highest distance based mass emission rates occur at the low speed cruise at 5 mph.

Table 6-5 Chassis testing modal CO_2 results

Activity	Diesel CO2 kg/kwh	CNG CO2 kg/kwh	Diesel CO2 kg/hr	CNG CO2 kg/hr	Diesel CO2 kg/mi	CNG CO2 kg/mi	Ratio CNG/Diesel
Cold Start Activity	1.20	0.87	51.03	37.05	6.77	4.92	0.73
Start Activity Following Engine Off	1.08	0.96	38.59	34.34	4.90	4.36	0.89
Start Activity Following Idle	1.13	0.96	41.42	35.22	5.13	4.36	0.85
Start Activity Hot-Stabilized	0.98	0.91	37.59	34.92	4.70	4.36	0.93
Arterial	0.90	0.78	49.16	42.74	2.35	2.04	0.87
Idle	2.90	1.42	21.42	10.48	-	-	0.49
Stationary Sweeping	0.90	0.86	36.22	34.52	-	-	0.95
Moving Sweeping	0.90	0.75	44.28	36.72	8.27	6.85	0.83
min	0.90	0.75	21.42	10.48	2.35	2.04	0.49
max	2.90	1.42	51.03	42.74	8.27	6.85	0.95

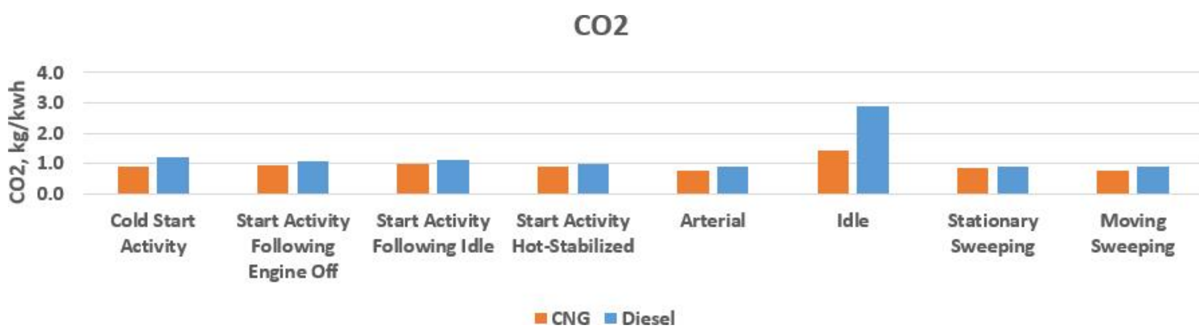

Figure 6-11 Chassis testing modal CO_2 comparison

6.4.5. CO Emissions

CO emission results for various modes of operation are presented in Table 6-6 in a g/kwh, g/hr, and g/mi basis, and in Figure 6-12 in a g/kwh basis. For diesel the CO energy based mass emissions were in the range from 1.08 g/kwh to 5.04 g/kwh, with the highest rate at idle. For CNG, the CO emissions range from 4.69 g/kwh to 15.10 g/kwh, with the highest rate occurs while "moving sweeping". The last column in Table 6-6 shows the ratio of CNG g/kwh CO emission rate to diesel CO g/kwh emission rate and shows that this ratio is between 1 and 10.8. The results show that while "moving sweeping", CO g/kwh emission rates are 10.8 times higher for CNG relative to diesel.

The CO time based mass emission rates for diesel range from 37.25 to 116.15 g/hr and for CNG from 37.13 to 740.13 g/hr. For diesel, the largest time based emission rate resulted from the cold start activity mode. For CNG the largest time based CO emission rate occurred during the "moving sweeping" mode. The largest time based CO emissions for CNG were roughly 6.4 times larger than the largest diesel time based CO emission rates.

The CO distance based emission rates for diesel range from 2.83 to 15.41 g/mi and for CNG they range from 21.41 to 138.14 g/mi. For diesel the highest time based emission rate occurred during the cold-start and for CNG the highest distance based CO emission rate occurred during "moving sweeping". The highest distance based CO emissions for CNG were roughly 9 times larger than the highest diesel distance based CO emission rates.

Table 6-6 Chassis testing modal CO results

Activity	Diesel CO g/kwh	CNG CO g/kwh	Diesel CO g/hr	CNG CO g/hr	Diesel CO g/mi	CNG CO g/mi	Ratio CNG/Diesel
Cold Start Activity	2.73	7.66	116.15	325.45	15.41	43.18	2.80
Start Activity Following Engine Off	1.82	7.10	65.30	254.20	8.28	32.25	3.89
Start Activity Following Idle	1.97	8.40	72.21	307.08	8.94	38.03	4.25
Start Activity Hot-Stabilized	1.52	4.69	58.49	180.22	7.31	22.52	3.08
Arterial	1.08	8.18	59.30	448.71	2.83	21.41	7.57
Idle	5.04	5.02	37.25	37.13	-	-	1.00
Stationary Sweeping	1.29	6.15	51.95	247.36	-	-	4.76
Moving Sweeping	1.39	15.10	68.28	740.13	12.74	138.14	10.84
min	1.08	4.69	37.25	37.13	2.83	21.41	1.00
max	5.04	15.10	116.15	740.13	15.41	138.14	10.84

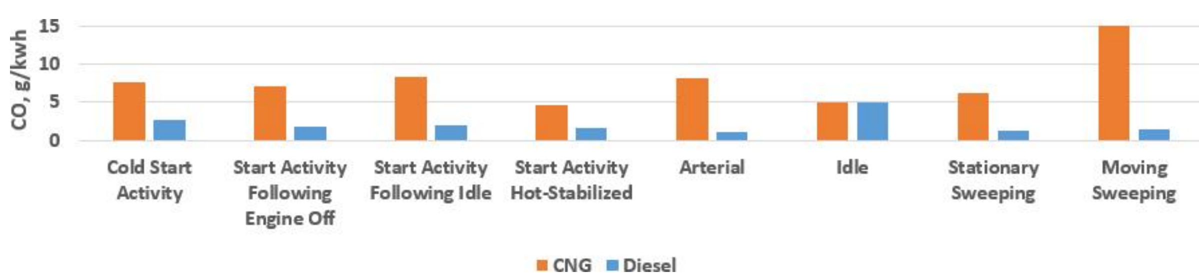

Figure 6-12 Chassis testing modal CO comparison

6.4.6. *THC Emissions*

THC emission results for various modes of operation are presented in Table 6-7 in a g/kwh, g/hr, and g/mi basis, and in Figure 6-13 in a g/kwh basis. For diesel the THC energy based mass emissions were in the range from 0.03 g/kwh to 0.13 g/kwh, with the highest rate at cold-start. For CNG, the THC emissions range from 0.07 g/kwh to 1.45 g/kwh. The last column in Table 6-7 shows the ratio of CNG g/kwh THC emission rate to diesel THC g/kwh emission rate and shows that this ratio is between 1.25 and as high as 21.93. The results show that while "moving sweeping", THC g/kwh emission rates are 21.93 times higher for CNG relative to diesel.

The THC time based mass emission rates for diesel range from 0.46 to 5.66 g/hr and for CNG from 1.09 to 71.02 g/hr. For diesel, the largest time based emission rate resulted from the cold start activity mode. For CNG the largest time based emission rate occurred during the "moving sweeping" mode. The largest time based emissions for CNG were roughly 12.55 times larger than the largest diesel time based emission rates.

The THC distance based emission rates for diesel range from 0.31 to 13.26 g/mi and for CNG they range from 0.14 to 0.75 g/mi. For diesel and CNG, the highest time based emission rate occurred during "moving sweeping". The highest distance based emissions for CNG were roughly 17.65 times larger than the highest diesel distance based emission rates.

Table 6-7 Chassis testing modal THC results

Activity	Diesel THC g/kwh	CNG THC g/kwh	Diesel THC g/hr	CNG THC g/hr	Diesel THC g/mi	CNG THC g/mi	Ratio CNG/Diesel
Cold Start Activity	0.133	1.154	5.66	49.02	0.751	6.504	8.66
Start Activity Following Engine Off	0.031	0.068	1.12	2.43	0.142	0.309	2.17
Start Activity Following Idle	0.035	0.195	1.27	7.14	0.157	0.884	5.63
Start Activity Hot-Stabilized	0.075	0.093	2.86	3.57	0.357	0.445	1.25
Arterial	0.056	0.368	3.06	20.17	0.146	0.962	6.58
Idle	0.062	0.148	0.46	1.09	-	-	2.36
Stationary Sweeping	0.059	0.569	2.36	22.89	-	-	9.69
Moving Sweeping	0.066	1.449	3.24	71.02	0.605	13.255	21.93
min	0.03	0.07	0.46	1.09	0.14	0.31	1.25
max	0.13	1.45	5.66	71.02	0.75	13.26	21.93

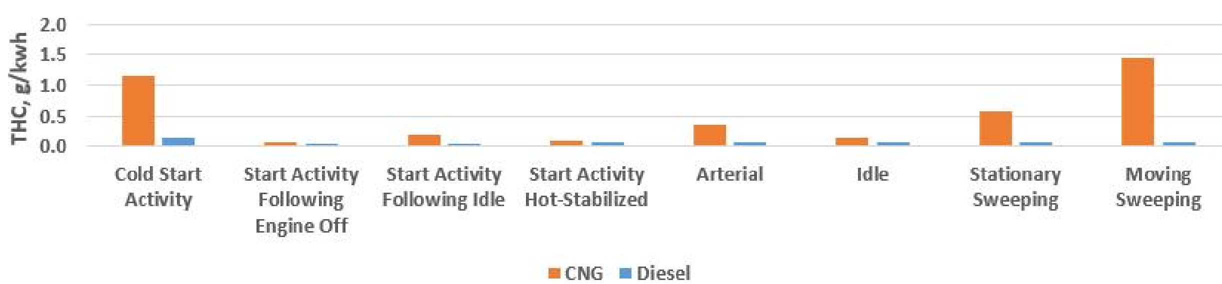

Figure 6-13 Chassis testing modal THC comparison

6.4.7. NO_x Emissions

NO_x emission results for various modes of operation are presented in Table 6-8 in a g/kwh, g/hr, and g/mi basis, and in Figure 6-14 in a g/kwh basis. For diesel the NO_x energy based mass emissions were in the range from 0.02 g/kwh to 1.88 g/kwh, with the highest rate at cold-start. For CNG, the NO_x emissions range from 0.01 g/kwh to 0.89 g/kwh. The last column in Table 6-8 shows the ratio of CNG g/kwh NO_x emission rate to diesel NO_x g/kwh emission rate and shows that this ratio is between 0.19 and 2.26. The results show that while "moving sweeping", NO_x g/kwh emission rates are 2.63 times higher for diesel relative to CNG.

The NO_x time based mass emission rates for diesel range from 0.67 to 79.68 g/hr and for CNG from 0.28 to 37.75 g/hr. For diesel and CNG, the largest time based emission rate resulted from the cold start activity mode. The largest time based emissions for diesel were roughly 2.11 times larger than the largest CNG time based emission rates.

The NO_x distance based emission rates for diesel range from 0.08 to 10.57 g/mi and for CNG they range from 0.12 to 5.01 g/mi. For diesel and CNG, the highest time based emission rate occurred during the cold-start. The highest distance based NOx emissions for CNG were roughly 2.11 times larger than the highest diesel distance based NOx emission rates. At idle, diesel NOx emissions are roughly 5.3 times higher than for CNG.

Table 6-8 Chassis testing modal NO_x results

Activity	Diesel NOx g/kwh	CNG NOx g/kwh	Diesel NOx g/hr	CNG NOx g/hr	Diesel NOx g/mi	CNG NOx g/mi	Ratio CNG/Diesel
Cold Start Activity	1.876	0.889	79.68	37.75	10.572	5.009	0.47
Start Activity Following Engine Off	0.121	0.058	4.32	2.09	0.549	0.265	0.48
Start Activity Following Idle	0.022	0.049	0.79	1.78	0.098	0.221	2.26
Start Activity Hot-Stabilized	0.048	0.084	1.83	3.23	0.229	0.404	1.76
Arterial	0.032	0.044	1.73	2.42	0.083	0.115	1.39
Idle	0.199	0.038	1.47	0.28	-	-	0.19
Stationary Sweeping	0.017	0.008	0.67	0.32	-	-	0.48
Moving Sweeping	0.091	0.035	4.45	1.71	0.830	0.319	0.38
min	0.02	0.01	0.67	0.28	0.08	0.12	0.19
max	1.88	0.89	79.68	37.75	10.57	5.01	2.26

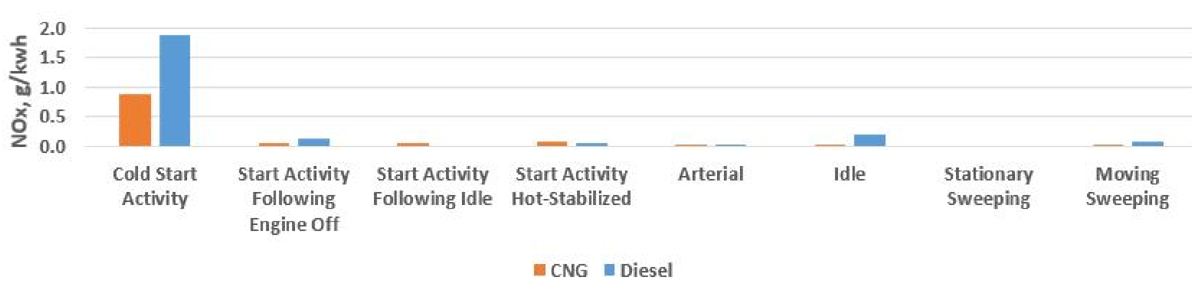

Figure 6-14 Chassis testing modal NO_x comparison

7. Operator and Maintenance Surveys

The primary objective of this research has been to comparatively evaluate a hydrogen fuel cell hybrid electric sweeper relative to existing diesel and CNG sweepers during standard Caltrans operations. In addition to activity and emission data that was collected in order to evaluate the performance of various sweeper platforms, surveys were developed that targeted sweeper operators and maintenance staff. Surveying personnel who have operational and maintenance experience with the Caltrans sweeper platforms provides unique and valuable insight.

7.1. Methodology

Caltrans owns and operates several different models of sweepers produced from multiple manufactures. Each sweeper platform has unique characteristics relative to drivability, broom operation, hopper configuration, in-cab components, and refueling methods. The goal of the operator and maintenance surveys was to determine if operational staff experienced consistent and identifiable differences between sweepers fueled by diesel, CNG, or hydrogen.

Diesel sweepers have been operated by Caltrans for decades and are the most traditional vehicle platform. Newer diesel sweepers have been equipped with DPF technology to meet environmental regulations and reduce particulate emissions. Sweepers operating within non-attainment air quality regions are subject to stricter emission regulations and have led Caltrans to deploy CNG powered sweepers. The CNG powered sweepers require gaseous fueling infrastructure, modified refueling procedures, and specialized maintenance requirements. Caltrans shop mechanics are unable to conduct repairs on CNG sweepers unless the shop facilities have been upgraded for gaseous fueled vehicles. Therefore, significant CNG based maintenance and repairs are outsourced to 3rd party repair facilities. The hydrogen fuel cell sweeper is the first to be deployed by Caltrans and the maintenance and repairs are conducted by the vehicle supplier. The hydrogen fuel cell sweeper has been deployed in the South Coast Air Basin and is therefore operating in conjunction with CNG sweepers.

The hydrogen fuel cell sweeper was initially deployed at the Caltrans Westdale yard in 2019 to provide support of Caltrans facilities in the vicinity of the I-405 and I-10 interchange. The vehicle utilized public hydrogen refueling stations. Two operators were trained at the Westdale yard to utilize and refuel the hydrogen sweeper. Subsequently, the hydrogen fuel cell sweeper was relocated to the Century yard in the vicinity of LAX. Two additional operators were trained to operate and refuel the hydrogen sweeper. Operator surveys were conducted with three of the four trained operators. Additionally, two maintenance staff were surveyed for maintenance and repairs. Finally, crew supervisors familiar with operation and repairs were also surveyed. In total four operator surveys were completed and four maintenance surveys were completed.

7.2. Operator Survey Results

The operator survey asks ten questions about sweeper functions that range from drivability and sweeping to in-cab comfort and refueling. The questions ask the respondent to select the answer from the options of: Best, Above Average, Average, Below Average, and Worst. Each question asks the respondent to answer for CNG, hydrogen, and diesel in the same question. Therefore, providing a relative comparison simultaneously. One respondent did not have experience with diesel sweepers and therefore answers were not provided on diesel.

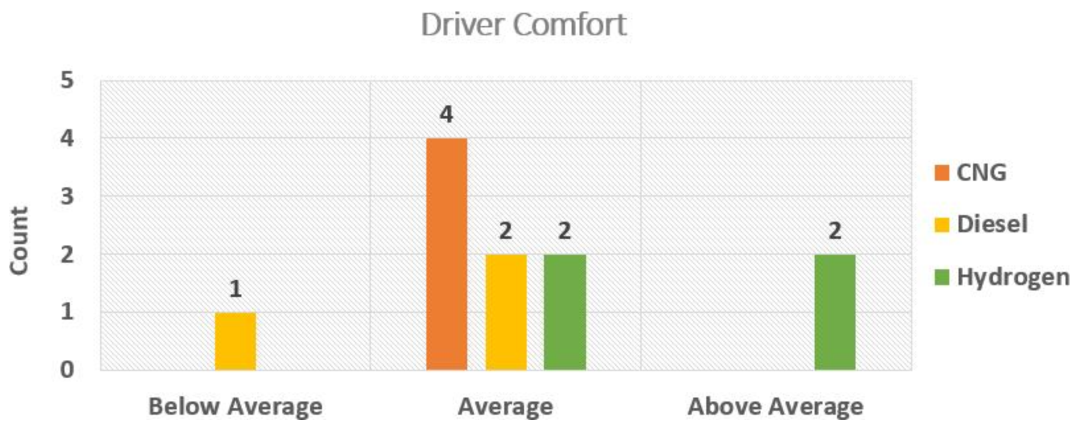

Figure 7-1 Driver comfort survey results

Figure 7-1 provides operator responses from four completed operator surveys. All respondents thought CNG provided average driver comfort relative to HVAC, seating, controls, and the in-cab environment. Two of the respondents also believed the hydrogen fuel cell and diesel were average regarding driver comfort. One respondent found diesel sweepers to be below average while two respondents found the hydrogen sweeper to be above average for driver comfort.

Relative to brush performance Figure 7-2 shows that two respondents felt that both diesel powered and CNG powered sweepers had below average performance while two respondents believed the hydrogen sweeper had above average performance. One respondent felt the hydrogen sweeper had the best performance due to the ability to independently control engine RPM and brush rotational speed. The remaining responses attributed average brush performance relative to powertrain.

Figure 7-2 Brush performance survey results

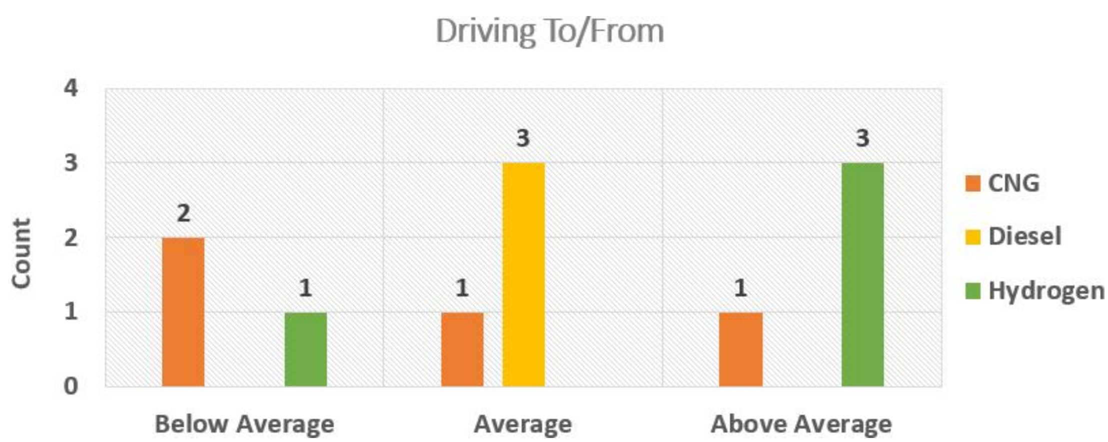

Figure 7-3 Driving to/from survey results

Vehicle performance in Figure 7-3 provides varied responses. Three surveyed operators believed the hydrogen sweeper performed above average driving to/from sweeping locations due to power and acceleration of the drivetrain. Three respondents stated the diesel powered sweepers were average while one respondent believed CNG to be average. Two respondents stated the CNG was below average in performance driving to/from sweeping location. One respondent stated the hydrogen sweeper was below average driving to/from sweeping locations.

Figure 7-4 Elevator performance survey results

Most respondents answered that hopper performance was average across the range of sweeper platforms (CNG, diesel, or hydrogen). One response selected above average for the hydrogen fuel cell powered sweeper.

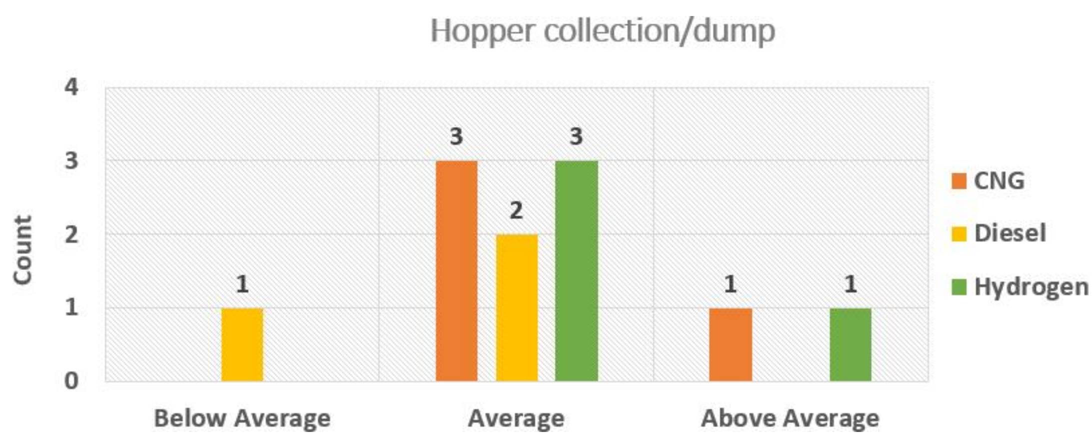

Figure 7-5 Hopper collection survey results

Most respondents considered hopper collection and dumping to be similar across the sweeper platforms. A few preferences existed due to material distribution within the hopper or dumping characteristics. One person considered the diesel platforms to be below average while two respondents viewed CNG and hydrogen to be above average.

Figure 7-6 Operational consistency survey results

Similarly, most respondents considered operational consistency to be similar across the sweeper platforms. Two respondents considered the diesel and hydrogen platforms to be below average while one respondent viewed CNG to be above average.

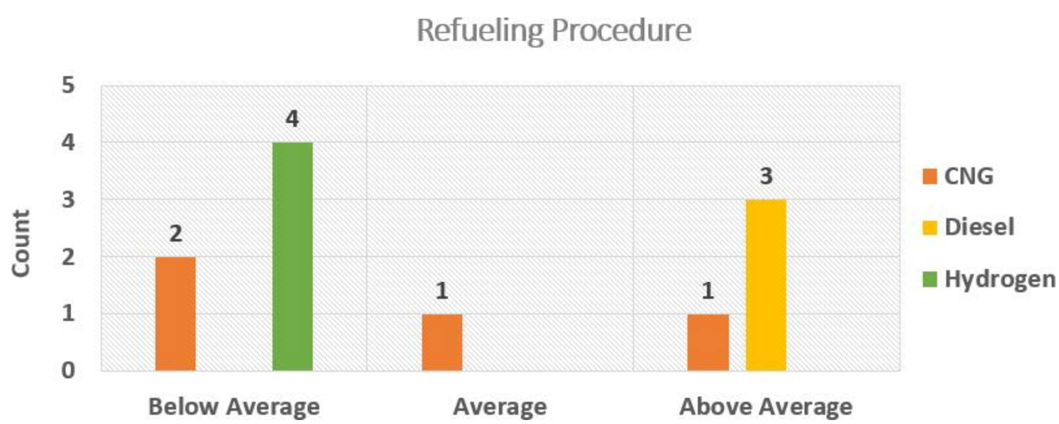

Figure 7-7 Refueling procedure survey results

The responses for refueling in Figure 7-7 mostly represent the availability and operational ease of vehicle refueling stations. All respondents view hydrogen refueling as below average while two respondents also view CNG as below average. Three respondents with diesel operating experience considered diesel refueling procedure as above average. The remaining responses listed CNG as average and above average.

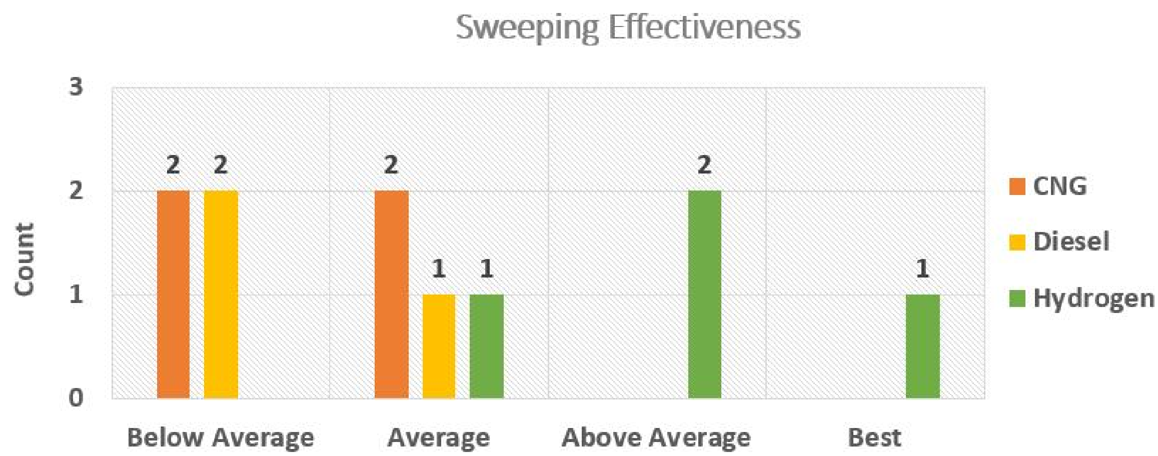

Figure 7-8 Sweeping effectiveness survey results

The responses for overall sweeping effectiveness are shown in Figure 7-8 . Two respondents felt that both diesels powered and CNG powered sweepers had below average overall sweeping performance while two respondents believed the hydrogen sweeper had above average performance. One respondent felt the hydrogen sweeper had the best performance due to the ability to independently control engine RPM and brush rotational speed. The remaining responses identified average overall sweeping performance.

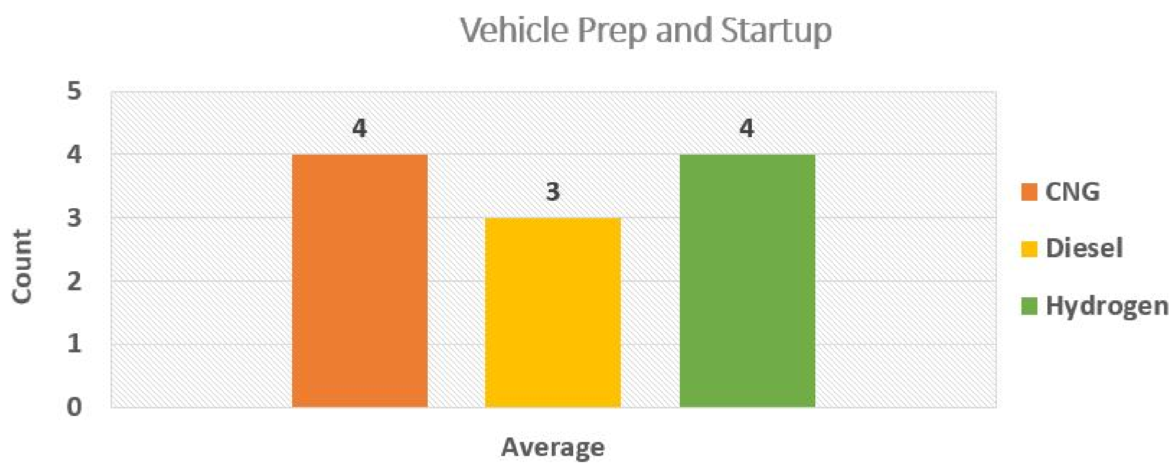

Figure 7-9 Vehicle pre and startup survey results

The respondents all considered the three vehicle platforms to be average for vehicle prep and startup as shown in Figure 7-9. Similarly, most respondents saw little difference in the water system effectiveness and functionality in Figure 7-10. One respondent found the hydrogen sweeper water system to be above average while one respondent found the diesel sweepers to have a below average water system performance.

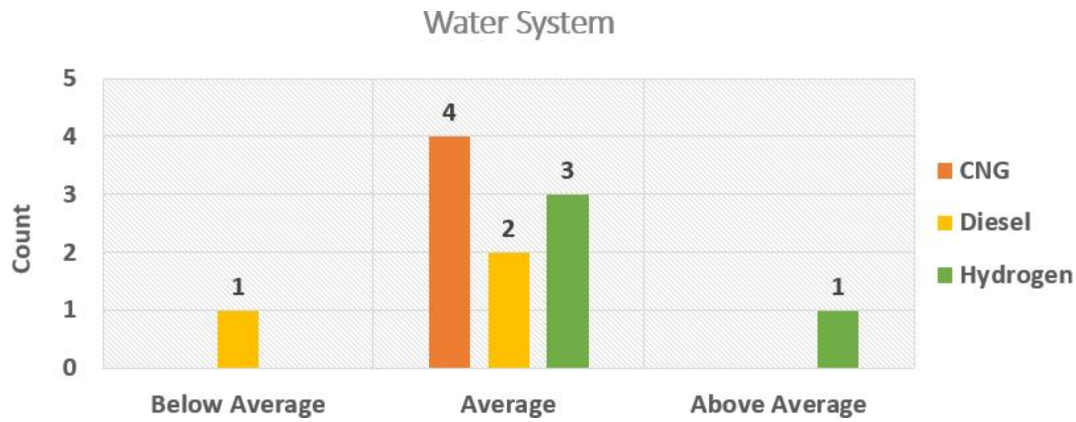

Figure 7-10 Water system survey results

Table 7-1 provides individual comments from respondents while the survey was being conducted. Statements were made relative to CNG and diesel sweepers having broom rotational speed couple to the engine RPM. This characteristic was viewed to limit the sweeping effectiveness. The hydrogen fuel cell sweeper was viewed to perform more effectively due to the ability to independently control broom speed separate from drive motor RPM. Additional comments were also noted relative to limitation of hydrogen refueling locations and requirements for computer resets of the vehicle control system.

Table 7-1 Comments from operator survey respondents

CNG
Sweeping PTO speeds coupled to engine RPM
Diesel
Avalanche diesel has more driver control settings and presets
Avalanche Diesel has more prep
Avalanche Diesel required mid trip distribution of material in hopper.
Rear dump preferred over side dump
Sweeping PTO speeds coupled to engine RPM
Hydrogen
Hydrogen has better acceleration
Hydrogen has independent broom speed adjustment
Hydrogen sometimes required computer reset upon startup
Hydrogen station sometime down with limited locations
Sweeping PTO speeds controlled independent powertrain

7.3. Maintenance Survey Results

Sweeper operations along California facilities requires frequent maintenance and repairs of the sweeper equipment being utilized. Much of the sweeper maintenance and repairs are completed by Caltrans equipment shop staff. Repairs and maintenance completed on new equipment are often completed by the manufacturer during the initial warranty period. The manufacturer frequently continues to perform maintenance and repairs due to special vehicle requirements, equipment, training or facility requirements. The maintenance survey focuses on the three powertrain platforms of: diesel, CNG, and hydrogen fuel cell. Diesel powertrain maintenance and repairs are often completed by Cantrans shop staff while CNG and hydrogen fuel cell vehicle repairs are most frequently sent out for manufacturer or 3rd party repairs. Whenever sweeper vehicle repairs are necessary the event is recorded in the Caltrans Assetworks database. The maintenance and repair data has been summarized in previous sections of this report.

Caltrans staff involved in performing and managing sweeper maintenance and repairs have been queried for this survey. The respondents have been affiliated with the maintenance of sweepers at the Westdale and Century yards during the hydrogen fuel cell sweeper deployment. The goal of the maintenance survey has to obtain a comparison of various sweeper platforms relative to frequency of maintenance and repairs. A copy of the maintenance survey is provided in the appendix with 6 questions addressing various sweeper components and systems. Survey respondents were also requested to provide comments regarding the most common maintenance and repair items on each platform.

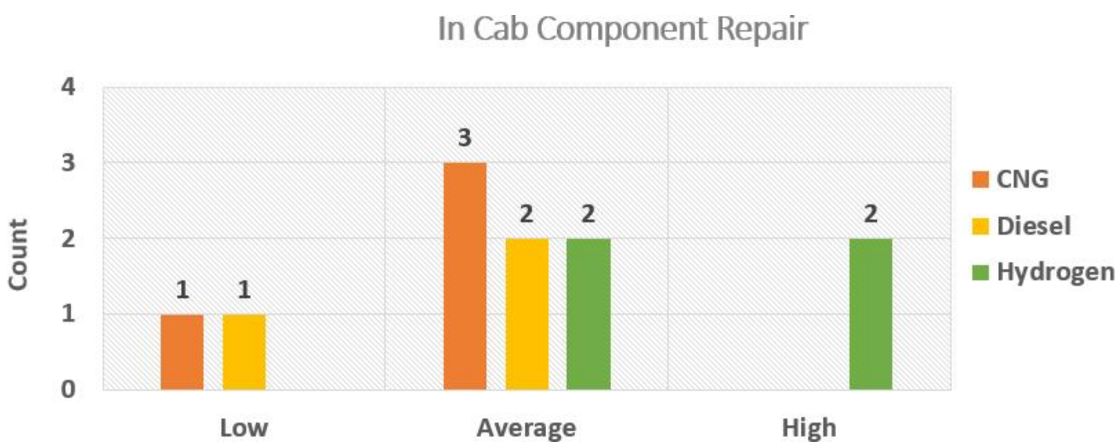

Figure 7-11 In-cab component repair

A total of four respondents answered questions relative to sweeper maintenance and repairs. Three of the respondents had familiarity with CNG, hydrogen, and diesel maintenance while one respondent only provided answers relative to CNG and hydrogen sweeper maintenance. Figure 7-11 asked respondents the frequency of repairs on in-cab components such as screens, switches, controls, buttons, seats, pedals, etc. Two of the respondents believed the hydrogen sweeper to have a high frequency of repair on in-cab components primarily related to electronic control systems of the battery control electronics. One respondent believed the diesel and CNG both had a low frequency of repairs on in-cab components. The remainder of the respondents believe stated the CNG, hydrogen, and diesel had an average frequency of repairs on in-cab components.

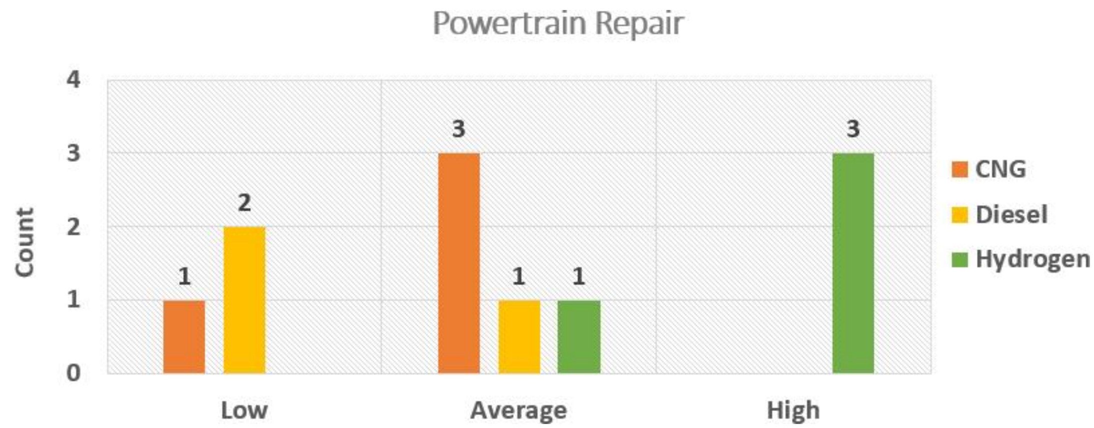

Figure 7-12 Powertrain repair survey results

Caltrans maintenance staff were asked about the frequency of repairs associated with drivetrain components on the sweeper platforms. Three of the respondents stated that the hydrogen based vehicle had high frequency of repairs on hydrogen, battery, or motor system components. Two respondents claimed the diesel sweepers has a low frequency of repairs. One respondent also believed the CNG sweepers to have a low frequency of repairs. Three of the respondents stated that CNG sweepers had an average frequency of repairs. One respondent also stated that hydrogen and diesel had average frequency of repair.

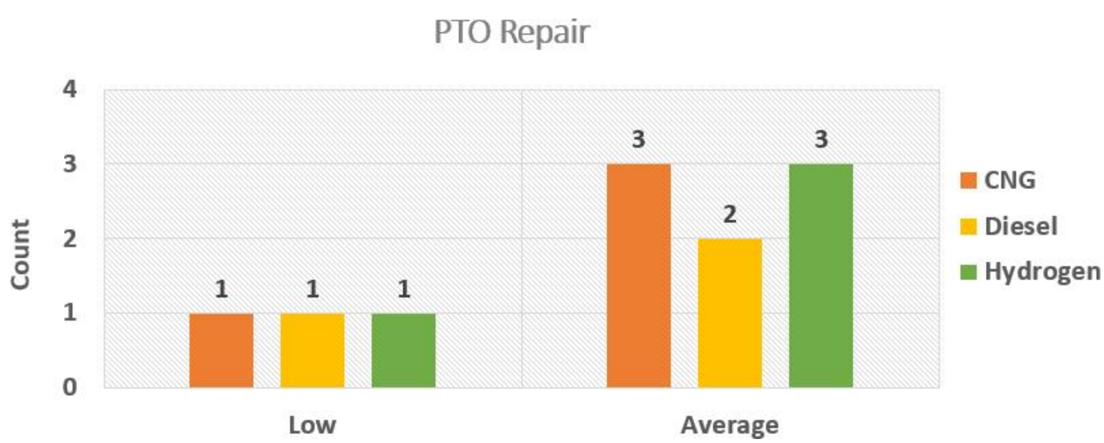

Figure 7-13 PTO repair survey results

The maintenance staff were also asked about the frequency of repairs associated with PTO systems associated with the brushes, brooms, and elevators. There was a single response for each for hydrogen, CNG, and diesel having a low frequency of PTO repairs and maintenance. The remainder of responses claimed an average frequency of maintenance and repairs on PTO systems.

Figure 7-14 Recurring maintenance survey results

The survey respondents were asked about frequency of recurring maintenance on items requiring repeat maintenance. This question was meant to identify design characteristics that required minimal or excessive maintenance. Once respondent replied that diesel based sweeper platforms had a high frequency of recurring maintenance. All other responses stated the various vehicle platforms had an average frequency of repairs.

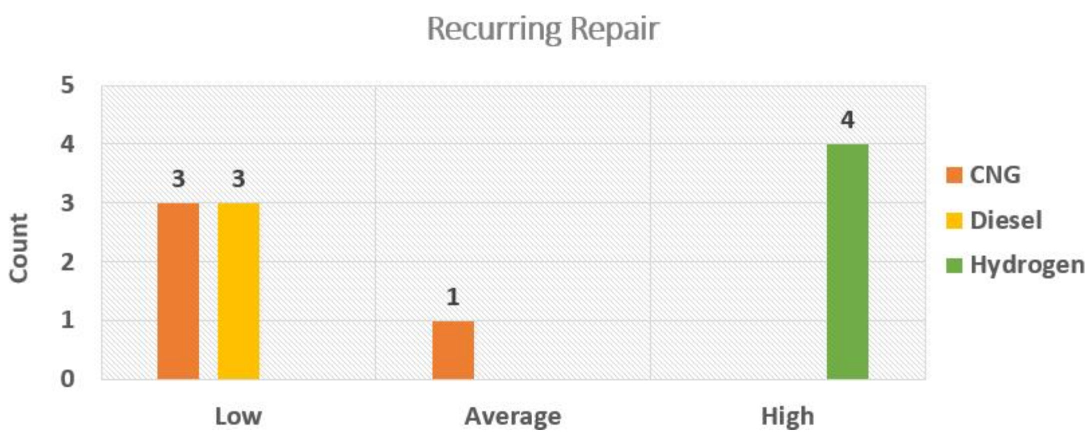

Figure 7-15 Recurring repair survey results

The survey respondents were asked about frequency of recurring repairs associated with specific powertrain platforms. One respondent replied that CNG based sweeper platforms had an average frequency of recurring repairs. All respondents stated that the hydrogen sweeper had a high frequency of recurring repairs. All other responses stated the various vehicle platforms had a low frequency of recurring repairs.

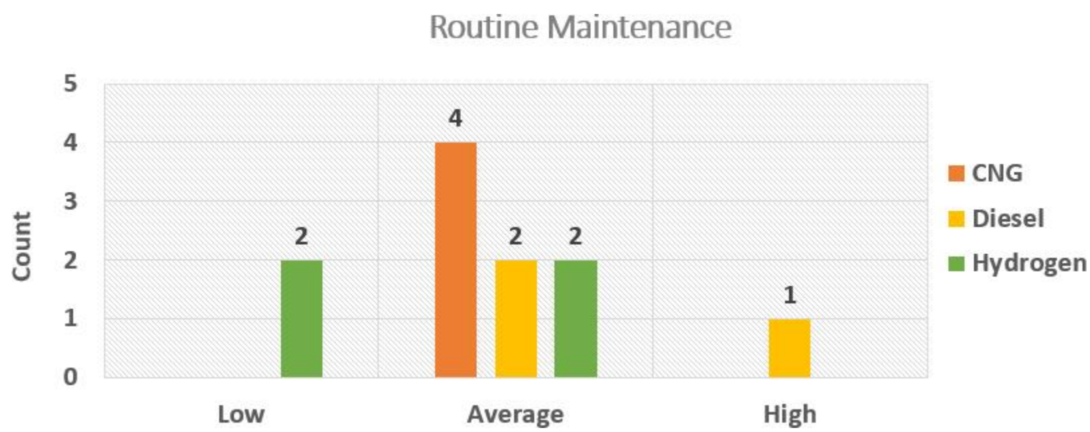

Figure 7-16 Routine maintenance survey results

The respondents were asked about routine maintenance requirements. Two respondents believed the hydrogen sweeper platform to have a low frequency of routine maintenance. One respondent stated the diesel platform to have a high frequency of routine maintenance. All other survey responses claimed an average frequency of routine maintenance. The respondents also were provided the opportunity to provide detailed comments regarding sweeper maintenance and repairs. The detailed comments are provided in Table 7-2. One respondent stated the CNG platforms had recurring gear repairs. One respondent noted frequent broom repairs on diesel platforms. The remainder of comments focused on electronics, sensors, battery, computer resets and repairs on the hydrogen platform.

Table 7-2 Comments from maintenance survey respondents

CNG
CNG had recurring gear repairs
Diesel
Diesel had proom repairs
Hydrogen
Batteries
Battery and battery drain for moisture, drivetrain electronics and programming, coolant pump
Cleaning on Hydrogen slightly for cumbersome
Hydrogen fuel level resets and cooling radiator cracks and mounting
Hydrogen has consistent power during operation
Hydrogen sweeper software resets needed
Hydrogn vehicle needed hydrogen fuel sensor and battery reapairs
Issues with Battery and Powertrain Control Computer

7.4. Weighted Decision Matrices

Decision matrices were created to evaluate survey results relative to fuel type. Survey responses were provided a score as follows. For the operator survey, below average = 1, average = 2, above average = 3, and best = 4. For the maintenance survey, since questions related to repair rates; high = 1, average = 2, and low = 3. The survey scores were averaged from each respondent for each question, weighted based on relative importance of the criteria, and tallied to produce a weighted overall score for each sweeper fuel type. Table 7-3 provides raw and weighted results for the operator survey. Note that in the operator survey, brush performance and sweeping effectiveness are very similar in the criteria they are evaluating, so they were weighted as 1.5 in order to produce a combined weight of 3. The operator survey favors the HFC sweeper and is influenced by brush performance.

Table 7-3 Operator survey weighted survey matrix.

		Diesel		CNG		HFC	
Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
Brush Performance	1.5	1.33	2.00	1.5	2.25	3.00	4.50
Sweeping Effectiveness	1.5	1.33	2.00	1.5	2.25	3.00	4.50
Driver Comfort	1	1.67	1.67	2	2.00	2.50	2.50
Driving To/From	3	2.00	6.00	1.75	5.25	2.50	7.50
Elevator Performance	3	2.00	6.00	2	6.00	2.25	6.75
Hopper collection/dump	2	1.67	3.33	2.25	4.50	2.25	4.50
Operational Consistency	2	1.67	3.33	2.25	4.50	1.75	3.50
Refueling Procedure	2	3.00	6.00	1.75	3.50	1.00	2.00
Vehicle Prep and Startup	1	2.00	2.00	2	2.00	2.00	2.00
Water System	1	1.67	1.67	2	2.00	2.25	2.25
Total		18.33	34.00	19.00	34.25	22.50	40.00

Table 7-4 provides raw and weighted results for the maintenance survey, which primarily focuses on repair and reliability. The results of the maintenance survey show similar scores for Diesel and CNG, which are favored over the HFC.

Table 7-4 Maintenance survey weighted survey matrix

		Diesel		CNG		HFC	
Criteria	Weight	Raw Score	Weighted Score	Raw Score	Weighted Score	Raw Score	Weighted Score
In Cab Component Repair	1	2.33	2.33	2.25	2.25	1.50	1.50
Powertrain Repair	3	2.67	8.00	2.25	6.75	1.25	3.75
PTO Repair	3	2.33	7.00	2.25	6.75	2.25	6.75
Recurring Maintenance	3	1.67	5.00	2.00	6.00	2.00	6.00
Recurring Repair	3	3.00	9.00	2.75	8.25	1.00	3.00
Routine Maintenance	3	1.67	5.00	2.00	6.00	2.50	7.50
Total		13.67	36.33	13.50	36.00	10.50	28.50

In both survey results, the trends in the unweighted scores and the weighted scores agree with each other and the weighting is not reversing any trends.

8. Analysis and Discussion

This section presents additional analysis and discussion of various data collected as part of this research project. The aim in this section is to further address relevant issues for determining the suitability of HFC street sweepers as an alternative to current diesel and CNG technologies.

8.1. Emission Reduction

The HFC street sweeper uses compressed hydrogen gas as fuel and produces only water and warm air. It is a zero-emission technology at the point of use. The primary benefit of interest from switching towards HFC street sweepers is the reduction of street sweeper emissions from internal combustion fuel technologies and complying with SCAQMD policies for transitioning state vehicles to ZEV platforms.

Data from this project was evaluated to estimate the potential reductions in emissions from replacing a typical CNG and Diesel sweeper in the Caltrans fleet. Activity data, broken down by mode, provided an estimate of the typical daily time spent in each of three basic modes of operation. Hourly mass emission rates from the PEMS portion of this work were used to calculate daily emission in each basic mode.

Using the annual operating days from the activity study and the typical daily emission estimates from the PEMS analysis, daily emissions estimates were calculated and are presented in Table 8-1 Daily emission production estimates for typical activity by fuel type.

Table 8-1 Daily emission production estimates for typical activity by fuel type.

Diesel	Idle	Sweeping	Traveling
Time hr/day	1.35	1.49	1.51
Median CO2 kg/hr	10.99	34.18	42.68
kg/day	14.84	50.93	64.45
		CO2 (kg/day)	130.21
Median CO g/hr	7.62	15.27	20.93
g/day	10.29	22.75	31.60
		CO (g/day)	64.64
Median THC g/hr	0.23	0.26	1.39
g/day	0.31	0.39	2.10
		THC (g/day)	2.80
Median NOx g/hr	8.03	14.49	23.26
g/day	10.84	21.59	35.12
		NOx (g/day)	67.55

CNG	Idle	Sweeping	Traveling
Time hr/day	1.35	1.49	1.51
Median CO2 kg/hr	10.8	42.16	41.56
kg/day	14.58	62.82	62.76
		CO2 (kg/day)	140.15
Median CO g/hr	75.59	973.5	478.47
g/day	102.05	1450.52	722.49
		CO (g/day)	2275.05
Median THC g/hr	9.75	49.86	31.94
g/day	13.16	74.29	48.23
		THC (g/day)	135.68
Median NOx g/hr	1.36	3.82	6.06
g/day	1.84	5.69	9.15
		NOx (g/day)	16.68

The annual activity rates for sweepers were applied to the daily emission rates to estimate the annual emissions for a typical sweeper by fuel technology. Activity rates from the diesel sweeper category, see Figure 4-32, were used since the diesel sweeper has a broader range of activity. The diesel activity values for the lower quartile, median value, and upper quartile were selected to provide a range and a representative activity value. The lower and upper quartile are boundaries that encompass 50% of the data surrounding the median value. The results are presented in Table 8-2. Note that the diesel NO_x emissions savings is Saturday.

Table 8-2 Annual emission estimates for representative diesel and CNG sweepers

Annual Operating Days for DSL sweeper

50	days lower quartile
75.5	days median
136.5	days upper quartile

Diesel Rates		Annual Emission Estimates	25%	50%	75%
CO2 (kg/day)	130.12	CO2 (tonne/year)	6.51	9.82	17.76
CO (g/day)	64.64	CO (kg/year)	3.23	4.88	8.82
THC (g/day)	2.80	THC (kg/year)	0.14	0.21	0.38
NOx (g/day)	67.55	NOx (kg/year)	3.38	5.10	9.22

CNG Rates		Annual Emission Estimates	25%	50%	75%
CO2 (kg/day)	140.26	CO2 (tonne/year)	7.01	10.59	19.15
CO (g/day)	2275.05	CO (kg/year)	113.75	171.77	310.54
THC (g/day)	135.68	THC (kg/year)	6.78	10.24	18.52
NOx (g/day)	16.68	NOx kg/year)	0.83	1.26	2.28

8.2. Hydrogen Fuel Cell Range

The stated range of the HFC is 180 miles per tank of hydrogen. Analysis of operating distances and refueling indicate that under normal mixed operation (driving and at least 20% of time sweeping), the HFC range is roughly between 51 to 66 miles, depending on the percentage of sweeping, idling, and at what fuel level the HFC is refueled. From the fleet management database, the median of the daily trip lengths for all diesel, CNG and HFC are 25.5, 19.2, and 16.6 miles. The median of the maximum trip lengths for each diesel, CNG and HFC are 64.9, 57.5 and 62.2 miles. Based on the results of fleet management data, the average of all the daily diesel and CNG sweeper trips are well within the lower end of the typical HFC daily range (51 miles), however, the maximum daily distances for all diesel and CNG sweepers exceed the lower daily HFC threshold. Only 28.6% of CNG had maximum daily distance traveled within the upper HFC threshold of 66 miles. It is unknown what percentage of sweeping the maximum daily trips consisted of.

8.3. Refueling Infrastructure

One of the difficulties related to hydrogen technology is that the infrastructure to support refueling is not readily available and hydrogen refueling locations are limited. This is even more so the case with heavy duty hydrogen relative to light duty hydrogen vehicles. Heavy duty applications are not well suited to passenger refueling infrastructure. Light duty infrastructure are not designed to dispense larger amounts of hydrogen. There is also the issue that the reliability of hydrogen refueling stations is lower than for traditional fuels.

8.4. Vehicle Reliability

The hybrid electric HFC street sweeper from US Hybrid is the first of its kind and is in the early stages of initial implementations. The reliability at this stage is unknown. During the course of this project, the HFC sweeper was converted from a two high-capacity battery system to a one high-capacity battery system to resolve a mechanical issue. Maintenance survey respondents rated the HFC as having high in cab component and powertrain repair. To inform on the issue of reliability, work order data for all sweepers was evaluated to determine the number of offline hours due to work order repairs. Work order data showed that diesels had the least median offline hours and that CNG and HFC offline hours were significantly higher and comparable to each other. Although the offline hours for the HFC were comparable to the CNG sweepers, the work order count for the HFC was about 30% higher for HFC. This may indicate that issues with the HFC were being addressed quickly.

9. Conclusions

The objective of this research was to evaluate the use of hydrogen fuel cell sweepers as a suitable alternative to existing sweeper fuel technologies in the Caltrans' fleet, namely diesel and CNG. The research team collected and processed data from various sources. The following data collection activities were performed and the data is summarized in the report:

- Evaluation of Caltrans fleet composition
- Data logger activity data collection
- PEMS real-world emission testing
- Chassis dynamometer testing
- Fleet management software data collection
- Operator and maintenance survey collection

Various observations can be made from the data. The median sweeping time, based on activity data, was around 30% to 33%, with little differences between sweeper fuel types. Preliminary analysis shows that the median sweeping distance is between 5 and 12 miles/day with the CNG in the activity dataset.

PEMS results show that the CNG sweeper has significantly higher CO and THC emissions than the diesel sweeper. The CNG sweeper CO g/hr sweeping rate is ~60 times higher than diesel and the THC g/hr sweeping rate for CNG is ~191 times higher than diesel. Results show ~4 times the NO_x emission relative to the CNG sweeper. NO_x emissions are a precursor to regional ozone and are a pressing public health issue.

Chassis dynamometer testing results show that cold-start NO_x emissions are significant in diesel with a 46 times increase in NO_x g/m relative to hot-stabilized moderate activity and cold-start THC emissions are significant for CNG with a 14.6 times increase in THC g/m relative to hot-stabilized moderate activity. With more aggressive activity, the cold-start difference is expected to be even greater. The cold-start duration is dependent on activity and lasted from 3 to 3.5 minutes in the test case scenario, but may take longer in a real-world scenario with increase air flow and cooling.

Analysis of activity data and chassis dynamometer testing showed that the energy recaptured from regenerative braking was in the range of 0.36% to 13.88%, depending on activity. Sweeping was performed at lower speeds and in a relatively continuous manner with little braking, so this showed the lowest regenerative braking energy. Freeway activity, although at higher speed, also did not contain significant braking events and also showed very low regenerative braking energy. Regenerative braking energy was significant for arterial driving and mixed real-world driving, with the latter as high as 13.88% in data that we observed.

In addition to activity and emission data, operator and mechanic surveys were collected. These surveys were conducted over the phone with various Caltrans personnel. As expected, the research team found that the availability of fueling is an issue for the fuel cell sweeper as is the range. Analysis of the fleet management work order dataset showed similar offline hours for the fuel cell sweeper relative to the CNG. This is not surprising since the repair response times from the fuel cell sweeper manufacturer are high. The median diesel offline hours are significantly less than those for the CNG or fuel cell sweepers, although the range for the fuel cell sweepers is higher. As far as the fuel cell sweeper performance, Caltrans staff mentioned that they were impressed with the fuel cell sweeper's acceleration and the fact that the fuel cell sweeper brooms operate independently of the drive train which is not the case for the CNG or diesel motors. Two weighted decision matrices were created from the operator and maintenance surveys in order to tally the results. The operator survey favors the HFC, while the maintenance survey favors the CNG and diesel.

10. Recommendations

The following recommendations are suggested:

- The HFC street sweeper tested for this project is a viable alternative to current street-sweeper technologies in the typical use case, provided that the hydrogen refueling infrastructure is there to support it. In areas of limited hydrogen refueling service, deployment of a hydrogen refueling infrastructure should coincide with or precede acquisition of the HFC street sweeper.

- Ensure the availability of local repair facility in the area of deployment.

- Educate operators and maintenance staff on the risks and safety concerns related to high pressure hydrogen systems as well as high capacity battery systems. This is important, not only to increase safety, but also to dispel any myths that users of the system may have.

- Hydrogen can be produced from renewable energy. Ensure that hydrogen is sourced from renewable based hydrogen.

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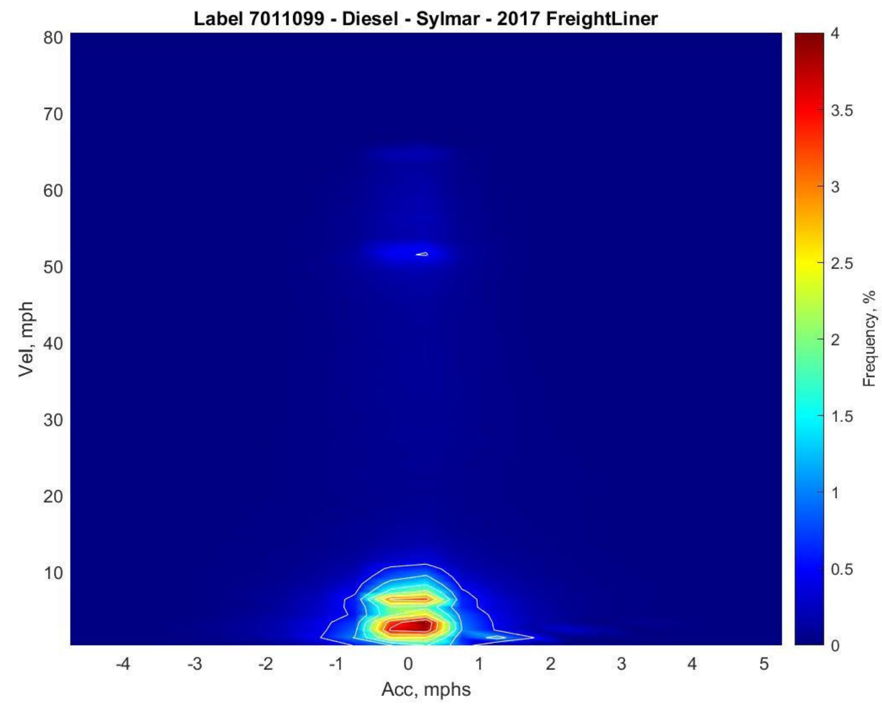
Appendix A: SAFD Plots for Activity Data

This appendix provides speed-acceleration frequency distribution (SAFD) plots from seven sweepers across three different fuel types.



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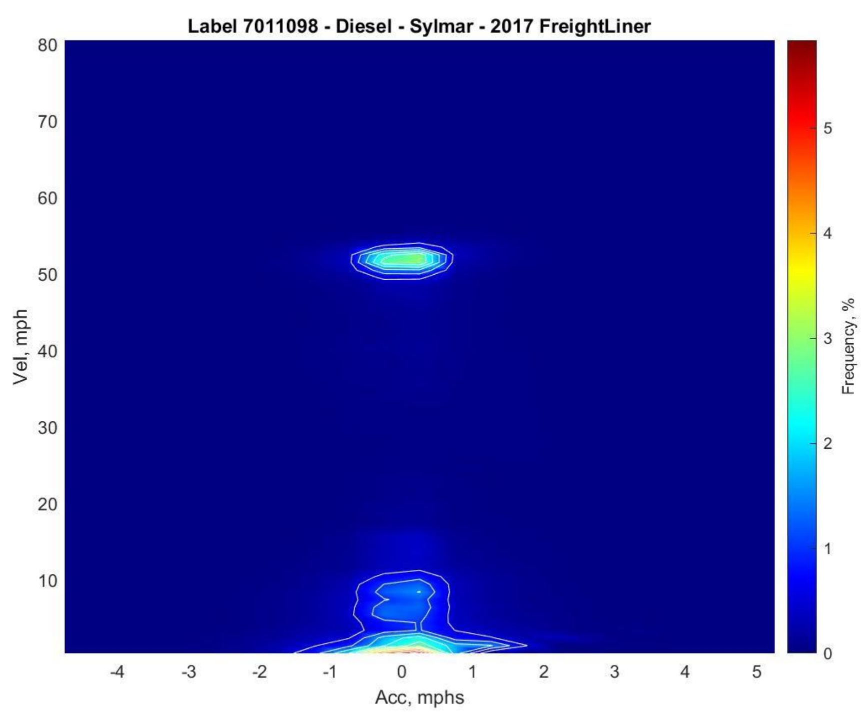
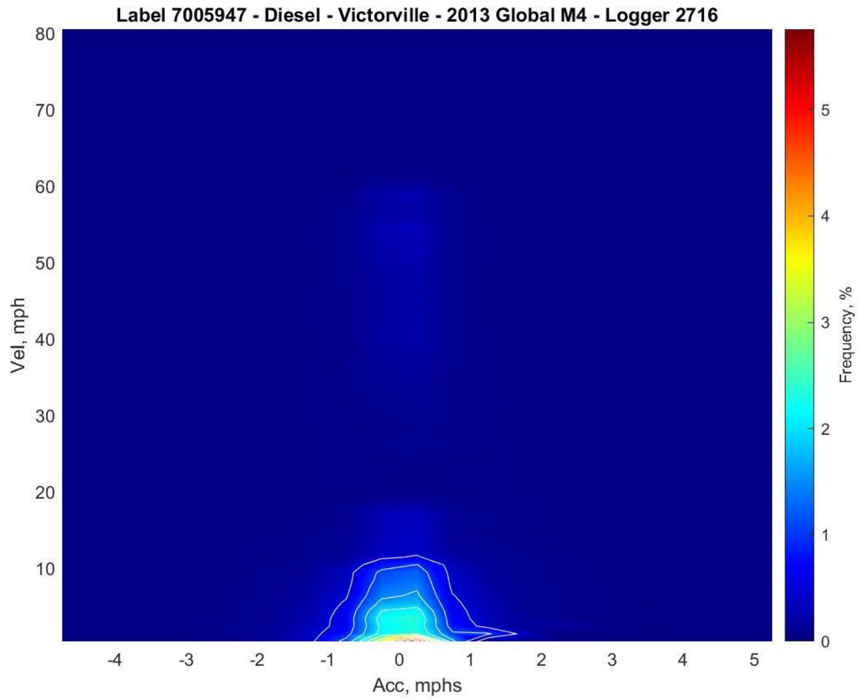
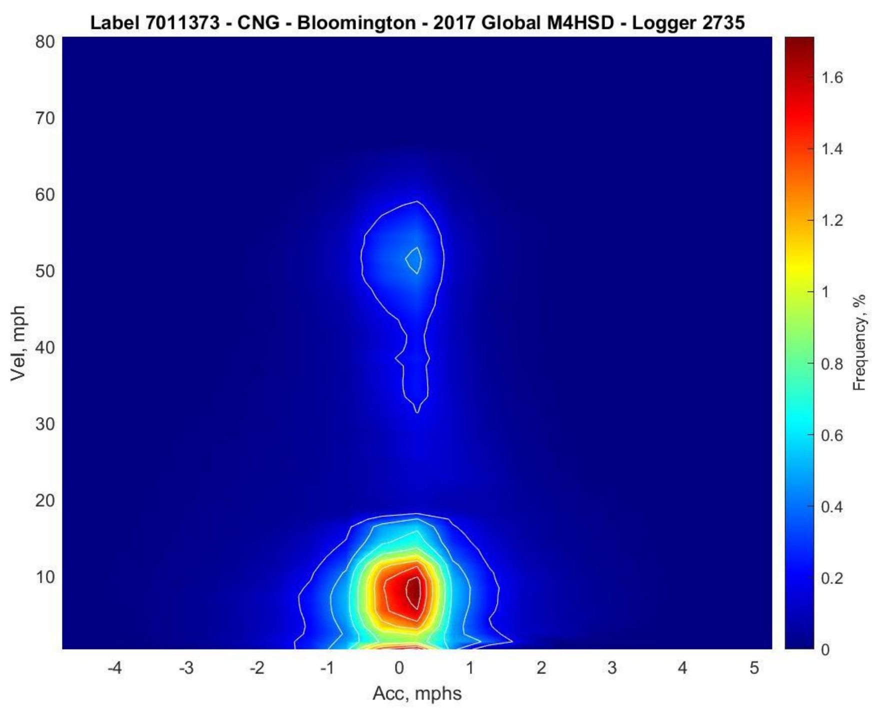
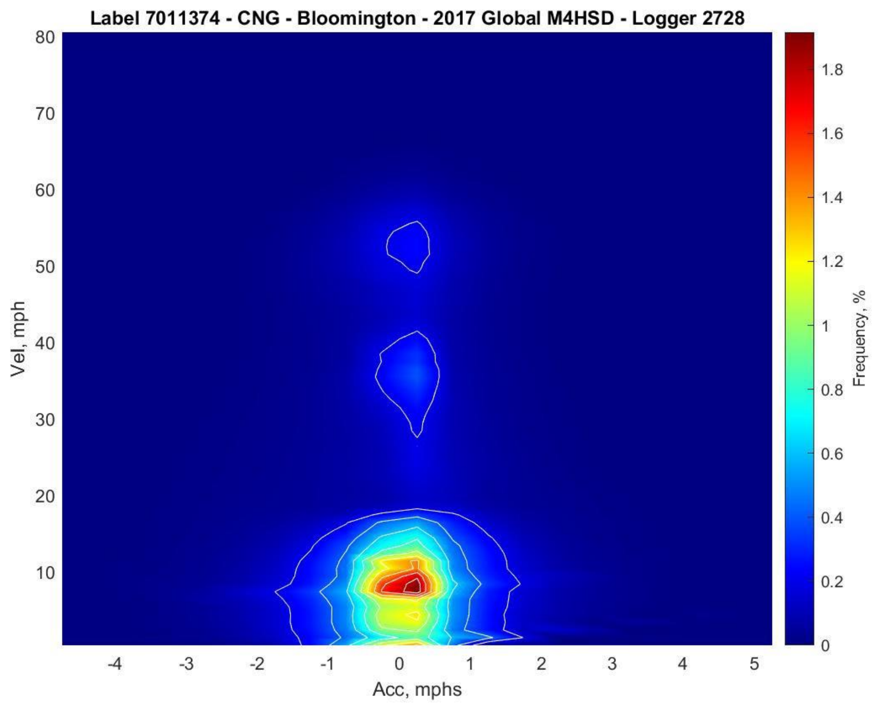
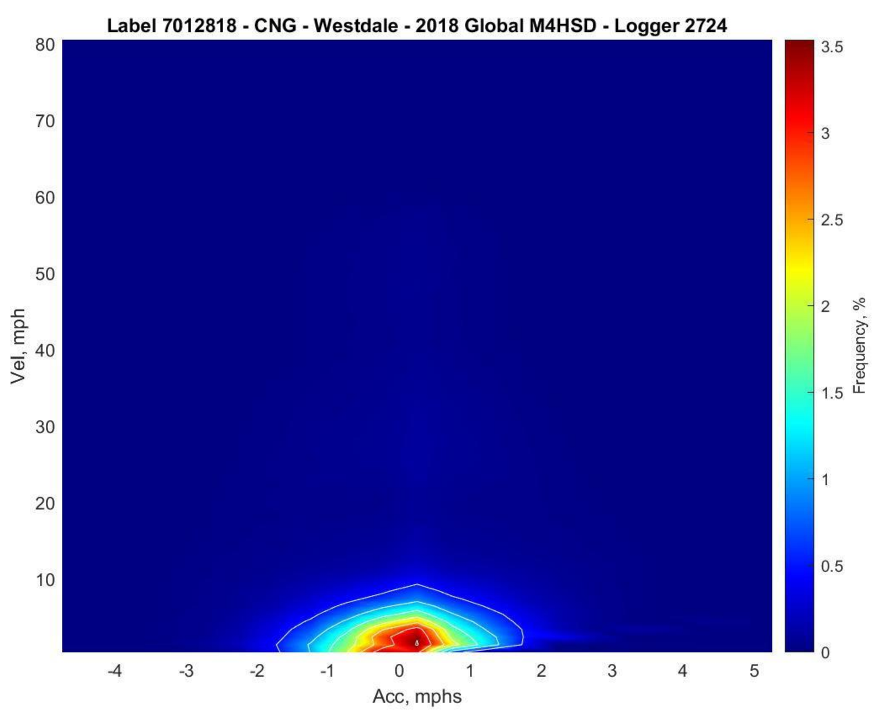
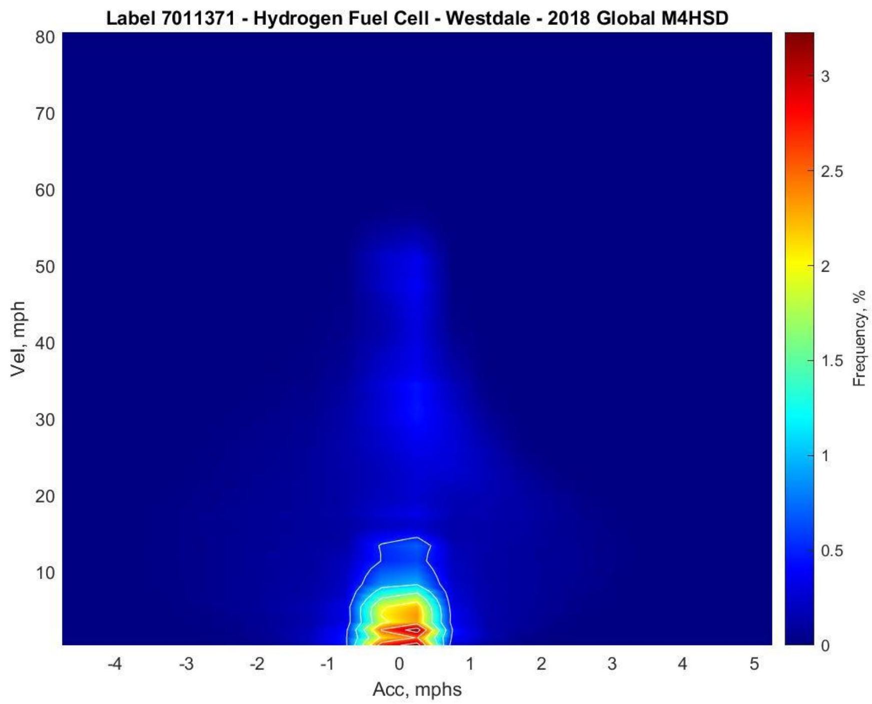



Label 7005947 - Diesel - Victorville - 2013 Global M4 - Logger 2716
Vel, mph
Acc, mphs
Frequency, %
80
70
60
50
40
30
20
10
-4
-3
-2
-1
0
1
2
3
4
5
0
1
2
3
4
5


Label 7011373 - CNG - Bloomington - 2017 Global M4HSD - Logger 2735
Vel, mph
Acc, mphs
Frequency, %
80
70
60
50
40
30
20
10
-4
-3
-2
-1
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

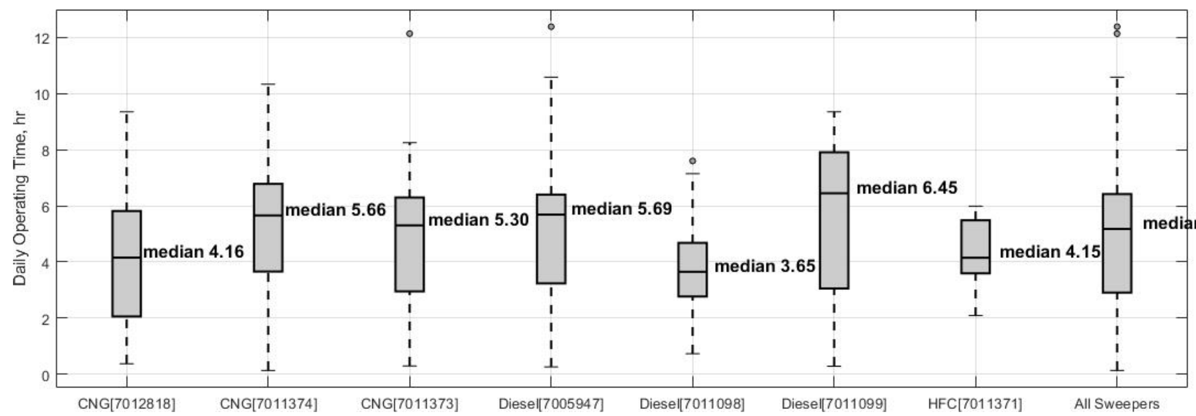

Label 7011374 - CNG - Bloomington - 2017 Global M4HSD - Logger 2728
Vel, mph
80
70
60
50
40
30
20
10
-4
-3
-2
-1
0
1
2
3
4
5
Acc, mphs
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Frequency, %

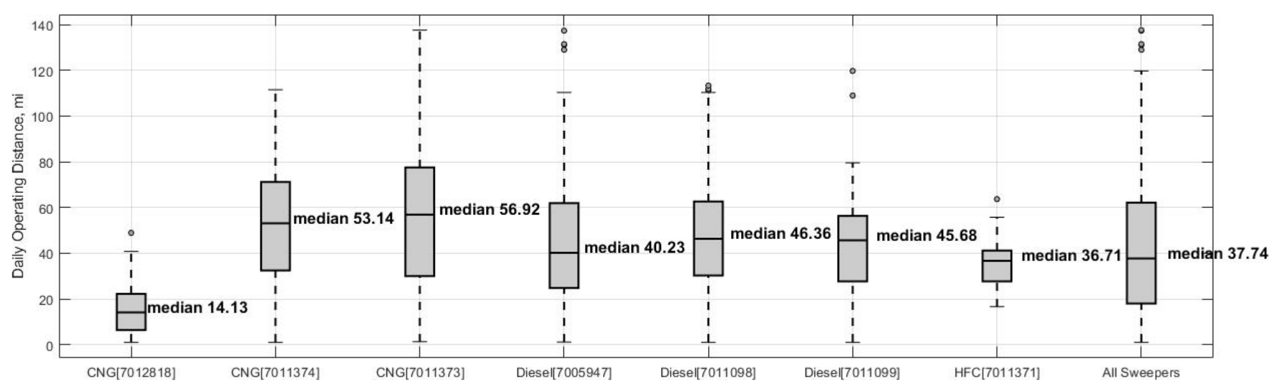

Label 7012818 - CNG - Westdale - 2018 Global M4HSD - Logger 2724
Vel, mph
80
70
60
50
40
30
20
10
-4
-3
-2
-1
0
1
2
3
4
5
Acc, mphs
3.5
3
2.5
2
1.5
1
0.5
0
Frequency, %

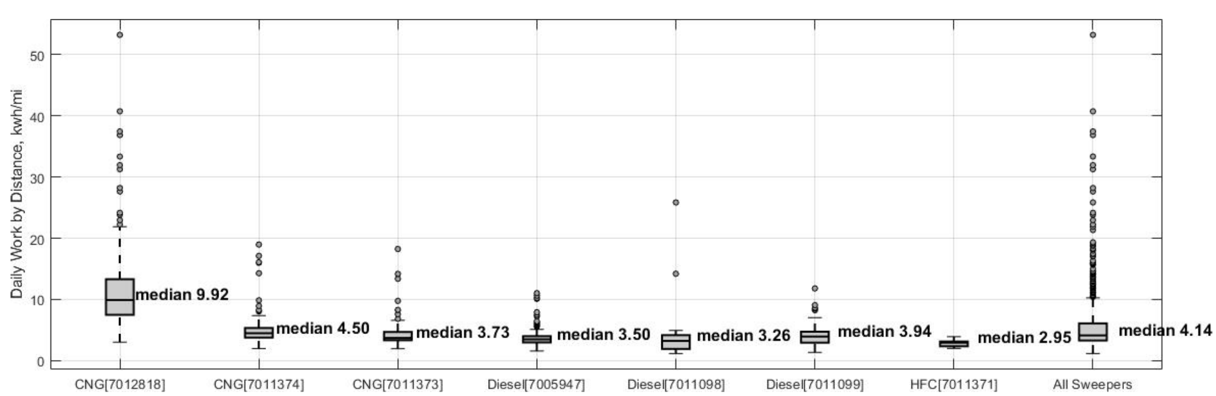

Label 7011371 - Hydrogen Fuel Cell - Westdale - 2018 Global M4HSD
Vel, mph
80
70
60
50
40
30
20
10
-4
-3
-2
-1
0
1
2
3
4
5
Acc, mphs
Frequency, %
3
2.5
2
1.5
1
0.5
0

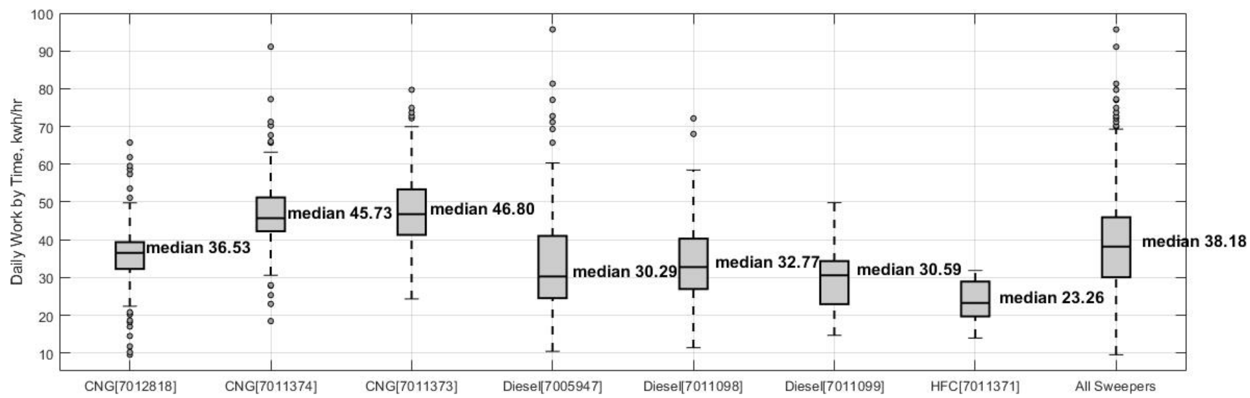
Appendix B: Activity Distribution by Sweeper

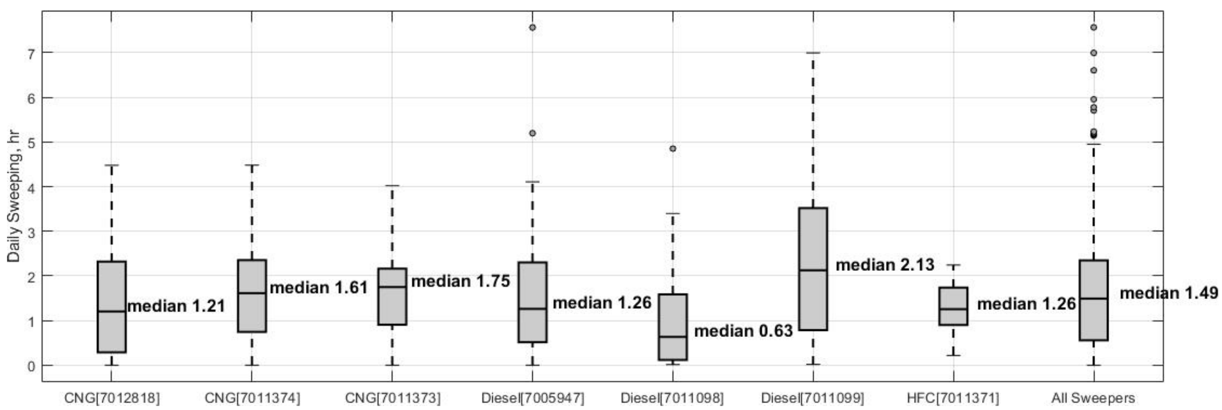
This appendix presents summarized activity data for individual sweepers. Activity data was recorded using HEM ECU data loggers and also includes data provided by US Hybrid for the HFC. Activity data collection is discussed in Chapter 4. The final entry in each plot provides the summarized statistic across all sweepers.

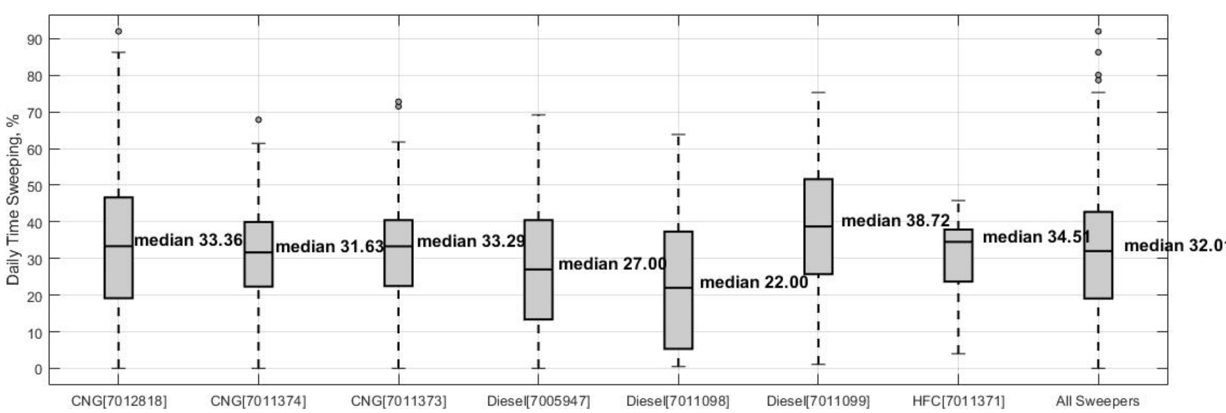


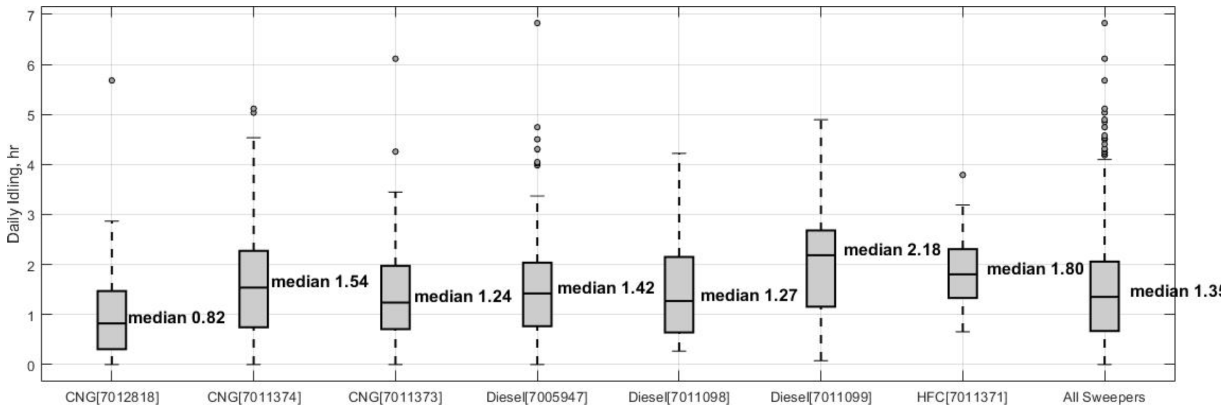




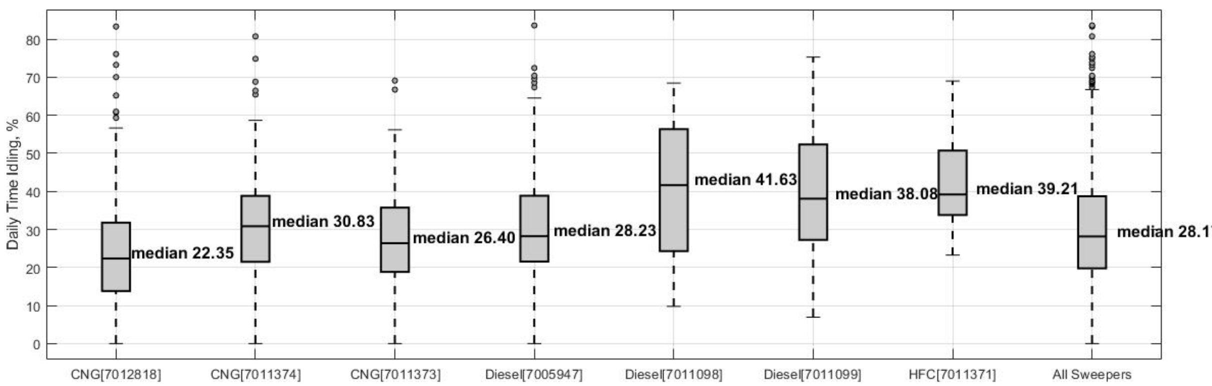

Daily Work by Time, kwh/hr
median 36.53
median 45.73
median 46.80
median 30.29
median 32.77
median 30.59
median 23.26
median 38.18
CNG[7012818]
CNG[7011374]
CNG[7011373]
Diesel[7005947]
Diesel[7011098]
Diesel[7011099]
HFC[7011371]
All Sweepers


Daily Sweeping, hr
median 1.21
median 1.61
median 1.75
median 1.26
median 0.63
median 2.13
median 1.26
median 1.49
CNG[7012818]
CNG[7011374]
CNG[7011373]
Diesel[7005947]
Diesel[7011098]
Diesel[7011099]
HFC[7011371]
All Sweepers


Daily Time Sweeping, %
median 33.36
median 31.63
median 33.29
median 27.00
median 22.00
median 38.72
median 34.51
median 32.01
CNG[7012818]
CNG[7011374]
CNG[7011373]
Diesel[7005947]
Diesel[7011098]
Diesel[7011099]
HFC[7011371]
All Sweepers



Daily Idling, hr
median 0.82
median 1.54
median 1.24
median 1.42
median 1.27
median 2.18
median 1.80
median 1.35
CNG[7012818]
CNG[7011374]
CNG[7011373]
Diesel[7005947]
Diesel[7011098]
Diesel[7011099]
HFC[7011371]
All Sweepers



Daily Time Idling, %
median 22.35
median 30.83
median 26.40
median 28.23
median 41.63
median 38.08
median 39.21
median 28.17
CNG[7012818]
CNG[7011374]
CNG[7011373]
Diesel[7005947]
Diesel[7011098]
Diesel[7011099]
HFC[7011371]
All Sweepers

Appendix C: PEMS Emission Rate Tables

Table B-0-1 Time based emission results for PEMS testing

Vehicle Label	7005947	7005947	7005955	7005955	7011373	7011373	7011374	7011374
Fuel Type	Diesel	Diesel	Diesel	Diesel	CNG	CNG	CNG	CNG
Test Date	4/23/2021	6/24/2021	7/29/2021	7/30/2021	1/13/2021	1/14/2021	1/20/2021	1/21/2021
Test Location	Victorville		Yucca Valley		Bloomington		Bloomington	
Test Identifier	Diesel 1 - Test 1	Diesel 1 - Test 2	Diesel 2 - Test 1	Diesel 2 - Test 2	CNG 1 - Test 1	CNG 1 - Test 2	CNG 2 - Test 1	CNG 2 - Test 2
CO2 (kg/hr)	39.14	35.07	27.62	36.34	30.4	26.38	37.6	30.94
CO2 Idle (kg/hr)	11.65	9.95	10.19	16.9	11.31	10.44	12.07	9.53
CO2 Sweeping (kg/hr)	39.58	35.26	28.63	33.1	42.95	43.21	41.31	41.36
CO (g/hr)	73	2.05	11.42	20.26	782.82	683.3	383.49	289.69
CO Idle (g/hr)	30.99	2.7	7.48	7.76	114.96	148.99	36.22	13.82
CO Sweeping (g/hr)	80.93	0.62	7.25	23.3	1358	1586.87	521.64	588.99
THC (g/hr)	1.92	0.25	0.29	0.25	36.85	44.86	31.76	21.06
THC Idle (g/hr)	0.91	0.33	0.13	0.01	14	23.83	1.79	5.49
THC Sweeping (g/hr)	1.92	0	0.26	0.26	55.82	87.86	43.91	29.08
NOx (g/hr)	22.03	3.2	54.41	9.41	3.32	4.19	3.55	3.6
NOx Idle (g/hr)	8.67	0.88	38.49	7.4	1.06	1.65	3.38	0.71
NOx Sweeping (g/hr)	21.13	2.67	46.96	7.86	3.91	6.44	3.74	2.6

Table B-0-2 Distance based PEMS emission results for PEMS testing

Vehicle Label	7005947	7005947	7005955	7005955	7011373	7011373	7011374	7011374
Fuel Type	Diesel	Diesel	Diesel	Diesel	CNG	CNG	CNG	CNG
Test Date	4/23/2021	6/24/2021	7/29/2021	7/30/2021	1/13/2021	1/14/2021	1/20/2021	1/21/2021
Test Location	Victorville		Yucca Valley		Bloomington		Bloomington	
Test Identifier	Diesel 1 - Test 1	Diesel 1 - Test 2	Diesel 2 - Test 1	Diesel 2 - Test 2	CNG 1 - Test 1	CNG 1 - Test 2	CNG 2 - Test 1	CNG 2 - Test 2
CO2 (kg/mi)	2.61	5.67	4.11	3.91	3.7	3.1	2.55	2.74
CO2 Sweeping (kg/mi)	4.26	7.15	6.2	8.12	4.09	4.27	3.11	3.89
CO (g/mi)	4.86	0.33	1.7	2.18	95.18	80.24	26	25.7
CO Sweeping (g/mi)	8.71	0.13	1.57	5.72	129.45	156.94	39.25	55.43
THC (g/mi)	0.13	0.04	0.04	0.03	4.48	5.27	2.15	1.87
THC Sweeping (g/mi)	0.21	0	0.06	0.06	5.32	8.69	3.3	2.74
NOx (g/mi)	1.47	0.52	8.09	1.01	0.4	0.49	0.24	0.32
NOx Sweeping (g/mi)	2.27	0.54	10.17	1.93	0.37	0.64	0.28	0.24

Table B-0-3 Distance based work rates based for PEMS testing

Vehicle Label	7005947	7005947	7005955	7005955	7011373	7011373	7011374	7011374
Fuel Type	Diesel	Diesel	Diesel	Diesel	CNG	CNG	CNG	CNG
Test Date	4/23/2021	6/24/2021	7/29/2021	7/30/2021	1/13/2021	1/14/2021	1/20/2021	1/21/2021
Test Location	Victorville		Yucca Valley		Bloomington		Bloomington	
Test Identifier	Diesel 1 - Test 1	Diesel 1 - Test 2	Diesel 2 - Test 1	Diesel 2 - Test 2	CNG 1 - Test 1	CNG 1 - Test 2	CNG 2 - Test 1	CNG 2 - Test 2
Work All (kwh/mi)	2.66	5.91	5.42	4.49	5.09	4.3	3.66	3.88
Work Sweeping (kwh/mi)	4.52	7.59	8.2	9.39	5.96	6.45	4.64	5.78

Table B-0-4 Work based emission results for PEMS tests

Vehicle Label	7005947	7005947	7005955	7005955	7011373	7011373	7011374	7011374
Fuel Type	Diesel	Diesel	Diesel	Diesel	CNG	CNG	CNG	CNG
Test Date	4/23/2021	6/24/2021	7/29/2021	7/30/2021	1/13/2021	1/14/2021	1/20/2021	1/21/2021
Test Location	Victorville		Yucca Valley		Bloomington		Bloomington	
Test Identifier	Diesel 1 - Test 1	Diesel 1 - Test 2	Diesel 2 - Test 1	Diesel 2 - Test 2	CNG 1 - Test 1	CNG 1 - Test 2	CNG 2 - Test 1	CNG 2 - Test 2
CO2 (kg/kwh)	0.98	0.96	0.76	0.87	0.73	0.72	0.7	0.71
CO2 Sweeping (kg/kwh)	0.94	0.94	0.76	0.87	0.69	0.66	0.67	0.67
CO2 Idle (kg/kwh)	2.42	1.84	0.99	1.34	1.13	1.05	1.05	1.02
CO (g/kwh)	1.83	0.06	0.31	0.49	18.7	18.64	7.11	6.63
CO Sweeping (g/kwh)	1.92	0.02	0.19	0.61	21.73	24.35	8.47	9.59
CO Idle (g/kwh)	6.44	0.5	0.73	0.61	11.51	15.02	3.15	1.48
THC (g/kwh)	0.05	0.01	0.01	0.01	0.88	1.22	0.59	0.48
THC Sweeping (g/kwh)	0.05	0	0.01	0.01	0.89	1.35	0.71	0.47
THC Idle (g/kwh)	0.19	0.06	0.01	0	1.4	2.4	0.16	0.59
NOx (g/kwh)	0.55	0.09	1.49	0.23	0.08	0.11	0.07	0.08
NOx Sweeping (g/kwh)	0.5	0.07	1.24	0.21	0.06	0.1	0.06	0.04
NOx Idle (g/kwh)	1.8	0.16	3.75	0.58	0.11	0.17	0.29	0.08

Appendix D: Survey Documents

Caltrans Sweeper Operator Survey

Operator Information
Name:___________________ Title: ___________________________
District(s) operating sweepers in the last 5 years: _____________________________
Shop/Yard locations in last 5 years:____
Years of operating sweepers _____years.
Experience driving diesel powered sweepers ___yes ____no; CNG powered ___yes ____no; Hydrogen powered ___yes ____no
Which sweepers have you operated in the last 5 years:
diesel powered sweepers ___yes ____no; CNG powered ___yes ____no; Hydrogen powered ___yes ____no
Comments:
____
____
____

Rank your experience operating sweepers (~2010 and newer) vs. all the sweepers you have operated: Provide relative comparison between Diesel, CNG, and Hydrogen Fuel Cell (H2).

Provide a “C” for CNG powered, and “H” for Hydrogen powered, and “D” for Diesel powered in the space representing relative performance of each type of powered vehicle. Multiple entries can be entered for a desired selection (for example C, H, D can each be entered in the same space)

Driving to/from sweeping location (speed, acceleration, steering, brakes, range, gauges, knobs):

___Best ___Above Average ___Average ___Below Average ___Worst

Vehicle prep and startup (ease of procedures to deploy)

___Best ___Above Average ___Average ___Below Average ___Worst

Refueling procedure and time (ease and frequency of problems)

___Best ___Above Average ___Average ___Below Average ___Worst

Sweeping effectiveness (overall integrated performance)

___Best ___Above Average ___Average ___Below Average ___Worst

Brush performance (settings, control, effectiveness)

___Best ___Above Average ___Average ___Below Average ___Worst

Elevator performance (settings, control, effectiveness)

___Best ___Above Average ___Average ___Below Average ___Worst

Water system (settings, control, effectiveness)

___Best ___Above Average ___Average ___Below Average ___Worst

Hopper collection and dumping (settings, control, effectiveness)

___Best ___Above Average ___Average ___Below Average ___Worst

Operational consistency (ease of use, consistent performance)

___Best ___Above Average ___Average ___Below Average ___Worst

Driver comfort (HVAC, seating, operational controls)

___Best ___Above Average ___Average ___Below Average ___Worst

Comments:

____

____

____

Caltrans Sweeper Mechanic/Maintenance Survey

Caltrans Mechanic/Maintenance Staff Information

Name:____________________ Title: ______Maintenance Supervisor_____________________

Years of maintaining sweepers _____years.

District(s) maintaining sweepers in the last 5 years: ____________________________

Shop/Yard locations in last 5 years:____

Experience maintaining diesel powered sweepers ___yes ____no; CNG powered ___yes ____no; Hydrogen powered ___yes ____no

Which sweepers have you maintained in the last 5 years:

diesel powered sweepers ___yes ____no; CNG powered ___yes ____no; Hydrogen powered ___yes ____no

Comments:

____

____

____

Provide a "C" for CNG powered, and "H" for Hydrogen powered, and "D" for Diesel powered in the space representing relative performance of each type of powered vehicle.

Frequency of needed repairs and maintenance on powertrain:
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency

Frequency of needed repairs and maintenance on PTO system
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency

Frequency of needed repairs and maintenance on in cab components/controls
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency

Frequency of recurring repair issues (premature component failure)
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency H- batteries

Frequency of recurring maintenance issues (adjustment, cleaning, lubricating, leaking, tightening)
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency

Routine maintenance interval/frequency
___Lowest Frequency ___Low Frequency ___Average Frequency ___High Frequency ___Highest Frequency

List most common issue for each

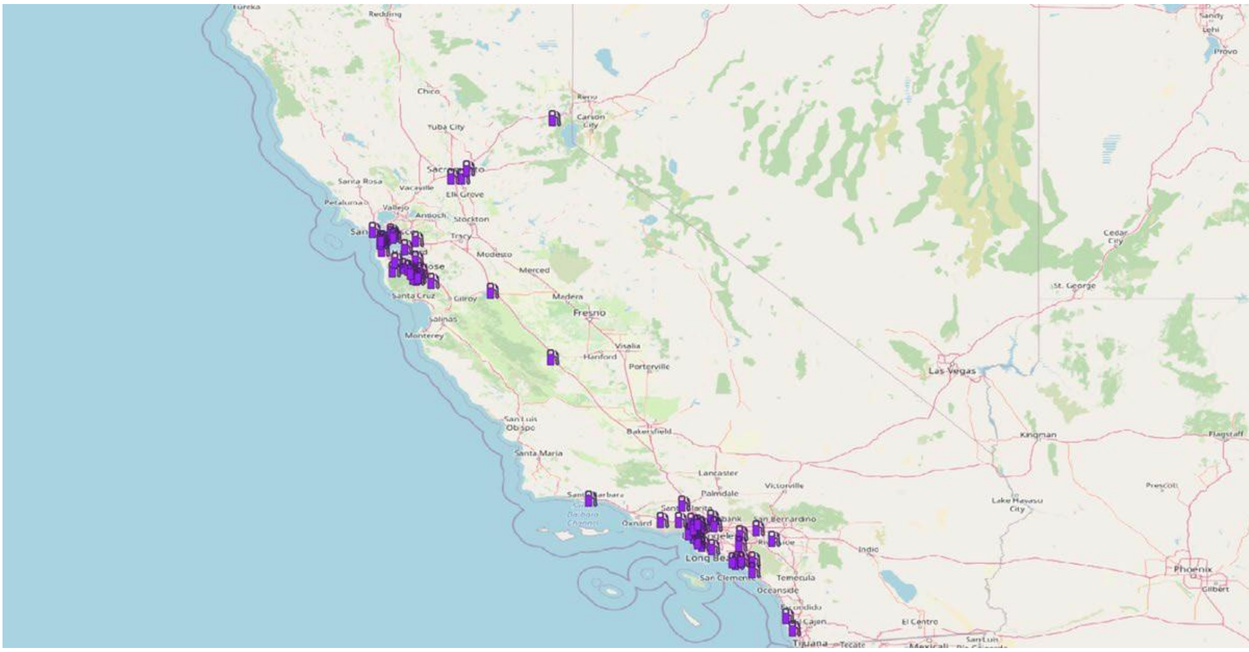
Diesel:

CNG:

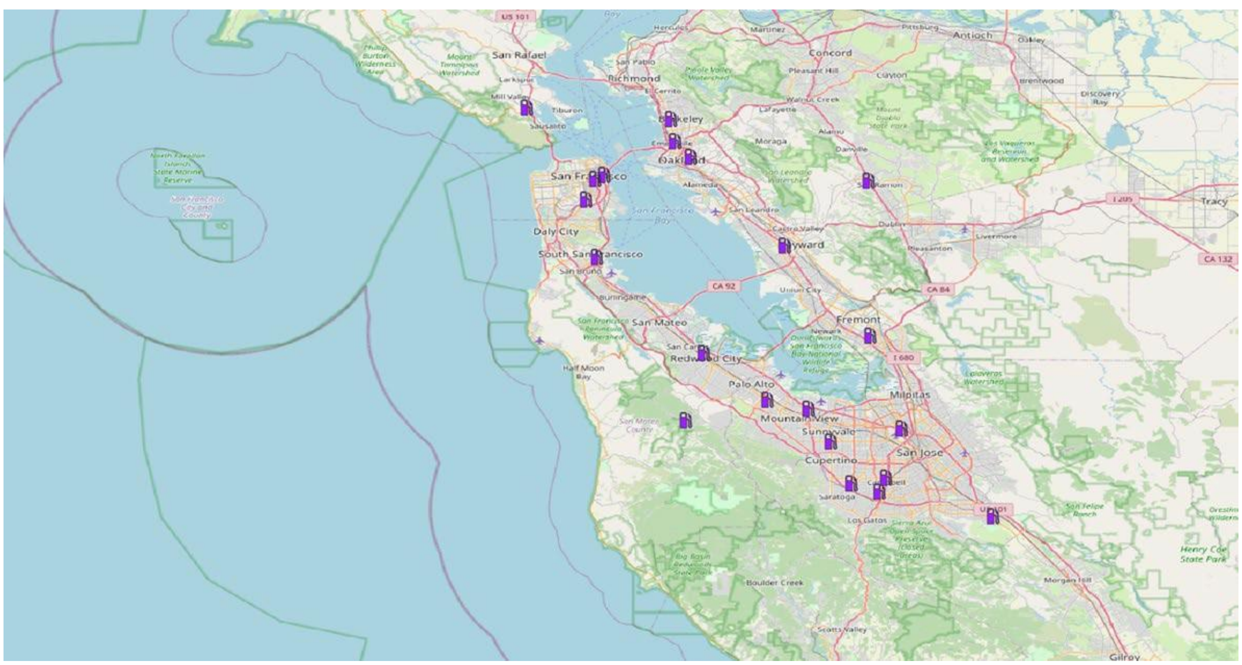
H2:

Comments:

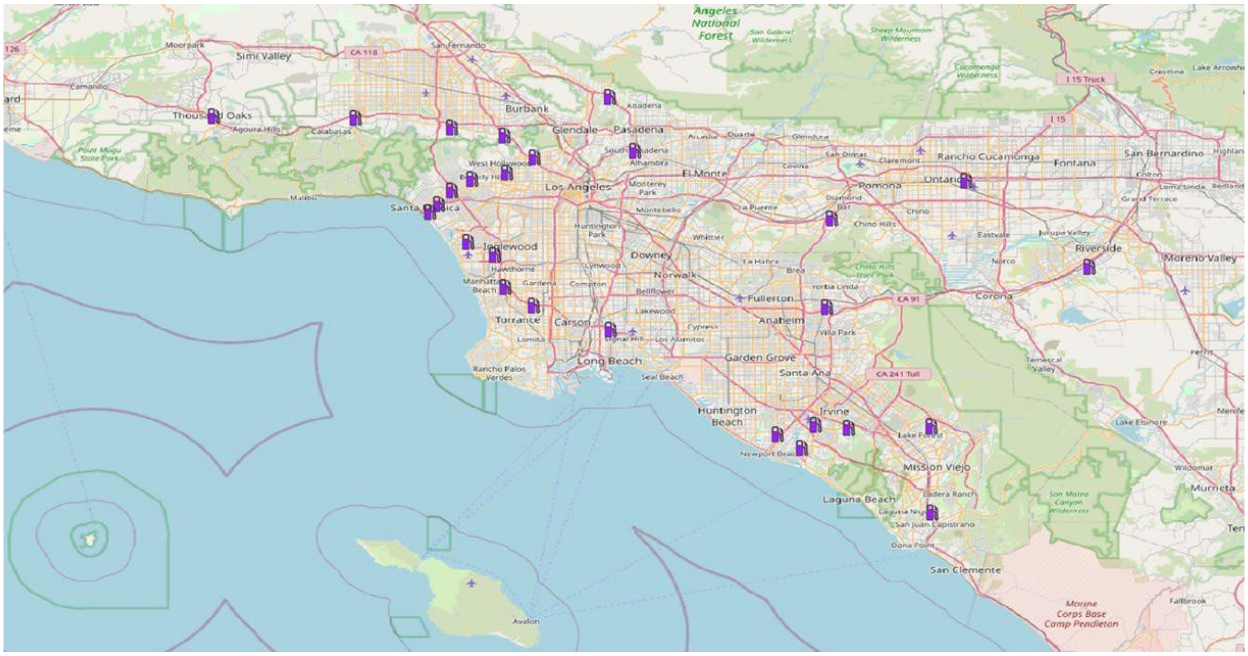
Appendix E: Hydrogen Refueling Stations



Hydrogen refueling stations in California



Hydrogen refueling stations in Northern California



Hydrogen refueling stations in Southern California