High Evaporative Emission Investigation Field Study

United States
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High Evaporative Emission Investigation Field Study

Assessment and Standards Division
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Executive Summary

Light-duty vehicle onboard diagnostic (OBD) systems monitor many of the components of emissions control systems to help ensure that those systems continue to operate as designed. However, today's OBD systems do not monitor the performance of the evaporative emissions control system canister, which captures and stores evaporative emissions for subsequent combustion in the engine. The U.S. Environmental Protection Agency (EPA) has been conducting a series of studies to determine if this approach is justified.

With the 1998 model year, regulations began to be phased in that required manufacturers to equip vehicles with evaporative emissions control systems that would reduce evaporative emissions generated during vehicle refueling. Refueling emissions are generated when the liquid gasoline put into the fuel tank displaces the tank's headspace vapor. The composition of headspace vapor varies with gasoline volatility and fuel tank temperature, but as a rule of thumb, headspace vapor is approximately 50 vol% hydrocarbon. Pre-1998 gasoline vehicles simply vent this vapor to the atmosphere. Typically, to help control refueling emissions, the new onboard refueling vapor recovery (ORVR) evaporative emissions control systems create a liquid seal by extending the fuel fill pipe inside the fuel tank to near its bottom. By various methodologies using different designs, the gasoline vapor is routed to the canister for capture and is prevented from returning through the fill pipe.

While today's ORVR systems are required to also control diurnal, hot-soak, and running loss evaporative emissions, they are most severely challenged by refueling emissions because a large mass of headspace vapor from the vehicle gas tank must be controlled over the short period when refueling occurs. This study takes advantage of this fact, and of the fact that all vehicles must refuel, by monitoring the refueling vapor emissions of a sample of the fleet at a commercial gas station.

Another source of refueling emissions is liquid gasoline spills and leaks from vehicles. These liquid sources are related to the behaviors of gasoline station customers, vehicle maintenance, and gas pump nozzle design. Accordingly, this study also collected data on the characteristics of liquid gasoline spills and leaks at a commercial gas station.

Overall, this study collected and analyzed gasoline station refueling data to evaluate gaseous and liquid refueling emissions on light- and medium-duty gasoline-fueled vehicles. Costco Wholesale participated in the study by allowing us to collect data at two of their gas stations in the Denver area from July 7 to 23, 2019. These gas stations pumped only gasoline, which had 9.0 psi RVP volatility and 10 vol% ethanol during the study period. The gaseous refueling emissions data was collected at the Arvada Costco gas station, and liquid refueling observational data was collected at the Thornton Costco gas station.

Data Collection of Refueling Vapor Emissions – At the Arvada station, we used the Rebellion Photonics gas cloud imaging (GCI) infrared hyperspectral video camera and video post-processing to identify refueling emission puffs and plumes on 2,854 vehicle refuelings. The gas station had two pumps on each side of three islands. On each day, the infrared camera was positioned about 110 feet in front of and about 30 feet above the two refueling positions on one side of an island to allow videoing of two vehicles refueling. Simultaneously, we recorded vehicle arrival and departure times and used license plates and a snapshot of the Colorado registration database to confirm vehicle identity while the vehicle was still there. Costco provided timestamps of pump nozzle lift-off and hang-up times and volume of fuel dispensed. EPA looked up fuel tank capacity and canister capacity for most of the Colorado vehicles videoed.

At the gas station, Colorado Department of Public Health and Environment (CDPHE) emission technical laboratory personnel produced 108 10-gallon/minute metered releases of known concentrations of butane and gasoline headspace vapor from three different locations on a CDPHE reference vehicle to determine the sensitivity of the infrared camera under different viewing conditions.

The various datasets from the Arvada station measurements were merged and time aligned to the nearest second. We viewed the 8,462 30-second infrared videos to identify refueling emissions occurrences from private vehicles and CDPHE test runs. Each private vehicle refueling was rated in an initial effort as either 0 (no emissions visible), L (low-density emissions visible), H (high-density emissions visible), or P (emissions from a puddle on the pavement).

Infrared Camera Detection Limits – Properly operating in-use ORVR vehicles should have refueling emissions below the standard of 0.2 gHC/gallon. At the other extreme, non-ORVR vehicles or ORVR vehicles with inoperative evaporative emissions control systems should have refueling emissions that have concentrations equal to the fuel tank headspace HC concentration. For the environmental and fuel properties at the time of this study, we estimate the headspace concentration would be about 4.6 gHC/gallon. Vehicles with partially operating control systems will have refueling emissions rates between 0.2 and 4.6 gHC/gallon. Of course, vehicles with fuel system liquid leaks, which we did see in the study, could have refueling emissions that are greater than 4.6 gHC/gallon.

Analysis of the CDPHE reference vehicle releases indicated that the probability of observing a refueling emission in a video depended on the location of the release on the vehicle and the hydrocarbon concentration in the release. The analysis indicated that, regardless of the vehicle release location, refueling emissions of properly operating ORVR vehicles (less than 0.2 gHC/gallon) probably would not be seen in GCI camera videos, but refueling emissions of non-ORVR or inoperative ORVR systems (about 4.6 gHC/gallon) would very likely be seen in GCI camera videos. This is good emissions detection behavior for the study since, in general, the videos will be able to distinguish between control systems with good and poor behavior. The probability of seeing refueling emissions in GCI videos of vehicles with partial control will vary depending on emissions release location, actual emissions rate, scene composition and illumination conditions.

Refueling Emissions Detection for Pre-ORVR Vehicles – We used the VINs looked up in the Colorado vehicle registration database to determine the vehicle classes and ORVR equipment of the refueling vehicles. Our analysis of the Colorado-registered vehicles indicated that about 90% of the vehicles refueling at the Costco Arvada gas station during this study were equipped with ORVR systems. Vehicles with model years before the start of the phase-in to full ORVR implementation should all produce observable refueling emissions. Preliminary analysis (see Table 3-6) of the 2,854 refuelings videoed showed that 82 refuelings were for pre-1998 (unambiguously pre-ORVR) vehicles, and 70 (85%) of those showed refueling emissions in their videos. Based on the GCI camera detection limits, which were discussed above, we would expect 100% of pre-ORVR vehicles to exhibit plumes in the videos. However, several factors can contribute to reducing the probability of observing emissions in videos of refueling events. These factors include the amount of fuel dispensed, the calibration and on/off status of the GCI camera at the time of the refueling, obstacles (other vehicles, people, car doors) in the line of sight, background illumination, and wind speed. No further analysis of pre-ORVR vehicle refueling emissions was undertaken.

Refueling Emissions for Confirmed ORVR Vehicles – The analysis of the Arvada station data concentrates on 1,990 refueling events of vehicles built after the respective model year of the full ORVR implementation, that is, 2000 MY for light-duty gasoline vehicles (LDGV), 2003 for light-duty gasoline trucks with gross vehicle weight less than 6,000 pounds (LDGT12), and 2006 for light-duty trucks with GVWR between 6,000 and 8,500 pounds (LDGT34). The above-mentioned initial video examinations revealed that emissions were rarely observed during the entire refueling event, but that emissions started and stopped. Additionally, emissions were made up of puffs and plumes, which we define for this study:

Puffs are short-term emission events associated with the removal of the gas cap, the beginning of fuel flow into the fuel fill pipe, the end of fuel flow when the pump nozzle automatically clicks off, customer's efforts to top off the fuel tank using extra nozzle clicks, or emissions from puddles on the ground produced by vehicle fuel line leaks or drips from the nozzle when it is transferred between the pump and the vehicle.

Plumes are generally longer-term emissions events when the fuel is flowing at a steady rate into the fuel fill pipe.

Because of the time-varying nature of the refueling emissions and because ORVR systems should control plumes but not necessarily puffs, we re-viewed the videos in a Phase 2 effort – but only those for confirmed ORVR vehicles that had initial video viewing results of Low density, High density, or Puddle. In the Phase 2 video viewings, we characterized each 5-second block of each video by giving separate characterization codes to puffs and to plumes so that separate analyses could be done on the two emission types. The Phase 2 puff and plume codes were used to assign each ORVR refueling event as one of three categories:

NoPuffsNoPlumes: We saw neither puffs nor plumes in any of the videos for the refueling event. 81% (=1109/1990) of the refuelings of confirmed ORVR-equipped vehicles were in this category.

OnlyPuffsNoPlumes: We saw at least one puff of any type (remove gas cap, begin fuel flow, nozzle click-off, topping off, puddles), but we did not see any plumes associated with periods of steady fuel flow. 15% (=292/1990) of the refuelings of confirmed ORVR-equipped vehicles were in this category.

ContinuousPlumes: We saw plumes associated with periods of steady fuel flow, and puffs of any type may or may not have been present. 3.9% (=77/1990) of the refuelings of confirmed ORVR-equipped vehicles were in this category.

It is important to recognize that the 81%, 15%, and 3.9% percentages of refuelings that were assigned to the three puff/plume categories depend strongly on the sensitivity of the video camera. All refuelings produce some level of emissions. Thus, if we had used a more sensitive video camera, plumes would have been seen for every refueling. Alternately, if we had used a low sensitivity video camera, no emissions would have been seen at all. These considerations should be taken into account when using this dataset for modeling.

The data collected at Arvada shows that camera sensitivity is influenced by viewing conditions. Since the identity of the gas station pump should be independent of the ORVR system state of repair, the fraction of ORVR vehicles that produce observable plumes at any of the pumps should be the same within statistical uncertainty. When we tested this assumption, we found that refuelings at the back row of pumps, which are farther from the video camera, had a

60% larger fraction of observable plumes than those at the front pumps. We believe that this difference was caused by the scene's background complexity and illumination. Back-pump backgrounds generally had smooth pavement and were illuminated by the sun, which caused stronger ambient infrared radiation. Front-pump backgrounds generally contained another vehicle and moving customers and were in the shadow of the gas station canopy. We also found that the observable plume sensitivity was enhanced by calm wind conditions.

Emissions video data that was collected under less sensitive video conditions should not be discarded. Also, emissions video data collected under more sensitive video conditions should not be believed more than data collected under less sensitive video conditions. Instead, all data should be analyzed by considering the differences of camera sensitivity and by recognizing which results trends are subject to the influence of camera sensitivity and which are not.

Major Findings of the Arvada Gas Station Study – We judged the refueling emissions behavior of ORVR vehicles as a function of vehicle class and model year. Because continuous plumes, but not puffs, should be controlled by ORVR systems, we judged emissions performance based on controlling continuous plumes. Judging criteria were the model-year dependence of continuous plume prevalence, which is the fraction of vehicles in the sample that had observable continuous plumes.

Here are the major findings of the Arvada gas station study for prevalence of continuous plumes for ORVR vehicles:

1) We found no statistical difference between the model year trends of continuous plumes for LDGV, LDGT12, and LDGT34 vehicles with ORVR systems.

2) The prevalence of continuous plumes (i.e. not puffs) is near zero for new vehicles (2019 model year in this study) that have ORVR systems.

3) As ORVR vehicles age, the occurrence of continuous plumes, as measured by prevalence, increases approximately proportionally with vehicle age, but the mass rate of emissions degradation is unknown.

The rate of increase of continuous plumes in older vehicles as measured in this study depends on camera sensitivity. For example, for back pumps, where the videoing sensitivity was higher, the prevalence increases at about 0.56%/model year. For front pumps, prevalence increases at about 0.41%/model year. Using only the results of this study, neither of those rates can be used directly for modeling purposes because those rates are not independent of camera and videoing conditions. For modeling, the degradation needs to be quantified on a mass basis so that it is independent of the measurement sensitivity.

Data Collection of Refueling Liquid Emissions – At the Thornton station, we randomly and sequentially selected vehicles arriving at the station to monitor the prevalence of liquid fuel drips, spills, leaks, and spitbacks and the behaviors and refueling conditions associated with them. For each of the 1,227 monitored vehicles, we recorded license plate, vehicle make and model, gas pump number, fuel nozzle orientation, the number of extra fuel nozzle clicks that the customer used to top off the fuel tank, the fuel nozzle hang-up time, the relative size of spills and spitbacks, and the gas station attendant's response to them. We also recorded situational information on extreme spill or spitback occurrences when they were noticed station-wide even if those vehicles had not been randomly selected. Costco provided timestamps of pump nozzle lift-off and hang-up times and volume of fuel dispensed.

Major Findings of the Thornton Gas Station Study – According to the 1,171 sequential refueling observations, 10.3% of gas station customers spilled gasoline, although most spills were small, nickel-sized spills. About two-thirds of customers accepted the automatic shut-off of the gas pump nozzle and did not try to top-off their tank. Only 8.4% of those refuelings resulted in a spill. When customers attempted to top-off their gas tank by adding extra clicks to their refueling nozzle, they tended to spill at a greater frequency. For example, 5% of all customers used two extra clicks of the nozzle, which resulted in a spill rate of 20.6% – two and one-half times the spill rate experienced by customers who accepted automatic nozzle shut-off. Extra clicks were also associated with larger spills. For example, 31 customers used between 10 and 18 extra clicks, and 2 of those refuelings produced large spills, which we called bucket-sized spills to reflect the fuel volume of a small bucket (diameter of bucket and higher). In contrast, 785 refuelings had no extra clicks, which produced only 1 bucket-sized spill. Thus, using 10 to 18 extra clicks was 50 times more likely to cause a bucket-sized spill than accepting automatic nozzle shut-off. The combined sequential observations and station-wide observations establish that the likelihoods of bucket-sized spills and spitbacks are approximately 0.4% and 0.2%, respectively.

Overview

Because all vehicles must refuel, the EPA saw that monitoring the refueling emissions of ORVR vehicles at gas stations was a means of conveniently evaluating the evaporative emissions control systems of large numbers of in-use vehicles. Accordingly, EPA conducted a preliminary two-day gas station study[1] in Austin, Texas in December 2015 to evaluate the capabilities of the

[1] T.H. DeFries, "Evaluation of Rebellion Photonics Gas Cloud Imaging Camera for Screening Refueling Evaporative Emissions from Light-Duty Vehicles," prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, EPA-160411, April 11, 2016.

Rebellion Photonics camera and a gas station pilot study at a Shell gas station in Wheat Ridge, Colorado in November 2018[2].

This report documents two essentially simultaneous studies at two Costco Wholesale gas stations – one in Arvada and the other in Thornton, Colorado. We describe the data collection, results, and analysis of refueling emissions. To prepare for this project under Work Assignment 2-23 for Contract EP-C-17-011, Eastern Research Group (ERG) wrote a work plan[3] and a quality assurance project plan[4]. ERG ran the studies for EPA.

The study at Arvada, Colorado (Sections 1, 2, and 3) focuses on gasoline vapor emissions, and the study at Thornton, Colorado (Sections 4, 5, 6, 7, and 8) focuses on gasoline liquid emissions, which, of course, soon evaporate. The field data collection for the Arvada study was conducted July 7-23, 2019 except for July 14 and 19, when video data was being downloaded from the field server.

CDPHE has a cooperative research agreement with EPA. CDPHE provided resources for the Arvada study including obtaining the Colorado registration database snapshots and providing, equipping, and operating the reference vehicle and its artificial refueling emissions releases. PG Environmental, which is a subsidiary of ERG, is in nearby Golden, Colorado and was a subcontractor to ERG. For the Arvada study, they developed the iPad data collection system, provided staff to collect data at the gas station using the iPad, and viewed the thousands of infrared videos to search for refueling emissions plumes and other refueling features. For the Thornton study, PG Environmental staff collected information on paper logsheets as they observed customers refueling. For the Arvada study, Rebellion Photonics, an ERG subcontractor, collected continuous infrared measurements using its Gas Cloud Imaging video camera and processed the data on site to produce Enhanced MidWave videos that could reveal refueling HC plumes. Jim Sidebottom and Jim Kemper were consultants on the study. Since they live in the Denver area and were formerly full-time CDPHE employees, they assisted making arrangements with CDPHE and local agencies and businesses before, during, and after the field data collection.

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[2] T.H. DeFries, "High Evaporative Emissions Investigation Field Study: November 2018 Pilot Study," draft report, prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, Austin, TX, EPA-190219, February 19, 2019.

[3] "High Evaporative Emissions Investigation Field Study, Work Plan, Version 3," prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, EPA-190424, April 24, 2019.

[4] T.H. DeFries. "High Evaporative Emissions Investigation Field Study, Quality Assurance Project Plan, Version 2," prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, EPA-190920, September 20, 2019.

Costco Wholesale was a key partner in both studies. ERG approached Costco via their corporate offices in Issaquah, Washington. At no cost to the project, Costco allowed us to work at and collect data at their Arvada gas station and Thornton gas station. Additionally, Costco provided the detailed timestamp and gallons dispensed data on each gas pump transaction at the two stations during the entire data collection period. The only requirement that Costco had was for ERG to keep the private information of its members confidential. Accordingly, ERG agreed not to reveal Costco member vehicle license plates or VINs to anyone outside of ERG and its subsidiary PG Environmental. Even EPA and CDPHE were not allowed to have member confidential information. Therefore, in this document we show no license plates and show only VIN stems.

A key EPA study requirement was to obtain all refueling event information without study personnel initiating interactions with vehicle owners in any way or touching their vehicles. Thus, direct access to vehicles, canisters, and OBD data was not allowed in these studies.

1.0 Arvada: Introduction to Vapor Refueling Emissions Study

This study estimates the prevalence of vehicles with elevated refueling emissions as vehicles are refueled at gas stations. The focus is on Tier 2 and Tier 3 vehicles, but the study collected data on all technologies. The measurement equipment provides an estimate of the distribution of relative refueling HC emissions at ground level as vehicles refuel. Elevated refueling emissions can occur because of canister degradation, which may not be OBD-detectable; OBD-detectable problems, which includes purge system issues and other evaporative emissions control system problems; or simple overwhelming of a problem-free evaporative emissions control system because of extreme environmental conditions such as elevated ambient temperature when the vehicle contains volatile fuel or driving patterns that prevent evaporative canister purge events. Thus, the distribution of refueling emissions are likely an upper estimate of the emissions based on canister degradation alone.

Testing for refueling plumes was conducted at the Costco Wholesale Arvada gas station, 5195 Wadsworth Boulevard, Arvada, Colorado 80022. This gas station was open for business Monday through Friday from 6 a.m. to 9 p.m. and on Saturday and Sunday from 7 a.m. to 7 p.m. The gas station was available for testing during all hours that the station was open for business. The customers at the Costco gas station must be Costco members. The methods of payments that are accepted at the gas station are credit card and debit card only. Cash is not accepted for gasoline purchases. The gas station pumps only gasoline and only regular and premium grades. No diesel fuel was available at the station. Two samples of gasoline were collected for analysis by CDPHE. The results indicated that the gasoline samples had a volatility of 9 psi RVP and 10% ethanol.

Figure 1-1 shows a Google Maps view of the Costco Arvada site with north being up in the photograph. The figure shows the canopy, which is approximately 32 by 86 feet. Traffic flows through the gas station from the southwest to the northeast, as shown by the arrows on the pavement. Customers cue up between the dashed lines on the pavement just southwest of the canopy. Traffic is not allowed to flow in the opposite direction.

Figure 1-1. Arvada Gas Station Site Used for Refueling Emissions Testing

Figure 1-2. Diagram of Arvada Gas Station Islands and Pumps

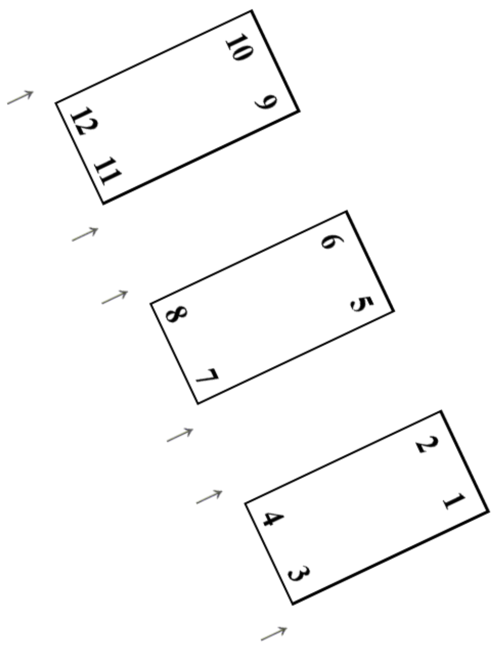


Figure 1-2 shows the three fueling islands and the numbering of the twelve fuel pumps under the canopy using the same orientation as Figure 1-1. The islands are far enough apart from each other that customers can enter or leave a fuel pumping area even if another vehicle is fueling in front of them. On any given testing day, video data was collected on either Pumps 5 and 7, Pumps 6 and 8, or Pumps 9 and 11. At the same time, a study technician collected refueling event and vehicle information on all four pump positions at the fueling island being monitored – either Island 5/6/7/8 or Island 9/10/11/12. The technician was safely positioned at the center of the targeted island to get a good view of vehicles and their license plates.

Two GoPro video cameras were placed on the northeast corner of the roof of the Costco gas station manager's building to record the movement of refueling vehicles. The location is shown by the green square in the right center of Figure 1-1. The study's weather station was placed on the top of the gas station manager's booth, which was in the center of the middle island.

The truck equipped with the gas cloud imaging camera was located about 40 meters to the northeast of Island 5/6/7/8 or Island 9/10/11/12 such that the line of sight of the camera was approximately on the centerline of the fueling island. The two locations used by the truck are shown in Figure 1-1 by the two yellow rectangles in the upper right-hand corner. The black circle inside the yellow rectangles represents the location of camera and its mast.

2.0 Arvada: Data Collection Methods and Procedures

The goal of the refueling emissions plume study was to collect data that could be used to estimate the prevalence of refueling plumes and, if possible, to quantify the level of refueling emissions. The focus was to be on Tier 2 and newer technologies, but the behavior of older technologies was of interest and is used as a positive control for plume presence. Specifically, all pre-ORVR vehicle refuelings are expected to produce refueling plumes. A part of the overall goal was to estimate how the evaporative emissions control systems of ORVR vehicles degraded with age. To meet these goals, ERG designed a test program with several components to get the needed information and devised a way to connect the information. This section describes the major methods that we used.

Rebellion Photonics Gas Cloud Imaging Camera (Section 2.1) – This 15-frame-per-second video camera measures infrared radiation and separates it into wavelength bands. Rebellion's special processing techniques can convert the data into enhanced videos where refueling plumes can be seen.

Reference Vehicle Metered Releases (Section 2.2) – CDPHE provided and set up a reference vehicle that released various concentrations of simulated refueling HC emissions from different release points. These releases, which were done at the same gas station pumps where private vehicles refueled, were used as a reference for judging the refueling emissions of the private vehicles in the fleet.

Gas Station Fuel Pump Transaction Data (Section 2.3) – Costco provided transaction data (scrubbed for private information) for every gasoline purchase during the study period. This included timestamps for credit card approval and nozzle hang-up and for volume of fuel dispensed.

Video Cameras (Section 2.4) – We photographed the gas station scene with video and high-resolution time-lapse cameras to document the movement of vehicles during data collection.

Weather Station (Section 2.5) – We installed a weather station to record temperature and the speed and direction of wind under the gas station canopy, which is where these environmental factors affect dispersion of refueling emissions plumes.

Colorado Vehicle Registration Information (Section 2.6) – CDPHE provided us with vehicle descriptions of all vehicles registered in Colorado so that we could confirm the identity of refueling vehicles via their license plates.

iPad Data Collection System (Section 2.7) – We developed and used, at the gas station, a custom iPad app that was linked to the cloud via a mobile Wi-Fi hotspot to collect and store timestamps for vehicle arrival and departure and to look up vehicle descriptions via observed license plates to visually confirm vehicle identity.

Gas Station Logsheets (Section 2.8) – We used paper logsheets to supplement the iPad data collection system with information on less common vehicle refueling behavior, such as refueling gas cans, lawn mowers, and jet skis; refueling multiple vehicles during a single gas pump transaction; and vehicle descriptions that were not found in the Colorado vehicle registration snapshot.

Refueling Event Listing (Section 2.9) – We wrote a SAS program that time-merged all of the previous data sources to provide a second-by-second chronological record of all refueling information for the four pumps at the gas station island where data was collected each day. Then, the program converted the chronological record into a listing where each event's refueling information was included in a single observation.

SharePoint Database (Section 2.10) – The refueling event listing was pulled into a Microsoft SharePoint database stored in the cloud. The database was a convenient tool for quality-checking, sorting, and viewing – including playing Rebellion videos – of all results of data collection for the gas station study.

2.1 Rebellion Photonics Gas Cloud Imaging Camera

For this project, Rebellion Photonics used its Gas Cloud Imaging (GCI) camera to screen for gasoline vapor being emitted from refueling vehicles in their surroundings. This camera is an infrared hyperspectral camera that collects video data. We had used the camera in a previous study[5] in Austin, Texas, and in the refueling emissions pilot study, which was conducted at a Shell gas station in Wheat Ridge, Colorado, in November 2018[6].

The GCI camera is part of a system constructed and operated by Rebellion Photonics. This system is made up of a pickup truck equipped with computers and associated electronics to store data and a vertical telescoping mast supporting the camera. In this study the mast was elevated to a height of about 30 feet. Figure 2-1 shows a close-up of the camera, and Figure 2-2 shows the camera system including the pick-up truck. Figure 2-3 shows a photograph of the camera system as viewed from one of the refueling position gas pumps in the study. Figure 2-4 shows a close-up of the mast with the camera on top viewed from the side of the pickup truck. The junction between the top of the mast and the bottom of the camera is fitted with a mount that can pan and tilt to change the vertical and horizontal view of the camera. The camera does not

[5] T.H. DeFries, "Evaluation of Rebellion Photonics Gas Cloud Imaging Camera for Screening Refueling Evaporative Emissions from Light-Duty Vehicles," prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, Austin, Texas, EPA-160411, April 11, 2016.

[6] T.H. DeFries, "High Evaporative Emissions Investigation Field Study: November 2018 Pilot Study," draft report, prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, Austin, TX, EPA-190219, February 19, 2019.

have the capability of zooming, and therefore the size of images can be adjusted only by changing the distance between the camera and the object that is being viewed.

Figure 2-1. Close-up of the Rebellion Photonics GCI Camera

Figure 2-2. GCI Camera Installation on Telescoping Mast on the Pick-up Truck

Figure 2-3. Rebellion GCI Camera System Viewed from Arvada Gas Pumps

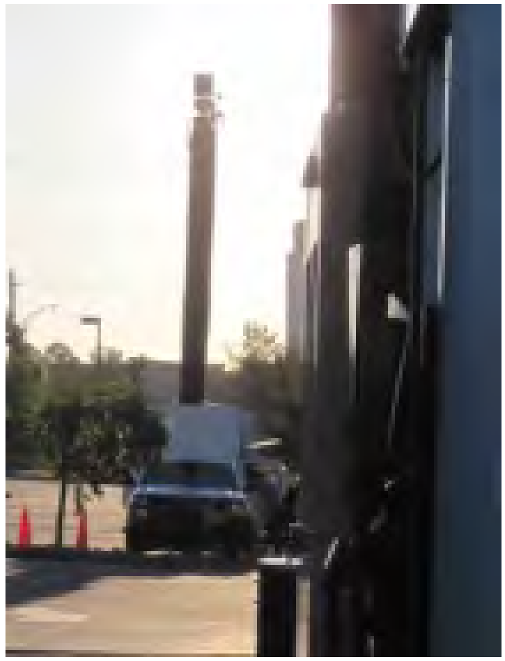


Figure 2-4. Rebellion GCI Camera on Telescoping Mast

The GCI camera measures the intensity of infrared radiation in the scene across the pixels of the camera sensor array. The infrared radiation falling on each pixel is separated into measurements in 10 to 15 wavelength bands between 3 and 14 micrometers. The video frame rate of the camera is 15 frames per second. The GCI camera generates raw data at approximately 1GB per minute. This data is stored on large hard drives located inside the cab of the pickup truck.

For this study, the GCI camera collected raw data continuously during almost all hours of gas station operation. The camera was aimed at one side of a chosen island for the day such that the front few inches of the gas pumps were on one side of the frame and the other side of the frame was on the far side of the vehicle being refueled. The GCI camera was elevated as high as possible so that video could be simultaneously obtained on the vehicle at the near pump and the vehicle at the far pump. The raw data was processed on site in 30-second blocks. One 30-second block of raw data was processed to produce a 30-second black and white Enhanced MidWave video. This video was stored on the hard disk. Thus, the hard disk contained all of the continuous raw data and a series of 30-second Enhanced MidWave videos. Because the processing of the 30-second block of raw data takes approximately 10 seconds, the 30-second Enhanced MidWave videos are separated by at least 10 seconds to allow time for processing.

While the raw data contains infrared measurements from 3.2 to 3.5 and 7.5 to 14 μm, the Enhanced MidWave videos are created only from the measurements obtained in the 3.2 to 3.5 μm band, which is the infrared region where most hydrocarbon molecules absorb infrared radiation.

The GCI camera produces infrared videos of hydrocarbon vapor emissions by imaging the ambient infrared radiation in the scene. Where hydrocarbon vapor is not present, the infrared measurements show the radiation from the background. However, when hydrocarbon vapor is present in the scene, the vapor absorbs some of the infrared radiation that is being emitted by the background, and the absorption is a function of time and space across the scene. This produces time-varying contrasts or discontinuities in the infrared video images. Because the camera produces video, the movement of these discontinuities is perceived by a person viewing the video as a cloud that is moving in the scene.

The GCI camera is recalibrated every 8 minutes by inserting a white card in the optical path. Recalibration is necessary because the sensor array can become saturated by strong infrared radiation, for example, from the reflection of sunlight from various shiny objects in the scene.

Calibration is performed automatically inside the GCI camera. It results in a white screen in the Enhanced MidWave videos.

At the end of each day of testing at the Arvada station, Rebellion Photonics personnel downloaded the Enhanced MidWave video files onto a thumb drive for archiving by ERG personnel. Rebellion personnel did not provide the raw GCI data. Two days were needed during the two weeks to download the data from the field servers, therefore no data was collected on July 14 or 19 during the study period July 7 – 23.

2.2 Reference Vehicle Metered Releases

During several days of GCI camera data collection, CDPHE provided a reference vehicle and released metered amounts of known hydrocarbon vapor concentrations. The objective was to use the metered releases as controls to judge the concentration of hydrocarbons emitted by refueling vehicles.

Two types of HC gases were released as artificial refueling emissions: butane, and gasoline headspace vapor. Mixtures of these gases with nitrogen were used to simulate refueling emissions. The artificial refueling releases were released from a reference vehicle that had low evaporative emissions of its own. Releases were made at the participating gas station at the same gas-pump locations used by private vehicles whose emissions were being monitored by the GCI camera.

The total flow of the artificial releases was 10 gallons/minute, which is a typical fuel dispensing flow of gas station fuel pumps. According to our ReddyEvap 2010 calculations, headspace vapor in Denver at summer temperatures is approximately 50 vol% HC vapor[7]. We used 10 gallons/minute and 50 vol% HC as the basis for determining artificial refueling emissions release flow and composition. Reference vehicle hydrocarbon vapor release mixtures were produced to simulate 10%, 30%, and 100% of the equilibrium gasoline headspace concentrations (i.e., of 50 vol% HC).

Figure 2-5 shows a photograph of the reference vehicle, a 2003 Ram pickup truck. CDPHE fitted the pickup truck with a butane tank, a gasoline caddy, and a pressurized cylinder of nitrogen to provide hydrocarbon / nitrogen mixtures to one of three vehicle locations: the

[7] We made ReddyEvap 2010 headspace calculations using the following inputs: 8.7 psi RVP fuel, 10 vol% ethanol in the fuel, 88 F ambient temperature, 0.83 atm barometric pressure. The partial pressures were: ethanol 62.53 mmHg, non-ethanol HC 289.96 mmHg. The barometric pressure was 631 mmHg (=0.83 * 760 mmHg). Therefore, the headspace composition was: ethanol 10 vol%, non-ethanol HC 46 vol%, and air 44 vol%.

actual fuel fill door on the left side of the vehicle, an artificial fuel fill location on the right side of the vehicle behind the passenger door, and the top of the fuel tank underneath the vehicle.

We needed to have a foolproof way to designate the reference vehicle test condition by including some physical element in the video scene. Test conditions were defined by gas released (butane, or gasoline headspace vapor), relative HC release concentration (100%, 30%, or 10%), and release point (left fuel fill door, right fuel fill door, or top of tank). The key challenge is that conventional printed text cannot be read in the infrared; we needed a shape that could be clearly seen in the infrared videos. Our solution was a pinwheel, whose orientation when placed on the test vehicle windshield, as shown in Figure 2-6 indicated the test condition. One side of the pinwheel was for butane releases and the other side for gasoline headspace vapor releases. The pinwheel had six rotational orientations that indicated the six combinations: 100/Door, 030/Door, 010/Door, 100/Tank, 030/Tank, and 010/Tank. To be able to distinguish the orientation, we placed a plastic container filled with ice, which has low infrared emissions, at a specified location on the pinwheel. Finally, the pinwheel was placed under the windshield wiper on the passenger's side, in the center, or on the driver's side to designate releases from the passenger-side fuel fill door, the top of the gas tank, or from the driver-side fuel door, respectively. For example, even though the text cannot be read on the pinwheel in Figure 2-6, the pinwheel location and configuration indicate that the test condition is for Butane/030/Tank.

Appendix A shows a listing of the successfully created reference vehicle test conditions and results.

Figure 2-5. Reference Vehicle Providing Metered Artificial Refueling Releases

Figure 2-7 shows a piping diagram for the butane / nitrogen mixing and flow regulation. Three rotameters on the outlet of the butane tank control the butane flow, a single rotameter on the outlet of the nitrogen cylinder control nitrogen flow, and a diverter valve is provided to send the mixture to either the left fuel fill door, the right fuel fill door, or the top of the gas tank. The flows of butane / nitrogen were adjusted so that the total flow of the mixture was maintained at 10 gallons per minute, which is the approximate refueling flow of the gas pumps at the station. Table 2-1 shows the flows of the components used to produce the butane mixtures.

Table 2-1. Test Conditions for Butane Releases

Test Condition Name	Relative Headspace HC Mass	Butane Flow	Carrier (i.e. N2) Flow	Total Gaseous Release
	(%)	(gal/min)	(gal/min)	(gal/min)
BUT100	100	5.0	5.0	10.0
BUT030	30	1.5	5.0	6.5
BUT010	10	0.5	5.0	5.5

Figure 2-8 shows the reference vehicle setup for releases of headspace vapor. Gasoline from the plastic caddy, which was placed in the bed of the pickup truck, was pumped through a flow meter to the vehicle’s gas tank. The inlet at the fuel fill pipe was sealed so that vapor from the vehicle's fuel tank was not allowed to come out the fuel fill pipe. Instead, the vapor from the top of the vehicle fuel tank was routed to the tee at the exit of the nitrogen cylinder. From there the mixture was routed to either of the fuel fill doors or the top of the gas tank underneath the vehicle. This arrangement allowed mixtures of 10% and 30% gasoline headspace vapor in nitrogen. To produce 100% fuel headspace vapor concentrations, gasoline was pumped directly from the Costco fuel pump into the test vehicle fuel tank. Table 2-2 shows the flows of the components used to produce the headspace vapor mixtures.

Table 2-2. Test Conditions for Head Space Vapor Releases

Test Condition Name	Relative Headspace HC Mass	Gasoline Flow into Fuel Tank	Liquid Gasoline Source	Carrier (i.e. N2) Flow	Total Gaseous Release
	(%)	(gal/min)		(gal/min)	(gal/min)
GAS100	100	10.0	Station gas pump	0.0	10.0
GAS030	30	3.0	Caddy	3.5	6.5
GAS010	10	1.0	Caddy	4.5	5.5

During releases of hydrocarbon / nitrogen mixtures from the reference vehicle, Rebellion personnel provided feedback to ensure that the raw data had been successfully collected by the GCI camera.

Figure 2-7. Reference Vehicle Set-Up for Butane Releases

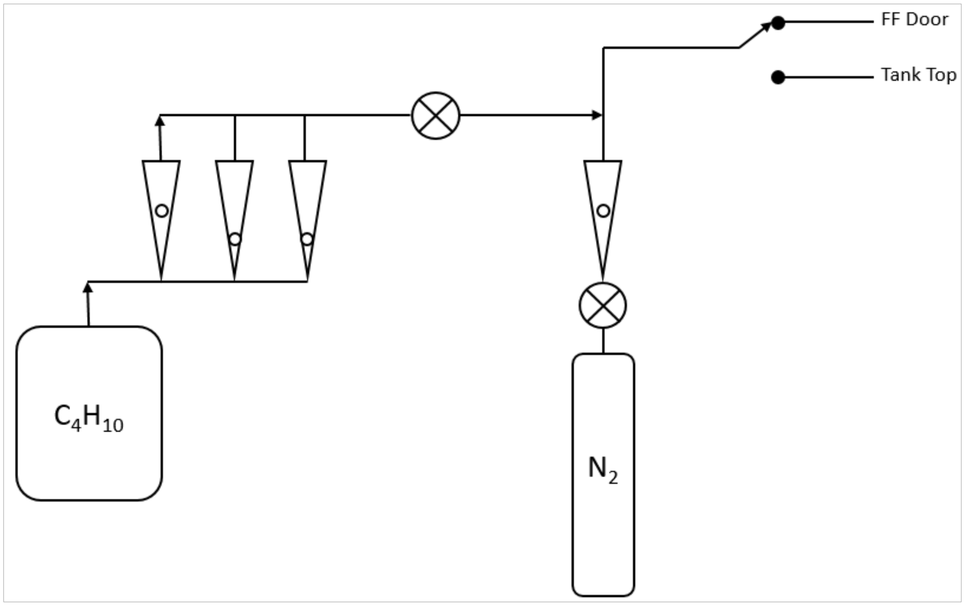
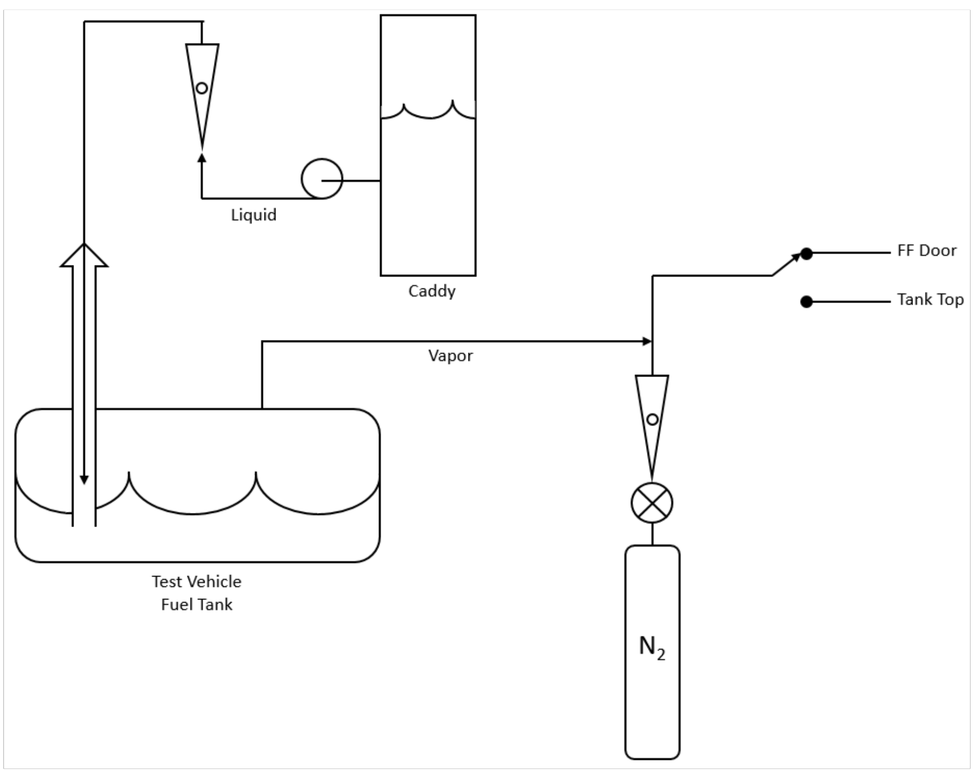


Figure 2-8. Reference Vehicle Set-Up for HeadSpace Vapor Releases



2.3 Gas Station Fuel Pump Transaction Data

Refueling events of large volumes of dispensed gasoline are potentially more likely to have larger refueling emissions than smaller volumes. Additionally, timestamps of transactions at each pump help confirm the timing of refueling activities. Costco provided pump transaction data with pump number, dispensed fuel grade and volume, date and time of credit card validation which occurs before refueling can begin, and the date and time of fuel nozzle hang-up for all transactions at the Arvada gas station during the data collection period.

2.4 Video Cameras

The entire gas station refueling area was filmed from a single fixed perspective during the hours that data collection took place. Two cameras were used, one for taking continuous video of the station, and one that took a still image every 10 seconds. The cameras used were GoPro Hero 5 cameras, mounted to a custom-built plate with gimbaled camera attachment points used to easily adjust the fields of view for each camera. The cameras were placed on top of the attendant’s monitoring building near the edge of the fueling station area.

To allow for the cameras to run continuously for 8-12 hours at a time, rechargeable USB batteries were used so that cameras could be plugged in to give them long run times. Batteries were charged overnight, and extra batteries were always in reserve for backup or if a battery could not be charged in time overnight.

The GoPro cameras could be controlled wirelessly and remotely via an iPad application that allowed for a live view of what the camera saw, adjustment of settings, and the starting and stopping of filming. This application was used to confirm the correct field of view for the cameras when positioning them on top of the building and to periodically check the units and ensure that they were still running and not out of storage space.

The GoPro Hero 5 model is capable of 12 mega-pixel still images and up to 4K resolution live video. For this project, the still images captured every 10 seconds were taken at 4000 x 3000 pixels and 72 dpi. Live video was filmed using 1920 by 1440 pixels to maximize storage space and reduce the heat created by the camera when continuously run.

Heat was a significant issue during filming and caused the cameras to shut down when they reached a critical temperature. Ambient temperatures during the sampling in July were in the 80s to 90s. A custom-built shade was constructed to shelter the cameras from direct sunlight and reduce the heat, however the cameras would still periodically shut down in the afternoon hours of the day when it was hottest.

Unfortunately, the combination of the limited maximum resolution available for these camera models and the camera-to-pump distance produced images and videos that were not sufficient to read individual license plates. It is recommended that for future efforts the cameras be placed on the fueling islands or other locations closer to the test vehicles, or budget for more advanced cameras that could capture legible license plates at the distances being used for the task. Adequate cooling and shelter for the devices should also be planned to prevent overheating.

2.5 Weather Station

An AcuRite model 06006 Weather Sensor was used to record key weather conditions including wind speed, wind direction, and temperature under the gas station canopy. The weather station, shown in Figure 2-9, was placed beneath the Costco Arvada gas station canopy to estimate the local conditions experienced by the refueling vehicles and their evaporative plumes. The weather station receiver logged comma delimited data of the following variables in 12-minute intervals: temperature, humidity, barometric pressure, rain, wind speed, wind speed average, peak wind, and wind direction. Because the weather station was placed beneath the gas station canopy, the rain measurements will not be used.

The weather data – particularly the wind speed and direction – could be used to explain plume behavior. The receiver was located about 40 meters from the weather sensor. For independence from Costco line power, the receiver was powered by a lead/acid car battery and an inverter, as shown in Figure 2-10. The weather data include timestamps written by the receiver, and the resultant comma-separated values files were individually saved and dated. The files were then merged with the Costco Arvada gas station dataset via the timestamps with the SAS program. Because the weather data were recorded in 12-minute intervals, the end-of-interval readings were applied to each span of time.

2.6 Colorado Vehicle Registration Information

For the purposes of analyzing the refueling data of different vehicles coming through the station, we wanted to be able to confirm a vehicle's identity at the time they were refueling. The reason for this was that our experience has been when recording license plates and vehicle descriptions, analysis or attempts to confirm identity of the vehicles later during analysis was unreliable. Therefore, for this study we developed a procedure for identifying vehicles as they were refueling by looking up their license plates in a recent snapshot of the Colorado vehicle registration database while it was still possible to further examine the vehicle before it drove away.

Figure 2-9. Weather Station Sensor Array

Figure 2-10. Weather Station Receiver, Display, and Logger Module

Making this possible at the time of vehicle sampling required that we had a method of using the observed vehicle's license plate to rapidly lookup the year, make, and model of the vehicle arriving at the gas pump. This was accomplished by having a technician use an iPad while on the refueling island to record the license plate of a vehicle refueling at that island. Once entered, the license plate accessed a lookup file created from the Colorado registration database that could present the vehicle year, make, and model to the technician for visual confirmation.

Accordingly, CDPHE obtained an April 2019 snapshot of the Colorado registration database and provided it to ERG for pre-processing before the beginning of field testing. ERG requested and received only registration database variables for license plate, VIN, year, make, model, and empty vehicle weight. Vehicle owner name and address were not requested so that the identity of owners was protected. The empty vehicle weight variable was the only registration database weight variable that was well populated to help determine vehicle class and, with model year, to determine the ORVR status of each vehicle. After the end of field testing and during the data analysis phase of the study, CDPHE provided a July 2019 snapshot, which allowed us to confirm identities of a few more Colorado vehicles that had refueled at the Arvada gas station during the field data collection period.

The 6,268,768 registration observations in the July 2019 snapshot were read by a SAS program[8], filtered for relevant observations, and output into a CSV data file for use by the iPad data collection system. After filtering, 4,976,046 registration observations remained for use by the iPad system. The following observation filters were used: delete missing plates; delete missing VINs; delete model years older than 1972; delete non-gasoline fuel types; delete trailers, motorhomes, buses, and special mobile machinery; and for replicate plates, keep only the observation with the most recent registration date.

In the Colorado registration database snapshot, the make and model fields were abbreviated. For example, a Jeep Renegade might be listed as make=JEEP model=REN. While makes were consistently spelled, models were not, and in many cases, values for models were blank. We wanted to maximize the iPad technician's ability to confirm vehicle identities by displaying unambiguous, non-abbreviated model descriptions on the iPad, e.g. Renegade not REN. Therefore, we used the ERG VIN Decoder to decode the VINs in the snapshot, and where the VIN decoded without error, the SAS program replaced the registration make and model with the decoded make and model.

[8] P:/CDPHE/Regis2019/COreg_find_mk_mod_yr.sas

For vehicles with out-of-Colorado plates, since we did not have vehicle registration information for the other 49 states, the iPad allowed for entering the plate number but allowed entering only that the plate was out-of-state. However, some iPad technicians took the initiative to write down the states, plates, and vehicle descriptions for such vehicles. During the analysis phase, we found that mycar.com could be used to look up several of the confirming vehicle descriptions for out-of-state vehicles using the plate state and plate number as inputs.

2.7 iPad Data Collection System

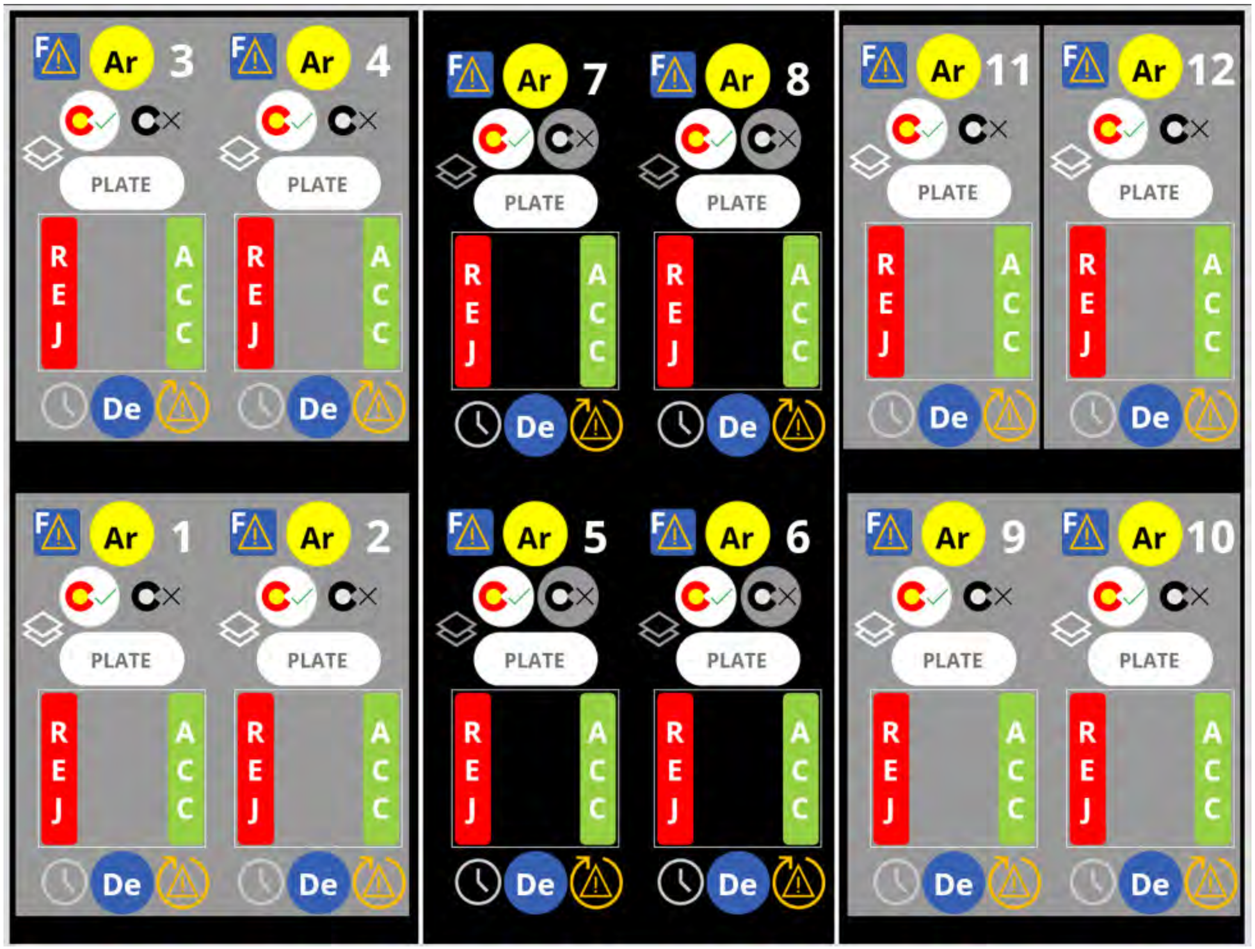
We expected that the Costco Arvada gas station would be very busy as customers waited in line and refueled their vehicles. Therefore, even though we were going to record data and observe refueling emissions at one refueling island at a time, we needed to develop a method of data collection that was reliable and easy for a technician who was stationed at the island to use. We also wanted to use procedures that would minimize concerns and questions asked by gas station customers. To meet these needs, we developed an electronic data collection system.

The Apple iPad was selected as the electronic field device for its ease of use and the high availability of programming resources and data collection applications already developed for it. The final designed and implemented data collection system was custom-built on the Microsoft PowerApps platform and used the corresponding Apple iOS operating system “PowerApps” application that allows PowerApps programs to run directly on the iPad. The data collection application presented a graphical user interface for the technician to enter information on the iPad for each fueling event while right at the gas pump. The graphical interface showed data entry fields for all pumps simultaneously so that multiple fueling events at different pumps could be tracked at the same time. Exact data entry steps for the application are detailed further below.

A mobile internet connection on the iPad allowed for the data to be uploaded in real time as it was collected, which was sent to a database located on a Microsoft SQL Server instance running on the cloud-based Microsoft Azure platform. A second database running on the same platform containing around 5 million Colorado vehicle registration records was used by the iPad application to rapidly look up license plates as the technician entered them in the license plate field and returned make, model, and year of the vehicle. During the active data collection portion of the project, the new data in the SQL Server database was exported daily to a flat text file that was reviewed for quality and preliminary analysis.

Figure 2-11 shows a screen capture of the iPad interface developed for this study. The screen is made up of three columns that represent the three islands at the gas station. The four gas pumps at each island are numbered 1 to 12 on the screen so that they correspond to their positions on the three islands. The arrangement of the pump numbers on the screen is the same as the arrangement of the physical pumps on the islands at the gas station. The background color in the screen indicates the island where data is currently be being collected. In Figure 2-11 the data is being collected on the center island since its background is black and the two side columns are "grayed out."

Figure 2-11. Refueling Vehicle Data Collection Interface for iPad



Each island area on the screen is made up of four sets of data collection displays and buttons, so that data from the four pumps can be collected simultaneously. Consider the buttons for Pump 7 at the top left of the center island in Figure 2-11. The technician pushes the top yellow button labeled "Ar" (Arrive) when a vehicle arrives at the pump. If the vehicle has a Colorado plate, they push the white and red "C✓" button, otherwise they push the gray and black "C×" button to indicate a non-Colorado plate. Then, the technician uses a keypad that appears on the iPad screen to enter the vehicle's license plate, which will appear in the white oval labeled "PLATE." If the plate is a Colorado plate, the iPad application requests a look-up over the internet connection from the cloud-hosted SQL Server database with Colorado vehicle registrations. If the Colorado plate registration can be found, the app displays the make, model, and year of the vehicle in the black rectangle below the white "PLATE" entry field. The technician then compares the iPad-displayed make and model with the vehicle that is in front of them at the gas pump. If they agree, the technician pushes the green "ACC" ("Accept") button. If they don't agree, he pushes the red "REJ" ("Reject") button. When the vehicle driver has finished refueling and begins to pull away from the gas pump, the technician pushes the blue "De" (Depart) button at the bottom of the screen pump display.

If the vehicle has a non-Colorado plate, then the technician enters the plate, but since the system does not contain registration databases for all states, it cannot display a year, make, and model.

Additional buttons for each pump area on the screen help the technician enter data for unusual situations and for special data collection needs. The blue "F" (Forgot) at the top left of each pump area is pressed by the technician in the event that a new vehicle has arrived at that pump and the technician had forgotten to press "De" (Depart) for the previous vehicle at that pump. The orange triangle with an exclamation mark at the bottom right of each screen pump area forces the data collection for the current vehicle to terminate and the entry fields to reset. The clock icon on the lower left of each screen pump area is used to put a clock synchronization timestamp in the database on demand, which was performed periodically by the technicians to place a benchmark in the database to be used later for synchronization from other data sources, such as videos or gas pump fueling data received from Costco.

Refueling activity at the gas station island is complex because activities at each pump are independent of each other. This means that individual vehicles can arrive and depart and pump fuel at any time regardless of what is occurring at other pumps on the island. Therefore, the iPad interface was designed so that the technician could collect data on all four pumps at the same time subject to the constraint that the order of button pushing for a given pump was constrained to follow a logical sequence. To help the technician determine where each vehicle's data entry was in the sequence, after buttons are pushed on the iPad screen, button backgrounds change color to a pink highlight to indicate that they have been pushed.

Individual data collection steps for observing a refueling event are recorded and uploaded as they are completed, rather than waiting for an entire fueling event to be completed and that full record to be uploaded. As buttons on the iPad interface are pushed for each observation step, a timestamp for each push and the corresponding keystroke event code for that button or information entered in a field are transmitted via the mobile internet connection to the cloud-hosted Microsoft SQL Server database. Table 2-3 gives the keystroke event codes. Table 2-4 shows an excerpt of the database to provide an idea of the format of the data being collected.

Table 2-3. iPad Keystroke Event Codes Written to Microsoft SQL Server Database[9]

Code	Meaning
A	"Arrive" New vehicle is arriving at the pump, but the plate state has not been entered yet.
C	Colorado plate.
O	Out of state plate.
R	"Reject" The make/model of the vehicle at the pump does NOT match the registration database make/model found by looking up the vehicle's license plate in the database.
T	"Accept" The entered plate is verified (good) against the vehicle appearance. The make/model of the vehicle at the pump DOES match the registration database make/model found by looking up the vehicle's license plate in the database.
D	"Depart" Vehicle is leaving the pump. Writes the plate and vehicle registration lookup results (VIN, year, make, model, empty vehicle weight).
F	"Forgot" Technician did not observe when vehicle left the pump and either now sees the pump is empty or that a different car is present. Writes the plate and lookup results to database, just as for "D".
E	"Reset" Start iPad data collection for this refueling event. Pump; plate and vehicle lookup results are NOT saved or written to database; they are only written on a "D" or "F".
S	"Sync" Clock synchronization timestamp.

The iPad interface was developed during repeated visits to the Costco Arvada gas station before the actual field study began. During these visits early prototypes of the iPad interface and the associated collection system were tested and then modified until the entire system was easy for the technician to use and could collect accurate vehicle and refueling data.

[9] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\QAPP/DataProcessingSteps_eMail-190711.msg

Table 2-4. Sample Data in Microsoft SQL Server Database as Uploaded from the iPad Interface[10]

dbo_GasStnMon2019v1

msEpochTime	Pump ID	Event	Recorded PLATE	Year	Make	Model	VIN	DbPlateID	TimeDateStamp	Empty Weight
1563936332205	5	D	ABC123*	2016	TOYOTA	Highlander XLE	5TDJKRFH1GS******	ABC123*	7/24/2019 2:45:54 AM	4400
1563936227562	5	T							7/24/2019 2:43:49 AM	
1563936207970	5	C							7/24/2019 2:43:29 AM	
1563936204659	5	A							7/24/2019 2:43:27 AM	
1563936146511	6	D	DEF456*	2002	SUBARU	Impreza	JF1GD29692G******	DEF456*	7/24/2019 2:42:41 AM	3100
1563936017867	4	E							7/24/2019 2:40:20 AM	
1563936014003	4	A							7/24/2019 2:40:16 AM	
1563935994433	6	T							7/24/2019 2:39:55 AM	
1563935971942	6	A							7/24/2019 2:39:37 AM	
1563935973132	6	C							7/24/2019 2:39:37 AM	
1563935969802	5	E							7/24/2019 2:39:32 AM	
1563935968079	5	A							7/24/2019 2:39:29 AM	
1563935832402	7	D	GHJ789*	2011	DODGE	Charger R/T	2B3CM5CTXB******	GHJ789*	7/24/2019 2:39:14 AM	4400
1563935772498	5	D	KLM321*	1992	FORD	F150 Regular Cab	1FTDF15H4NK******	KLM321*	7/24/2019 2:36:15 AM	4200
1563935770742	7	T							7/24/2019 2:36:12 AM	
1563935723696	7	C							7/24/2019 2:35:25 AM	
1563935672015	7	A							7/24/2019 2:34:34 AM	
1563935598359	5	T							7/24/2019 2:33:19 AM	
1563935567212	5	C							7/24/2019 2:32:48 AM	
1563935561897	5	A							7/24/2019 2:32:43 AM	
1563935513204	7	D	PQR654*	2002	CHEVROLET	Blazer 4WD	1GNDT13S822******	PQR654*	7/24/2019 2:32:10 AM	4600
1563935366552	7	T							7/24/2019 2:29:28 AM	
1563935337335	7	C							7/24/2019 2:28:58 AM	
1563935336026	7	A							7/24/2019 2:28:58 AM	
1563935325620	5	D	STU987*	2009	JEEP	Patroit LHD 4WD	1J4FF28B69D******	STU987*	7/24/2019 2:28:54 AM	3200
1563935251707	5	T							7/24/2019 2:27:33 AM	
1563935234319	5	C							7/24/2019 2:27:16 AM	
1563935233292	5	A							7/24/2019 2:27:15 AM	
1563934944319	7	D	VWX123*	2007	CHEVROLET	1500 4WD	3GNFK12347G******	VWX123*	7/24/2019 2:26:55 AM	5700

2.8 Gas Station Logsheets

As testing began at the Arvada Costco gas station, it became apparent that the refueling behavior of customers was sometimes unusual. In these special cases, the iPad data collection interface could not be used to document everything that was happening. Therefore, we began collecting supplemental information on paper logsheets for potential use during data analysis. The logsheets had columns for day of the week, date, pump number, nozzle hang-up time, and comments.

The types of events that produced paper logsheet entries included: multiple vehicles refueled on a single purchase, refueling of gas cans either by themselves or with a vehicle refueling, refueling lawn mowers brought to the gas station by a lawn mowing company, break-down of a vehicle at a fuel pump thereby blocking the pumps for use by others, multiple refuelings with multiple purchases on one vehicle at a pump, vehicles that entered credit card information on the pump but did not actually pump any fuel, notes regarding incorrect iPad button pushes, vehicles that partially fueled at one pump then pulled up and continued fueling at

[10] License plate numbers in this table are artificial.

a second pump, make and model information on non-Colorado license plate vehicles, and license plates of the additional vehicles refueled on the same credit card purchase.

2.9 Refueling Event Listing

After field data collection was complete, a SAS program combined each refueling event from the iPad data into one entry and synchronized the information to several other sources of data that were obtained at the same time, such as weather conditions, fueling volumes and credit-card timestamps from Costco, and file names of videos of each refueling event captured by the Rebellion Photonics GCI camera. This synchronizing and merging of multiple data sources produced a flat data file with a single-line entry for each fueling event.

The Arvada gas station field data collection effort produced several datasets:

- GCI camera 30-second Enhanced MidWave video files,
- iPad keystroke data,
- Weather station data, and
- Gas station pump transaction data.

We merged the above datasets in a way that produced a list of events with a single observation for each refueling event. We call that listing the event-by-event listing (ExE). After the ExE was created, we imported it into a SharePoint database so that all videos for a given refueling event could be viewed and evaluated. Then, the results of the video viewings were also appended to the SharePoint database.

Merging the datasets and creating the ExE was done by a SAS program[11]. Because the different datasets contain information on events as a function of time, we needed to merge them in the time domain. The problem with time-merging was that events from the different datasets never occurred at exactly the same time as events from another dataset. So, we could not simply merge by the time variable. Our solution was to put all data in a time-based listing that we call the piano roll[12]. The piano poll construction began with a file that had a time scale with one observation for each second and for all seconds from the beginning to the end of the field data

[11] P:\EPA_RefuelingEmissions_WA2-23\Summer2019\Analysis/read_field.sas

[12] Piano roll refers to the roll of paper used to operate the keys on a player piano. As the piano roll moves, punched holes in the paper tell which and when each piano keyboard key is depressed. A visual inspection of the piano roll tells when each key should be activated, or in our case, when each dataset activity was occurring.

collection period. Except for the Linking DateTime field, all other fields were initially blank. We created a group of fields for each of the four pumps (A, B, C, D) at an island.

Since the video filenames contained the date and time of the beginning of each video, and each video was exactly 30 seconds long, the filename was written to the filename field, which is common to all pump positions at the island; otherwise, the video filename field was left blank. The iPad keystroke information, which included vehicle description information, was entered for each pump position variable in a similar fashion since each keystroke had an associated timestamp. The vehicle descriptions were lagged down the piano roll vehicle fields to reflect when a vehicle was at the pump. Thus, for one refueling event, the vehicle descriptions at a given pump were the same from the time when the vehicle arrived until it departed. After that time period, the vehicle description fields were blank until the next vehicle arrived at the pump. Similarly, the gas station transaction data was used to enter the gallons dispensed for each pump position from the credit card approval timestamp through the pump nozzle hang-up timestamp. The weather station data was added to the piano roll so that all weather fields were filled based on the weather station’s average values for each 12-minute datalogging period. Finally, we brought in the transcribed reference vehicle test conditions and timing information.

We used the piano roll to check the time-alignment of the different datasets – particularly the Rebellion video time, the iPad keystroke time, and the Costco transaction time. We found that all three were already synchronized within 3 seconds. So, we made no adjustments to the time bases. The one exception was that we found that the transactions from Pump 9 were off by 4 minutes for a period on July 9. We corrected the times for that period.

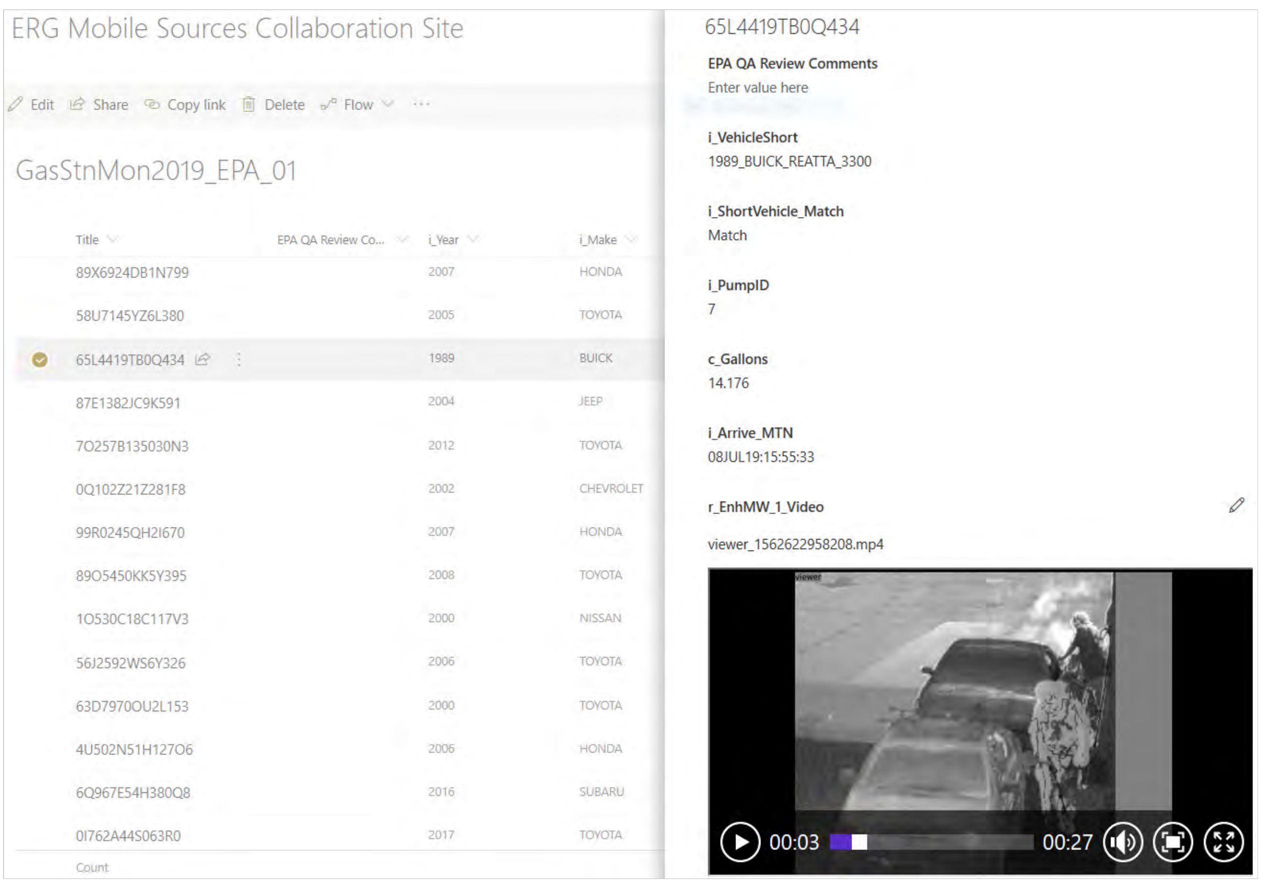
Once the piano roll was complete, the SAS program used it to create the ExE listing. That process worked by looking down the time series at the set of variables assigned to each pump position and retaining values for each refueling event appropriately. For example, a typical refueling event would start with a timestamp for arrival for one pump position. Then, as the program worked its way down the piano roll, it would retain credit card approval timestamp, video filenames for videos taken during the refueling event, nozzle hang-up timestamp, gallons dispensed, vehicle description, and finally the departure timestamp. We decoded the VINs in the ExE to provide vehicle types.

The counts of observations as merging proceeded give an indication of how merging and filtering affects the size of the final set of data to be analyzed. We videoed on one side of each day’s selected island from 9:14 a.m. on July 8 through Jul 23. On the fourteen days that we videoed, there were 27,689 gas pump transactions. On those days and on both sides of the videoed islands, there were 8,729 refuelings. During this period, we recorded 31,487 iPad keystroke event codes on refuelings on both sides of the selected island and, thereby, collected iPad information on 7,240 refuelings on both sides of the island. After considering that videos were only of refueling on one side of the island, we counted 3,817 refueling events where we have both iPad information and videos. We have 2,895 refueling events with videos on vehicles with Colorado plates that led to confirmed vehicle descriptions (VIN, year, make, model, and vehicle type). Of these, 2,376 had clear vehicle type assignments of LDGV, LDGT12, or LDGT34.

2.10 SharePoint Database

The ExE listing that was created by read_field.sas was read into a Microsoft SharePoint database using a program developed using the Microsoft Flow platform to automatically create and populate list entries on a Microsoft SharePoint Online website where team members could easily review the data, as shown by the example in Figure 2-12.

Figure 2-12. Example SharePoint Refueling Event Selected for Review



Each entry on the left side of the screen in the list represents a refueling event. By clicking on the Title in this list, the details of the refueling appear, as shown on the right side of the screen. In this example, the video in the lower right shows the refueling plume of the rear vehicle, a 1989 Buick Reatta (pre-ORVR), as a white fog. Each refueling event contained one to six videos, depending on the amount of time that a vehicle was at a gas pump. As part of the SAS merging program, the correct video was embedded into each SharePoint list record entry so that the reviewing technician could easily find and watch the videos for the event and make observations. During review the technician entered additional data into SharePoint records, such as the volume of fumes observed in the video during the fueling event. After all the records were reviewed, the entire SharePoint list of events was exported for importing into SAS to update the ExE listing to produce a final dataset for detailed analysis.

3.0 Arvada: Analysis of Refueling Data

We viewed Enhanced MidWave videos for the subset of all refueling events where we had a complete set of vehicle and plume information. Specifically, the subset of videos that were viewed had the following criteria: the vehicle had a Colorado license plate, a corresponding registration database VIN with non-missing model year, make, and model, a refueling event with at least one Enhanced MidWave video, and the video contained the vehicle that was refueling. We did not view videos of vehicles with non-Colorado plates, Colorado plates that could not be found in the April or July 2019 vehicle registration database snapshots, VINs that could not be decoded without errors or vehicles that were not videoed by the GCI camera.

The Enhanced MidWave videos were viewed in two phases. Initially, in Phase 1 we viewed all videos for refueling events that were selected as described above. The viewing instructions are presented in Appendix B. The results of those Phase 1 (preliminary) viewings are described in Section 3.4. During analysis of the Phase 1 viewings, we realized that short-duration puffs of emissions were occurring in many refueling events. Most of these puffs seemed to be associated with refueling activities, such as gas cap removal, start of fuel flow, nozzle click-off at the end of fuel flow, fuel tank topping-off, and not associated with the bulk fuel flow. We suspected that under these puff circumstances the as-designed evaporative emissions control systems of any vehicle may not be able to control the puffs. We judged that the Phase 1 video viewing results indicated an artificially high level of evaporative emission control system malfunction in the fleet. Therefore, in Phase 2 we re-viewed the videos of refueling events on confirmed ORVR vehicles that had any refueling emissions seen in the Phase 1 video examinations. The Phase 2 viewing instructions are given in Appendix C. The analysis of those results begins in Section 3.5.

3.1 Characteristics of the Sampled Vehicles

Before we describe the analysis of refueling emissions, this subsection presents characteristics of the sample of the Denver area vehicle fleet that refueled at the Arvada Costco gas station where the data was collected. Because the sample is from just a single gas station and the customers can only be Costco members, we cannot claim that the sample is representative of the Denver-area fleet; however, trends in the data can be used to explore behaviors and relationships that may be present in other fleet samples. Here we consider only those vehicles with refuelings that produced usable GCI videos.

Several different classes of vehicles refueled at the Arvada gas station during the study. Table 3-1 shows the eight vehicle classes evaluated and their gross vehicle weight rating

(GVWR) range descriptions. Because the pairs LDGT1 and LDGT2, and LDGT3 and LDGT4 have the same GVWR range descriptions, in this report we refer to them as LDGT12 and LDGT34.

Table 3-1. Description of Gasoline Vehicle Classes

Vehicle Class	Description	GVWR Range (pounds)
LDGV	Light-Duty Gasoline Vehicles	Passenger Cars
LDGT1	Light-Duty Gasoline Trucks 1	0 – 6,000
LDGT2	Light-Duty Gasoline Trucks 2	0 – 6,000
LDGT3	Light-Duty Gasoline Trucks 3	6,001 – 8,500
LDGT4	Light-Duty Gasoline Trucks 4	6,001 – 8,500
HDGV2B	Class 2b Heavy-Duty Gasoline Vehicles	8,501 – 10,000
HDGV3	Class 3 Heavy-Duty Gasoline Vehicles	10,001 – 14,000
HDGV4	Class 4 Heavy-Duty Gasoline Vehicles	14,001 – 16,000

The presence or absence of an ORVR system on a vehicle can be expected to have a large effect on the size of refueling emissions. Since the on-site technician used the iPad app, the license plate, and the Colorado registration database to visually confirm the identity of the Colorado vehicles at the Arvada gas station, we can determine the ORVR equipment in the sampled fleet. We used the VIN in the registration database to determine the gasoline vehicle class and model year for each vehicle. We used that information with the ORVR implementation schedule to determine ORVR equipment.

ORVR implementation schedules depend on vehicle class and model year. We have evaluated these vehicle classes in the sample: LDGV, LDGT1, LDGT2, LDGT3, LDGT4, and HDGV2b. We did not evaluate sampled vehicles in heavier vehicle classes since their ORVR implementations are complex and there were only about 16 of those vehicles anyway.

In Table 3-2 we group vehicle classes that have the same ORVR implementation schedule. As an example, for LDGVs, all model years before 1998 had no ORVR equipment, and all model years 2000 and after did have ORVR. 1998 and 1999 were ORVR implementation transition model years for LDGVs. For the transition model years, we have just estimated the number of non-ORVR and ORVR counts by applying the minimum phase-in percentage that manufacturers had to follow to the vehicle count in each transition model year. Since the number of sampled vehicles in the transition years is a relatively small fraction of the total number of vehicles in the sample, estimating the ORVR/non-ORVR apportionment for transition model years contributes only a small uncertainty. The table shows that about 90% of the Costco Arvada customers that we sampled during the three-week study in July 2019 were originally equipped with ORVR systems.

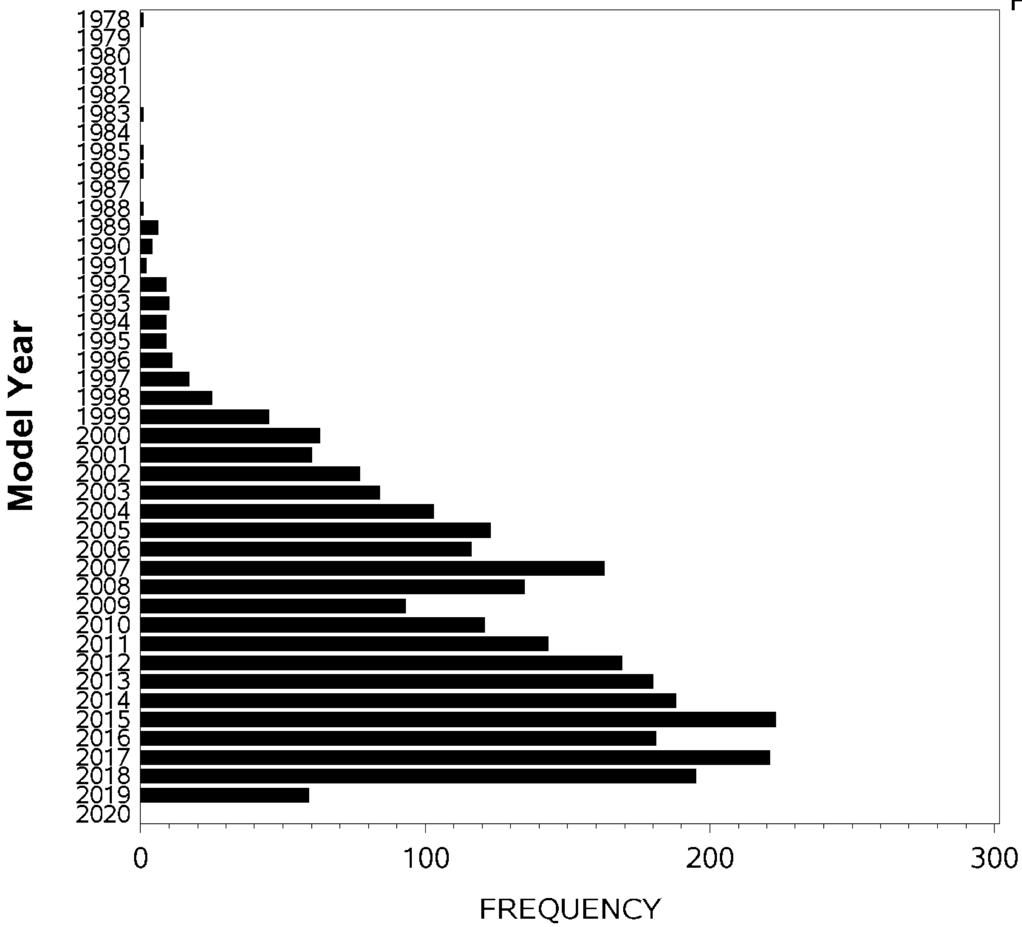
Table 3-2. ORVR Equipment in the Arvada Sample[13]

Vehicle Class (GVWR Range)	Model Year Group	ORVR Implementation	Vehicle Count	non-ORVR	ORVR
LDGV (passenger cars)	pre-1998	0%	23	23	
	1998	40% min	9	est 5	est 4
	1999	80% min	17	est 3	est 14
	2000-2019	100%	723		723
LDGT1 and LDGT2 (0 - 6000 lbs)	pre-2001	0%	78	78	
	2001	40% min	25	est 15	est 10
	2002	80% min	30	est 6	est 24
	2003-2019	100%	1046		1046
LDGT3 and LDGT4 (6,001 - 8500 lbs) HDGV2B (8,501 - 10,000 lbs)	pre-2004	0%	108	108	
	2004	40% min	27	est 16	est 11
	2005	80% min	25	est 5	est 20
	2006-2019	100%	490		490
Total			2601	259	2342
(%)			100%	10.0%	90.0%

Figure 3-1 through Figure 3-4 show distributions of vehicle model year, empty weight, tank capacity, and canister capacity. The refueling vehicles generally had newer model years, shown in Figure 3-1. Less than 10% of vehicles were model year 2001 or older, and about half of vehicles were model year 2012 or newer. We used the Colorado vehicle registration database and the vehicle's license plate to look up the vehicle empty weight, which was the only weight variable widely populated in the database. Figure 3-2 shows the distribution of empty vehicle weights. EPA was able to determine the fuel tank capacities (gallons) and evaporative emission control system canister capacities (g) for most of the videoed vehicles in the study, as shown in Figure 3-3 and Figure 3-4. For some trucks, different options for multiple fuel tanks were offered by manufacturers. In such cases, the tank and canister capacities could not be determined from generic VIN information.

[13] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Data QC/EventByEvent_200225_ORVRdistribution.xlsx

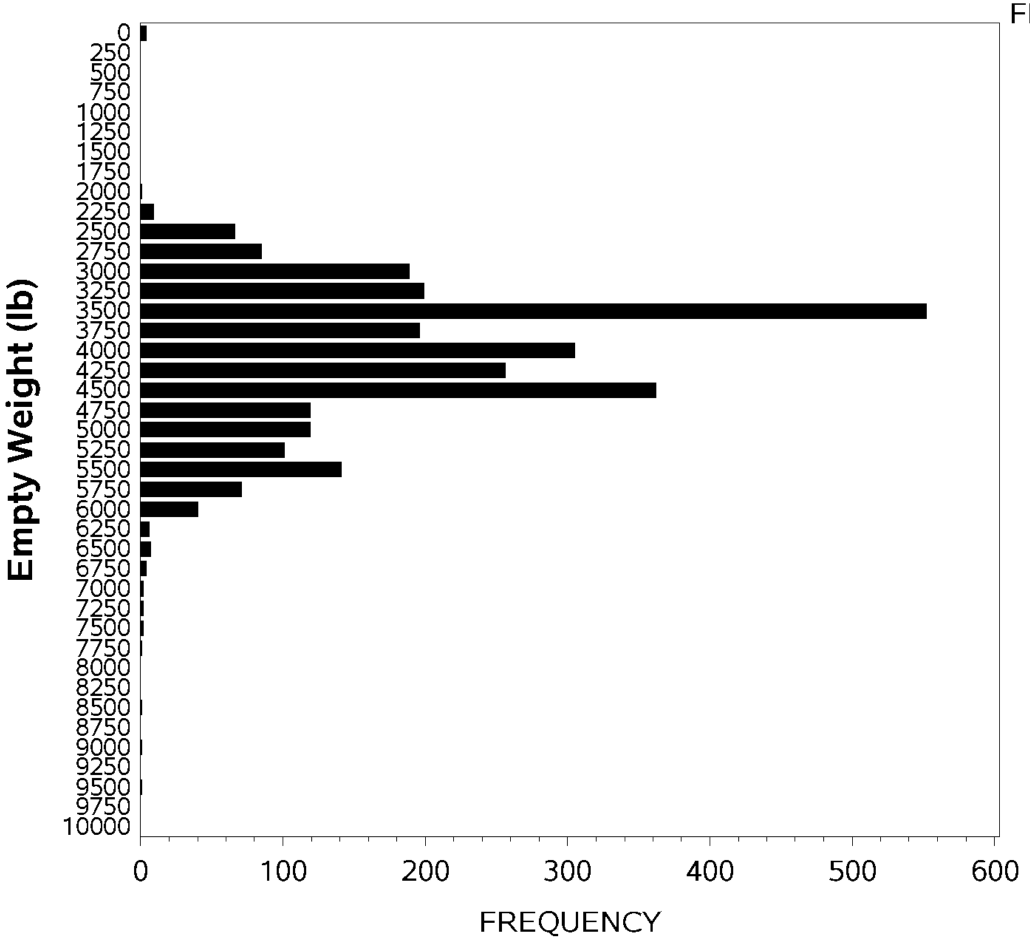
Figure 3-1. Model Year Distribution of Sampled Vehicles



Model Year	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
1978	1	1	0.04	0.04
1979	0	1	0.00	0.04
1980	0	1	0.00	0.04
1981	0	1	0.00	0.04
1982	0	1	0.00	0.04
1983	1	2	0.04	0.07
1984	0	2	0.00	0.07
1985	1	3	0.04	0.11
1986	1	4	0.04	0.14
1987	0	4	0.00	0.14
1988	1	5	0.04	0.18
1989	6	11	0.21	0.39
1990	4	15	0.14	0.53
1991	2	17	0.07	0.60
1992	9	26	0.32	0.91
1993	10	36	0.35	1.26
1994	9	45	0.32	1.58
1995	9	54	0.32	1.90
1996	11	65	0.39	2.28
1997	17	82	0.60	2.88
1998	25	107	0.88	3.76
1999	45	152	1.58	5.34
2000	63	215	2.21	7.55
2001	60	275	2.11	9.65
2002	77	352	2.70	12.36
2003	84	436	2.95	15.30
2004	103	539	3.62	18.92
2005	123	662	4.32	23.24
2006	116	778	4.07	27.31
2007	163	941	5.72	33.03
2008	135	1076	4.74	37.77
2009	93	1169	3.26	41.03
2010	121	1290	4.25	45.28
2011	143	1433	5.02	50.30
2012	169	1602	5.93	56.23
2013	180	1782	6.32	62.55
2014	188	1970	6.60	69.15
2015	223	2193	7.83	76.97
2016	181	2374	6.35	83.33
2017	221	2595	7.76	91.08
2018	195	2790	6.84	97.93
2019	59	2849	2.07	100.00
2020	0	2849	0.00	100.00

/proj1/EPA_RefuelingEmissions_WA2-23/Summer2019/Analysis/find_plumes_ORVR.sas 27FEB20 17:22

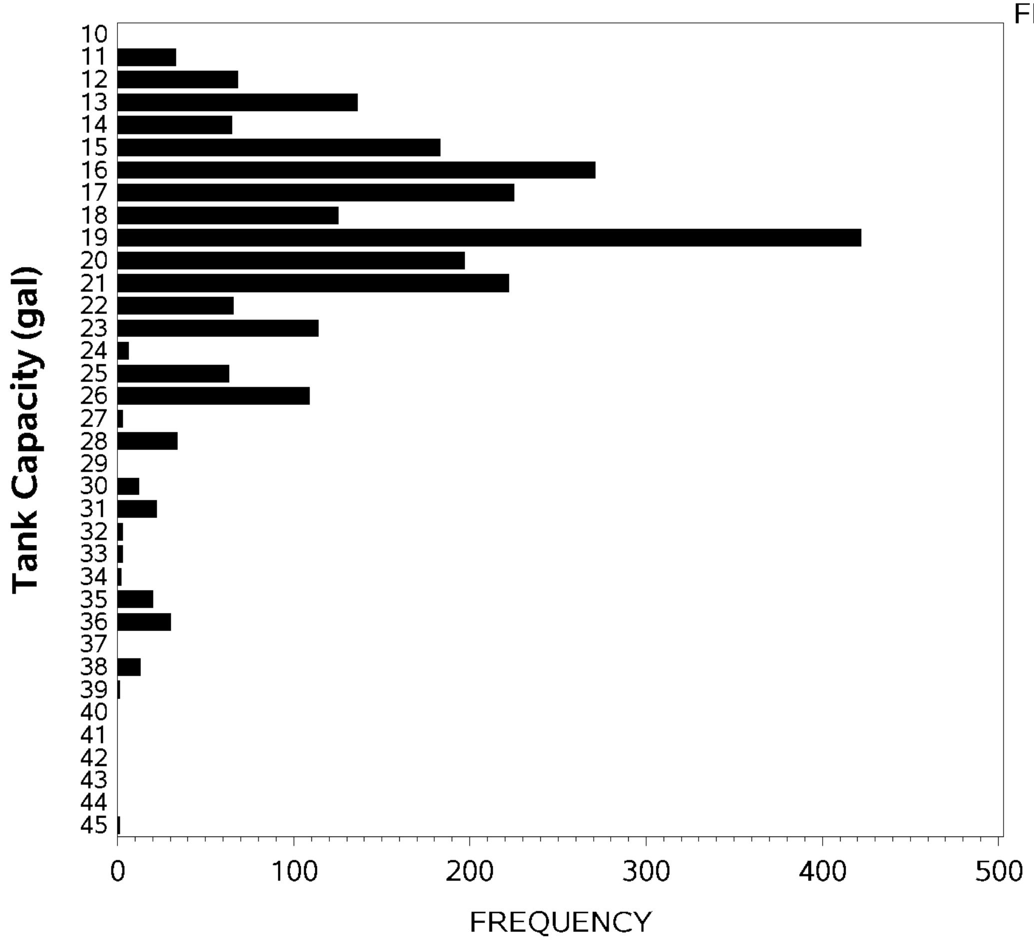
Figure 3-2. Empty Weight Distribution of Sampled Vehicles



Empty Weight (lb)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	4	4	0.14	0.14
250	0	4	0.00	0.14
500	0	4	0.00	0.14
750	0	4	0.00	0.14
1000	0	4	0.00	0.14
1250	0	4	0.00	0.14
1500	0	4	0.00	0.14
1750	0	4	0.00	0.14
2000	1	5	0.04	0.18
2250	9	14	0.32	0.49
2500	66	80	2.32	2.81
2750	85	165	2.99	5.81
3000	189	354	6.65	12.46
3250	199	553	7.00	19.46
3500	552	1105	19.42	38.88
3750	196	1301	6.90	45.78
4000	305	1606	10.73	56.51
4250	256	1862	9.01	65.52
4500	362	2224	12.74	78.25
4750	119	2343	4.19	82.44
5000	119	2462	4.19	86.63
5250	101	2563	3.55	90.18
5500	141	2704	4.96	95.14
5750	71	2775	2.50	97.64
6000	40	2815	1.41	99.05
6250	6	2821	0.21	99.26
6500	7	2828	0.25	99.51
6750	4	2832	0.14	99.65
7000	2	2834	0.07	99.72
7250	2	2836	0.07	99.79
7500	2	2838	0.07	99.86
7750	1	2839	0.04	99.89
8000	0	2839	0.00	99.89
8250	0	2839	0.00	99.89
8500	1	2840	0.04	99.93
8750	0	2840	0.00	99.93
9000	1	2841	0.04	99.96
9250	0	2841	0.00	99.96
9500	1	2842	0.04	100.00
9750	0	2842	0.00	100.00
10000	0	2842	0.00	100.00

/proj1/EPA_RefuelingEmissions_WA2-23/Summer2019/Analysis/find_plumes_ORVR.sas 27FEB20 17:22

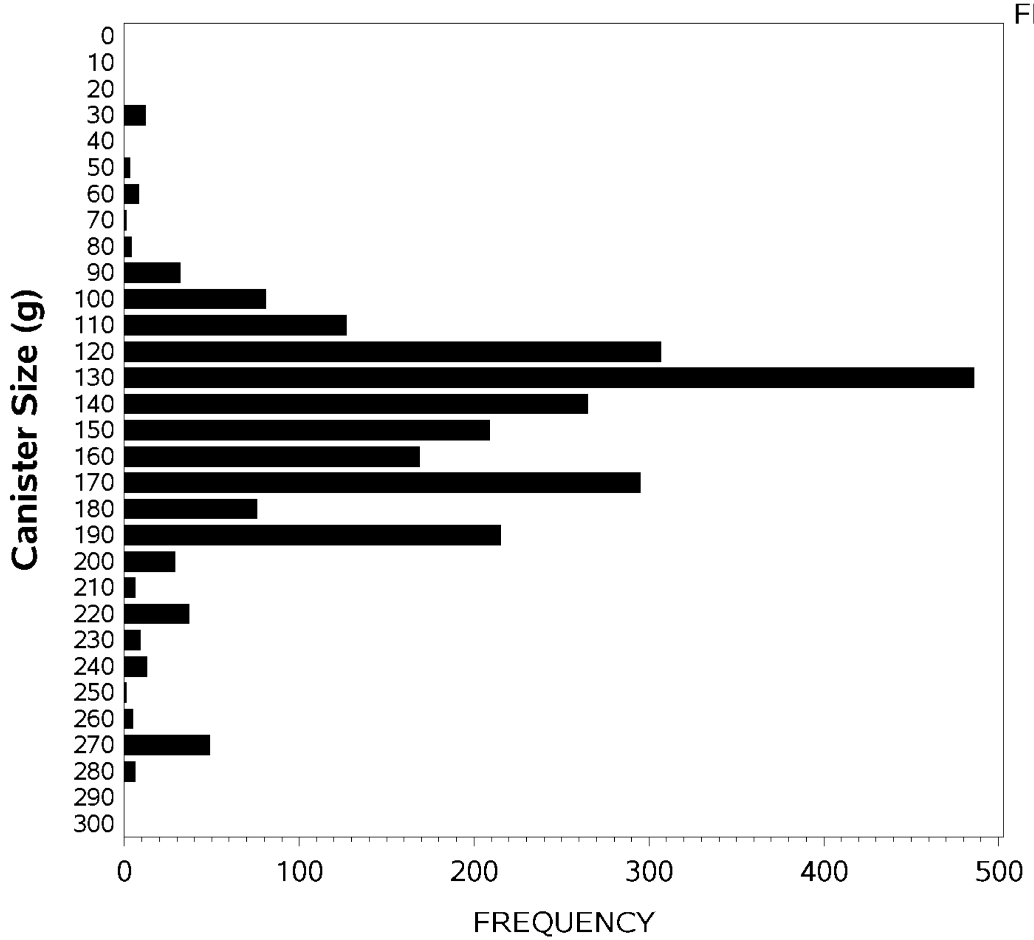
Figure 3-3. Fuel Tank Capacity of Sampled Vehicles



Tank Capacity (gal)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
10	0	0	0.00	0.00
11	33	33	1.35	1.35
12	68	101	2.78	4.12
13	136	237	5.55	9.68
14	65	302	2.65	12.33
15	183	485	7.47	19.80
16	271	756	11.07	30.87
17	225	981	9.19	40.06
18	125	1106	5.10	45.16
19	422	1528	17.23	62.39
20	197	1725	8.04	70.44
21	222	1947	9.06	79.50
22	66	2013	2.69	82.20
23	114	2127	4.65	86.85
24	6	2133	0.24	87.10
25	63	2196	2.57	89.67
26	109	2305	4.45	94.12
27	3	2308	0.12	94.24
28	34	2342	1.39	95.63
29	0	2342	0.00	95.63
30	12	2354	0.49	96.12
31	22	2376	0.90	97.02
32	3	2379	0.12	97.14
33	3	2382	0.12	97.26
34	2	2384	0.08	97.35
35	20	2404	0.82	98.16
36	30	2434	1.22	99.39
37	0	2434	0.00	99.39
38	13	2447	0.53	99.92
39	1	2448	0.04	99.96
40	0	2448	0.00	99.96
41	0	2448	0.00	99.96
42	0	2448	0.00	99.96
43	0	2448	0.00	99.96
44	0	2448	0.00	99.96
45	1	2449	0.04	100.00

/proj1/EPA_RefuelingEmissions_WA2-23/Summer2019/Analysis/find_plumes_ORVR.sas 27FEB20 17:22

Figure 3-4. Canister Capacity Distribution of Sampled Vehicles

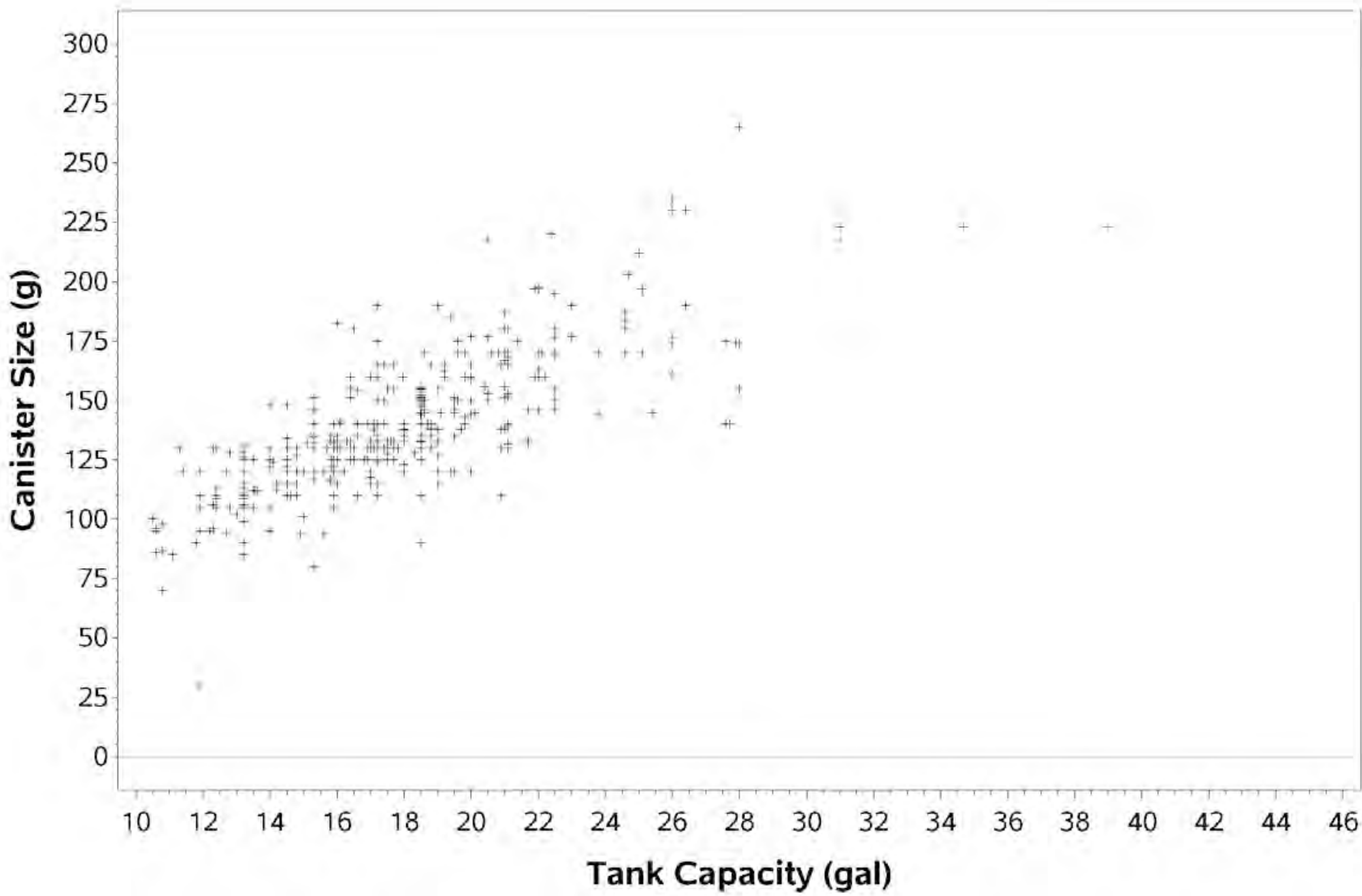


Canister Size (g)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0	0	0	0.00	0.00
10	0	0	0.00	0.00
20	0	0	0.00	0.00
30	12	12	0.49	0.49
40	0	12	0.00	0.49
50	3	15	0.12	0.61
60	8	23	0.33	0.94
70	1	24	0.04	0.98
80	4	28	0.16	1.15
90	32	60	1.31	2.45
100	81	141	3.31	5.77
110	127	268	5.19	10.96
120	307	575	12.56	23.52
130	486	1061	19.88	43.39
140	265	1326	10.84	54.23
150	209	1535	8.55	62.78
160	169	1704	6.91	69.69
170	295	1999	12.07	81.76
180	76	2075	3.11	84.87
190	215	2290	8.79	93.66
200	29	2319	1.19	94.85
210	6	2325	0.25	95.09
220	37	2362	1.51	96.61
230	9	2371	0.37	96.97
240	13	2384	0.53	97.51
250	1	2385	0.04	97.55
260	5	2390	0.20	97.75
270	49	2439	2.00	99.75
280	6	2445	0.25	100.00
290	0	2445	0.00	100.00
300	0	2445	0.00	100.00

/proj1/EPA_RefuelingEmissions_WA2-23/Summer2019/Analysis/find_plumes_ORVR.sas 27FEB20 17:22

The median gasoline tank capacity was 19 gallons with a range of 11 to 38 gallons. The median canister capacity was 140 grams with a range of 30 to 275 grams. We expected that vehicles with larger gas tanks would be fitted with larger capacity canisters since larger gas tanks impose a larger demand on the evaporative emission control system. The burden is particularly large for ORVR vehicles since the control system must limit refueling emissions. Therefore, Figure 3-5 shows a plot of canister capacity against tank capacity for LDGV, LDGT12, and LDGT34 vehicles with confirmed ORVR evap systems. The slope of the linear trend of canister capacity with tank capacity is about 6.2 grams/gallon.

Figure 3-5. Canister Size vs. Fuel Tank Capacity for Confirmed ORVR Vehicles



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For most refueling events, we were able to calculate the refueling percentage as the ratio of the gasoline dispensed (from the Costco transaction data) and the tank capacity (from the EPA look-ups). Figure 3-6 shows the refueling percentage as a function of model year. Events with percentages over 100% can arise when customers fuel gas cans or non-road vehicles, such as jet skis or lawnmowers, or when tank capacity records are inaccurate. The distribution of refueling percentages is shown in Figure 3-7. The median refueling percentage was 71%. About 6% of customers pumped 90% or more of their vehicle's tank capacity.

Figure 3-6. Percent Refueling vs. Model Year for Sampled Vehicles

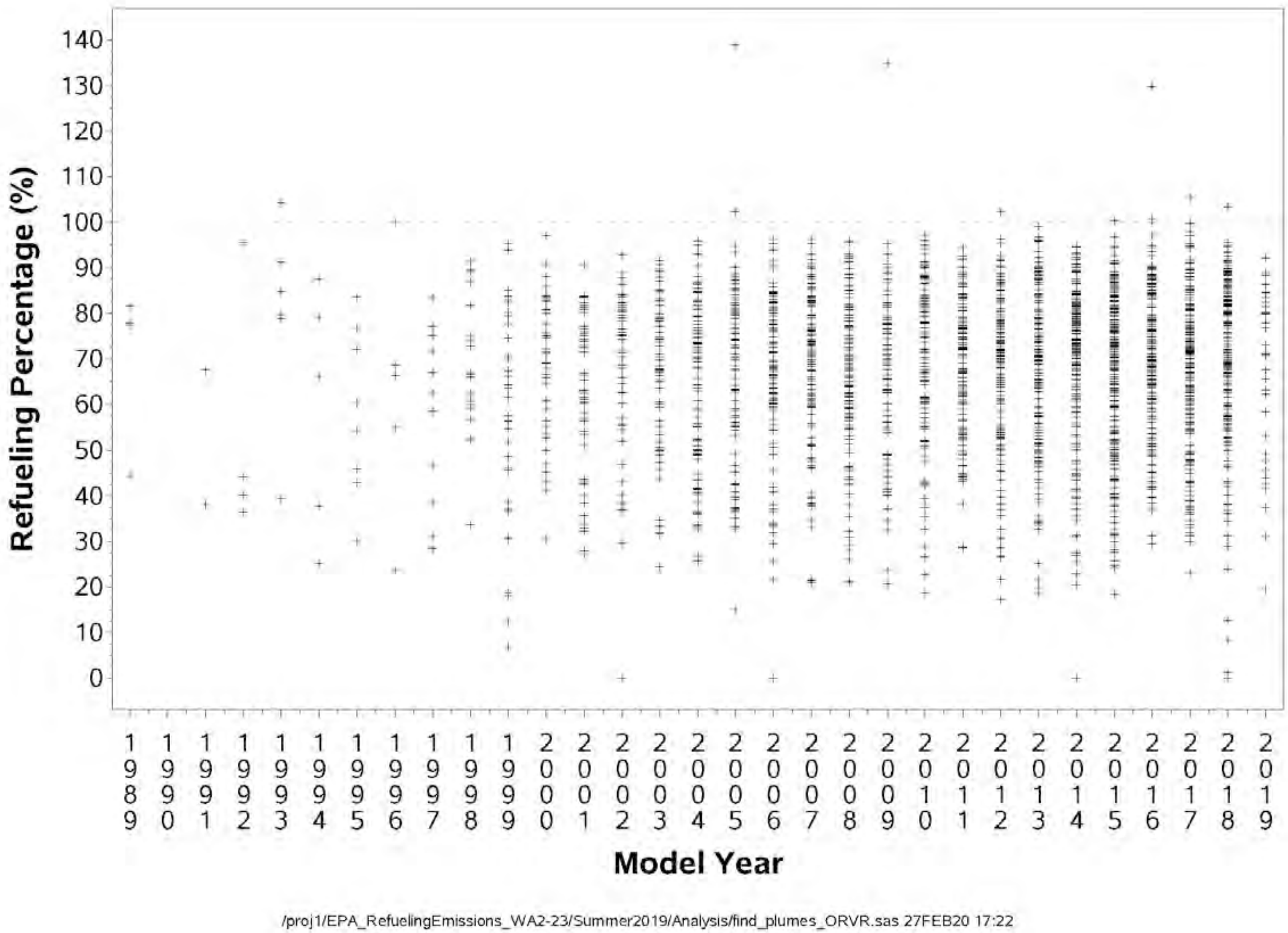
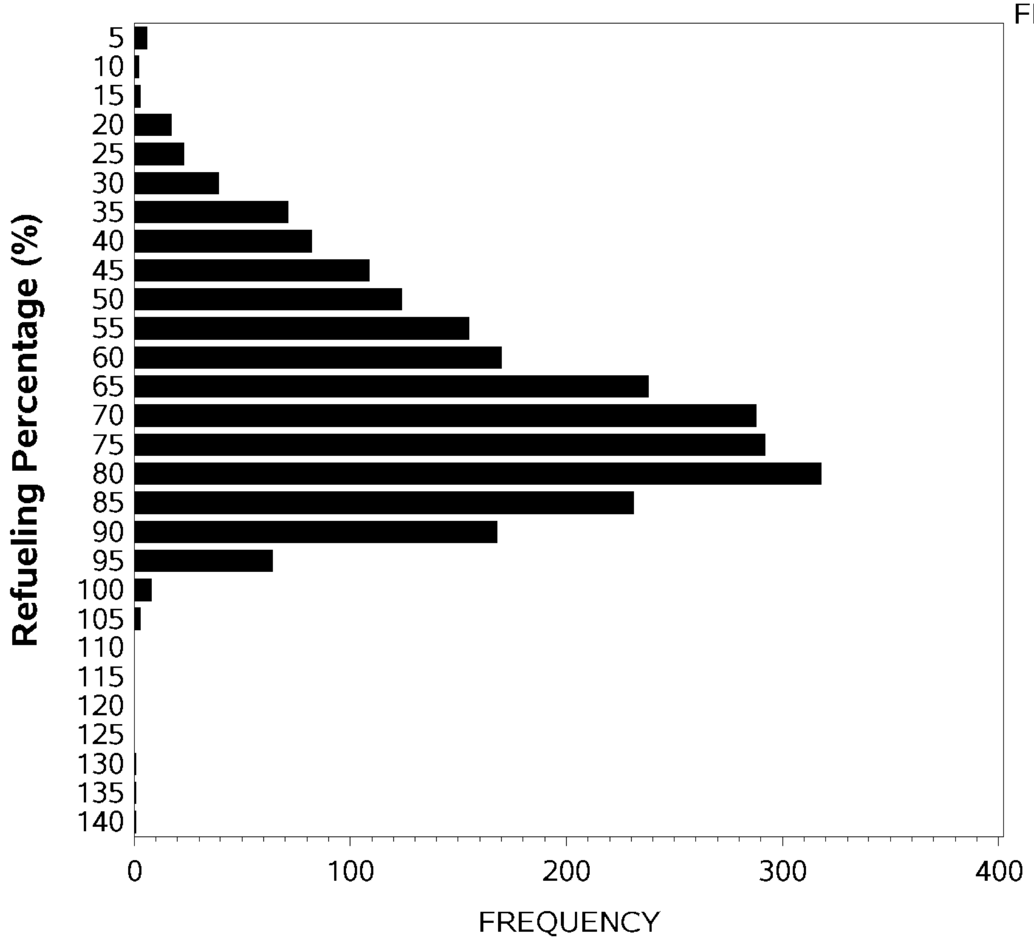


Figure 3-7. Distribution of Refueling Percentage for Sampled Vehicles



	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
5	6	6	0.25	0.25
10	2	8	0.08	0.33
15	3	11	0.12	0.46
20	17	28	0.70	1.16
25	23	51	0.95	2.11
30	39	90	1.62	3.73
35	71	161	2.94	6.67
40	82	243	3.40	10.07
45	109	352	4.52	14.58
50	124	476	5.14	19.72
55	155	631	6.42	26.14
60	170	801	7.04	33.18
65	238	1039	9.86	43.04
70	288	1327	11.93	54.97
75	292	1619	12.10	67.07
80	318	1937	13.17	80.24
85	231	2168	9.57	89.81
90	168	2336	6.96	96.77
95	64	2400	2.65	99.42
100	8	2408	0.33	99.75
105	3	2411	0.12	99.88
110	0	2411	0.00	99.88
115	0	2411	0.00	99.88
120	0	2411	0.00	99.88
125	0	2411	0.00	99.88
130	1	2412	0.04	99.92
135	1	2413	0.04	99.96
140	1	2414	0.04	100.00

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3.2 Analysis of Reference Vehicle Artificial Refueling Emissions Releases

The metered releases of artificial refueling emissions from the reference test vehicle were described in Section 2.2. For 30 seconds, mixtures of butane or gasoline headspace vapor were released at a rate of 10 gallons/minute from either the vehicle's left fuel fill door (LDOOR), an imaginary right fuel fill door (RDOOR), or from on top of the fuel tank (TANK). These releases produced continuous plumes – not puffs as will be observed and discussed later during gas station customer refuelings. The mixtures had nominal concentrations of 10%, 30%, or 100% relative to the equilibrium headspace HC vapor concentration. The 100% relative concentration was a 50% molar concentration in nitrogen. For butane, the 100% relative HC concentration was 4.5 g butane/gallon of mixture vapor[14]. For gasoline headspace vapor, the 100% relative HC concentration was 4.6 g HC/gallon of headspace vapor (see Appendix E for the estimate.).

The test conditions and results of viewing the Enhanced MidWave videos are tabulated in Appendix A. A summary of those results as a function of HC vapor type (butane, gasoline headspace vapor), release location, and relative HC concentration in the release mixture is shown in Table 3-3. The denominator of the ratio within each cell of the table gives the number of runs at the test condition, and the numerator gives the number of runs that had an observable plume in the video. Of the 108 valid releases that were successfully videoed, 94 had observable plumes.

Table 3-3. Video Plume Visibility Responses to Test Vehicle Conditions[15]

		Relative HC Concentration		
HC Type	**Release Location**	**10%**	**30%**	**100%**
Butane (BUT)	**LDOOR**	5/6	6/6	6/6
	RDOOR	5/6	7/7	7/7
	TANK	2/6	7/7	6/6
Gasoline Headspace Vapor (GAS)	**LDOOR**	4/6	6/6	5/5
	RDOOR	6/6	6/6	5/5
	TANK	1/6	5/6	5/5

94/108

[14] (0.5 ft^3 butane/ft^3 mixture) * (28.3 L/ft^3 butane) * (1 mole butane/22.4 L butane STP) * (492°R/530°R) * (58 g butane/mole butane) * (1 ft^3 mixture/7.48 gal mixture) = 4.5 g butane/gal mixture

[15] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final/RefVehicleCounts.xlsx

The green cells in Table 3-3 indicate the test conditions where all of the runs had observable plumes. The yellow cells indicate the test conditions where most, but not all, runs had observable plumes. The pink cells indicate the test conditions where less than half of the runs had observable plumes. The clearest trend in the table is that as the relative HC concentration decreases the chances of observing a plume in the video decreases. Also, the results for 10% relative HC concentration demonstrate that the chances of observing a plume are about the same for release from the left door and the right door, but releases from under the rear of the vehicle on top of the gas tank are less likely seen in the Enhanced MidWave videos.

We wanted to use the reference vehicle test results to quantify the ability of the GCI camera and observations of plumes in the Enhanced MidWave videos. We used logistic regression to explore the influences of relative HC concentration, refueling emissions release location (left door, right door, top of fuel tank), release HC type (butane, headspace vapor), fuel pump location (front, back), and air movement (calm, non-calm) on plume visibility. For modeling purposes, we used the natural log of the relative HC concentration and defined calm air movement when the measured wind speed was less than or equal to 1.3 mph. Release location, release HC type, pump location, and air movement were categorical variables in the regression. Plume visibility was the logistic regression response variable: 1 = a plume was observed in the Enhanced MidWave video, or 0 = no plume was observed.

After exploring several logistic regressions[16], the best regression described plume visibility as depending on relative HC concentration and release location with strongly significant coefficients. The other variables had no significant influence. The predicted probabilities (fractions) and their 95% confidence intervals for the test conditions are given in Table 3-4 and compare well with the counts in Table 3-3.

[16] P:\EPA_RefuelingEmissions_WA2-23\Summer2019\Analysis/find_plumes_RefVeh.sas

Table 3-4. Video Plume Visibility Probabilities for Test Vehicle Conditions[17]

		Relative HC Concentration		
HC Type	**Release Location**	**10%**	**30%**	**100%**
Butane (BUT)	**LDOOR**	0.919 **0.757** 0.460	0.999 **0.993** 0.916	1.000 **0.999** 0.986
	RDOOR	0.989 **0.918** 0.595	0.999 **0.998** 0.967	1.000 **0.999** 0.995
	TANK	0.535 **0.239** 0.079	0.990 **0.934** 0.656	1.000 **0.999** 0.925
Gasoline Headspace Vapor (GAS)	**LDOOR**	0.919 **0.757** 0.460	0.999 **0.993** 0.916	1.000 **0.999** 0.986
	RDOOR	0.989 **0.918** 0.595	0.999 **0.998** 0.967	1.000 **0.999** 0.995
	TANK	0.535 **0.239** 0.079	0.990 **0.934** 0.656	1.000 **0.999** 0.925

The logistic regression model can also predict plume visibilities at relative HC concentrations different from those tested with the reference vehicle releases. We used the regression model developed from the reference vehicle data to calculate the plume visibility probabilities for the three release locations across the full range of relative HC concentrations. The results are shown in Figure 3-8. The figure has two x-axes to indicate the relative HC concentrations (%) and the estimated refueling emissions concentrations (g/gal) using 4.6 g/gal at 100% as the basis. The concentrations with a 50% probability of observing refueling emissions for the three release locations were 0.2, 0.3, and 0.7 gHC/gallon, respectively.

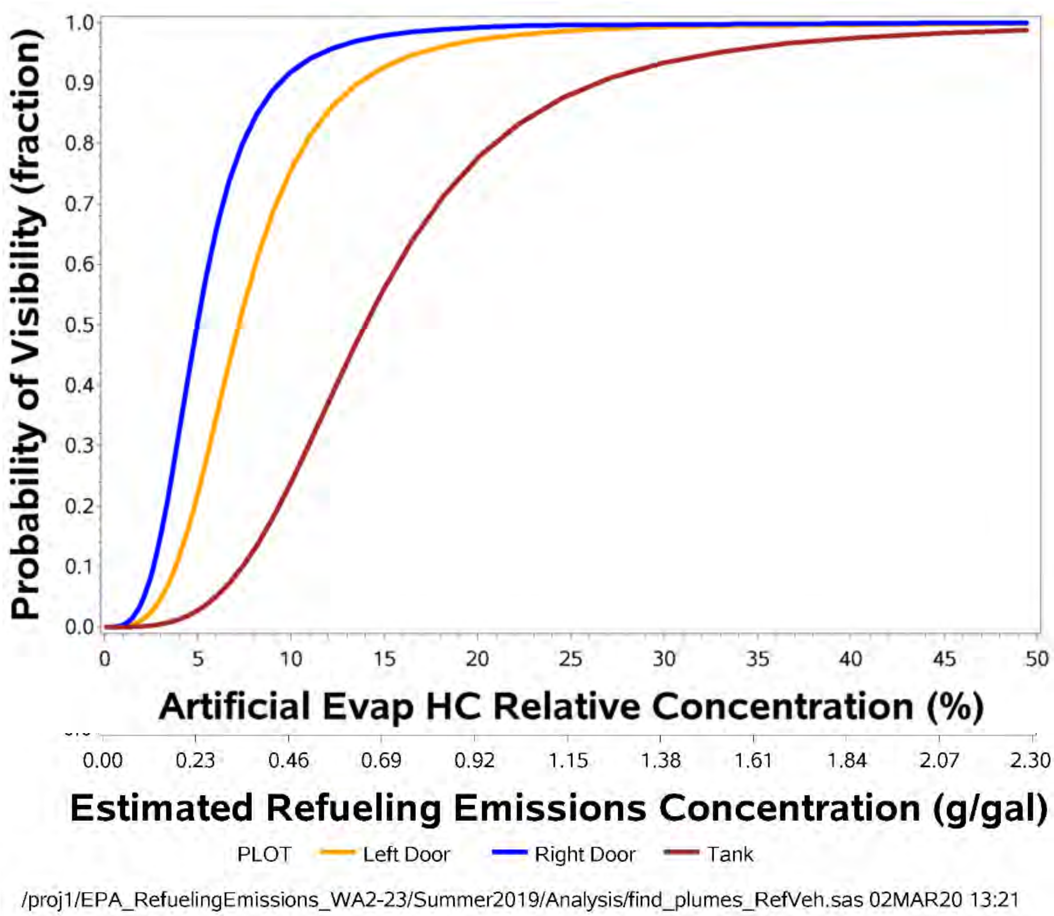
In Figure 3-8, the curves for the right and left door release locations are to the left of the curve for the tank release location. This means that plumes from releases from the right and left doors can be seen to lower relative HC concentrations than plumes from releases on top of the tank under the rear of the vehicle. This makes sense because refueling emissions from release points under a vehicle disperse to a greater extent before they can be videoed by the GCI camera.

The curves in Figure 3-8 can be used to roughly classify the refueling emission rate of private vehicles. Consider the curve (blue) for the right door. The blue curve has a “wall” in the

[17] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final/RefVehicleCounts.xlsx

3% to 9% relative HC concentration range, where the plume visibility probability increases rapidly from 10% to 90%. This wall can be used to separate plumes into low emissions and high emissions behavior. For example, suppose the video of a vehicle's refueling event shows a plume coming from the fuel fill door of a vehicle. The blue curve indicates that it is likely that the relative HC concentration of the emissions in the plume at the point in the refueling event that the plume is between 5%, which is the 50% probability value of the blue curve, and 100%, which is the relative concentration of uncontrolled fuel tank headspace vapor. On the other hand, at times in videos when no plume is observable from the fuel fill door, the blue curve indicates that the refueling emission rate would be low – likely between 0% and 5% relative HC concentration.

Figure 3-8. Trends of Plume Visibilty Probability by Release Location



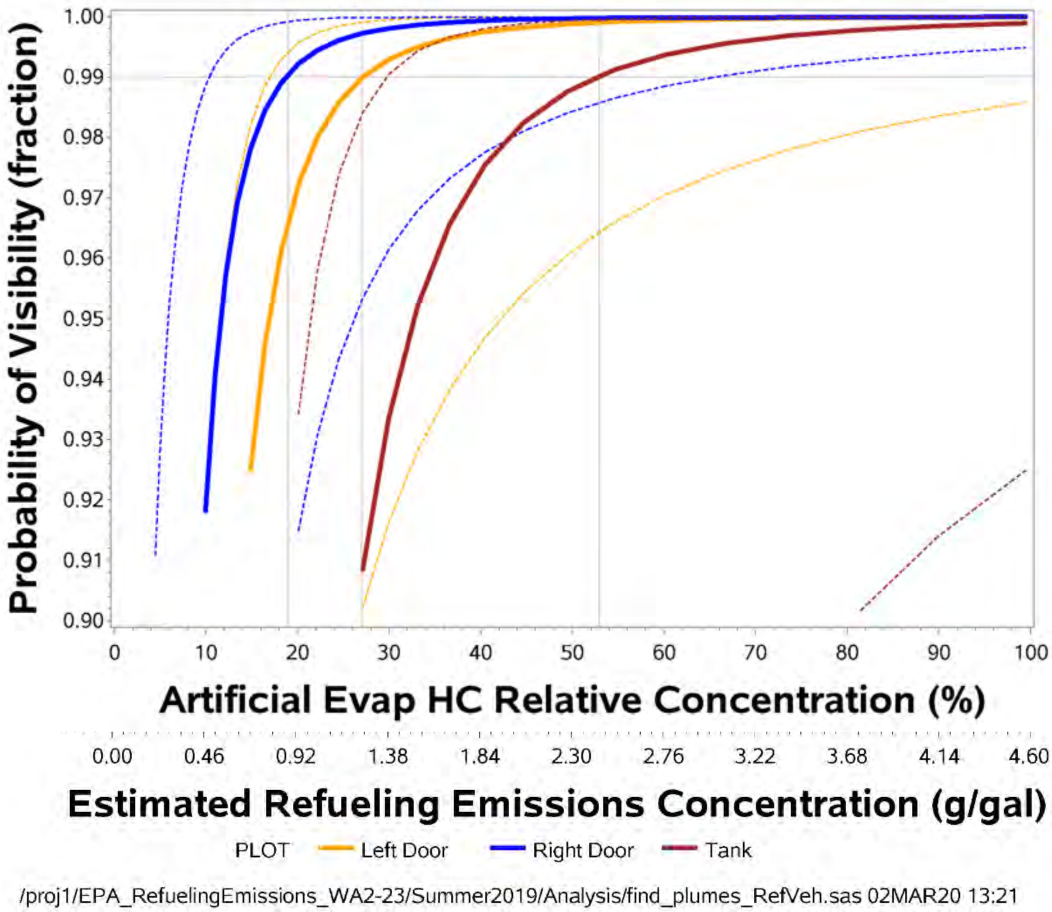
Sometimes, viewing a video can suggest that the emissions location is near the fuel fill door, but in other cases the source of the refueling emissions plume cannot be determined. Vehicle manufacturers have varied the location of the canister vent for maintaining functionality of the canister. Therefore, we do not necessarily know which curve in Figure 3-8 should be used to classify the plume emission rate. If the source location is unknown, then all three curves could be used to define a "fuzzy wall" that extends from about 3% to 25% relative HC concentration.

The predicted probability curves can also be used to estimate the GCI camera detection limit for plume detection by observing Enhanced MidWave videos. In the simplest terms, and as described in 40 CFR Part 136 App B, the minimum detection limit (MDL) is a statistical estimate of the lowest concentration at which there is a 99% chance that the concentration is greater than zero. Figure 3-9 shows a zoomed-in version of Figure 3-8. The thin, black, horizontal reference line at 0.99 indicates that the detection limits of the right door, left door, and tank release locations are 19%, 27%, and 53% relative HC concentration, respectively. Using 4.6 gHC/gallon of vapor as the 100% relative HC concentration,[18] these three detection limits correspond to 0.9, 1.2, and 2.4 gHC/gallon of vapor, respectively. The solid, thick curves give the best estimate of the plume visibility probabilities, and the thin, dashed curves give the 95% confidence intervals. These widely spaced confidence interval pairs of dashed lines in the figure indicate uncertainty in these detection limit estimates.

To put these values in perspective, consider the current applicable refueling standard of 0.2 gHC/gallon, and the estimated concentration of uncontrolled refueling emissions of 4.6 gHC/gallon, which is equal to the vehicle fuel tank headspace hydrocarbon vapor concentration for the average testing conditions. The detection limits and 50% probability reference values fall between the 0.2 gHC/gallon standard and the 4.6 gHC/gallon uncontrolled emissions value. Therefore, in this study, the GCI camera videos can image refueling emissions from evaporative emission control systems that have no control and probably systems with moderate control, but systems that have very good control will probably produce refueling videos with no observable plume. This is good emissions detection behavior for the study since, in general, the videos will be able to distinguish between control systems with good and poor behavior.

[18] See Section 2.2 and Appendix E for using ReddyEvap 2010 to estimate headspace HC vapor concentration at the field conditions in this study.

Figure 3-9. Determination of Detection Limit by Release Location



3.3 Potential Effect of Open Driver's Door on Plume Observations

Field data collection, Enhanced MidWave video viewing, and data analysis personnel all observed that a substantial number of customers left their door open during refueling at the Costco Arvada gas station. The concern was that open doors could completely obscure otherwise observable plumes from being seen by the GCI camera.

If doors obscured plumes, then we would expect to see higher plume rates for events with closed doors. To determine if open doors hid plumes, we randomly selected refueling events of 2007+ model year vehicles with observed plumes and without observed plumes and re-viewed their Enhanced MidWave videos to determine if the door was open or closed. Table 3-5 shows the results of the analysis. For the 2007+ model years, 1626 events had no observable plumes, 329 events had light plumes, and 121 had heavy plumes. We viewed videos of 100 of the no-plume events, of 33 of the light-plume events, and of all 121 heavy-plume events. To make a distinction between doors open just for drivers to get in and out of the vehicle and extended door-open durations, we considered a door open if it stayed open for at least 5 seconds.

Table 3-5. Estimated Effect of Open vs. Closed Door on Plume Observability

Type of Event	Total Events	Sampling Method	Sampled Events	Door Open > 5s	% Open ± 95% CLM
no plume	1626	random	100	37	37% ± 10%
Light plume	329	random	33	13	39% ± 17%
Heavy plume	121	all	121	51	42% ± 9%

The table shows that for the three types of plume events, the rate of doors open was always around 40%. The 95% confidence limits were estimated using pq/N as the estimate of the variance. We would expect a higher percent-open rate for the no-plume events than for the plume events, if open doors hid plumes. Since 37% is not larger than 39% and 42% – at the least not within the uncertainty, we conclude that open doors probably do not greatly affect the ability to observe plumes. The data indicates that there is no reason to believe that the different types of plumes had different door-open fractions.

3.4 Model Year Trends in Phase 1 Plume Observations

We watched all videos of each selected refueling event using the Phase 1 viewing instructions given in Appendix B and judged the Phase 1 plume status: a) no plume, b) light-density plume, c) heavy-density plume, or d) gasoline puddle with plume after the vehicle left and were given codes 0, L, H, and P, respectively. The definitions of light-density vs. heavy-density plumes were arbitrary and left to the video observer to judge. The plumes in the Enhanced MidWave videos of the reference vehicle were used as a guide. The plume status was determined without regard to the duration of the plume or when a plume occurred in the video or in the refueling event. We did attempt to target Phase 1 plume status observations between the customer’s credit card validation at the gas pump and the fuel nozzle hang-up at the end of each refueling event – if those activities could be determined from the video images. Sometimes it was difficult to attribute a plume to the front or rear vehicle at the island.

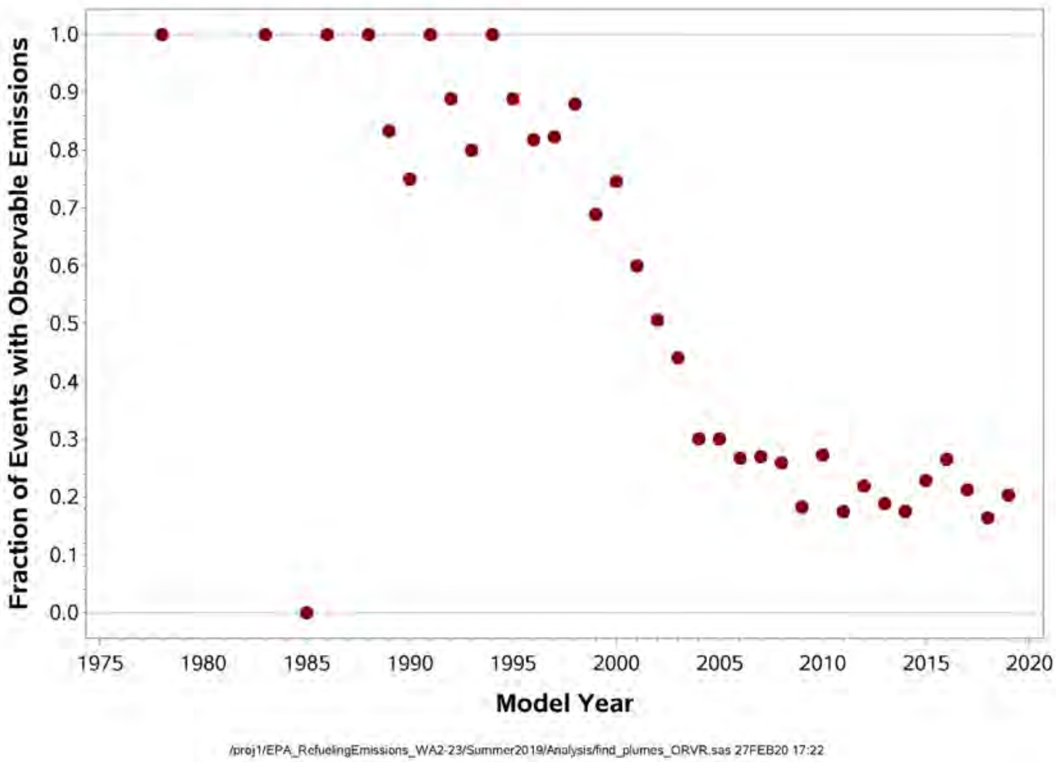
The Phase 1 plume status results for the 2,854 selected refueling events are given in Table 3-6. The model year trend of the fraction of refuelings with observable plumes, which is the last column in Table 3-6 is shown in Figure 3-10. The preliminary trend is characterized by observable refueling plume fractions near 100% for pre-ORVR vehicles (pre-1998) and moderately low fractions for the newest (2007+) vehicles with a downward trend during the 1998 through 2006 model years.

Table 3-6. Phase 1 Status of Refueling Events that Met Selection Criteria[19]

Model Year	Refueling Event Plume Status				Total Events	Events with Plumes (fraction)
	No Plume	Light Plume	Heavy Plume	Puddle Plume		
1978	0	0	1	0	1	1.00
1983	0	1	0	0	1	1.00
1985	1	0	0	0	1	0.00
1986	0	0	1	0	1	1.00
1988	0	0	1	0	1	1.00
1989	1	0	5	0	6	0.83
1990	1	0	3	0	4	0.75
1991	0	0	2	0	2	1.00
1992	1	2	6	0	9	0.89
1993	2	0	8	0	10	0.80
1994	0	0	9	0	9	1.00
1995	1	0	8	0	9	0.89
1996	2	1	8	0	11	0.82
1997	3	1	13	0	17	0.82
1998	3	3	19	0	25	0.88
1999	14	5	26	0	45	0.69
2000	16	7	40	0	63	0.75
2001	24	8	28	0	60	0.60
2002	38	12	27	0	77	0.51
2003	47	16	21	0	84	0.44
2004	72	16	14	1	103	0.30
2005	86	25	12	0	123	0.30
2006	85	19	11	1	116	0.27
2007	119	31	14	0	164	0.27
2008	101	22	13	0	136	0.26
2009	76	13	4	0	93	0.18
2010	88	25	6	2	121	0.27
2011	118	18	7	0	143	0.17
2012	132	23	15	0	170	0.22
2013	147	29	5	0	181	0.19
2014	155	20	13	0	188	0.18
2015	173	39	12	0	224	0.23
2016	133	37	10	1	181	0.27
2017	174	39	8	0	221	0.21
2018	163	25	7	0	195	0.16
2019	47	8	4	0	59	0.20
Total	*2023*	*445*	*381*	*5*	*2854*	*0.29*

[19] C:\Users\TDeFries\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final\PlumeVideoCounts.xlsx

Figure 3-10. Phase 1 Model Year Trend of Observable Plumes, Puffs, and Puddles



The table shows that only 3% (=82/2854) of the events were for refueling on pre-1998 vehicles. For these vehicles, which are unambiguously pre-ORVR, 85% (=70/82) of refuelings had observable plumes in the Enhanced MidWave videos. For comparison, since none of these vehicles had ORVR systems, the expected observable plume rate would be 100%. The cause of the discrepancy between 85% and the expected 100% is unknown. As discussed later in this report, several site factors (pump position, wind, background infrared illumination, obstacles in the camera's line of site, movement of people and vehicles) influence the visibility of emissions in the videos. Until then, we note that the rate for the front row of pumps was 83% (=35/42), and the rate for the back row of pumps was 87% (=35/40).

For the newest (2007+) model year vehicles, 22% (=450/2076) of refuelings had Phase 1 observable plumes in the Enhanced MidWave videos. Additionally, Figure 3-10 shows only a weak decrease in the plume rate from 2007 to 2019. We found it hard to believe that 20% of almost brand new 2018 and 2019 vehicles would produce refueling emission plumes unless something unexpected or unusual was occurring with vehicle pre-refueling driving behavior, with GCI camera sensitivity, or with Enhanced MidWave video viewing.

Therefore, we examined factors that we hypothesized could affect the plume observation rate: vehicle class (LDGV, LDGT12, LDGT34), vehicle make, gallons of fuel dispensed, refueling time of day, wind speed, ambient temperature, distance between fuel pump and fuel fill door, and fuel pump number. We were specifically looking for a variable that had a large influence on Phase 1 values of the plume observation rate for the newest (2007+) vehicles.

Except for the differing implementation transition years (LDGV: 1998-1999, LDGT12: 2001-2002, LDGT34: 2004-2005), the Phase 1 plume observation rates for the three vehicle classes were quite similar. The model year trends for the four most common makes in the dataset (Toyota: 699 observations, Honda: 329 observations, Ford: 310 observations, Chevrolet: 207 observations) were quite similar. Whether the amount of fuel dispensed was larger or smaller than the median 12.5 gallons had no significant effect on the Phase 1 plume observation rate. Similarly, time of day (6am to 10am, 10am to 5pm, after 5pm), wind speed (less than 3.4 mph median, greater than 3.4 mph median), ambient temperature (less than 85.5 F median, greater than 85.5 F median), and fuel pump to fuel-fill door distance (near, far) had no significant effect on the Phase 1 plume observation rate.

We also thought that it was possible that one fuel pump nozzle might be consistently leaking gasoline liquid or vapor. Therefore, we looked at the model year trends for the six fuel pumps used in the study. We did not find any evidence of a leaking nozzle. However, we found that all three pumps (7, 8, 11) in the back row, i.e. farthest from the GCI camera, had a higher rate of observed plumes than the three pumps (5, 6, 9) in the front row, i.e. closer to the GCI camera. Figure 3-11 and Figure 3-12 show the model year trends of Phase 1 plume observations for the 2,076 refueling events plotted in Figure 3-10 divided into the 983 refuelings at the back pumps and the 1,093 refuelings at the front pumps, respectively. The difference in plume rates is seen most clearly in Figure 3-11 and Figure 3-12 for the 2007+ vehicles. For refuelings of 2007+ model year vehicles, the average Phase 1 observed plume rate was 13% ± 2% (=137/1093) at the front pumps and 32% ±3% (=313/983) at the back pumps; where the uncertainties give the 95% confidence intervals. Thus, the plume observation rates of refueling at the front and back pumps are statistically different.

Figure 3-11. Phase 1 Model Year Trend of Front Pump (5, 6, 9) Plumes

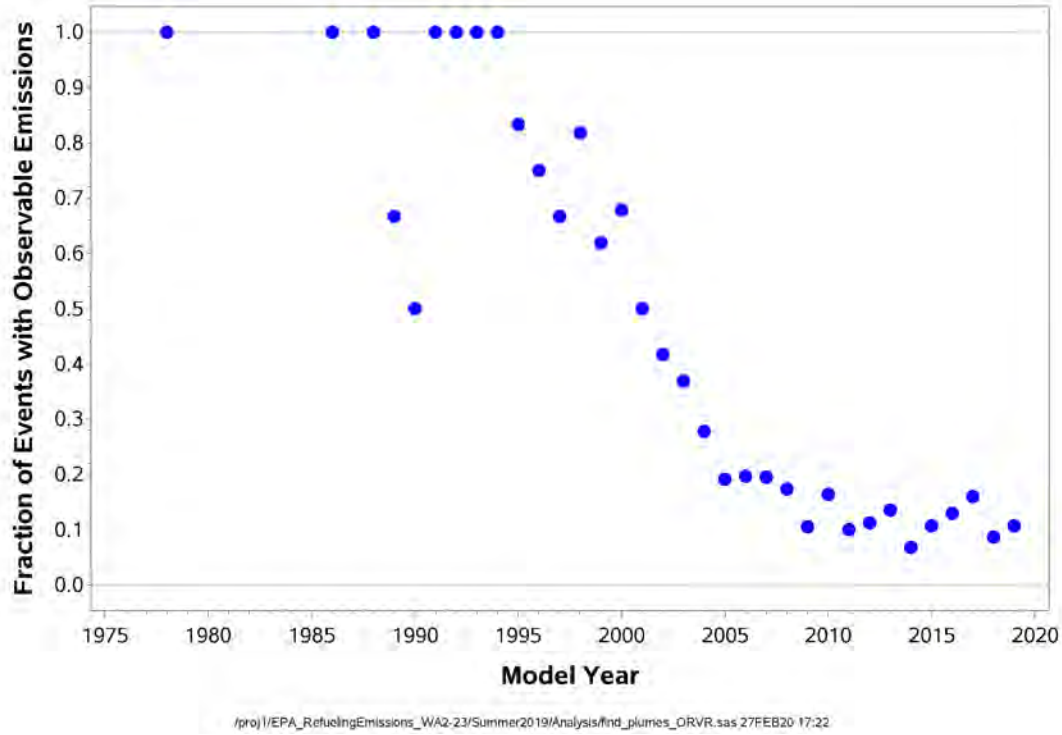
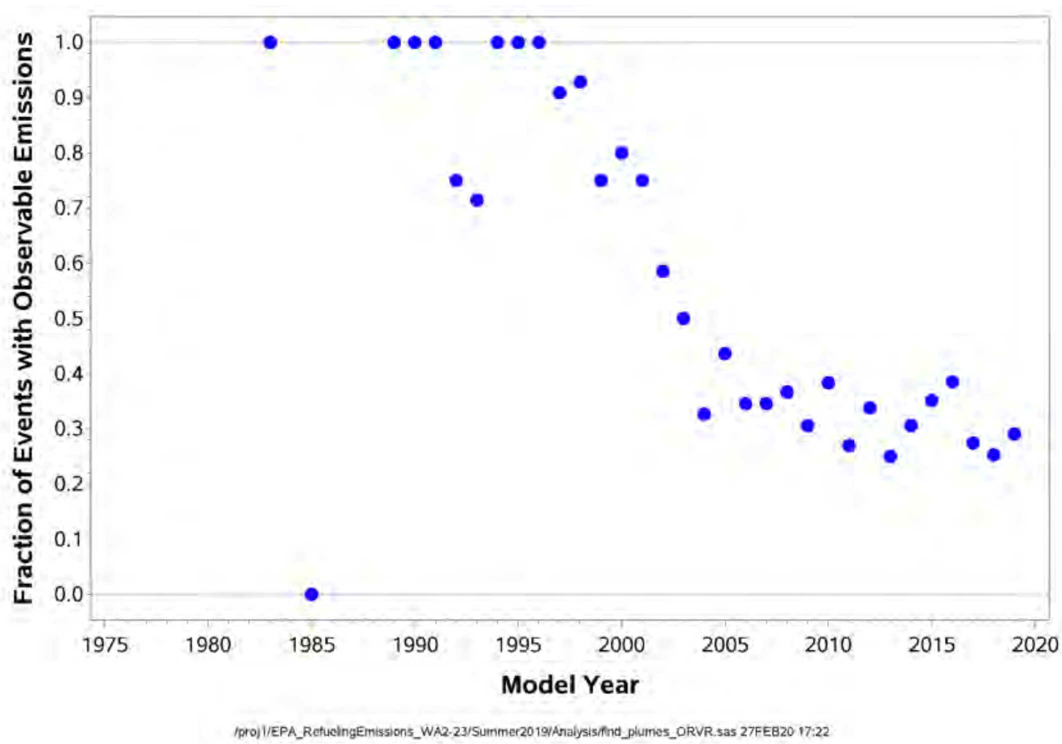


Figure 3-12. Phase 1 Model Year Trend of Rear Pump (7, 8, 11) Plumes



We further refined the analysis of front vs. back pumps by restricting the vehicle dataset by using refuelings only for 2007-2018 model year vehicles with vehicle classes unambiguously assigned as LDGV, LDGT12, and LDGT34. This eliminated HDGV2b class vehicles, vehicles for which vehicle classes were missing when they were not easily available, and medium-duty vehicles. This resulted in the dataset dropping from 2,076 refuelings to 1,692 refuelings with 890 refuelings at the front pumps and 802 at the back pumps. Of the 890 refuelings at the front pumps, 87 had light plumes and 26 had heavy plumes for a plume observation rate of 12.7% ± 2.2% (=113/890). Of the 802 refuelings at the back pumps, 179 had light plumes and 64 had heavy plumes for a plume observation rate of 30.3% ± 3.2% (=243/802). Thus, there was still a significant difference in Phase 1 plume observation rates between the front and back pumps.

Since this front pump vs. back pump difference is not likely caused by three leaking back pump nozzles or high emissions vehicles refueling preferentially at the back pumps, we suspected that a bias in the Phase 1 viewing of the Enhanced MidWave videos was somehow occurring.

To gain insight into possible reasons for the difference in Phase 1 observations of plumes for front pumps and back pumps, we examined the videos of selected refueling events for 2007-2019 model year vehicles shown in Table 3-6. We looked at a random 30 (10%) of the 329 refueling events designated as Light Plume in Table 3-6. We also looked at the videos for all 121 refueling events that were assigned as Heavy Plume or Puddle in Table 3-6. We saw that plume duration was correlated with the light and heavy plume assignments. Specifically, all 30 of the light plumes also had short durations (less than 20 seconds), while many of the heavy plumes had long durations (more than 20 seconds).

Also, it appeared that the shadow of the gas station canopy on the pavement and the complexity of the background had an influence on plume assignments. If the pavement behind the vehicle was shaded by the canopy, then the GCI camera was less likely to make a plume observable. The back-pump row was more likely to have an illuminated pavement background since the pavement behind the rear pump vehicles was not under the canopy. On the other hand, the pavement behind front pump vehicles is always under the canopy and therefore more often in a shadow. Additionally, the front pump vehicles typically had vehicles refueling behind them. This caused the background of front pump vehicles to be more complex. We believe that the decreased illumination and increased complexity of backgrounds for front pump vehicles may be responsible for the lower rate of Phase 1 plume assignments of front pump vehicles relative to back pump vehicles – especially if plumes had a short duration.

Based on that video investigation, we again re-examined the videos of the sample of the dataset of 1,692 refueling events (that is, the 802 back-pump refuelings and the 890 front-pump refuelings, described above) with an eye toward plume duration as well as front vs. back pump row. We used 20 seconds as a demarcation between short- and long-duration plumes. Because we had seen no long-duration plumes in the 30 light plumes that were sampled, we examined only the heavy plumes and thus presumed (at this point) that there would likely be no long-duration light plumes in the dataset.

The results of this long-duration, heavy-plume re-examination indicated no bias between the front and back pumps. Specifically, of the 890 front-pump refuelings, 13 (1.5%) had heavy plumes with durations longer than 20 seconds. Of the 801 back-pump refuelings, 12 (1.5%) had heavy plumes with durations longer than 20 seconds. Thus, we see that by considering the duration of the refueling emissions, the difference in the Phase 1 plume observation rate between the front and back pumps has gone away. We believe that this may be because long duration plumes may be more likely to be seen in the videos regardless of background complexity.

During the re-examination of the 1,692 refuelings, we postulated that refuelings might be divided into three Phase 1 (preliminary) categories:

- **Category 1)** 79.0% (=1336/1692) had no observable plumes in the videos,
- **Category 2)** 19.5% (=331/1692) were estimated to have light or heavy plumes of short duration (puffs) usually occurring at standard refueling activities (gas cap removal, the very beginning of fuel flow, the end of fuel flow when the nozzle clicked off, and/or when the pump nozzle was being carried to or from the vehicle’s fuel fill door), and
- **Category 3)** 1.5% (=25/1692) had heavy plumes lasting at least 20 seconds.

Category 1 events are of no concern since no refueling emissions were seen. Category 2 events are of some concern since emissions were observed. However, the Category 2 emission episodes were brief, probably resulted in a low mass of emissions, and the episodes occurred during activities when the ORVR system could not control the emissions. Category 3 events are of most concern because they were long duration and occurred while fuel was being pumped, may have produced larger masses of refueling emissions, and the ORVR system should have been able to control the emissions.

3.5 Phase 2 Re-Viewing Refueling Videos for Time Trends of Refueling Plumes

We needed to re-view the Enhanced MidWave videos of each of the events to determine the time trends of plumes seen in the videos. The reason is that in many cases, brief plumes, which we call “puffs,” appeared when the gas cap was removed, when fuel flow started, when the nozzle clicked off, or when customers used extra clicks to “top off” their fuel tanks. We want to distinguish instances of that behavior from the behavior when continuous plumes are being produced during steady fuel-flow periods.

Refueling emissions appear in the videos as swirling white fog. Figure 3-13 shows a frame from a video that contains a topping-off puff. The puff is just above the rear vehicle’s driver’s left hand. Figure 3-14 shows a still from a video that contains a continuous plume from the front vehicle. The plume is visible to the right of the driver’s side mirror.

The analysis of the data in the previous section indicated that refuelings might be able to be described using three categories that are defined by plume duration and standard refueling activities. Since the Phase 1 plume observations of the videos did not consider plume duration and refueling activities, we decided to re-view the refueling videos of confirmed ORVR vehicles. We also wanted to evaluate vehicles with model years earlier than 2007, where possible and convenient, to see trends on older ORVR vehicles. This would allow us to better evaluate the postulated 3-category classification scheme presented above.

For this recoding of plume information, we considered only vehicles that had confirmed ORVR systems and only LDGVs, LDT12s, and LDT34s. Additionally, we considered only vehicles with Colorado plates and those where we could find VIN, model year, make, and model in the snapshot of the Colorado registration database. To avoid looking up the ORVR equipment of individual make/model combinations in the transition model years of ORVR implementation, we examined events for only the following combinations of model year and vehicle class: 2000-2018 LDGVs, 2003-2018 LGDT12s, and 2006-2018 LDGT34s. Table 3-7 shows the model-year distribution of Phase 1 plume observation results for these confirmed ORVR vehicles by vehicle class.

If the Phase 1 plume observations of a refueling event did not indicate any plume in a refueling event’s videos, we did not need to re-view the videos for that event. As shown in Table 3-7, 1535 refueling events fell in this no-observed-plume category. Accordingly, we re-viewed the videos of the refueling events in Table 3-7 only for light, heavy, and puddle Phase 1 observation results. The resulting dataset contained 455 refueling events made up of 1,373 30-second videos.

Figure 3-13. A Frame with a Topping-Off Puff in a Video for the Rear Vehicle

Figure 3-14. A Frame with a Continuous Plume in a Video for the Front Vehicle

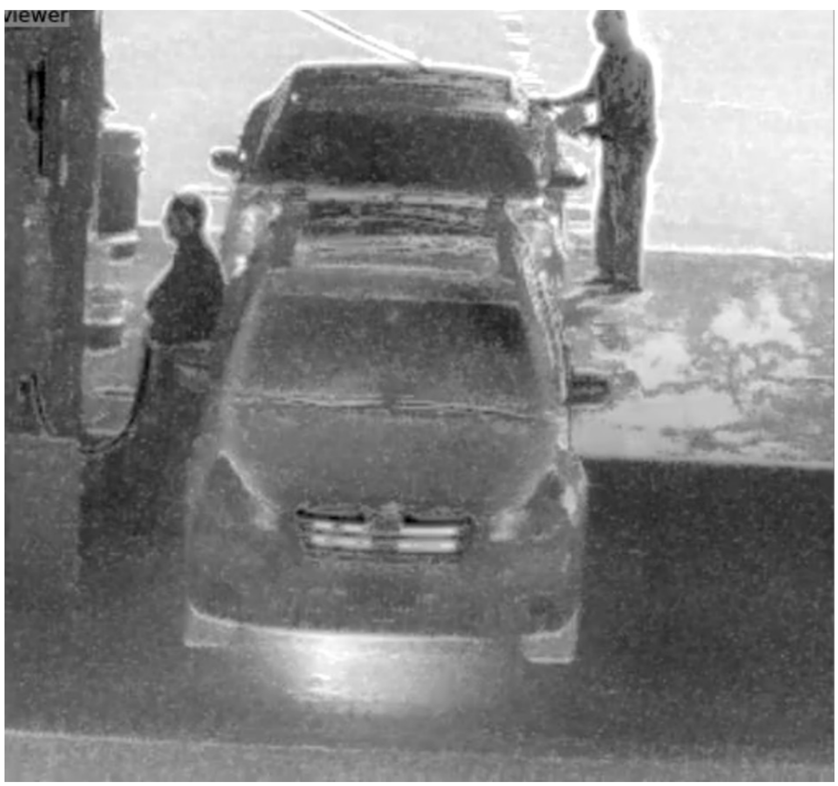


Table 3-7. Phase 1 Status of Refueling Events for Confirmed ORVR Vehicles[20,21,22]

	LDGVs				
	Refueling Event Plume				
Model Year	None	Light	Heavy	Puddle	Total Events
2000	12	4	6	0	22
2001	10	4	6	0	20
2002	15	3	3	0	21
2003	17	6	2	0	25
2004	21	7	1	0	29
2005	27	11	5	0	43
2006	25	4	4	0	33
2007	37	9	2	0	48
2008	26	9	5	0	40
2009	35	6	3	0	44
2010	27	9	2	0	38
2011	27	5	1	0	33
2012	38	7	6	0	51
2013	50	10	0	0	60
2014	41	7	3	0	51
2015	35	4	1	0	40
2016	26	8	0	0	34
2017	28	5	1	0	34
2018	14	3	3	0	20
Total	*511*	*121*	*54*	*0*	*686*

	LDGT1s + LDGT2s				
	Refueling Event Plume				
Model Year	None	Light	Heavy	Puddle	Total Events
2003	24	7	4	0	35
2004	33	6	3	0	42
2005	34	8	1	0	43
2006	39	10	3	1	53
2007	45	11	8	0	64
2008	39	6	3	0	48
2009	20	5	0	0	25
2010	31	9	0	1	41
2011	28	4	2	0	34
2012	47	6	2	0	55
2013	47	11	0	0	58
2014	51	3	5	0	59
2015	73	18	6	0	97
2016	48	14	3	0	65
2017	85	22	3	0	110
2018	64	5	2	0	71
Total	*708*	*145*	*45*	*2*	*900*

	LDGT3s + LDGT4s				
	Refueling Event Plume				
Model Year	None	Light	Heavy	Puddle	Total Events
2006	17	3	2	0	22
2007	25	8	2	0	35
2008	18	4	2	0	24
2009	5	0	0	0	5
2010	14	2	3	0	19
2011	36	4	2	0	42
2012	29	5	2	0	36
2013	30	4	2	0	36
2014	38	6	4	0	48
2015	33	11	2	0	46
2016	22	6	3	1	32
2017	31	3	3	0	37
2018	18	3	1	0	22
Total	*316*	*59*	*28*	*1*	*404*

[20] P:\EPA_RefuelingEmissions_WA2-23\Summer2019\Analysis\find_plumes_ORVR.sas

[21] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final/PlumeVideoCounts.xlsx

[22] Vehicle classes have not been determined for 2019 vehicles in this table. In this table, the first model year in each vehicle class is the first full-implementation model year for the class. Therefore, no non-ORVR vehicles and no vehicles in transition model years are counted for this table.

We developed the Phase 2 evaluation method for re-viewing the videos of the selected refueling events. Puffs of HC vapor are short-duration plumes that seem to be associated with the customer's removal of the gas cap, beginning of gasoline flow, or end of fuel flow at nozzle click-off. After viewing all videos of the 455 selected refueling events, we discovered that customers topping-off after the fuel nozzle had automatically clicked off also sometimes produced puffs. Therefore, we went back again and re-viewed any refueling events where we had seen continuous plumes during the first pass through during Phase 2. In several cases, some of the initially assigned continuous plumes were actually multiple puffs caused by topping off.

Overall, the procedure was designed to characterize each of the six 5-second blocks within each video. The Phase 2 instructions given in Appendix C were used to assign one of the codes in Table 3-8 to each 5-second block in a video.

Table 3-8. Phase 2 Codes Used to Characterize Video 5-second Blocks

Code	Meaning
R	Puff at gas cap removal
B	Puff at beginning of fuel flow when the customer first pulls the nozzle handle
E	Puff at end of fuel flow when the nozzle clicks off
T	Puff caused by topping-off behavior after the nozzle automatically clicked-off
P	Puff coming from a puddle of gasoline on the pavement
1	Small, low-contrast, continuous plume
2	Small, high-contrast, continuous plume or a large, billowing, continuous plume
0	No plume and no puff can be seen
X	Screen is entirely white (from GCI calibration)

The codes for a 30-second video produce a 6-character string that summarizes what was seen in the video. For example, 000R11 would indicate no emissions for about 15 seconds, a puff at gas cap removal, followed by 10 seconds with a light plume. Obviously, this coding scheme does not convey everything that can be observed in a video, but it does convey information about refueling event emissions time trends for convenient analysis.

While we recorded 6-character strings for each video, we also judged the Phase 2 category of the refueling event:

NoPuffsNoPlumes: We saw neither puffs nor plumes in any of the videos for the refueling event,

OnlyPuffsNoPlumes: We saw at least one puff of any type (remove gas cap, begin fuel flow, nozzle click-off, topping off, puddle), but we did not see any plumes associated with periods of steady fuel flow, and

ContinuousPlumes: We did see plumes associated with periods of steady fuel flow, and puffs of any type may or may not have been present.

OnlyPuffsNoPlumes as a category includes non-steady-state activities, such as, removing a gas cap, beginning fuel flow, nozzle click-off, and topping off fuel tanks. These events are likely included in the ORVR standard of 0.2 grams/gallon HC but would require further testing to verify. We selected ContinuousPlumes as a category to measure the occurrence of refueling events that today’s evaporative emissions control systems are designed to control. Refueling events in the ContinuousPlumes category might represent events that could be caused by malfunctioning evaporative emissions control systems or canisters that are already partially loaded.

3.6 Evaluation of GCI Camera Sensitivities in Phase 2 Plume Observations

The analysis in Section 3.2 revealed a bias in the model year trend of the Phase 1 fraction of refuelings with observable emissions between the front and back pumps (see Figure 3-11 and Figure 3-12). We attribute the difference in video-observable refueling emissions between front and back pumps to a difference in the sensitivity of the GCI camera because of background complexity and infrared lighting differences. Additionally, during that analysis, we hypothesized that short-duration emission events might be more difficult to detect at front pumps than at back pumps. Accordingly, to see if Phase 2 video viewings avoided, or at least reduced, the viewing bias, we analyzed the Phase 2 viewing results for puffs, which tended to be short-duration events, separate from continuous plumes, which tended to be longer duration events. For the analysis we selected data for 2000-2018 LDGVs, 2003-2018 LDGT12s, and 2006-2018 LDGT34s, which all have ORVR systems. This dataset contains 1,990 refueling events.

First, the analysis focuses on rates of Phase 2 continuous plumes at the front and back pumps. Table 3-9 shows that the back-to-front ratio of continuous plume abundances was 1.6 (=4.8%/3.0%). That ratio is still larger than 1, but it is closer to 1 than the Phase 1 back-to-front ratio of 2.4 (=30.2%/12.7%).

Table 3-9. Continuous Plumes Observed at Front and Back Row Pumps[23]

Pump Row	Total Refuelings (count)	Continuous Plumes Observed (count)	Continuous Plumes Observed (%)
Front	1037	31	3.0%
Back	953	46	4.8%
Total	*1990*	*77*	*3.9%*

Table 3-10 shows that the back-to-front ratios for R, B, and E puff types are 5.7 (=4.0%/0.7%), 3.4 (=12.4%/3.6%), and 2.3 (=14.2%/6.2%), respectively. All are substantially greater than the Phase 2 continuous plume ratio of 1.6.

Table 3-10. Puff Types Observed at Front and Back Row Pumps

Pump Row	Total Refuelings (count)	R: Gas Cap Removal Puff (count)	B: Begin Fuel Flow Puff (count)	E: Nozzle Click-Off Puff (count)	R: Gas Cap Removal Puff (%)	B: Begin Fuel Flow Puff (%)	E: Nozzle Click-Off Puff (%)
Front	1037	7	37	64	0.7%	3.6%	6.2%
Back	953	38	118	135	4.0%	12.4%	14.2%
Total	*1990*	*45*	*155*	*199*	*2.3%*	*7.8%*	*10.0%*

Because more than one puff type can occur in a refueling event, we also consider the abundance of one or more puffs. Table 3-11 shows that the back-to-front any-puff abundance ratio is 2.5 (=24.2%/9.5%), which is still larger than the 1.6 ratio of the continuous plumes.

Table 3-11. Any Puffs Observed at Front and Back Row Pumps

Pump Row	Total Refuelings (count)	Refuelings with Puff (count)	Refuelings with Puff (%)
Front	1037	99	9.5%
Back	953	231	24.2%
Total	*1990*	*330*	*16.6%*

Overall, the analysis results described above show that separating puff from plume results diminishes the difference in the fraction of video-observable plumes of front versus back pumps. Nevertheless, a difference between front and back pumps still exists. This does not mean that results from front pumps are useless, invalid, or should be thrown out. It just means that GCI camera videos of front pump refuelings tend to be less sensitive to imaging refueling emissions.

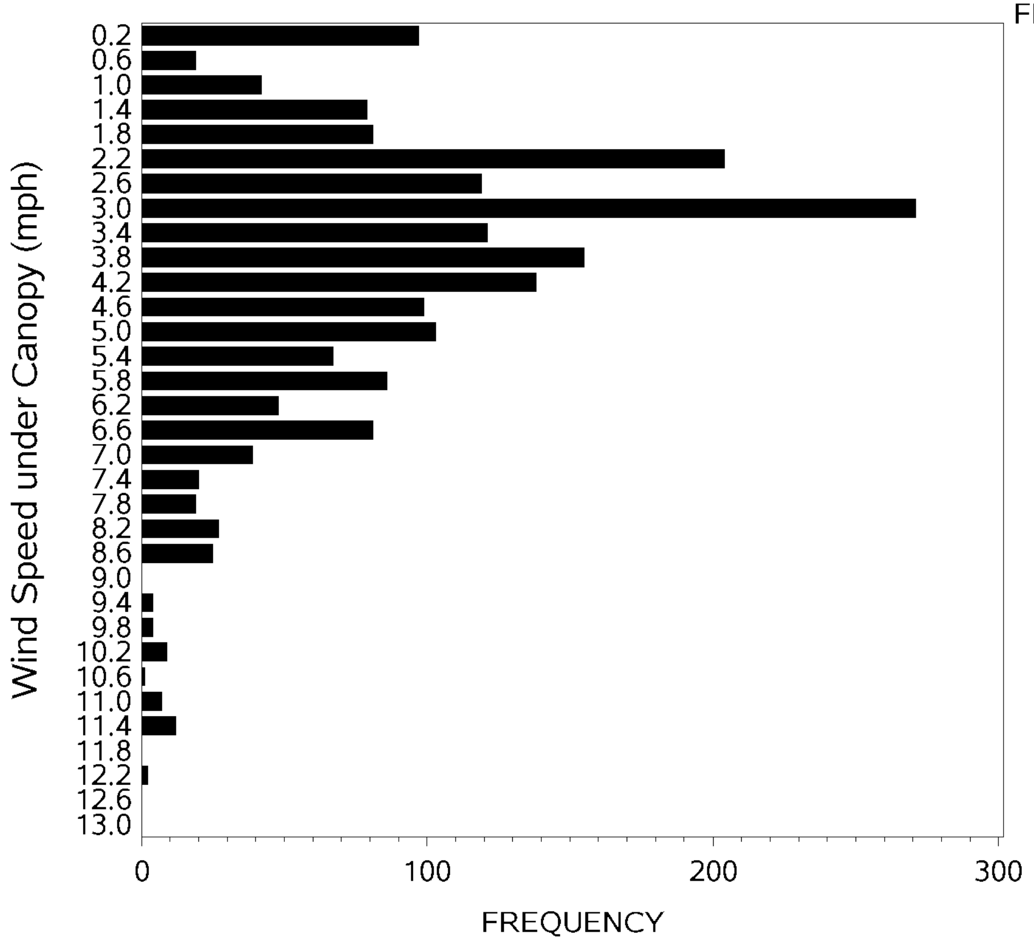
[23] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Analysis_Videos/ContinuousPlume Front v. Back.xlsx

In Section 3.2, the analysis of Phase 1 video observations was used to evaluate the influence of several factors on refueling emissions visibility in the GCI camera videos. Now, we re-evaluate those factors for the plumes (not the puffs) identified by the Phase 2 re-viewing of videos while using all of the Phase 2 confirmed ORVR data and while accounting for the acknowledged difference in video sensitivity between front and back pumps.

We used logistic regression to determine the statistical significance of seven categorical factors (wind speed, outdoor temperature, gallons of fuel dispensed, refueling time of day, vehicle class, vehicle make, and distance between fuel pump and fuel fill door) after accounting for front- vs. back-pump sensitivity. Figure 3-15 through Figure 3-21 show the distributions of the factors for the confirmed ORVR dataset. Vehicle class, vehicle make, and distance between fuel pump and fuel fill door are natural categorical variables as seen in Figure 3-19 through Figure 3-21. However, the other four factors are continuous variables. To convert them to categorical variables, we split each of the distributions at the 10, 25, 50, 75, and 90 percentiles and created a high group and a low group for each split.

Table 3-12 shows the split point values for the four continuous factors. For example, splitting the wind speed distribution using the 10-percentile value of 1.3 mph creates a high wind speed group with observations with wind speeds greater than 1.3 mph and a low wind speed group of observations with wind speeds less than or equal to 1.3 mph.

Figure 3-15. Under-Canopy Wind Speed during Confirmed ORVR Refuelings



Wind Speed under Canopy (mph)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0.2	97	97	4.90	4.90
0.6	19	116	0.96	5.86
1.0	42	158	2.12	7.98
1.4	79	237	3.99	11.98
1.8	81	318	4.09	16.07
2.2	204	522	10.31	26.38
2.6	119	641	6.01	32.39
3.0	271	912	13.69	46.08
3.4	121	1033	6.11	52.20
3.8	155	1188	7.83	60.03
4.2	138	1326	6.97	67.00
4.6	99	1425	5.00	72.01
5.0	103	1528	5.20	77.21
5.4	67	1595	3.39	80.60
5.8	86	1681	4.35	84.94
6.2	48	1729	2.43	87.37
6.6	81	1810	4.09	91.46
7.0	39	1849	1.97	93.43
7.4	20	1869	1.01	94.44
7.8	19	1888	0.96	95.40
8.2	27	1915	1.36	96.77
8.6	25	1940	1.26	98.03
9.0	0	1940	0.00	98.03
9.4	4	1944	0.20	98.23
9.8	4	1948	0.20	98.43
10.2	9	1957	0.45	98.89
10.6	1	1958	0.05	98.94
11.0	7	1965	0.35	99.29
11.4	12	1977	0.61	99.90
11.8	0	1977	0.00	99.90
12.2	2	1979	0.10	100.00
12.6	0	1979	0.00	100.00
13.0	0	1979	0.00	100.00

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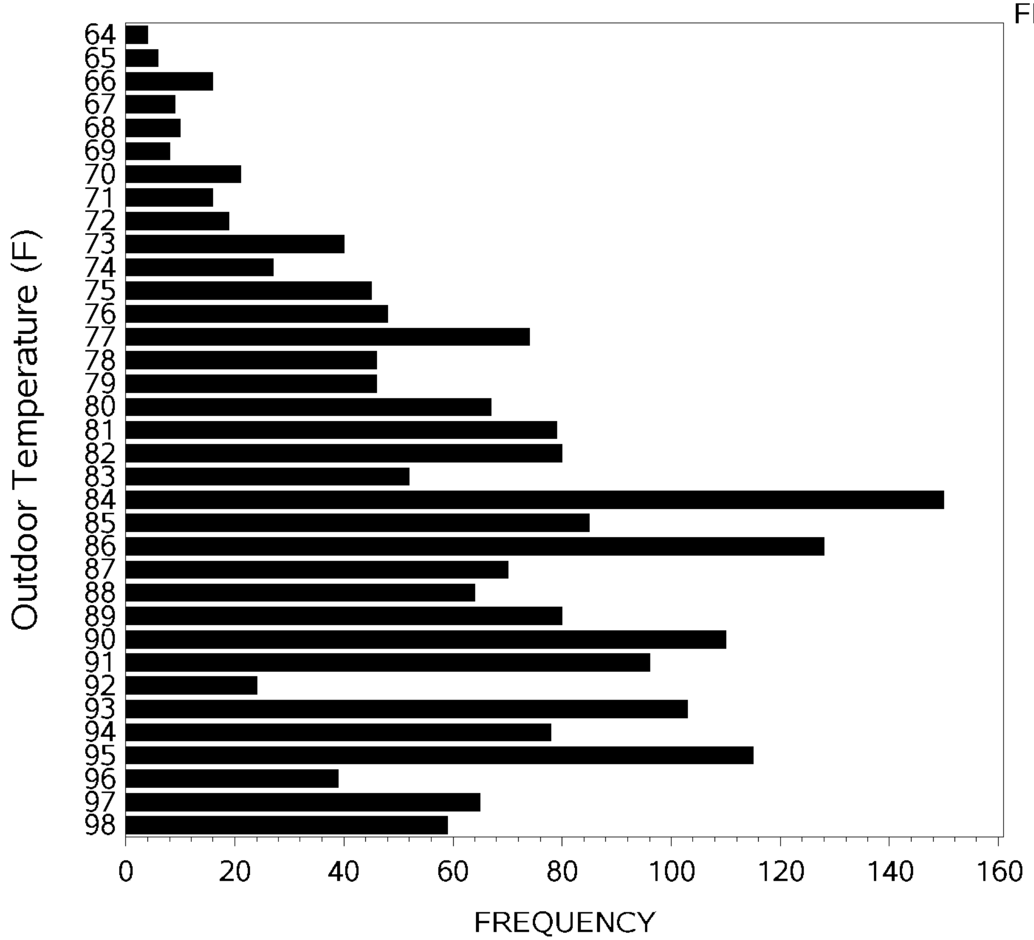
Figure 3-16. Under-Canopy Temperature during Confirmed ORVR Refuelings



FREQ	CUM. FREQ	PCT.	CUM. PCT.
4	4	0.20	0.20
6	10	0.30	0.51
16	26	0.81	1.31
9	35	0.45	1.77
10	45	0.51	2.27
8	53	0.40	2.68
21	74	1.06	3.74
16	90	0.81	4.55
19	109	0.96	5.51
40	149	2.02	7.53
27	176	1.36	8.89
45	221	2.27	11.17
48	269	2.43	13.59
74	343	3.74	17.33
46	389	2.32	19.66
46	435	2.32	21.98
67	502	3.39	25.37
79	581	3.99	29.36
80	661	4.04	33.40
52	713	2.63	36.03
150	863	7.58	43.61
85	948	4.30	47.90
128	1076	6.47	54.37
70	1146	3.54	57.91
64	1210	3.23	61.14
80	1290	4.04	65.18
110	1400	5.56	70.74
96	1496	4.85	75.59
24	1520	1.21	76.81
103	1623	5.20	82.01
78	1701	3.94	85.95
115	1816	5.81	91.76
39	1855	1.97	93.73
65	1920	3.28	97.02
59	1979	2.98	100.00

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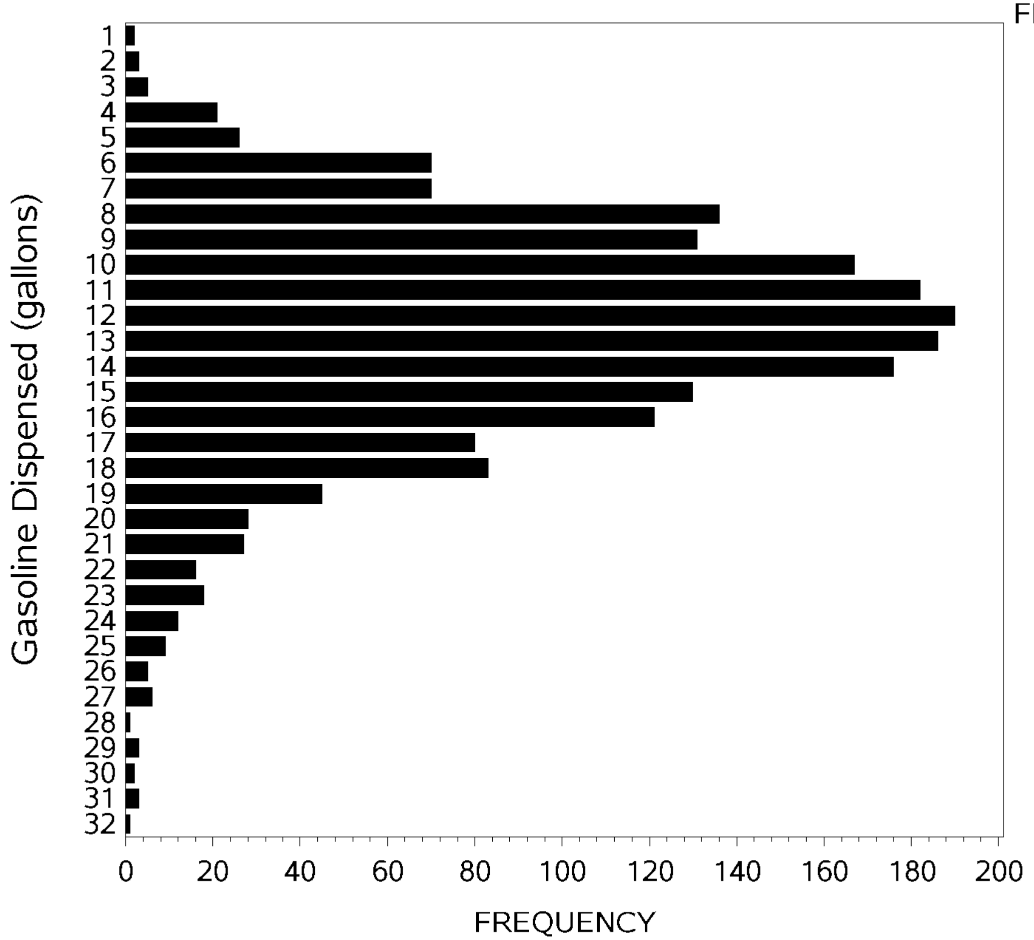
Figure 3-17. Gallons Dispensed during Confirmed ORVR Refuelings



Gallons	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
1	2	2	0.10	0.10
2	3	5	0.15	0.26
3	5	10	0.26	0.51
4	21	31	1.07	1.59
5	26	57	1.33	2.92
6	70	127	3.58	6.50
7	70	197	3.58	10.08
8	136	333	6.96	17.03
9	131	464	6.70	23.73
10	167	631	8.54	32.28
11	182	813	9.31	41.59
12	190	1003	9.72	51.30
13	186	1189	9.51	60.82
14	176	1365	9.00	69.82
15	130	1495	6.65	76.47
16	121	1616	6.19	82.66
17	80	1696	4.09	86.75
18	83	1779	4.25	91.00
19	45	1824	2.30	93.30
20	28	1852	1.43	94.73
21	27	1879	1.38	96.11
22	16	1895	0.82	96.93
23	18	1913	0.92	97.85
24	12	1925	0.61	98.47
25	9	1934	0.46	98.93
26	5	1939	0.26	99.18
27	6	1945	0.31	99.49
28	1	1946	0.05	99.54
29	3	1949	0.15	99.69
30	2	1951	0.10	99.80
31	3	1954	0.15	99.95
32	1	1955	0.05	100.00

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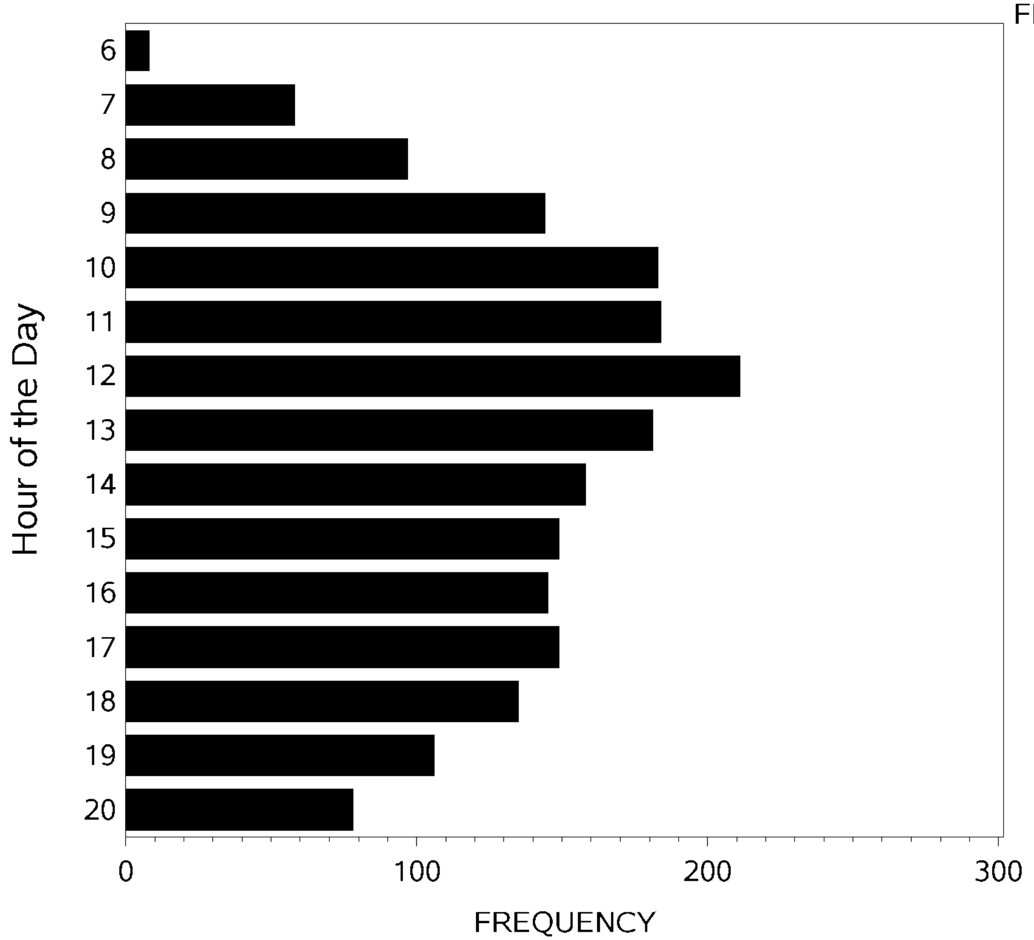
Figure 3-18. Hour of the Day for Confirmed ORVR Refuelings



Hour of the Day	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
6	8	8	0.40	0.40
7	58	66	2.92	3.32
8	97	163	4.88	8.21
9	144	307	7.25	15.46
10	183	490	9.21	24.67
11	184	674	9.26	33.94
12	211	885	10.62	44.56
13	181	1066	9.11	53.68
14	158	1224	7.96	61.63
15	149	1373	7.50	69.13
16	145	1518	7.30	76.44
17	149	1667	7.50	83.94
18	135	1802	6.80	90.74
19	106	1908	5.34	96.07
20	78	1986	3.93	100.00

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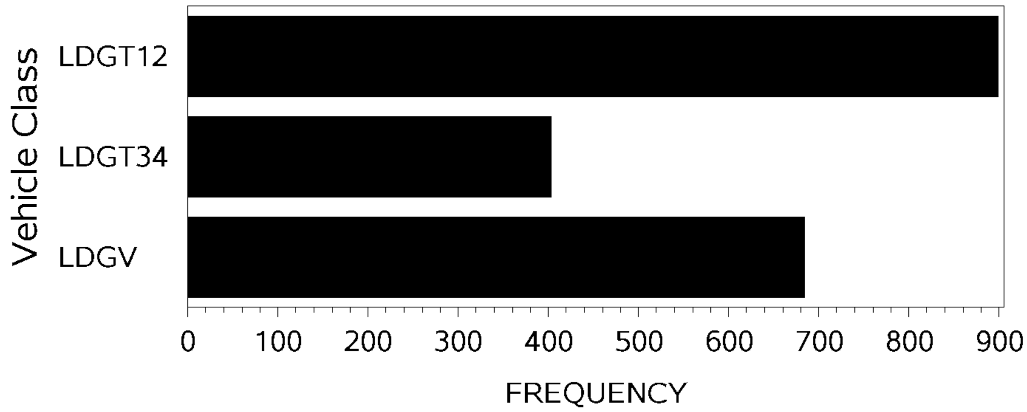
Figure 3-19. Vehicle Class for Confirmed ORVR Refuelings



	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
LDGT12	899	899	45.27	45.27
LDGT34	403	1302	20.29	65.56
LDGV	684	1986	34.44	100.00

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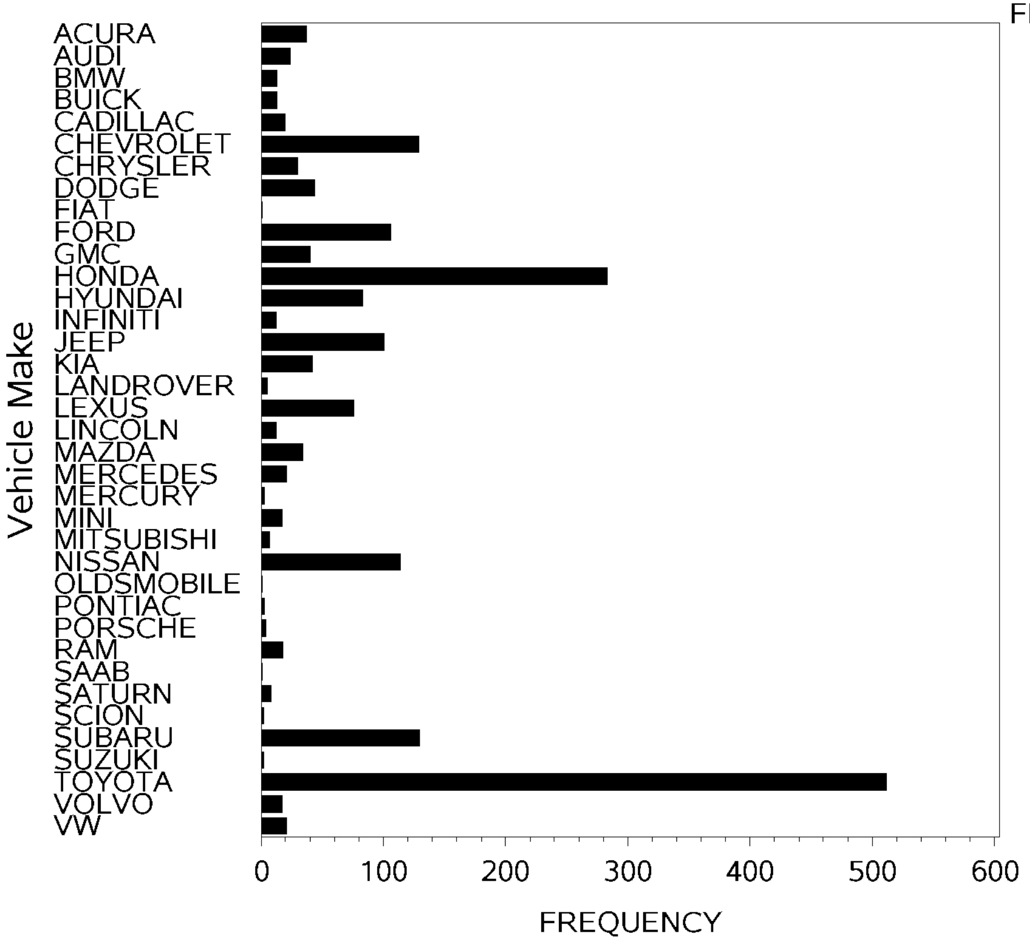
Figure 3-20. Vehicle Make for Confirmed ORVR Refuelings



Vehicle Make	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
ACURA	37	37	1.86	1.86
AUDI	24	61	1.21	3.07
BMW	13	74	0.65	3.73
BUICK	13	87	0.65	4.38
CADILLAC	20	107	1.01	5.39
CHEVROLET	129	236	6.50	11.88
CHRYSLER	30	266	1.51	13.39
DODGE	44	310	2.22	15.61
FIAT	1	311	0.05	15.66
FORD	106	417	5.34	21.00
GMC	40	457	2.01	23.01
HONDA	283	740	14.25	37.26
HYUNDAI	83	823	4.18	41.44
INFINITI	12	835	0.60	42.04
JEEP	101	936	5.09	47.13
KIA	42	978	2.11	49.24
LANDROVER	5	983	0.25	49.50
LEXUS	76	1059	3.83	53.32
LINCOLN	12	1071	0.60	53.93
MAZDA	34	1105	1.71	55.64
MERCEDES	21	1126	1.06	56.70
MERCURY	3	1129	0.15	56.85
MINI	17	1146	0.86	57.70
MITSUBISHI	7	1153	0.35	58.06
NISSAN	114	1267	5.74	63.80
OLDSMOBILE	1	1268	0.05	63.85
PONTIAC	3	1271	0.15	64.00
PORSCHE	4	1275	0.20	64.20
RAM	18	1293	0.91	65.11
SAAB	1	1294	0.05	65.16
SATURN	8	1302	0.40	65.56
SCION	2	1304	0.10	65.66
SUBARU	130	1434	6.55	72.21
SUZUKI	2	1436	0.10	72.31
TOYOTA	512	1948	25.78	98.09
VOLVO	17	1965	0.86	98.94
VW	21	1986	1.06	100.00

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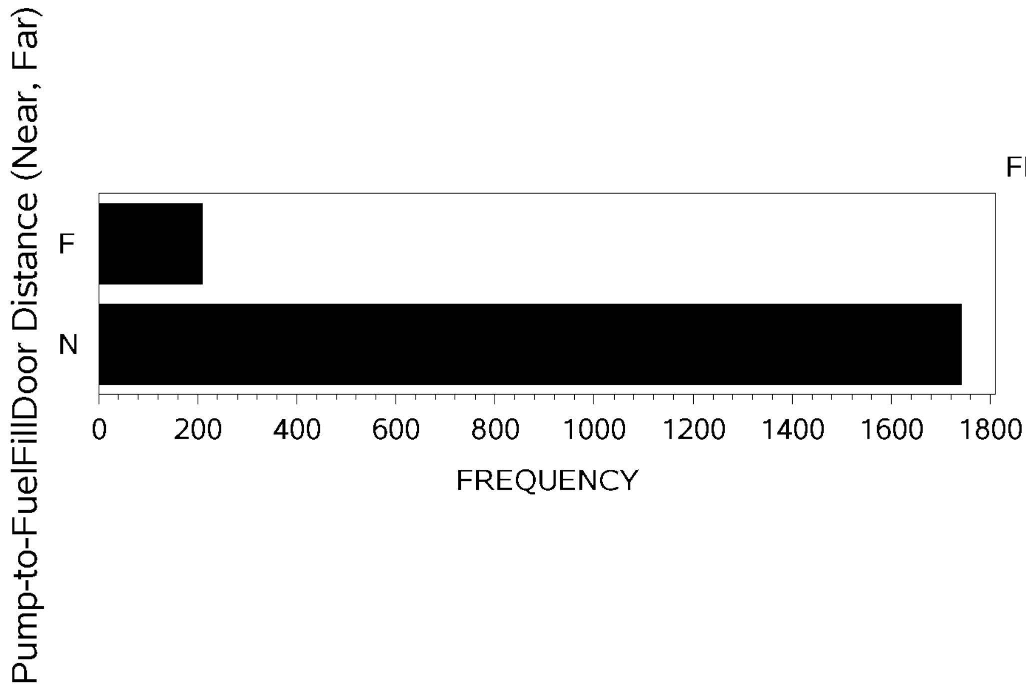
Figure 3-21. Pump to Fuel Fill Door Distance for ORVR Refuelings



	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
F	209	209	10.71	10.71
N	1742	1951	89.29	100.00

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Table 3-12. Continuous Variable Split Values

Split Point (percentile)	Wind Speed (mph)	Outdoor Temperature (F)	Fuel Volume Dispensed (gallons)	Refueling Hour of Day (24-hour)
10	1.3	75	7.49	9
25	2.3	80	9.66	11
50	3.3	86	12.38	13
75	4.9	91	13.27	16
90	6.6	95	18.31	18

We used logistic regression to simultaneously determine the statistical significance of pump position (front pump vs. back pump) and the factor category (for example, high wind speed vs. low wind speed) on the probability that a plume (not a puff) would be observable in the video. Thus, we performed twenty logistic regressions for the four variables and five splits shown in Table 3-12. For the three natural categorical variables we performed an additional three regressions.

In all 23 regressions, pump position (front vs. back) was statistically significant. Specifically, we are 95% confident that the difference in average probabilities of continuous plumes being seen in videos of refueling at the back pumps and at front pumps did not occur by chance alone. Of the 23 regressions, after the effect of pump position was accounted for, only one regression indicated a significant effect for the factor being investigated; all of the other factors were found to have non-significant effects on the probability of an emissions plume being seen in the video.

The one factor that showed an effect was the wind speed when 1.3 mph was used to split the wind speed distribution into a low wind speed group and a high wind speed group. Table 3-13 shows the modeled observable plume probabilities for the four combinations of pump position and wind speed when the wind speed distribution is split at 1.3 mph. The four cells in the table also show the number of dataset observations for the plume and no-plume cases. For example, for the low-wind speed, back-pump refueling condition, the table shows that the logistic regression predicts that 8.0% of refuelings will produce a video with a visible plume. That cell in the table shows that 7 plume videos and 75 no-plume videos were observed for that refueling condition.

Table 3-13. Logistic Regression Results for Wind Speed and Pump Position

	Observable Plume Probability	
	Low Wind Speed (≤ 1.3 mph)	**High Wind Speed (> 1.3 mph)**
Back Pumps	8.0% Plume=7 NoPlume=75	4.3% Plume=37 NoPlume=832
Front Pumps	5.1% Plume=6 NoPlume=122	2.7% Plume=25 NoPlume=882

Analogous regressions when the wind speed distribution was split at higher speeds do not show a significant effect on observable plume probability. Thus, it seems that the especially low wind speeds (≤ 1.3 mph) particularly enhance the visibility of plumes in the GCI videos. In summary, plumes are most visible in the GCI videos when a vehicle refuels at a back-row pump, which tends to have a well illuminated and non-complex background, and when the wind is near calm. Plumes are least visible at front-row pumps and when there is some air movement.

The quantified influences of pump position and wind on plume visibility make sense. However, those factors cannot influence the refueling emissions themselves. The other six factors (outdoor temperature, gallons of fuel dispensed, refueling time of day, vehicle class, vehicle make, and distance between fuel pump and fuel fill door) could influence emissions, and that is the reason they were explored with logistic regression. Higher outdoor temperatures and more gallons dispensed would be more likely to result in saturated canisters. Refuelings early in the day might be associated with smaller canister purge volumes if customers lived close to the gas station. Refuelings near evening rush hour might be associated with higher fuel tank temperatures and therefore higher fuel tank vapor generation. Some vehicle classes or vehicle makes might be more likely to have inadequately designed evaporative emissions control systems. When fuel pump hoses are stretched far to reach a fuel fill door on the opposite side of the vehicle, refueling emissions could occur because of unusual orientations of the nozzle in the fuel fill pipe. However, we saw none of these effects in the data since, as mentioned earlier, none of the regressions on these factors were statistically significant.

3.7 Model Year Trends in Phase 2 Plume Observations

The Phase 2 re-examination of the videos for puffs and plumes effectively changes the distribution of refueling emissions characteristics from the Phase 1 categories (Category 1, Category 2, and Category 3) to the Phase 2 categories (NoPuffsNoPlumes, OnlyPuffsNoPlumes, and ContinuousPlumes). To show and analyze the distribution shift, Table 3-14 shows the same counts of videos as were used to create the Phase 1 Table 3-7 but now using Phase 2 categories. Table 3-14 again has the three major tables for LDGVs, LDGT12s, and LDGT34s, but the subheadings refer to the three new refueling characteristics of Phase 2 viewing. In addition, we show a NotAssigned category, which was created because a few of the refueling events could not be unambiguously categorized. Categorization was not possible for these events because we could not determine whether the emissions were from the target vehicle or from the other vehicle also refueling on the same side of the island.

Table 3-14. Phase 2 Status of Refueling Events for Confirmed ORVR Vehicles[24,25]

	LDGVs				
	Refueling Event Category				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2000	12	7	2	1	22
2001	11	3	5	1	20
2002	15	5	1	0	21
2003	19	4	1	1	25
2004	21	6	2	0	29
2005	29	9	5	0	43
2006	25	4	3	1	33
2007	41	5	2	0	48
2008	28	10	2	0	40
2009	37	4	3	0	44
2010	27	8	3	0	38
2011	27	4	2	0	33
2012	40	9	1	1	51
2013	52	7	1	0	60
2014	42	7	2	0	51
2015	36	3	1	0	40
2016	27	7	0	0	34
2017	30	4	0	0	34
2018	16	3	1	0	20
Total	*535*	*109*	*37*	*5*	*686*

	LDGT1s + LDGT2s				
	Refueling Event Plume				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2003	26	5	3	1	35
2004	35	6	1	0	42
2005	37	4	1	1	43
2006	41	7	5	0	53
2007	49	12	3	0	64
2008	40	4	3	1	48
2009	21	4	0	0	25
2010	31	9	1	0	41
2011	31	3	0	0	34
2012	47	7	1	0	55
2013	51	7	0	0	58
2014	51	7	1	0	59
2015	77	17	2	1	97
2016	50	12	3	0	65
2017	88	20	1	1	110
2018	67	4	0	0	71
Total	*742*	*128*	*25*	*5*	*900*

	LDGT3s + LDGT4s				
	Refueling Event Plume				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2006	17	3	2	0	22
2007	27	6	1	1	35
2008	19	4	1	0	24
2009	5	0	0	0	5
2010	14	4	1	0	19
2011	37	3	2	0	42
2012	32	3	1	0	36
2013	31	4	1	0	36
2014	38	8	1	1	48
2015	37	5	4	0	46
2016	24	7	1	0	32
2017	31	6	0	0	37
2018	20	2	0	0	22
Total	*332*	*55*	*15*	*2*	*404*

[24] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final/PlumeVideoCounts.xlsx

[25] Vehicle classes have not been determined for 2019 vehicles in this table. In this table, the first model year in each vehicle class is the first full-implementation model year for the class. Therefore, no non-ORVR vehicles and no vehicles in transition model years are counted for this table.

Refueling Emissions Prevalence – We expect that results from only the ContinuousPlumes category represent potential malfunctions of evaporative emissions control systems.

Figure 3-22, Figure 3-24, and Figure 3-26[26] show the model year trends for the fraction of refueling events categorized as ContinuousPlumes. The other category that is of interest is the OnlyPuffsNoPlumes category. Figure 3-23, Figure 3-25, and Figure 3-27 show the model year trends for the fraction of refueling events categorized as OnlyPuffsNoPlumes for LDGV, LDGT12s, and LDGT34s, respectively. Figure 3-22 through Figure 3-27 are made only for the model years of those vehicle types where ORVR was required on all vehicles in the type. Figure 3-28 shows an overlay plot of the continuous plume model-year averages for the three vehicle classes. Figure 3-29 shows an overlay of the puff trends seen in Figure 3-23, Figure 3-25, and Figure 3-27.

The three ContinuousPlume plots show that each vehicle type tends to have a downward trend as vehicles get newer. The downward trend is most obvious for the LDGVs in Figure 3-22 where 37 vehicles with ContinuousPlumes support the trend (see Table 3-14). The downward trend in the Figure 3-26 plot for the LDGT34s is not so obvious because only 15 vehicles support the trend. Since it may be that all three vehicle types have similar trends, we combined the 77 counts for all three vehicle types to create Figure 3-30. In the figure, the bubble symbols have shading and areas proportional to the number of total refuelings for the model year. The data is taken by combining the Table 3-14 ContinuousPlumes and Total Events data for the three vehicle classes. For example, the symbol for 2002 is based on 21 refuelings (1 had a ContinuousPlume) and 2015 is based on 183 refuelings (8 had a ContinuousPlume). The symbols for 2006-2018 are for LDGVs, LDGT12s, and LDGT34s combined. The symbols for 2003-2005 are for only LDGVs and LDGT12s, and the symbols for 2000 and 2002 are for only LDGVs. The symbols show a downward trend toward 0% ContinuousPlumes for new vehicles.

The three OnlyPuffsNoPlumes plots (Figure 3-23, Figure 3-25, and Figure 3-27) with the open circles show that the model year trends for puffs caused by the combined effects of removing gas cap, beginning fuel flow, click-off at the end of fuel flow, and topping off are relatively flat with model year. This might be the expected trend since puffs are probably not influenced by the evaporative emission control system. Also, note that the combined bubble plot in Figure 3-31, using the OnlyPuffsNoPlumes and Total Events data from Table 3-14, shows that

[26] C:\\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Report_Final/ PlumeVideoCounts.xlsx

the model-year average fraction of OnlyPuffsNoPlumes for all three vehicle types is about the same at 14% (=243/1710). As for ContinuousPlume prevalence, the rate of puff occurrence depends on camera sensitivity.

Figure 3-22. Model Year[27] Trend of ContinuousPlume Fraction for LDGVs

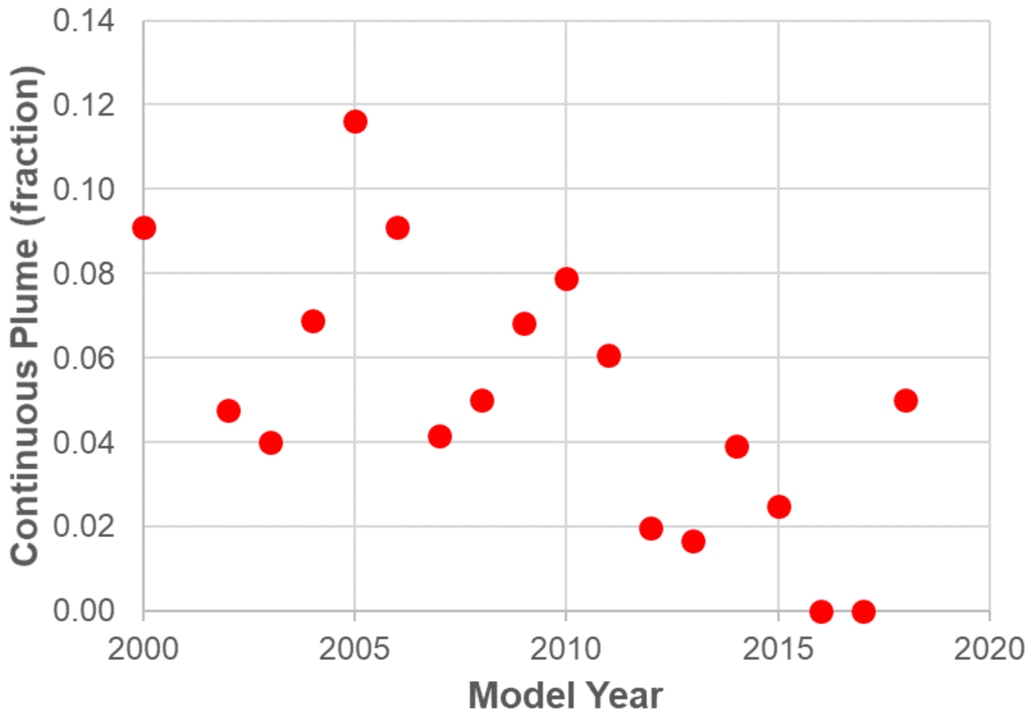
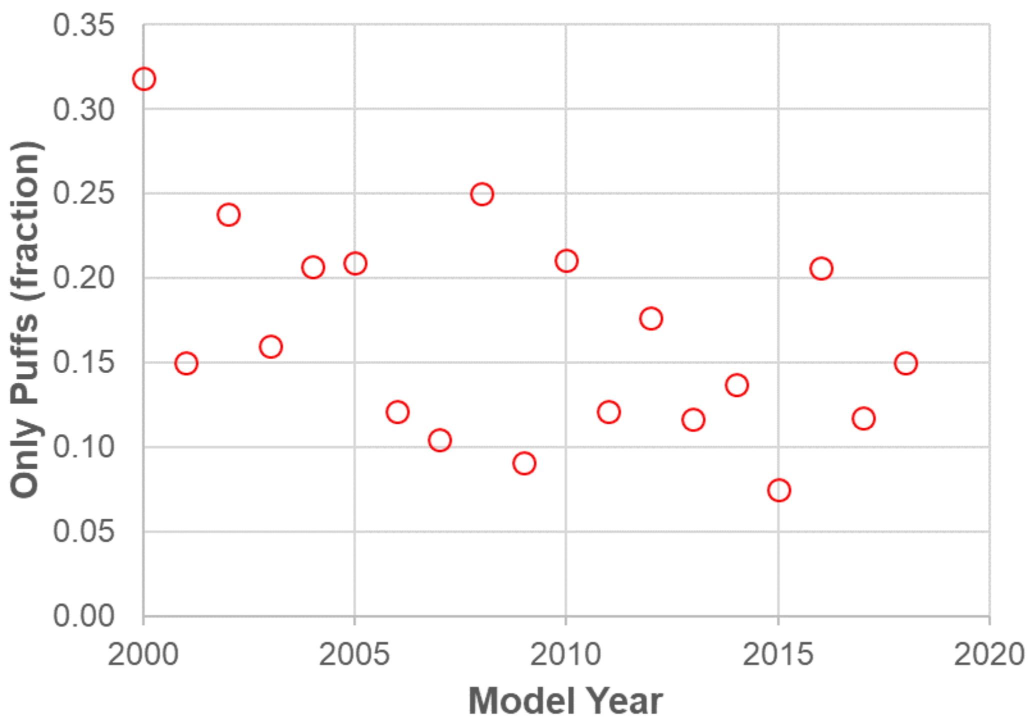


Figure 3-23. Model Year Trend of OnlyPuffsNoPlumes Fraction for LDGVs



[27] The data point for 2001 is off scale at 0.25.

Figure 3-24. Model Year Trend of ContinuousPlume Fraction for 0-6,000 lb GVWR trucks (LDGT12s)

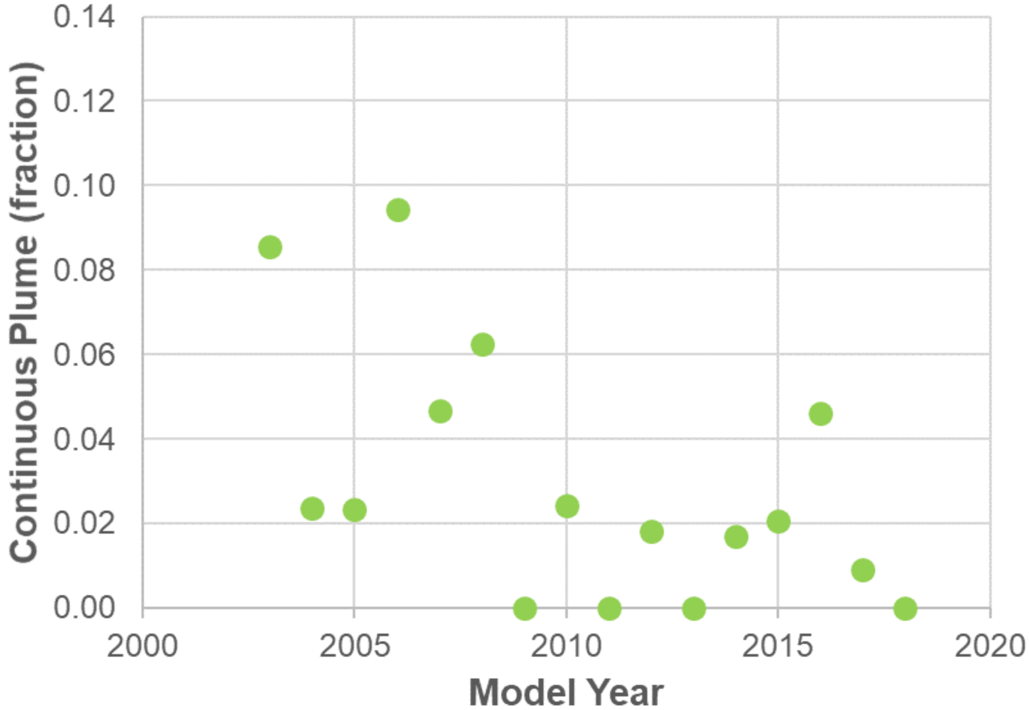


Figure 3-25. Model Year Trend of OnlyPuffsNoPlumes Fraction for 0-6,000 lb GVWR trucks (LDGT12s)

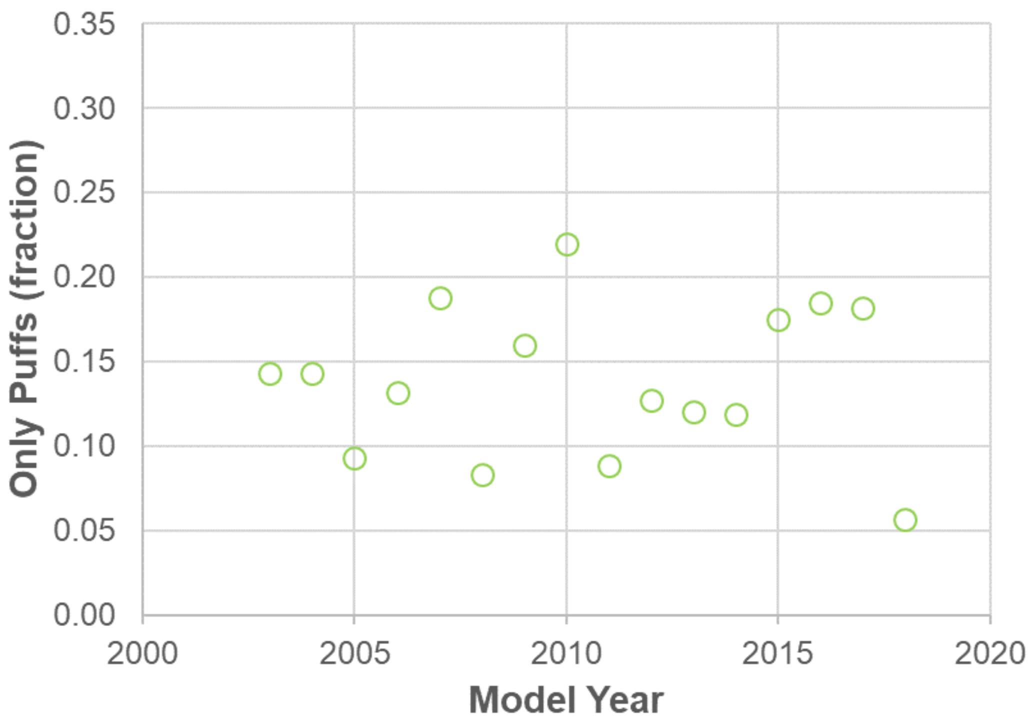


Figure 3-26. Model Year Trend of ContinuousPlume Fraction for 6,001-8,500 lb. GVWR (LDGT34s)

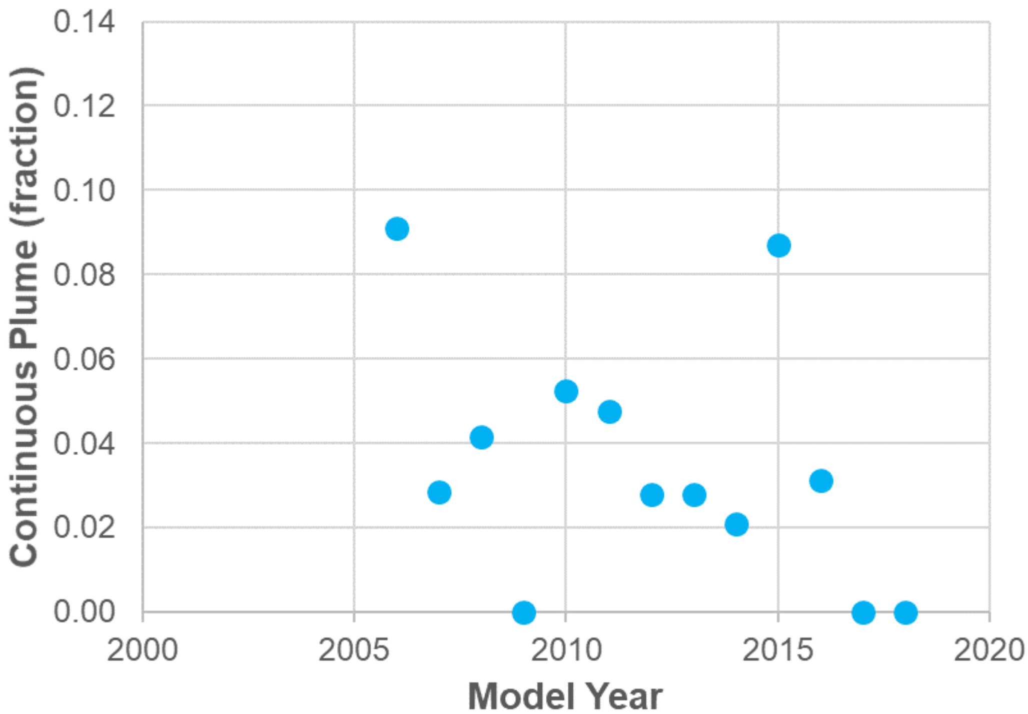


Figure 3-27. Model Year Trend of OnlyPuffsNoPlumes Fraction for 6,001-8,500 lb. GVWR (LDGT34s)

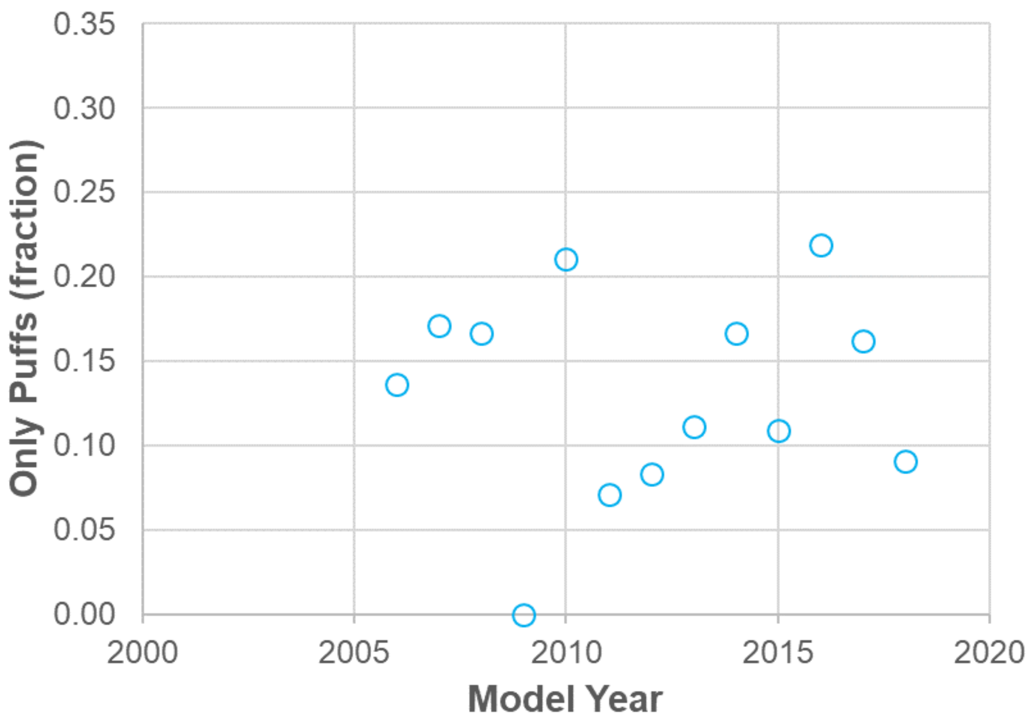


Figure 3-28. Overlaid Model Year Trend of ContinuousPlume Fraction

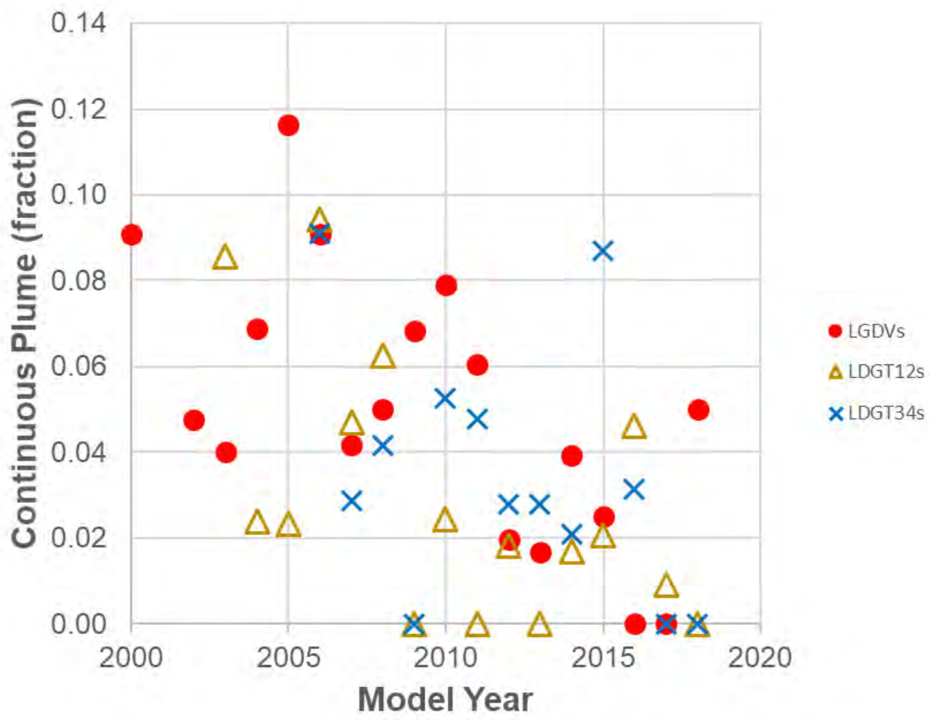


Figure 3-29. Overlaid Model Year Trend of OnlyPuffsNoPlumes Fraction

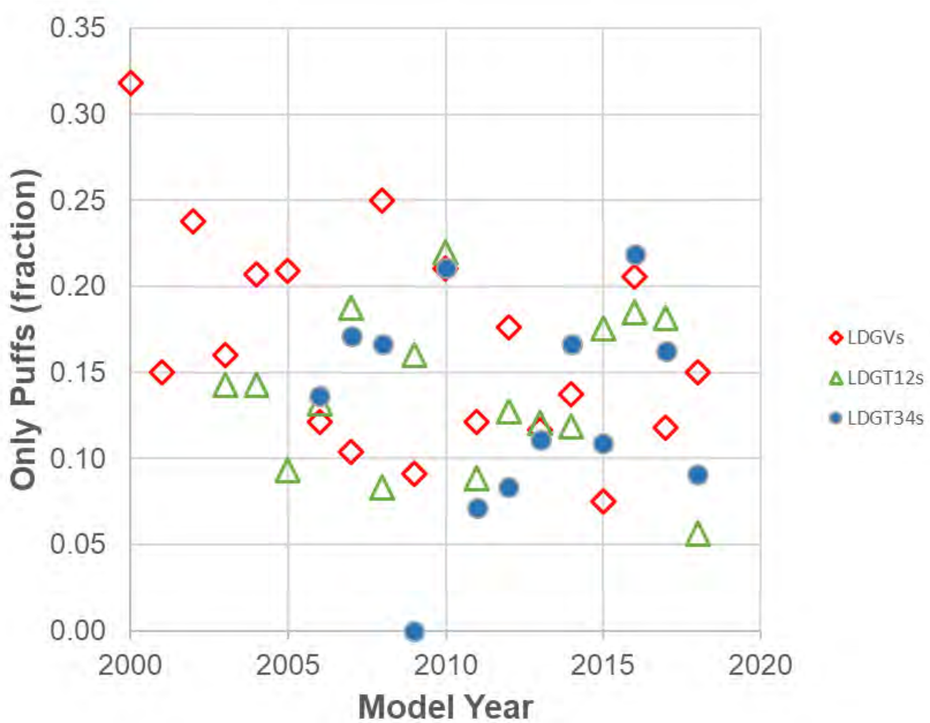


Figure 3-30. Model Year Trend of ContinuousPlume Fraction for Combined LDGVs, LDGT12s, and LDGT34s

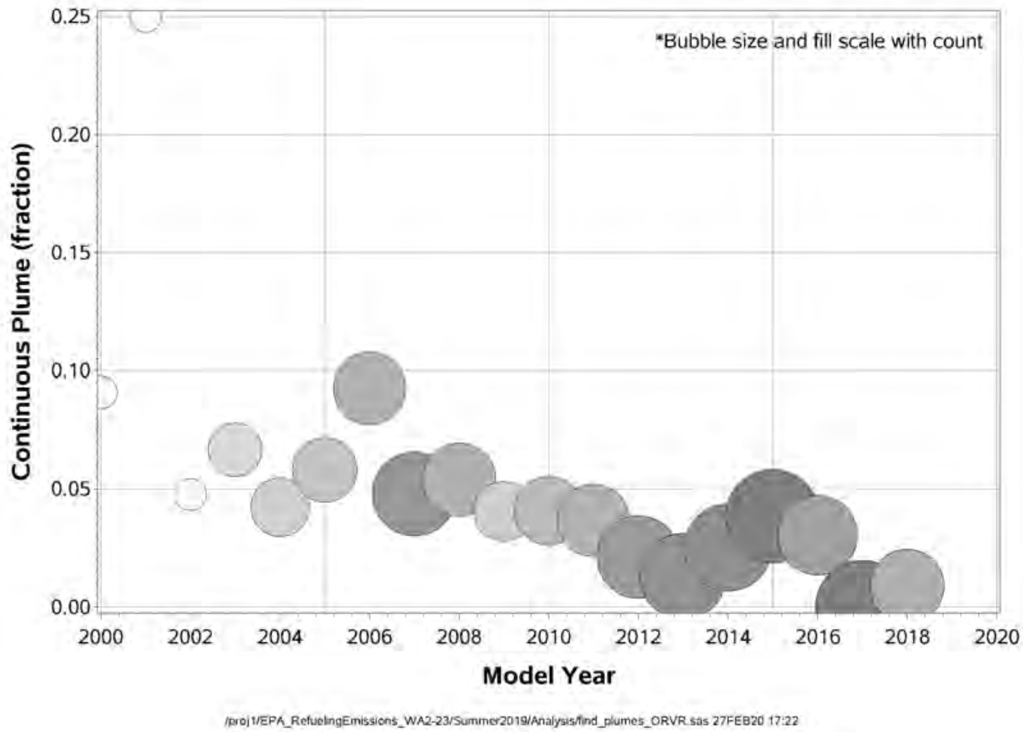
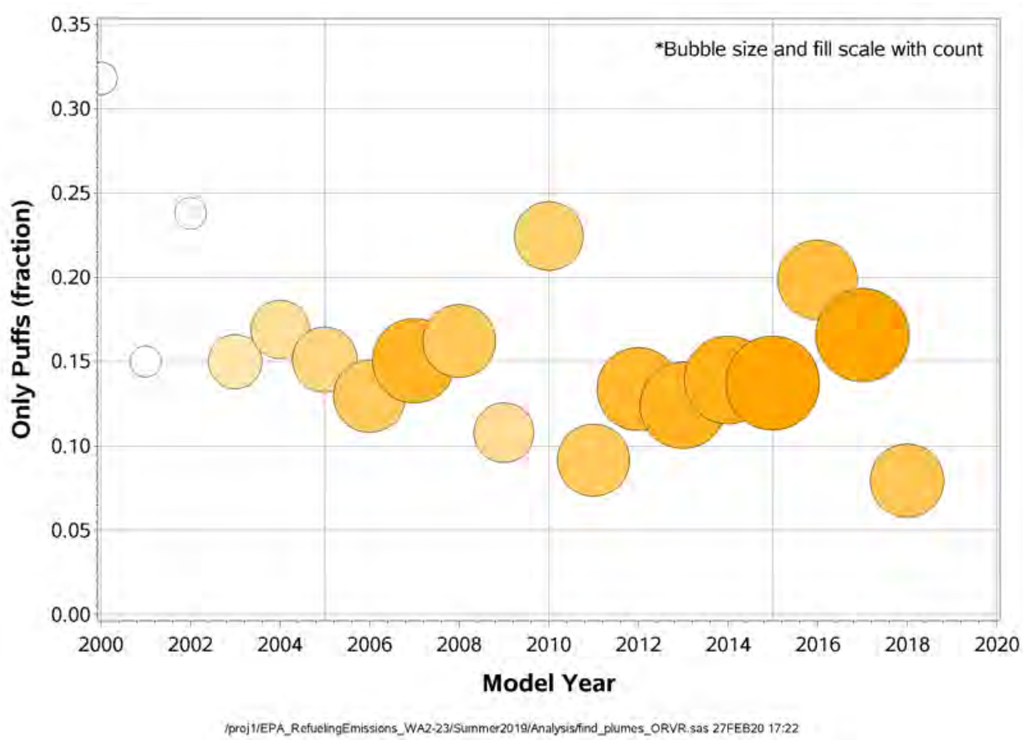
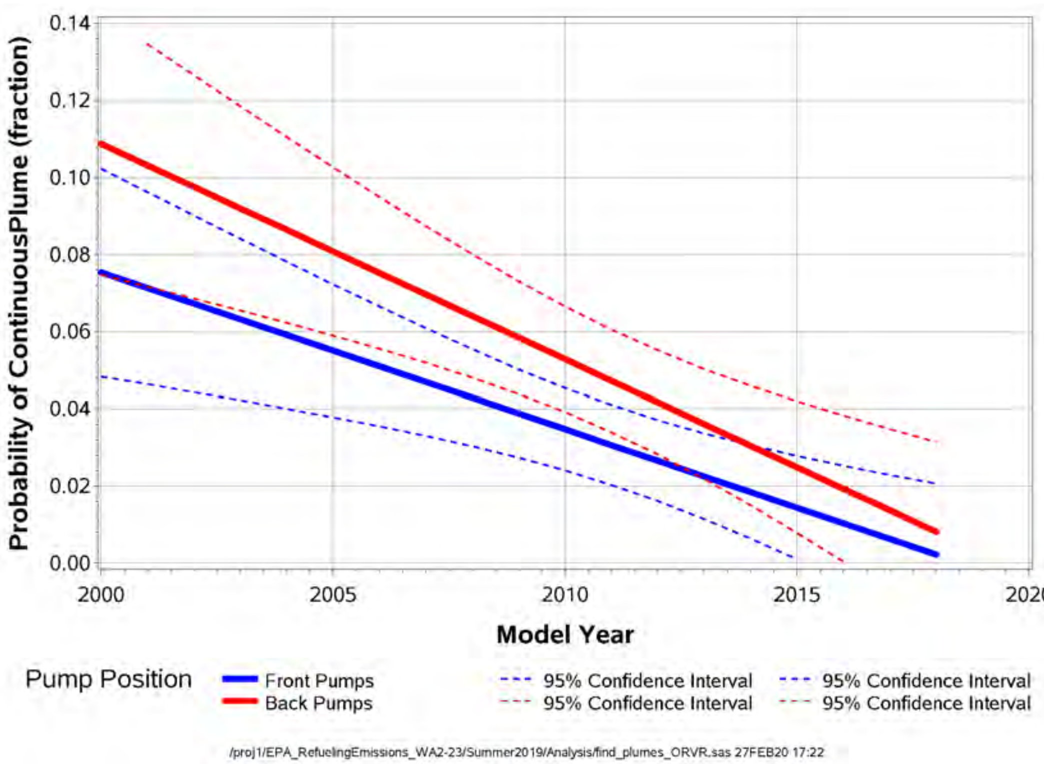


Figure 3-31. Model Year Trend of OnlyPuffsNoPlumes Fraction for Combined LDGVs, LDGT12s, and LDGT34s



We explored the continuous plume observation trends in the confirmed ORVR dataset with ordinary least squares regression. For each of the 1,990 observations, the ContinuousPlume variable had a value of either 1 (plume was observed) or 0 (plume was not observed). We considered the influences of model year, vehicle type, and pump position (front vs. back). Regressions indicated that model year had a statistically significant effect on the probability that a refueling on an ORVR vehicle would produce an observable plume in a video. After model year, regressions indicated a difference in the slope of the model-year trends between the front pumps and back pumps. Finally, after model year and pump position were in the model, the regressions found no significant differences in model year trends among the three vehicle types (LDGVs, LDGT12s, LDGT34s). Therefore, we assumed that the model year trend was the same for all three vehicle types and regressed all 1,990 observations on model year and pump position together. The fitted trends produced by the regression are shown in Figure 3-32 with the 95% confidence limits for the mean trend. The slope of the fit for the back pumps (red) is -0.56%/year ± 0.18%/year standard error and for the front pumps it is -0.41%/year ± 0.13%/year standard error.

Figure 3-32. Regression of Continuous Plume Probability against Model Year and Pump Position



Separate model year regressions for the back pumps and the front pumps also produced the trend lines with the different slopes as seen in Figure 3-32. One feature of these trend lines is that they intersect with each other and with the model-year axis around the 2019 model year. This can be interpreted as indicating that the probability of observing continuous plumes on brand new, 2019 vehicles is very low and possibly zero, and that whether the refueling occurs at front pumps or at back pumps, that conclusion is the same.

For the analysis plots and figures in this section, we had not at first been able to decode the VINs of the 2019 vehicles to get the vehicle classes. After the analysis was complete, we were able to decode 56 of the 59 2019-model-year VINs used in Table 3-15. The results of the Phase 2 video viewings of the 56 refuelings are shown in Table 3-15. No continuous plumes were observed in any of the videos of the 2019 light-duty vehicle refuelings. Thus, this result is consistent with the trend in Figure 3-30 and the notion that the probability of observing continuous plumes in new vehicles is near zero. OnlyPuffsNoPlumes were seen in 18% (=10/56) of the refuelings. This value is also consistent with the flat trend seen in Figure 3-31.

We suggest that the probability vs. model year trend lines pivot around the (2019, 0) point as a function of the GCI camera viewing conditions. If the camera viewing conditions are favorable to a high sensitivity by observing plumes, the trend line will be steep but will tend to pass through, or near, (2019, 0). Conversely, if viewing conditions are not favorable, the trend line will have a shallow slope but will still tend to pass through (2019, 0). The camera sensitivity is affected not just by background illumination and complexity and wind speed; it is also affected by the inherent sensitivity of the camera itself. Since we surmise that all gasoline vehicles produce some, though perhaps tiny, refueling emissions, a sensitive camera would potentially image plumes from all refuelings.

Thus, the important “take-away” from this analysis is that 1) brand new vehicles have a near-zero probability of producing observable refueling plumes, and 2) as vehicles age, the probability of having an observable plume increases approximately linearly. The slopes of the model-year trends for the two sensitivities (front pumps and back pumps) shown in Figure 3-32 or for any particular camera or viewing condition sensitivity are not relevant since the slope depends on the sensitivity of the camera and the viewing conditions. These considerations should be taken into account when using this dataset for modeling.

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Table 3-15. Phase 2 Viewing Results for 2019 Light-Duty Vehicles

	LDGVs				
	Refueling Event Category				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2019	3	1	0	0	4

	LDGT1s + LDGT2s				
	Refueling Event Plume				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2019	31	2	0	0	33

	LDGT3s + LDGT4s				
	Refueling Event Plume				
Model Year	NoPuffs NoPlumes	OnlyPuffs NoPlumes	Continuous Plumes	Not Assigned	Total Events
2019	12	7	0	0	19

Refueling Emissions Timing – The previous discussion reveals the prevalence of refueling of ORVR vehicles with plumes and puffs. Now, we consider the timing of the plumes and puffs. Since ORVR evaporative emissions control systems are required to control emissions while refueling from 0 to 90% fuel tank levels but not greater than 90% full, ContinuousPlumes that occur just before the nozzle automatic click-off may not represent control system malfunctions. For a vehicle tank with a capacity of 20 gallons and a 10 gallon/minute fuel flow, fueling from 90% to 100% full would occur for about the last 12 seconds before the nozzle clicked off. Therefore, we might expect to see ContinuousPlumes in the last two 5-second blocks before nozzle click-off.

We determined the timing of plumes, puffs, and customer activities by viewing the videos and recording the codes described in Table 3-8 for each 5-second block of the video. This synthesized the video content into a short descriptor that contains the essential video information. To help analyze the code strings for each video, we wanted to compare them to the Costco transaction data that provided refueling event timestamps for credit card approval and fuel nozzle hang-up. Potential refueling emissions were detected by the GCI camera collecting infrared data and displaying it in a series of one to six 30-second Enhanced MidWave videos. The videos were separated from each other by approximately 10-second gaps while storing data from the previous video. Therefore, we concatenated the video code strings for the videos of each refueling event and then compared the codes with the transaction timestamps to produce a combined time profile of credit card approval and nozzle hang-up with the coded plume observations for each block.

Figure 3-33, Figure 3-34, and Figure 3-35 show time profile plots that represent the Phase 2 re-viewing results for refuelings of LDGVs, LDGT12s, and LDGT34s, respectively. The plots are shown only for ORVR vehicles and only for those that we judged had at least one 5-second block of ContinuousPlume no matter how weak or strong the emission plume appeared to be. The plots are sorted by increasing model year within each vehicle type. The text beneath each plot is a concatenation of the vehicle identifier, model year, make, model, empty vehicle weight, vehicle class, and the 6-digit codes of the videoing viewings. The 6-digit codes should match the solid lines and square symbols on the plot, as described below.

Figure 3-33. Refueling Emission Profiles with ContinuousPlumes for LDGVs

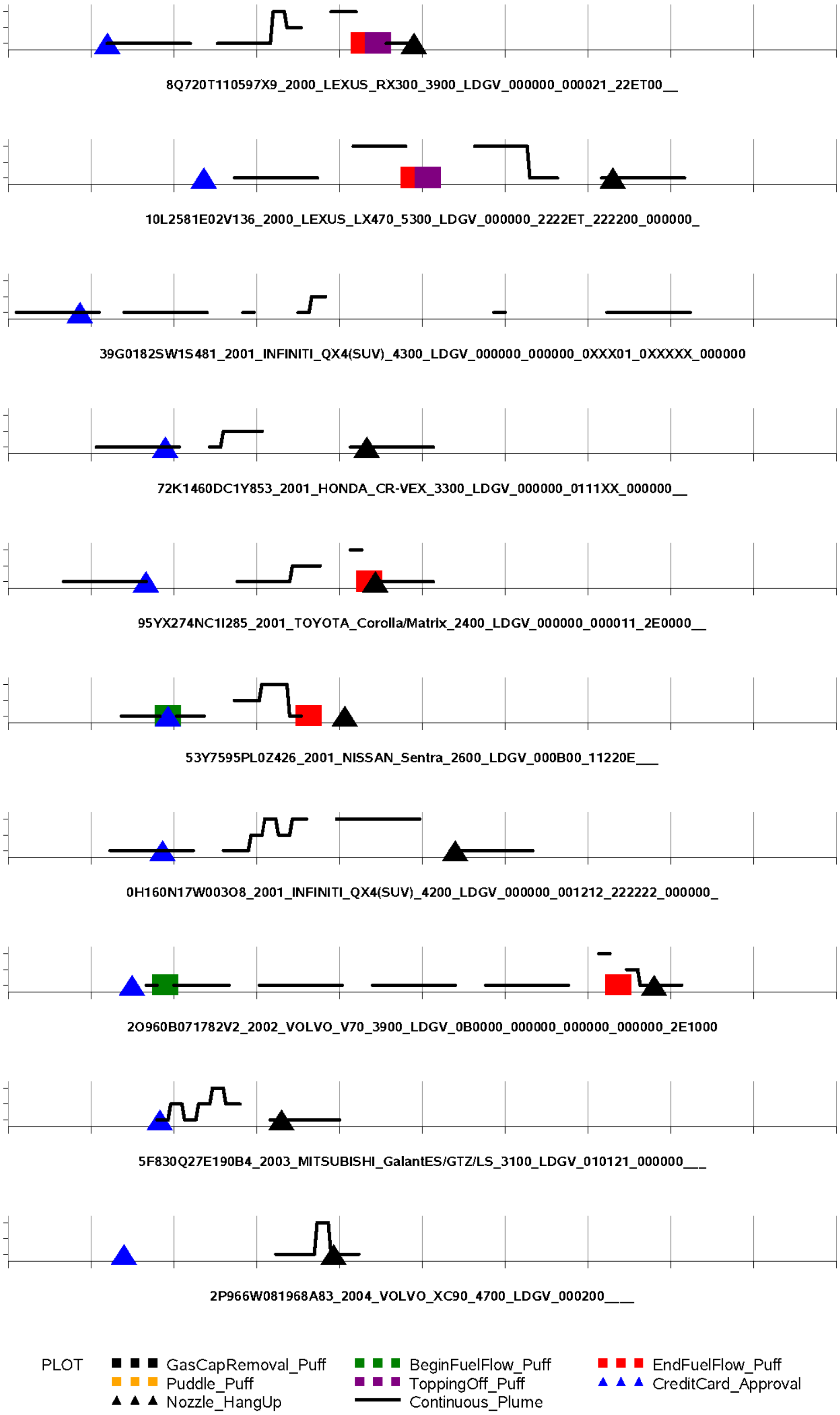


Figure 3-33 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGVs

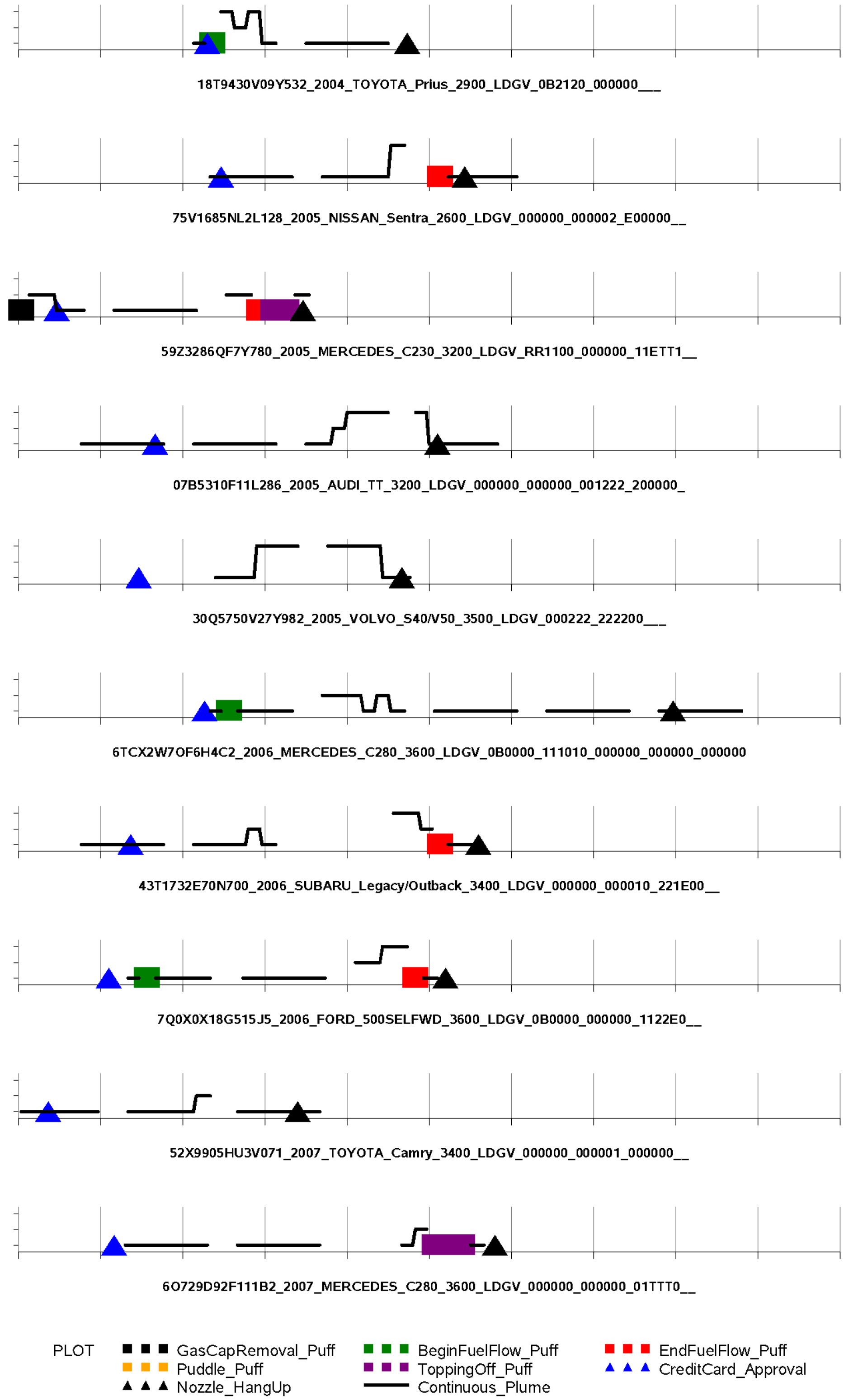


Figure 3-33 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGVs

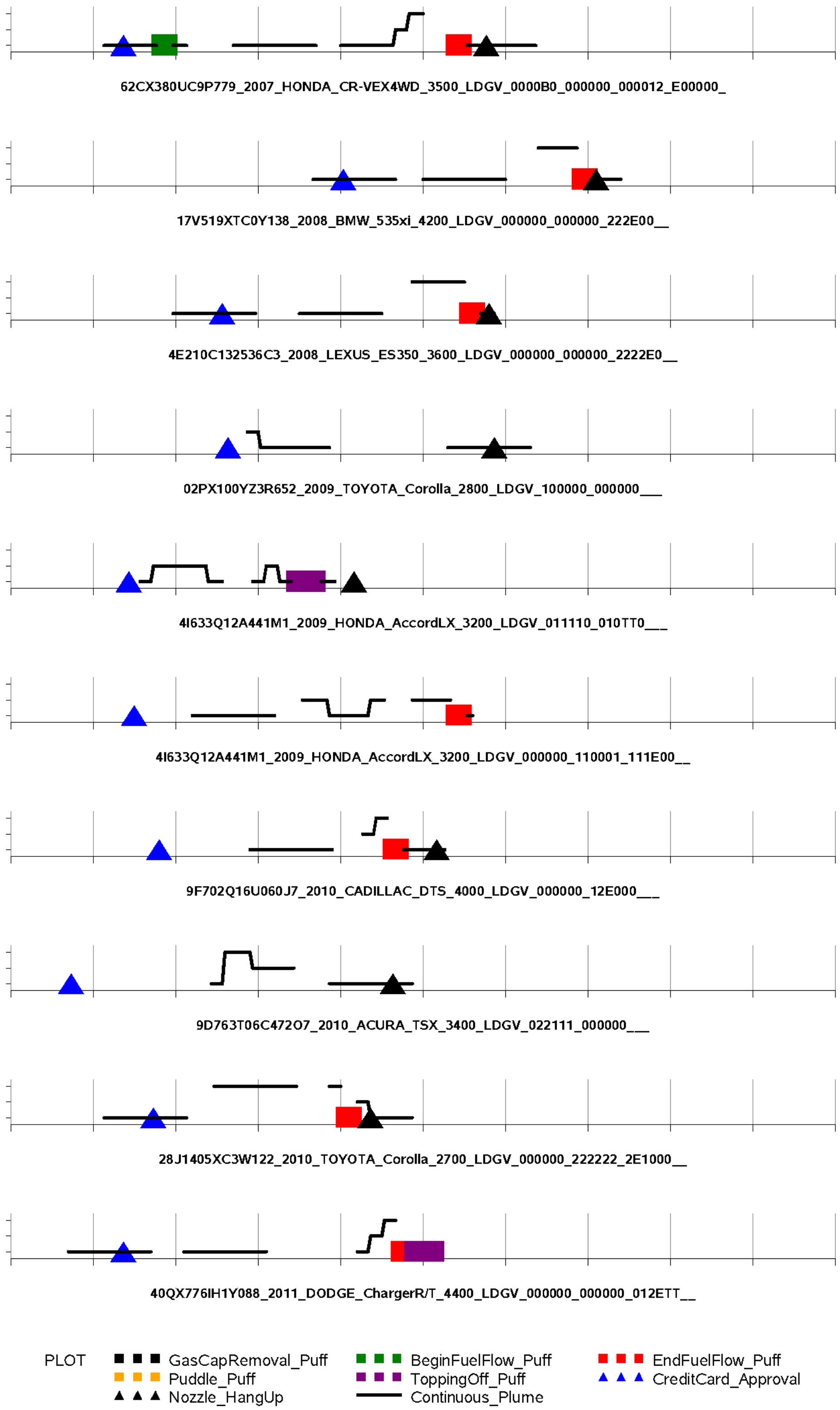


Figure 3-33 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGVs

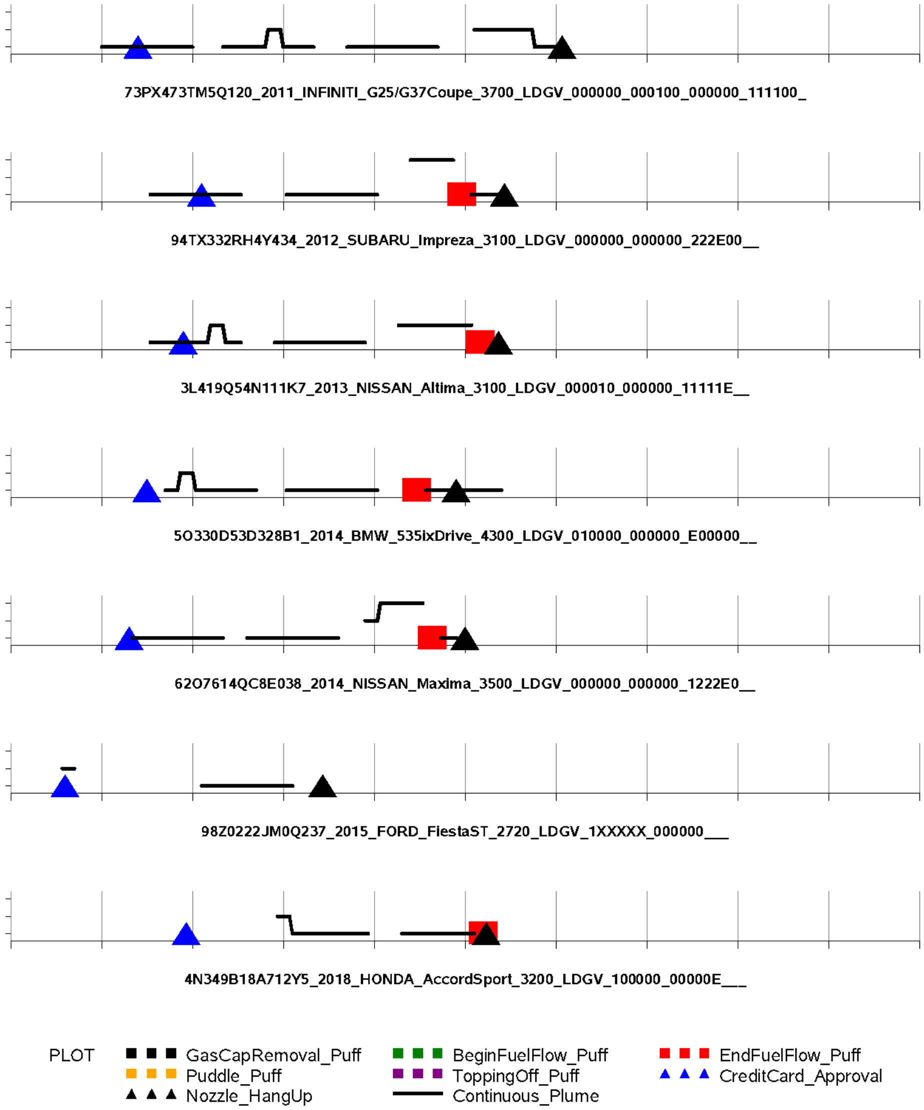


Figure 3-34. Refueling Emission Profiles with ContinuousPlumes for LDGT12s

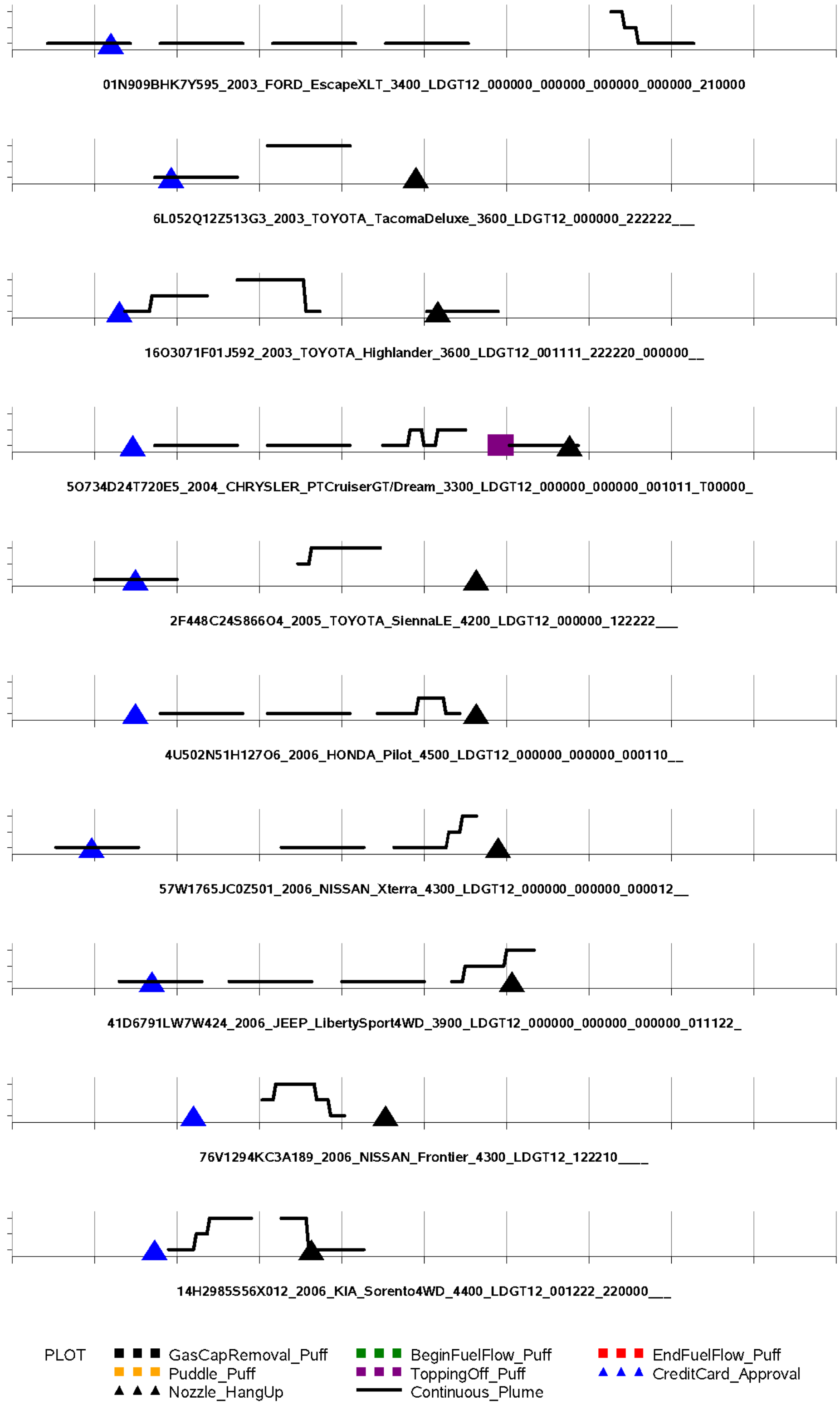


Figure 3-34 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGT12s

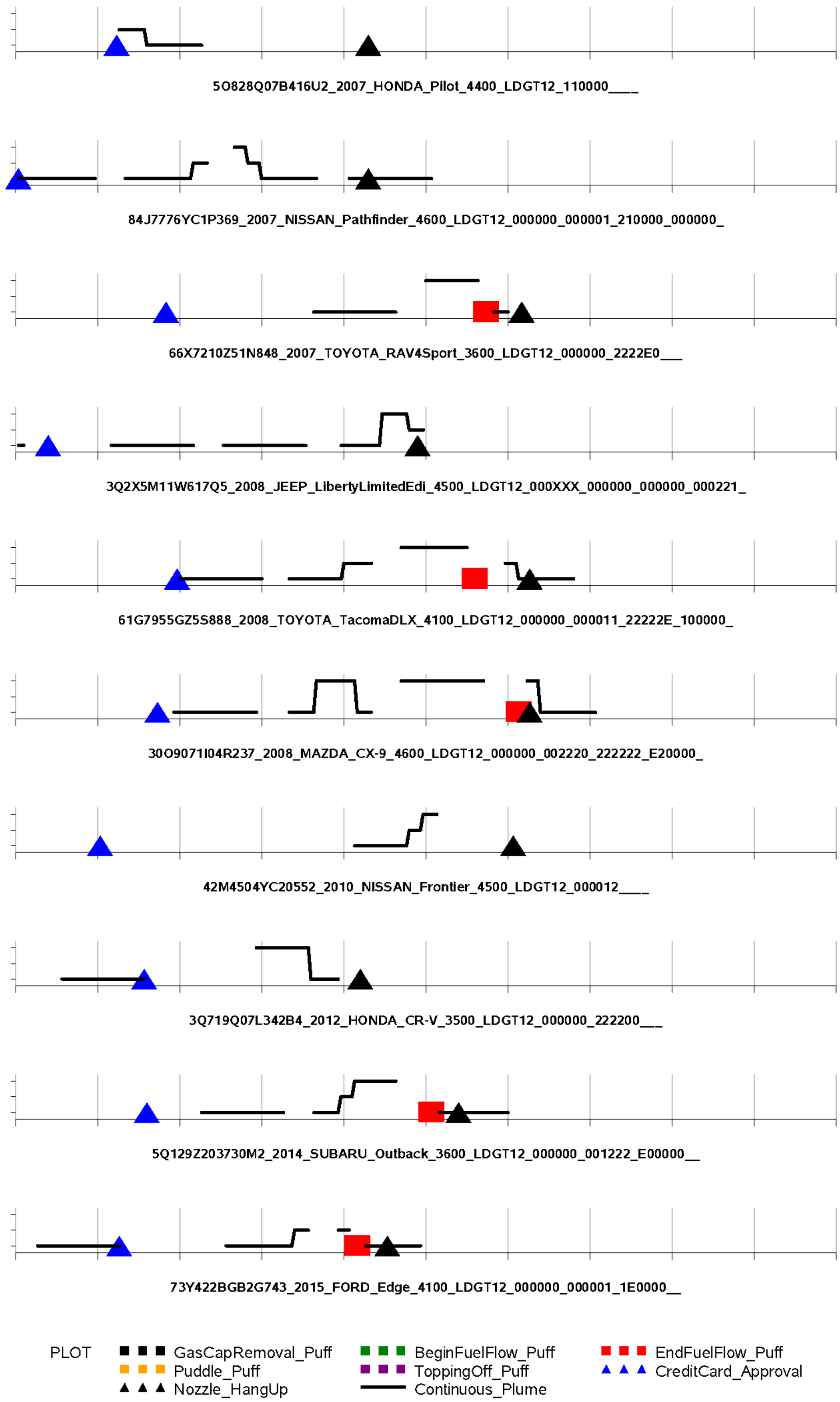


Figure 3-34 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGT12s

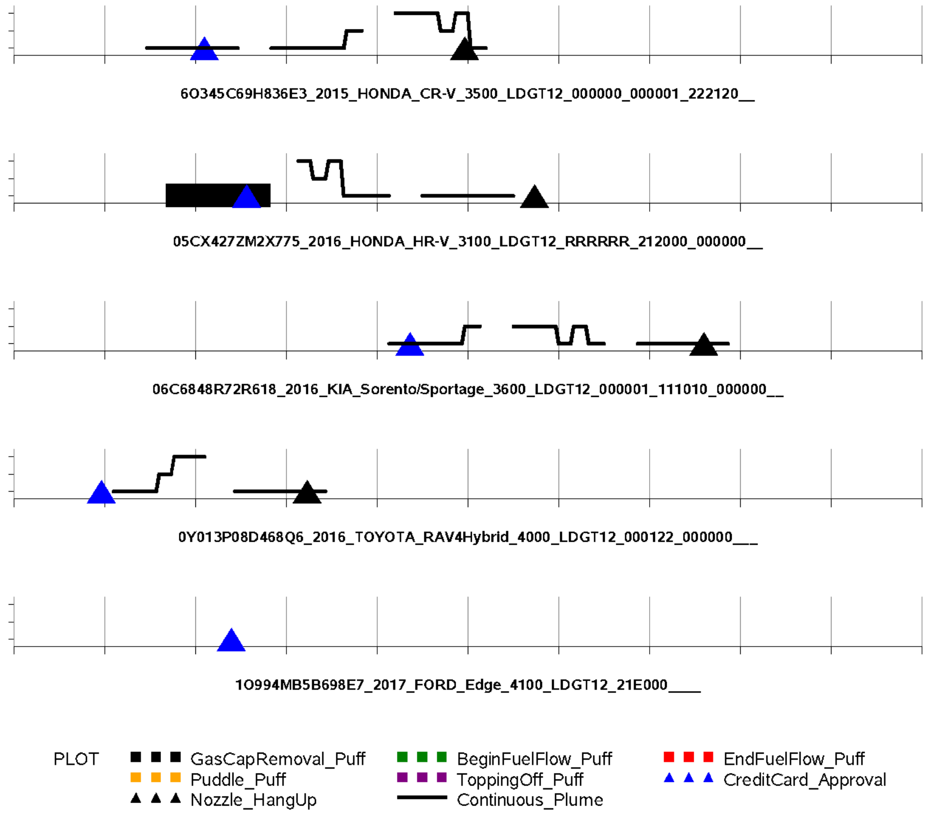


Figure 3-35. Refueling Emission Profiles with ContinuousPlumes for LDGT34s

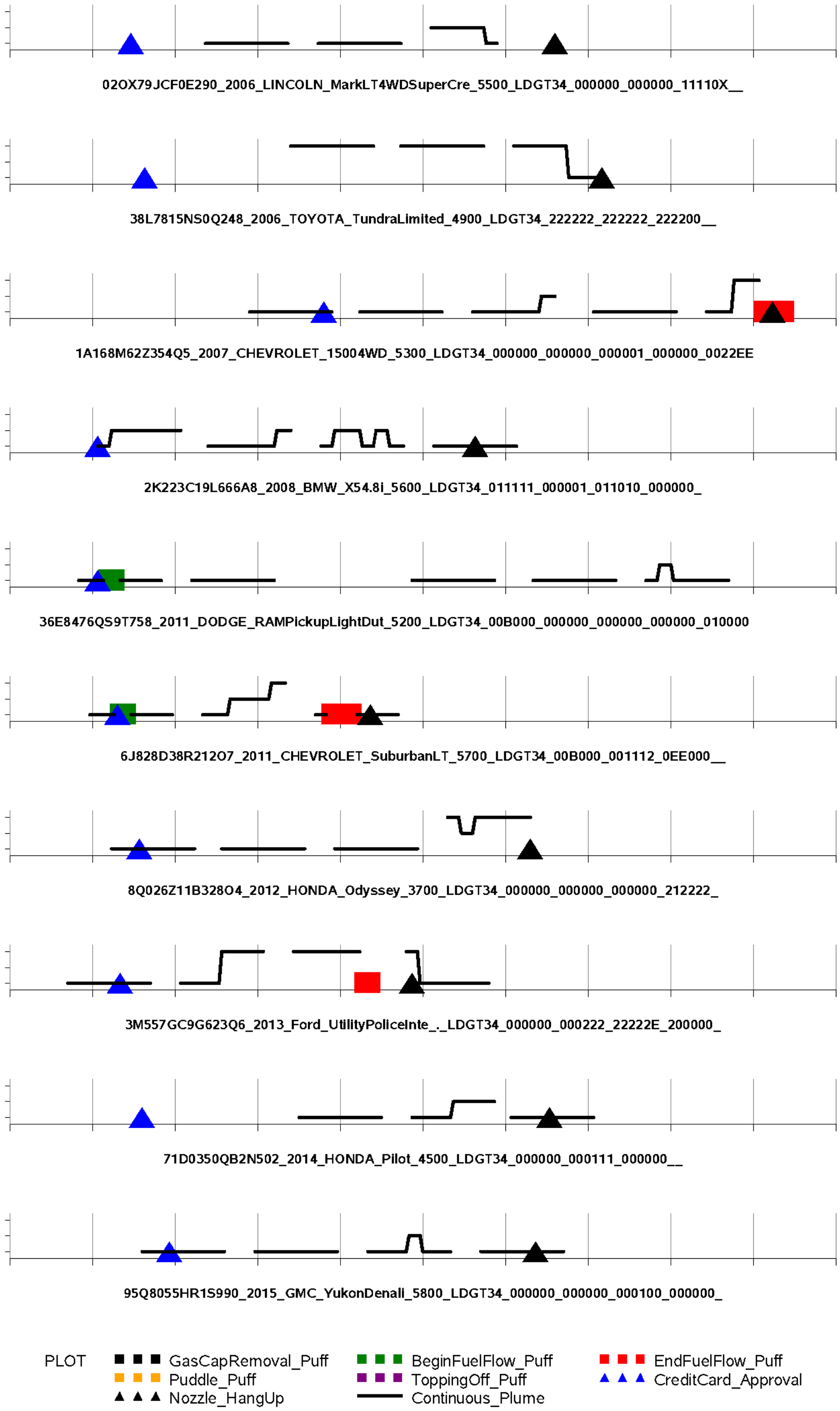
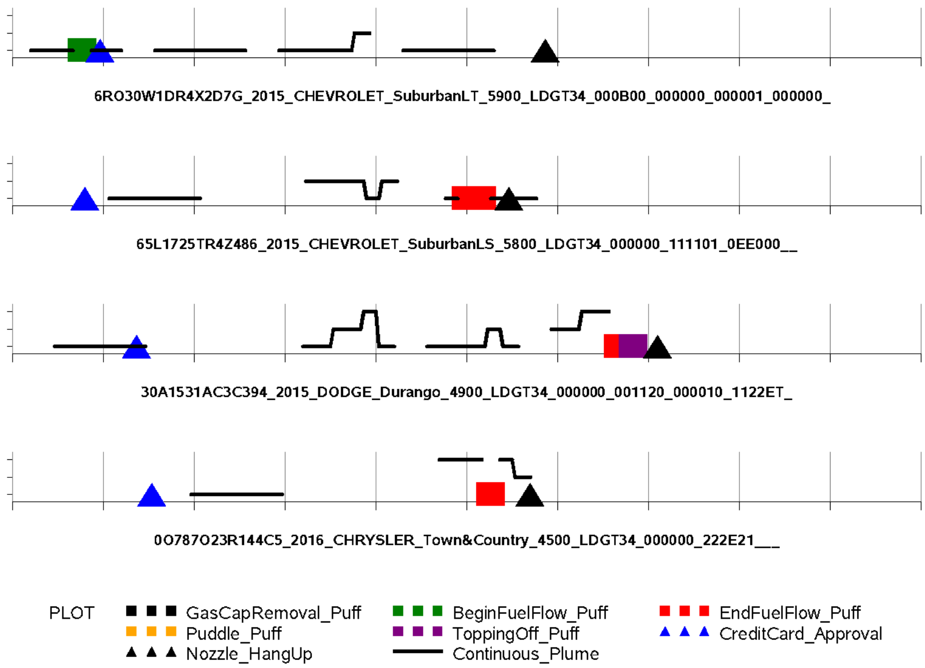


Figure 3-35 (continued). Refueling Emission Profiles with ContinuousPlumes for LDGT34s



Since these plots are unconventional, they require some explanation. The x-axis is time since the vehicle arrived at the pump. The gray vertical grid lines are spaced 30 seconds apart. The y-axis is the scale for ContinuousPlume contrast, which is plotted using the solid black line. The bottom y-axis tick mark represents 0 (no plume), and the top tick mark represents 2 (high contrast or large billowing plume). The trend of the plotted black line reveals the trend of the ContinuousPlume. Each black line segment is 30 seconds long with gaps of about 10 seconds between the segments. This reflects the 30-second videos and 10-second gaps between videos. No emissions information can be obtained during the gaps since there is no video to observe during that time.

The symbols on the plots represent Costco transaction events (triangles) and puffs (squares). The blue triangle marks the time when the customer's credit card was approved by the gas pump. The start of fuel flow must occur after the approval, but it may not occur immediately after approval. The black triangle marks the time when the fuel nozzle is hung up on the fuel pump at the end of refueling. Again, the time between the end of fuel flow and the hang-up may be short or long, but the end of fuel flow must be before the hang-up.

The square symbols represent puffs that we observed in the videos at gas cap removal (black), at the beginning of fuel flow (green), at the nozzle click-off (red), at customer topping-off activities (purple), and from a gasoline puddle on the pavement (orange, note that none were seen in the continuous plume samples plotted in these figures, but the symbol is included for completions since they were present in the puffs seen). Keep in mind that these symbols mark those activities only if we saw puffs during those activities. So, if we did not see a puff or if we did not see or could not determine when the activity occurred, there is no symbol for it.

Vehicles with Repeat Refuelings – Since the study extended over 3 weeks, there was a chance that we might obtain videos on vehicles that returned to the Arvada station for repeat refuelings. We found that of the 1,990 ORVR light-duty vehicle refuelings, 111 refuelings were repeat refuelings of 55 vehicles. 54 vehicles came twice. Of these 54 vehicles, 37 had NoPuffsNoPlumes both times. The other 17 of the 54 vehicles had NoPuffsNoPlumes one time and OnlyPuffsNoPlumes the other time. The one vehicle that came three times had ContinuousPlumes two times and NoPuffsNoPlumes the third time. The time profiles for the ContinuousPlume events for this vehicle (a 2009 Honda Accord) are shown in the fifth and sixth plots on the third page of Figure 3-33.

To demonstrate the variability of refueling emissions and the variety of conditions that make explaining plume visibility difficult, we examine the details of the 2009 Honda Accord in more detail. This vehicle actually came four times (July 10, 17, 20 and 21) to the fuel island that we were monitoring; it is possible that it came on other occasions to fuel islands that we were not monitoring. On July 17 the refueling event was not videoed, so we cannot determine refueling emissions. On July 10, 20, and 21, this was the respective information: ContinuousPlume, NoPuffsNoPlumes, ContinuousPlume; 10.4, 8.9, 9.0 gallons dispensed; front, back, front pump; 3.3, 5.1, 0.2 mph wind; NE, N, S wind direction.

Refueling Mass Emissions Rate – The original plans for this study called for quantification of the mass of HC present in the Rebellion Photonics infrared data. This data analysis activity was not carried out.

The GCI camera records a large amount of "raw" infrared spectral data for all of the camera's pixels each 1/15 second. The 30-second Enhanced MidWave videos that we have used for this analysis were produced on site from this raw data. The plan called for Rebellion to post-process the raw data to produce ColoredVIS videos for 2,000 selected 30-second segments. ColoredVIS videos are 15 frame/second videos made up of conventional visible-range video overlaid with a false coloration of the plume. ColoredVIS videos are routinely made by Rebellion for their other clients. The coloration is based on the optical mass (ppm-m) measured by the GCI camera. Thus, a ColoredVIS video would present all of the optical information that the camera detected in the context of the HC emissions. The processing could also output the optical mass for each pixel and each video frame for those pixels that the post-processing determined were part of the emissions plume. We would not have been able to determine the refueling emission rate, but we would have been able to determine the mass of HC visible to the camera at any given instant. The plan called for first checking the efficacy of the post-processing to make ColoredVIS videos by applying the technique to the GCI camera data collected on the reference vehicle runs since we knew the emissions concentrations and flow rates for those runs.

We submitted 18 reference vehicle runs to Rebellion to test the capability of ColorVIS video production. Unfortunately, we judged that ColorVIS post-processing would not be able to produce useful information for the study. We found that while the post-processing could detect strong HC plumes, it was poor at detecting weak ones. Additionally, the processing always falsely assigned large artifacts to the plume thus hugely elevating the plume optical mass. This unacceptable behavior was caused by the complex background in the gas stations scenes: moving vehicles, moving people, wisps of plumes, plumes obscured by opening car doors, and inconsistent background lighting (sometimes brightly lit, sometimes in the shade of the canopy). Accordingly, we decided that the possible benefit of plume quantification could not be reasonably achieved within the desired accuracy and within the budget.

3.8 Investigation of Refueling Plumes from Medium-Duty Vehicles

During analysis of the Arvada gas station data, EPA asked us if there were any refuelings on medium-duty vehicles. Since we had removed motorhomes and buses from the Colorado vehicle registration snapshot look-up table, medium-duty vehicles did not appear in the study's master dataset. To answer the question, we wrote a special SAS program[28] to search for medium-duty vehicles. After filtering, we found five motorhomes and a gasoline "bus" that had not been in the ExE listing before. When these six vehicles were added to the others that were already in the ExE listing, there were a total of 59 vehicle refuelings with vehicle classes HDGV2b, HDGB, HDGV3, and HDGV4, as shown in Table 3-16, [29] Table 3-17, Table 3-18, and Table 3-19, respectively.

Refueling data was captured on 43 HDGV2b vehicles, as shown in Table 3-16. These refuelings all appear to be on complete vehicles (not incompletes). For this class: pre-ORVRs were MY 2003 and before, implementation transition years were MY 2004-2005, and ORVR were MY 2006 and after. The table shows 13 pre-ORVR refuelings with 10 (77%) having Light or Heavy Phase 1 emissions visible in the videos. For this vehicle class, there were 27 ORVR refuelings with 8 (30%) refuelings with Light or Heavy Phase 1 emissions visible.

Four of the 27 refuelings were by one individual vehicle on different days: JUL 15, 16, 22, and 23. The first two refuelings had ContinuousPlumes, the third had OnlyPuffsNoPlumes, and the fourth had NoPuffsNoPlumes. The volumes of fuel dispensed were quite consistent: 16.1, 15.9, 16.9, and 16.6 gallons. The pump positions for the four refuelings were front, front, back, and front, respectively. The details of the repeated refuelings do not provide clarity for the reason that plumes and puffs were sometimes seen and sometimes not.

Refueling data was captured on 5 HDGV3 vehicles, as shown in Table 3-17. Three of these refuelings appear to be on complete vehicles, and two are on incompletes, which happened to be recreational vehicles. For this HDGV3 class, ORVR is not required until the 2017 model year; however, manufacturers are believed to commonly install ORVR systems according to the HDGV2b schedule – unless they are incompletes. Therefore, we expect that the two incompletes have no ORVR systems. We are uncertain whether the three completes in the table have ORVR systems of not. Taken altogether, the 4 out of 5 HDGV3 vehicles produced Heavy Phase 1 emissions.

[28] P:/CDPHE/Regis2019/REGmissing.sas

[29] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Analysis_Videos/MDV_masterlist-200217.xlsx

Refueling data was captured on 4 HDGV4 vehicles, as shown in Table 3-18. All of these vehicles are incompletes and are before the 2017 model year when HDGV4 completes must have ORVR systems. Therefore, we expect that all four vehicles probably do not have ORVR systems. The Phase 1 results in the table show that all four refueling produced heavy emissions.

The refuelings for HDGB vehicles are shown in Table 3-19. Three of the vehicles are before 1999 and therefore are likely pre-ORVR. All 3 of these refuelings produced Phase 1 Light or Heavy emissions in the videos. The other 4 refuelings are for HDGVs with model years 2012 and newer. Only one of these produced a Light Phase 1 emission.

We considered the Phase 2 re-viewings only on refuelings when ORVR systems are expected to be on vehicles. Accordingly, we did not re-view videos for Phase 2 results if we knew that the vehicle was pre-ORVR or no-ORVR, which is the reason that some cells in the Phase 2 results in the tables are blank.

For the HDGV2b ORVR vehicles, Table 3-16 shows that 3 (11%) of 27 refuelings had ContinuousPlumes. Two of those continuous plumes were produced by one vehicle. Adjusting for this and stating the results by vehicle, 2 (8%) of 24 vehicles has ContinuousPlumes.

Table 3-17 for the HDGBs shows that none of the 4 non-pre-ORVR HDGB vehicles produced ContinuousPlumes.

In Table 3-18, both of the two newest HDGV3 vehicles had ContinuousPlumes, but we could not assign ORVR equipment status to these vehicles.

Since all of the four HDGV4 vehicles in Table 3-19 were incompletes, they are not expected to have ORVR systems. The three vehicles with Phase 2 results indicated ContinuousPlumes.

Table 3-16. Refueling Plume Results for HDGV2b

Vehicle Class	ORVR Assignment	Vehicle Description	Phase 1 Emissions Summary	Phase 2 Emissions Summary	VehID	i_Depart_MTN (LinkTime)
HDGV2b	pre-ORVR	1990_FORD_F250RegularCab_4400	H		10Y619ATC6Y811	18JUL19:20:12:37
HDGV2b	pre-ORVR	1994_FORD_F250SuperCab4WD_5700	H		0F055PB3K064O9	18JUL19:14:25:53
HDGV2b	pre-ORVR	1999_FORD_F250SuperCab4WD_5600	H		91Z341AEE9N628	23JUL19:14:45:34
HDGV2b	pre-ORVR	1999_FORD_F250SuperCab4WD_5700	L		0E620CD5E380O3	22JUL19:17:18:39
HDGV2b	pre-ORVR	2000_CHEVROLET_Express35002WD_5300	H		9L555O201185E5	10JUL19:08:44:00
HDGV2b	pre-ORVR	2000_FORD_ExcursionLimited4_6900	H		0U5X6MB7E127O2	22JUL19:16:41:04
HDGV2b	pre-ORVR	2001_CHEVROLET_K2500Pickup4WD_6700	0	NoPuffsNoPlumes	05Z3211LF0X084	12JUL19:18:13:15
HDGV2b	pre-ORVR	2001_FORD_E2502WD_5100	H		75V007BQH3C694	23JUL19:12:09:44
HDGV2b	pre-ORVR	2001_FORD_F2502WD_4900	0	NoPuffsNoPlumes	21W120BQE8Z401	15JUL19:13:12:27
HDGV2b	pre-ORVR	2002_CHEVROLET_3500Van2WD_6300	H		5H776R171131Q7	18JUL19:14:53:41
HDGV2b	pre-ORVR	2002_DODGE_RamVan/Wagon3500_4800	H		0H548R11K491O2	08JUL19:09:56:28
HDGV2b	pre-ORVR	2002_GMC_Sierra2500Pickup4_6200	0	NoPuffsNoPlumes	98F4852VE9I454	22JUL19:16:13:27
HDGV2b	pre-ORVR	2003_FORD_F250SuperDuty4WD_5800	H		73Y383ALE7X290	16JUL19:19:20:40
HDGV2b	transition	2004_FORD_E2502WD_5100	0	NoPuffsNoPlumes	0Q112KB1H268G1	09JUL19:08:11:28
HDGV2b	transition	2005_CHEVROLET_K2500Pickup4WD_6000	H		7F097Q81F266B1	09JUL19:11:59:18
HDGV2b	transition	2005_GMC_Sierra2500Pickup4_5700	H		38H0352UE3Y486	21JUL19:10:06:28
HDGV2b	ORVR	2007_CHEVROLET_25004WD_5800	0	NoPuffsNoPlumes	8H265Q16E928I8	09JUL19:15:01:11
HDGV2b	ORVR	2007_CHEVROLET_25004WD_5900	0	NoPuffsNoPlumes	76S4515XE1S241	09JUL19:17:38:46
HDGV2b	ORVR	2007_FORD_E2502WD_5200	0	NoPuffsNoPlumes	3I093ZB2D386Q4	12JUL19:12:23:43
HDGV2b	ORVR	2008_FORD_E2502WD_5206	0	NoPuffsNoPlumes	6B145DA8D232F4	15JUL19:18:50:53
HDGV2b	ORVR	2008_FORD_F2504WDSRW_6600	L	OnlyPuffsNoPlumes	5O194ND2E758T9	12JUL19:10:21:57
HDGV2b	ORVR	2008_FORD_F2504WDSRW_6600	0	NoPuffsNoPlumes	89H029DKE9U569	23JUL19:19:20:23
HDGV2b	ORVR	2008_FORD_F250SuperDuty4WD_6300	0	NoPuffsNoPlumes	7Q397LA7E098Z9	12JUL19:12:57:48
HDGV2b	ORVR	2009_CHEVROLET_Silverado/Suburba_5700	0	NoPuffsNoPlumes	86X0531NE2O507	21JUL19:11:40:51
HDGV2b	ORVR	2009_FORD_F250SupercabSRW4W_6300	H	ContinuousPlume	6E061CA8E444H6	21JUL19:08:54:56

Vehicle Class	ORVR Assignment	Vehicle Description	Phase 1 Emissions Summary	Phase 2 Emissions Summary	VehID	i_Depart_MTN (LinkTime)
HDGV2b	ORVR	2010_CHEVROLET_Silverado2500_5800	L	OnlyPuffsNoPlumes	97O9541TZ7Z205	18JUL19:12:20:59
HDGV2b	ORVR	2010_FORD_EconolineE350_5400	0	NoPuffsNoPlumes	1Q286ZA9D591K7	18JUL19:18:07:47
HDGV2b	ORVR	2010_FORD_EconolineE350_9500	0	NoPuffsNoPlumes	04Y599AJD6H683	23JUL19:16:24:49
HDGV2b	ORVR	2011_FORD_EconolineE350_5200	0	NoPuffsNoPlumes	4Q578KA7D364I3	22JUL19:07:24:34
HDGV2b	ORVR	2014_NISSAN_NV1500/NV2500/NV3_6100	0	NoPuffsNoPlumes	38A0711IN0V413	16JUL19:08:50:03
HDGV2b	ORVR	2015_FORD_F250_6500	0	NoPuffsNoPlumes	72V845CQE1R228	10JUL19:09:13:36
HDGV2b	ORVR	2015_FORD_TransitT150_4800	L	NoPuffsNoPlumes	62L236BGK2Q276	09JUL19:09:31:05
HDGV2b	ORVR	2015_FORD_TransitT250_5000	0	NoPuffsNoPlumes	80Q569ASK7T900	15JUL19:17:56:43
HDGV2b	ORVR	2015_GMC_Savana3500_5700	L	OnlyPuffsNoPlumes	80P2732X13S620	23JUL19:12:06:38
HDGV2b	ORVR	2016_FORD_TransitT250_4800	0	NoPuffsNoPlumes	8O203CA8K293R1	16JUL19:11:50:48
HDGV2b	ORVR	2016_NISSAN_NV1500/NV2500/NV3_6000	H	ContinuousPlume	0U009J89N123Q8	15JUL19:10:23:36
HDGV2b	ORVR	2016_NISSAN_NV1500/NV2500/NV3_6000	H	ContinuousPlume	0U009J89N123Q8	16JUL19:11:18:47
HDGV2b	ORVR	2016_NISSAN_NV1500/NV2500/NV3_6000	H	OnlyPuffsNoPlumes	0U009J89N123Q8	22JUL19:18:33:04
HDGV2b	ORVR	2016_NISSAN_NV1500/NV2500/NV3_6000	0	NoPuffsNoPlumes	0U009J89N123Q8	23JUL19:11:04:58
HDGV2b	ORVR	2017_GMC_Sierra2500_6700	0	NoPuffsNoPlumes	1N503B21F428W3	10JUL19:17:42:36
HDGV2b	ORVR	2017_NISSAN_NV1500/NV2500/NV3_6200	0	NoPuffsNoPlumes	5I864A83N068O8	15JUL19:17:10:08
HDGV2b	ORVR	2018_FORD_TransitT150_3968	0	NoPuffsNoPlumes	4D886CA9K230Z4	18JUL19:18:14:54
HDGV2b	ORVR	2018_FORD_TransitT250_4934	0	NoPuffsNoPlumes	3E995CB6K550L7	16JUL19:10:24:49

Table 3-17. Refueling Plume Results for HDGBs

Vehicle Class	ORVR Assignment	Vehicle Description	Phase 1 Emissions Summary	Phase 2 Emissions Summary	VehID	i_Depart_MTN (LinkTime)
HDGB	pre-ORVR	1994_FORD_E350SuperWagon_6100	H		1D9X0CA5H415N9	09JUL19:09:59:12
HDGB	pre-ORVR	1996_FORD_E350SuperWagon_5900	L		71H663BUH5C837	12JUL19:15:25:10
HDGB	pre-ORVR	1998_FORD_E350SuperWagon_6100	H		6P168WA8H289B54	22JUL19:12:02:57
HDGB	?	2013_FORD_EconolineE350_5800	0	NoPuffsNoPlumes	0V646OA4D579H0	23JUL19:14:51:49
HDGB	?	2014_FORD_EconolineE350_5800	L	OnlyPuffsNoPlumes	51S066AQD0W454	12JUL19:20:26:16
HDGB	?	2015_FORD_TransitT350_5900	0	NoPuffsNoPlumes	9H765CA0K823Q7	15JUL19:12:03:22
HDGB	?	2016_FORD_TransitT350_5900	0	NoPuffsNoPlumes	8L699OA1K625H7	21JUL19:13:40:49

Table 3-18. Refueling Plume Results for HDGV3s

Vehicle Class	ORVR Assignment	Vehicle Description	Phase 1 Emissions Summary	Phase 2 Emissions Summary	VehID	i_Depart_MTN (LinkTime)
HDGV3	no ORVR	1990_JAMB_FordIncomplete_9000	H		4B537SB1H808O2	23JUL19:14:21:49
HDGV3	no ORVR	1993_CON_FordIncomplete_10300	H		F02C62JFCF02C6	23JUL19:13:14:11
HDGV3	pre-ORVR	2002_FORD_E350SuperDuty2WD_7100	0	NoPuffsNoPlumes	8L765CB7H263P4	08JUL19:08:43:56
HDGV3	?	2006_CHEVROLET_35002WD_6700	H	ContinuousPlume	17Z1582QE5W244	23JUL19:13:20:30
HDGV3	?	2015_GMC_Savana3500_7660	H	ContinuousPlume	9D005C201060S4	15JUL19:08:34:25

Table 3-19. Refueling Plume Results for HDGV4s

Vehicle Class	ORVR Assignment	Vehicle Description	Phase 1 Emissions Summary	Phase 2 Emissions Summary	VehID	i_Depart_MTN (LinkTime)
HDGV4	no ORVR	1997_FLE_FordIncomplete_11000	H		W17S37VWSW17S3	18JUL19:14:25:47
HDGV4	no ORVR	2007_WINN_FordIncomplete_16300	H	ContinuousPlume	18D610AZD76201	12JUL19:09:13:46
HDGV4	no ORVR	2011_FORD_FordIncomplete_missing	H	ContinuousPlume	T96L56QTLT96L5	18JUL19:10:20:45
HDGV4	no ORVR	2016_THOR_FordIncomplete_9700	H	ContinuousPlume	7QK6FK8767QK6F	22JUL19:11:41:48

4.0 Thornton: Introduction to Liquid Refueling Emissions Study

ERG collected field data at the Thornton, Colorado, Costco Wholesale gas station with the purpose of characterizing liquid gasoline spills made by customers as they refueled their personal vehicles. This activity was performed in July 2019 as part of EPA Work Assignment 2-23 under Contract EP-C-17-011 with the permission and assistance of Costco local, regional, and national management. The goal of the study was to quantify the prevalence and magnitude of private vehicle refueling liquid spills and their association with customer behavior and other potential factors.

With one technician at the station at a given time, four technicians investigated the occurrence of gasoline spills between 8 a.m. and 4 p.m. for fourteen days between July 7 and 23. By the end of the study period, the technicians had observed 1,227 refueling events and had identified 153 spills of various sizes. In addition to spill characteristics, the technicians recorded factors and behaviors that could possibly affect the likelihood and severity of spills. These variables include the pump number, location of fuel fill door with respect to fuel pump, nozzle orientation, number of extra clicks (attempts to top off the vehicle tank), and idling state.

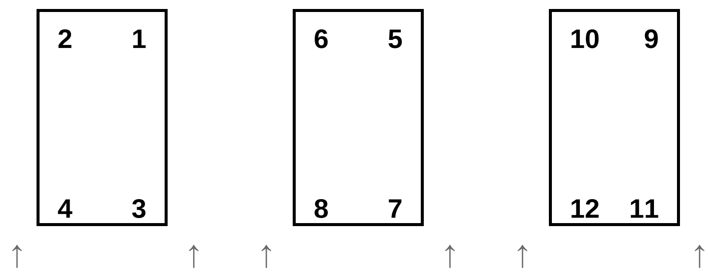
Monitoring for gasoline station refueling behavior and clicks, spills, and spitbacks was conducted at the Costco Wholesale Thornton Colorado gas station, 16375 Washington Street, Thornton, Colorado 80023. This gas station was open for business Monday through Friday from 6 a.m. to 9 p.m. and on Saturday and Sunday from 7 a.m. to 7 p.m.

A Google Maps photograph of the Costco Thornton site is shown in Figure 4-1. The approximate dimension of the gas station canopy is 32 by 86 ft. Traffic is allowed to flow into the gas station one way from the south as shown by the arrows on the pavement in the photograph. The Thornton gas station is made up of 12 gas pumps on three islands. The layout of the islands is shown in Figure 4-2. The direction of traffic, which flows north, is indicated by the arrows in Figure 4-2. Customers are not permitted to enter the station from the exit driveway. The arrangement of the islands and pumps in the figure corresponds to the same arrangement in the Google Maps photograph in Figure 4-1.

For the data collected at the Costco Thornton station, the PG environmental technician was not located at a single pump or island for testing but instead moved around the site to monitor refueling behavior and liquid gasoline emissions.

Figure 4-1. Costco Thornton Site Used for Spills Evaluations

Figure 4-2. Diagram of Costco Thornton Gas Station Islands and Pumps



5.0 Thornton: Data Collection Methods

Each technician collected on-site data using two strategies: 1) sequential and 2) station-wide. To do so, they recorded their observations in data packets containing: 1) white-page datasheets and 2) pink-page datasheets. The technician instructions are given in Appendix D. The technicians used the white-page datasheets to follow the vehicles sequentially for each vehicle's entire refueling activity. After the conclusion of one vehicle's refueling activity, the technician was instructed to select the next vehicle to be monitored by looking for the next customer that exited their vehicle to refuel, regardless of whether there were other customers already refueling. The white-page procedure was used to routinely monitor randomly selected vehicle refueling; however, if a liquid spill anywhere in the station caused a station-wide commotion, the technician was instructed to abort the current white-page data entry so that they could investigate the source of the incident using the pink-page datasheets. This was an effort to gather station-wide data on major spills and spitbacks.

After the completion of the onsite data collection, the technicians transcribed their own written records into Excel spreadsheets. The spreadsheets were processed before analysis began, while the paper datasheet packets were kept for back-up. The four technicians made a total of 1,193 sequential (white-page) observations and 34 station-wide (pink-page) observations. The analysis described below covers both the 1,193 sequential observations and the 34 station-wide observations.

6.0 Thornton: Data Processing and Database Assembly

Table 6-1 shows the datasheet format and two transcribed entry samples. The first entry is incomplete. In the Text data field, the technician made a note that they moved to observe a station-wide event. For interrupted entries, or where customers did not refuel their vehicle, the entire observation was removed from further analysis. Of the 1,193 sequential observations, 22 were omitted because of station-wide event interruptions or non-refueling vehicles. This results in 1,171 complete sequential observations over the fourteen days of data collection.

The second entry is complete except for the Spill Source, Spill Size, and Attendant Action data fields. In instances where data fields were missing, the paper datasheet entries were checked for transcription omissions. If the transcription was the source of the error, then the Excel spreadsheet was corrected. If both the paper datasheet and the Excel spreadsheet had the same fields missing, then the entry was used for further analysis except where blank. These blank data fields were noted as missing for subsequent count and percentage calculations. Other minor operations were coded within a SAS environment[30] to account for typos, inconsistent labeling conventions between technicians, and text comments.

[30] P:\EPA_RefuelingEmissions_WA2-23\Summer2019\Analysis\CSS\Analysis\Analysis_CSS.sas

Table 6-1. Two Transcribed Datasheet Entries.

Date	Day of Week	Pump Number	License: State	License: Plate	Make	Model	Fueling Side (**N**ear, **F**ar)	Nozzle Orientation: **R**ight**S**ide**U**p **U**p**S**ide**D**own **S**ide**W**ays	Number of Extra Clicks (0=auto shut-off only)	Nozzle Hang-Up Time (hh:mm:ss)	Spitback? (**Y**es, **N**o)	Spills: Source: **F**ill neck **U**nder car	Spills: Size: **N**ickel **T**ennis **G**rapefruit **B**ucket	Attendant Action (**N**one, **K**itty, **S**pray, **C**one)	Idling (**Y**es, **N**o)	**Text:** If there was an event, tell about it in the cells below this heading. i.e., Use the full width of the page to enter your text.
07/15/2019	Mon	9	CO		Ford	Fusion	N	RSU								went to pink pages
8-Jul	Mon	5	CO		Subaru	Outback	N	RSU	1	3:21:22	N				N	

7.0 Thornton: Results

For the sequential observations, as shown in Table 7-1, 10.3% of vehicles spilled gasoline, though most spills were small. The technicians categorized spills using representative diameter sizes: none, nickel-sized, tennis-ball-sized, grapefruit-sized, but if a spill was substantially larger than the diameter of a grapefruit, it was called bucket-sized to reflect the fuel volume of a small bucket (diameter of bucket and larger). As shown in Table 7-2, only 27 of the 120 gasoline spills were larger than nickel-sized, and a total of 6 bucket-sized spills occurred. In addition, three of the spills were also spitbacks as shown in Table 7-3. Spitbacks are violent events in which a vehicle's fuel tank expels gasoline during an otherwise routine refueling. Spitbacks are sometimes attributed (by consumers) to faulty fueling nozzles, malfunctioning emission control systems, or user error, but the root cause of such events is not fully understood. Spill occurrence, spill size, and spitback frequencies are shown in Table 7-1, Table 7-2, and Table 7-3, respectively.

Table 7-1. Spill Occurrence Frequency for Sequential Observations

Spill Occurred[31]	Frequency	*Percent*
No	1046	*89.7*
Yes	120	*10.3*
Total	1166	*100*

Table 7-2. Spill Size Frequency for Sequential Observations

Spill Size[32]	Frequency	*Percent*
None	1046	*89.8*
Nickel	92	*7.9*
Tennis Ball	16	*1.4*
Grapefruit	5	*0.4*
Bucket	6	*0.5*
Total	1165	*100*

Table 7-3. Spitback Frequency for Sequential Observations

Spitback[33]	Frequency	*Percent*
No	1167	*99.7*
Yes	3	*0.3*
Total	1170	*100*

[31] 5 observations were missing an indication of Spill Occurrence.

[32] 6 observations were missing an indication of Spill Size.

[33] 1 observation was missing an indication of Spitback.

The station-wide observations include information on 33 additional spills, including 22 bucket-sized spills and 12 spitbacks. There was one station-wide observation in which the customer did not spill gasoline but idled while refueling.

The gas station had three islands with twelve different pumps, labeled by different pump numbers, as shown in Figure 4-2. Table 7-4 shows the frequency in which each pump was visited. For the white sheet data, the technicians observed Pump 7 over nine times more frequently than Pump 4. The customer's fuel fill door location, where the customer entered the gas station, and the ease of access of specific pumps may have affected the frequency in which each pump was visited.

Table 7-4. Pump Number Frequency for Sequential Observations

Pump Number[34]	Frequency	*Percent*
1	150	*12.9*
2	26	*2.2*
3	75	*6.4*
4	19	*1.6*
5	128	*11.0*
6	116	*9.9*
7	174	*14.9*
8	36	*3.1*
9	147	*12.6*
10	134	*11.5*
11	89	*7.6*
12	73	*6.3*
Total	1167	*100*

The overall rates of the various fueling sides, nozzle orientations, and extra clicks are detailed in Table 7-5 to Table 7-7. Each of these variables was thought to possibly have some effect on the likelihood of spills. Typically, customers fueled from the near side, i.e., most customers parked their vehicle so that their fuel fill door faced the pump (89.2%), oriented their nozzles right-side up (96.2%), added no extra clicks (67.5%), and did not idle (99.9%). Notably, almost one-third of customers added at least one extra click after the automatic shut-off of their nozzle. The relatively large proportion of customers attempting to add more gasoline by using

[34] 4 observations were missing an indication of Pump Number.

extra clicks suggests that customers do not believe that the nozzle's automatic shut-off produces full tanks.

Table 7-5. Fueling Side Frequency for Sequential Observations

Fueling Side	Frequency	*Percent*
Near	1044	*89.2*
Far	127	*10.8*
Total	1171	*100*

Table 7-6. Nozzle Orientation Frequency for Sequential Observations

Nozzle Orientation	Frequency	*Percent*
Right-side Up	1127	*96.2*
Sideways	40	*3.4*
Upside Down	4	*0.3*
Total	1171	*100*

Table 7-7. Extra Clicks Frequency for Sequential Observations

Extra Clicks[35]	Frequency	*Percent*
0	787	*67.5*
1	148	*12.7*
2	63	*5.4*
3	53	*4.6*
4-9	84	*7.2*
10-18	31	*2.7*
Total	1166	*100*

Table 7-8 shows the idling characteristics of the Costco Thornton vehicles at the gas station in the dataset. The technicians were not instructed to note the idling state until the second day of the study, leading to the 95 missing values. The National Fire Prevention Association code 30A does not allow the idling of vehicles and equipment during fueling. The fraction of vehicles idling at Costco gas stations may be lower than at stations of other companies because Costco employs attendants who circulate among the customers. If needed, the gas station attendants remind customers to turn off their engines while refueling.

[35] 5 observations has a missing value for number of Extra Clicks.

Table 7-8. Idling Frequency for Sequential Observations

Idling[36]	Frequency	*Percent*
No	1075	*99.9*
Yes	1	*0.1*
Total	1076	*100*

[36] 95 observations were missing an indication of Idling.

8.0 Thornton: Analysis

The factors and behaviors that were associated with the likelihood and severity of spills were reviewed using logistic regression procedures in SAS.

Fueling from the far side, where the customer drags the fueling hose over or around their vehicle to refuel, was examined for a correlation with spill occurrence. The Thornton gas station had 14-foot fuel pump hoses so that customers could easily refuel from the far side. Being able to refuel from either side increases the efficiency of refueling traffic, but it was not known whether fueling from the far side increases spill occurrence. Table 8-1 shows the percentage of total spills versus the percentage of all refuelings that occurred for the near and far fueling sides. 11.7% of all spills occurred when customers refueled from the far side, while 10.8% of all refuelings occurred from the far side. The difference between each side’s spill and refuel frequency is within 1%. With the small variation and a P-value of 0.75, we cannot claim that the likelihood of spills is affected by the fueling side (we fail to reject the null hypothesis). The fueling side has minimal correlation with spill occurrence.

Table 8-1. Fueling Side Frequency v. Total Spills and Refuelings for Sequential Observations

	Spills		Refuelings	
Fueling Side	**Number**	***Percent***	**Number**	***Percent***
Near	106	*88.3*	1044	*89.2*
Far	14	*11. 7*	127	*10.8*
Total	120	*100*	1171	*100*

The nozzle orientation at insertion was another candidate for influencing the spill occurrence. A total of 44 customers refueled with sideways nozzles or upside-down nozzles. The percentage of total spills are minimally different from the percentage of all refuelings that occurred for each nozzle orientation, as shown in Table 8-2. Like the results for fueling side, each nozzle orientation’s spill and refueling percentages were within 1% of each other. Upside-down nozzles were associated with one spill (0.8% of total spills) out of four refuelings (0.3% of total refuelings). Although the difference is less than 1%, the magnitude of the spill percentage is more than double that of the refueling percentage. However, with the small number of upside-down refuelings, a single decrease in its number of spills would have resulted in zero spills for the orientation. With the small variation and a P-value of 0.55, we cannot claim that the likelihood of spills is affected by the nozzle orientation (we fail to reject the null hypothesis). The nozzle orientation has minimal correlation with spill occurrence.

Table 8-2. Nozzle Orientation Frequency v. Total Spills and Refuelings for Sequential Observations

Nozzle Orientation	Spills Number	Spills *Percent*	Refuelings Number	Refuelings *Percent*
Right Side Up	116	*96. 7*	1127	*96.2*
Side Ways	3	*2.5*	40	*3.4*
Up Side Down	1	*0.8*	4	*0.3*
Total	120	*100*	1171	*100*

The number of extra clicks is the key factor that is positively correlated with both the occurrence and size of spills. Extra clicks occur when customers attempt to add additional gasoline to their tank after the automatic shut-off of their pump nozzle. An automatic shut-off with no further attempt to add gasoline is considered as "no extra clicks," while each additional attempt to add gasoline results in one extra click.

In this study, customers who added any number of extra clicks spilled more frequently than those who accepted an automatic shut-off. Table 8-4 show the number of spills and refuelings as a function of number of extra clicks. The last column shows the spill rate, which is the percent of refuelings that had a spill. The spill rate is lowest (8.4%) for zero extra clicks and highest (20.6%) for two extra clicks. Table 8-4 shows the relative occurrences of spills and refuelings. That table shows that when two extra clicks were added, 10.9% of all spills occurred, but only 5.4% of all customers added two extra clicks.

Table 8-3. Spill Rate v. Extra Clicks for Sequential Observations

Extra Clicks[37]	Number of Spills	Number of Refuelings	Spill Rate (%)
0	66	787	*8.4%*
1	18	148	*12.2%*
2	13	63	*20.6%*
3	7	53	*13.2%*
4-9	11	84	*13.1%*
10-18	4	31	*12.9%*
Total	119	1166	*10.2%*

[37] 5 observations had a missing value for number of Extra Clicks.

Table 8-4. Extra-Clicks Frequency v. Total Spills and Refuelings for Sequential Observations

	Spills		Refuelings	
Extra Clicks[38]	**Number**	***Percent of Total***	**Number**	***Percent of Total***
0	66	*55.5*	787	*67.5*
1	18	*15.1*	148	*12.7*
2	13	*10.9*	63	*5.4*
3	7	*5.9*	53	*4.6*
4-9	11	*9.2*	84	*7.2*
10-18	4	*3.4*	31	*2.7*
Total	119	*100*	1166	*100*

The output of the logistic regression relating extra clicks to spill occurrence is shown in Figure 8-1. A good fit is established when the spill occurrence is modeled as a function of the natural logarithm of extra clicks, resulting in a P-value of 0.0089. The predicted spill likelihood is 8.9% at zero extra clicks and rises to 20.2% at 18 extra clicks. Because the P-value < 0.05, we conclude that the number of extra clicks has a significant effect on the probability of a spill occurring (we reject the null hypothesis that extra clicks have no effect on spill occurrence).

Table 8-5 relates the number of extra clicks by the spill size. When no extra clicks were added, any spills that occurred were most likely to be nickel-sized. Furthermore, the spills of customers who added any number of extra clicks were on average larger than the spills of customers who accepted an automatic shut-off. The correlation is most apparent for the category of bucket-sized spills. There was a total of 6 bucket-sized spills within the 1,171 sequential observations. Of the 785 refuelings with no extra clicks, only one bucket-sized spill occurred. However, 2 bucket-sized spills occurred for the 31 refuelings in the range of 10 to 18 extra clicks. From the sequential observations, the likelihood of a bucket-sized spill is about 50 times greater for customers adding 10 to 18 extra clicks when compared to customers accepting an automatic nozzle shut-off.

[38] 5 observations had a missing value for number of Extra Clicks.

Figure 8-1. Logistic Regression Total Spill Probability vs. Extra Clicks

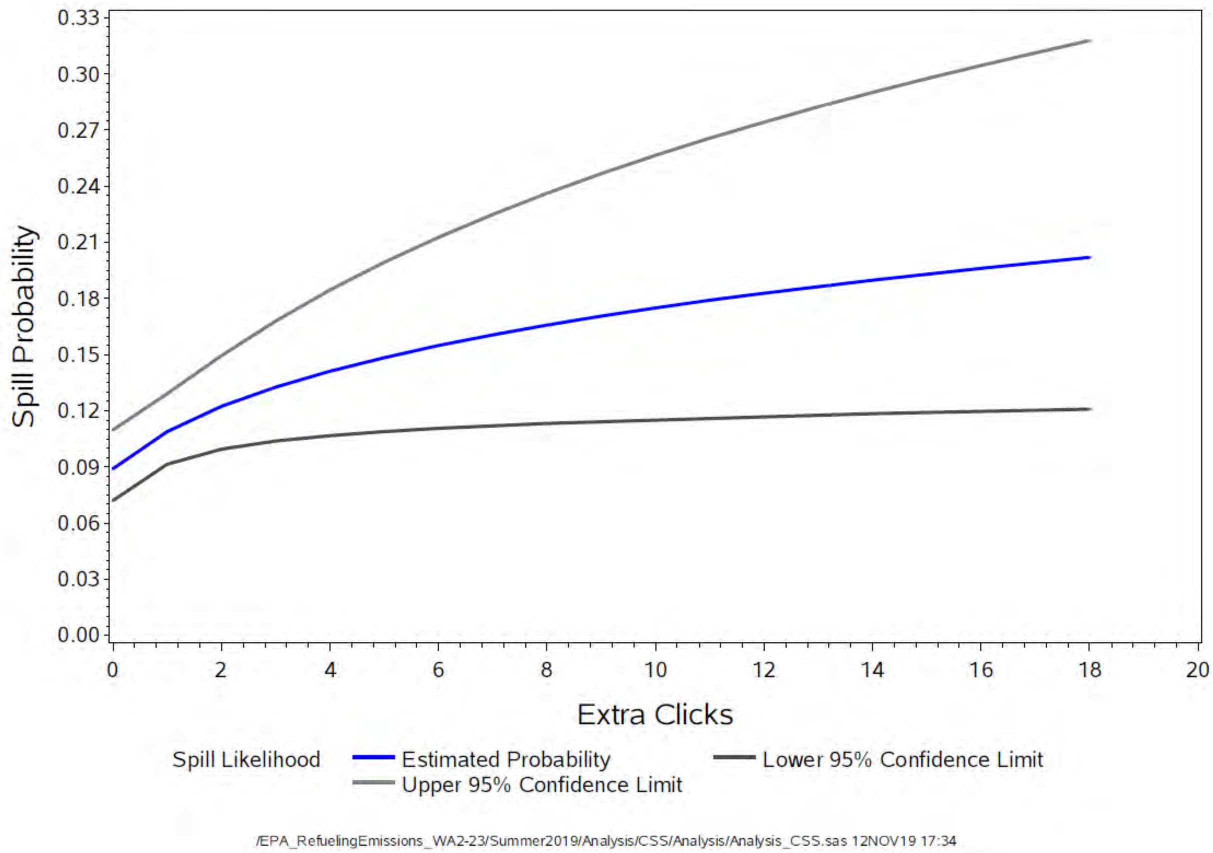


Table 8-5. Extra Clicks Frequency by Spill Size for Sequential Observations

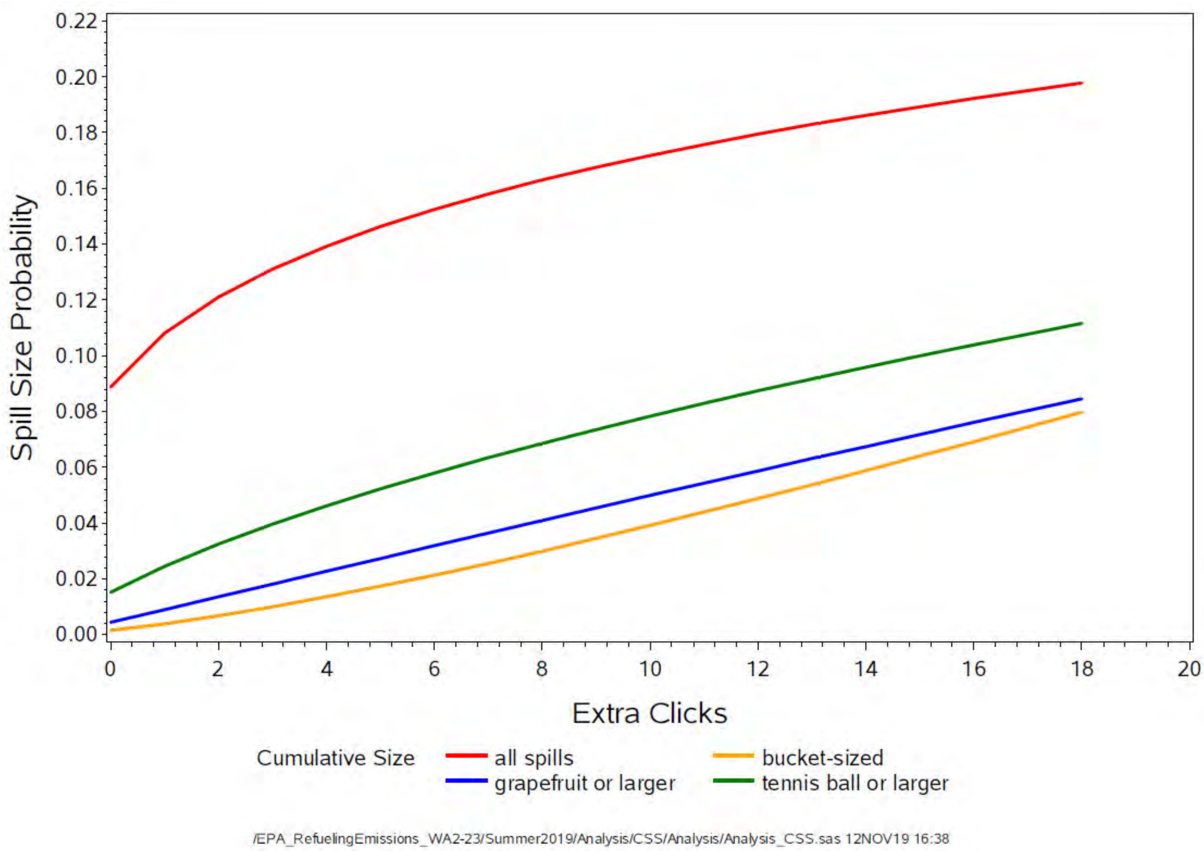
Extra Clicks[39]	Spill Size					Total
	None	Nickel	Tennis Ball	Grapefruit	Bucket	
0	719	55	8	2	1	785
1	129	14	2	1	1	147
2	50	7	3	1	1	62
3	45	6	1	0	0	52
4-9	73	8	1	1	1	84
10-18	27	1	1	0	2	31
Total	1043	91	16	5	6	1161

[39] 10 observations were missing an indication of number of Extra Clicks, of Spill Size, or of both.

The result of a logistic regression relating extra clicks to the size of spills confirms the trends seen in Table 8-5. The effect of the natural logarithm of extra clicks and the interaction of size and the natural logarithm of extra clicks on the cumulative size response produce P-values of <0.0001 and 0.015, respectively. Thus, the logistic regression supports the notion that extra clicks affect the spill size likelihood.

The output of the logistic regression relating extra clicks to the spill size is shown in Figure 8-2. In the figure, the spill sizes are modeled cumulatively as indicated by the legend. The increased spill likelihood at large numbers of extra clicks is primarily due to the emergence of grapefruit and bucket-sized spills. The model reconfirms that bucket-sized spills are very infrequent at no extra clicks (0.15%) but become far more likely by 18 extra clicks (8.0%).

Figure 8-2. Logistic Regression Cumulative Spill Probability vs. Extra Clicks



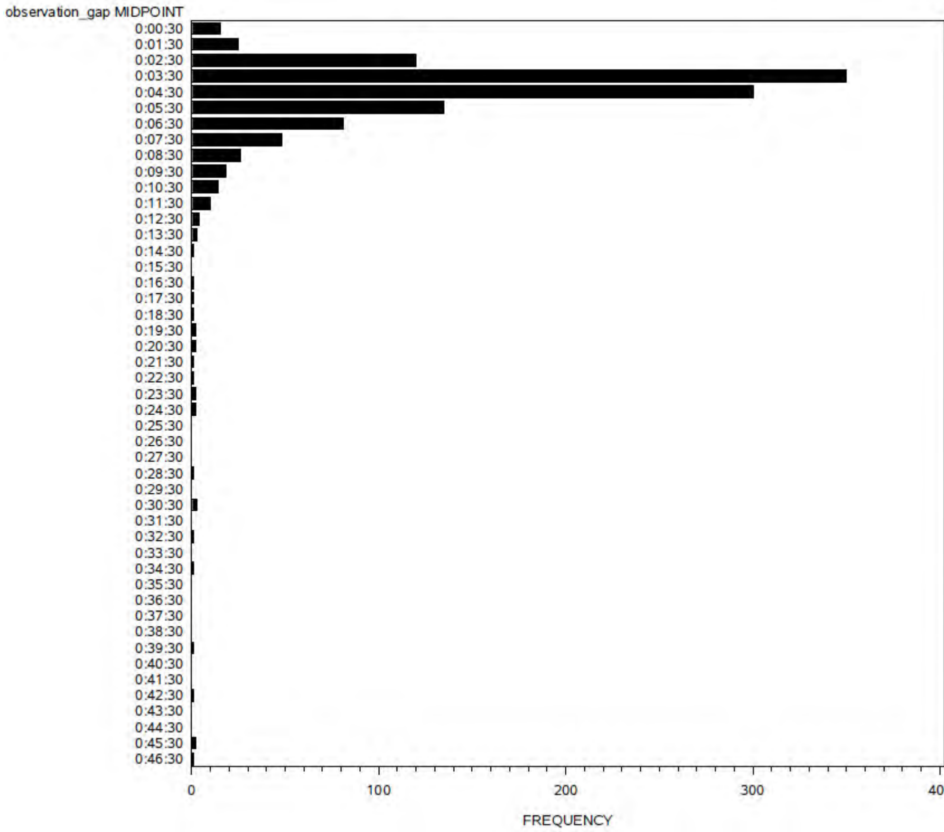
Human error may be why extra clicks result in more spills. A typical nozzle will automatically shut off when gasoline reaches its sensing port near the tip of its nozzle spout. When an automatic shut-off occurs, disregarding false click-offs, the nozzle has functioned properly. While hanging up the nozzle, a small spill may still occur due to gasoline coating the nozzle outlet pipe, but large spills should not arise unless the nozzle lever is accidentally pressed by the customer. If a nozzle fails to automatically shut off, then a spitback may occur. However, spitback incidents are rare and are not limited to 0 extra clicks. Within the sequential observations, one of the 3 spitbacks occurred after 2 extra clicks, and only one bucket-sized spitback was recorded.

When customers pay using a credit or debit card, the automatic shut-off does not lock out additional clicks. The gas pumps at the Costco Thornton station accept only cards for gasoline purchases. Some customers who disregard the automatic shut-off partially raise their nozzle spout to continue to refuel. Gasoline must reach the new level of the sensing port before another shut-off click can be triggered. Modern-day nozzles can have flow rates of up to 10 gallons/minute and depending on the height in which the nozzle is raised, different types of spills may occur. If the subsequent automatic shut-off does not trigger in time, a spitback may take place. If the nozzle spout is too high, then the customer's stream may simply miss the fill pipe. With additional sources of human error, larger spills become more common.

Station-wide (pink-page) observations were made to help confirm sequential results for bucket-sized spills and spitbacks, which might not have been sampled well enough by the sequential method. The station-wide observations contained an additional 22 bucket-sized spills and 12 spitbacks. Station-wide observations were made only when significant incidents were noticed, so the spills and extra clicks typically occurred prior to the technician's presence at the pump having the spill or spitback. Consequently, only six of the bucket-sized spill observations contained data on the number of extra clicks. A larger study would enable a more thorough assessment of the impact of extra clicks on large gasoline spills.

An aggregate count of refuelings only when the technician was on duty is needed to assess whether the sequential refueling observations adequately quantified the fraction of refuelings that produced bucket-sized spills and spitbacks. Only refuelings that occurred while the technician was on duty could result in a station-wide observation. The refuelings were determined from the Costco transaction data. Any transactions that occurred prior to the first observation, during breaks, or after the last observation of each day are not included in the aggregate refuelings. The frequency of elapsed times between adjacent refueling observations is given in Figure 8-3. The distribution in the figure shows a clear change in characteristics at an elapsed time of 15 minutes. Times shorter than 15 minutes have a smooth distribution; times longer than 15 minutes are rare and widely scattered. Thus, we designated elapsed times of fifteen or more minutes as technician breaks. Over the fourteen-day study, 9,038 refuelings occurred while a technician was on duty.

Figure 8-3. Elapsed Times between Adjacent Refueling Observations



observation_gap MIDPOINT	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
0:00:30	15	15	1.28	1.28
0:01:30	25	40	2.13	3.41
0:02:30	120	160	10.22	13.63
0:03:30	350	510	29.81	43.44
0:04:30	300	810	25.55	68.99
0:05:30	135	945	11.50	80.49
0:06:30	81	1026	6.90	87.39
0:07:30	48	1074	4.09	91.48
0:08:30	26	1100	2.21	93.70
0:09:30	18	1118	1.53	95.23
0:10:30	14	1132	1.19	96.42
0:11:30	10	1142	0.85	97.27
0:12:30	4	1146	0.34	97.61
0:13:30	3	1149	0.26	97.87
0:14:30	1	1150	0.09	97.96
0:15:30	0	1150	0.00	97.96
0:16:30	1	1151	0.09	98.04
0:17:30	1	1152	0.09	98.13
0:18:30	1	1153	0.09	98.21
0:19:30	2	1155	0.17	98.38
0:20:30	2	1157	0.17	98.55
0:21:30	1	1158	0.09	98.64
0:22:30	1	1159	0.09	98.72
0:23:30	2	1161	0.17	98.89
0:24:30	2	1163	0.17	99.06
0:25:30	0	1163	0.00	99.06
0:26:30	0	1163	0.00	99.06
0:27:30	0	1163	0.00	99.06
0:28:30	1	1164	0.09	99.15
0:29:30	0	1164	0.00	99.15
0:30:30	3	1167	0.26	99.40
0:31:30	0	1167	0.00	99.40
0:32:30	1	1168	0.09	99.49
0:33:30	0	1168	0.00	99.49
0:34:30	1	1169	0.09	99.57
0:35:30	0	1169	0.00	99.57
0:36:30	0	1169	0.00	99.57
0:37:30	0	1169	0.00	99.57
0:38:30	0	1169	0.00	99.57
0:39:30	1	1170	0.09	99.66
0:40:30	0	1170	0.00	99.66
0:41:30	0	1170	0.00	99.66
0:42:30	1	1171	0.09	99.74
0:43:30	0	1171	0.00	99.74
0:44:30	0	1171	0.00	99.74
0:45:30	2	1173	0.17	99.91
0:46:30	1	1174	0.09	100.00

/EPA_RefuelingEmissions_WA2-23/Summer2019/Analysis/CSS/Analysis/Pink_Analysis_Transaction_Data.sas 07OCT19 12:48

During the sequential observations, bucket-sized spills occurred at a rate of 0.5% (see Table 7-2) and spitbacks occurred at a rate of 0.3% (see Table 7-3). The aggregate frequencies of bucket-sized spills and spitbacks, based on white and pink-page data, are given in Table 8-6 and Table 8-7, respectively. The frequencies are composed of both sequential (white-page) and station-wide (pink-page) observations. The observed resultant rates of 0.31% for bucket-sized spills and 0.17% for spitbacks are lower than their true probabilities because there could have been cases where large spills were not noticed and therefore were not recorded. A portion of the station-wide observations were recorded after the attendant notified the on-duty technician of a spill. The gas station attendants are more likely to encounter station-wide events than the technicians. The attendants do not need to record refueling observations, and some customers who experience large spills or spitbacks will ask an attendant for help. Given that some station-wide events go unnoticed, the real probability of bucket-sized spills and spitbacks at the Costco gas station in Thornton, Colorado should be considered at least 0.31% and 0.17%, respectively. Therefore, we regard these station-wide rates for bucket-sized spills (0.31%) and spitbacks (0.17%) to be in substantial agreement with the sequential rates of 0.5% and 0.3%, respectively.

Table 8-6. Bucket-Sized Spill Frequency for Station-Wide Refuelings

Bucket-sized Spill	Frequency	*Percent*
Confirmed	28	*0.31*
Other Refuelings	9010	*99.69*
	9038	*100*

Table 8-7. Spitback Frequency for Station-Wide Refuelings

Spitback	Frequency	*Percent*
Confirmed	15	*0.17*
Other Refuelings	9023	*99.83*
	9038	*100*

9.0 Concluding Thoughts for Future Consideration

During collection and analysis of the Arvada and Thornton refueling data, we had ideas for improvements that can be made on the data collection methods and possible follow-on studies for characterizing evaporative emissions control systems in the field:

1) The Rebellion Photonics Gas Cloud Imaging camera used at Arvada was effective at detecting refueling emissions (puffs and plumes) in the Enhanced MidWave videos, which are created from infrared absorption in the 3.2 to 3.5 μm region. Rebellion uses special processing of 7.5 to 14 μm infrared absorption data, in addition to the 3.2 to 3.5 μm data, to quantify emissions for its clients. However, after examining trial processing of selected reference vehicle videos, we concluded that the infrared quantitative processing that Rebellion offered would not be successful in quantifying the emissions for each refueling event with the accuracy desired. This was a consequence of vehicle and people movement in the background, inconsistent background illumination, and low emissions concentrations for properly functioning control systems.

Since the Rebellion approach would not be likely to quantify refueling emissions, a less expensive approach might be possible. A non-quantification study using infrared video to image refueling vapor emissions using a forward-looking infrared (FLIR) video camera might be considered. This type of camera is more common than the GCI camera and operates in the same 3.2 to 3.5 μm infrared region. We have not investigated the sensitivity of FLIR cameras for this study to determine if the technique would be capable of imaging refueling emissions. However, ERG has experience with FLIR cameras in other areas of emissions study.

2) If quantification of refueling emissions vs. time is desired, a brute-force, lower-tech method might be used. For example, with a cooperative gas station owner, a portable SHED (PSHED) with sealable fabric entry and exit doors might be set up at one fuel pump. A hydrocarbon analyzer could measure HC concentration as the owner refueled his vehicle through an opening in the side of the PSHED. The concentration vs. time profile of each refueling event could be used to calculate the emission mass. A stratified, random plan based on model year might be used to sample vehicle candidates. Drivers might be enticed to participate by offering free gasoline. With efficient logistics, the refueling emissions, including puffs and plumes, could be measured rapidly.

3) One unanswered question in this study was the determination of the causes of continuous plumes from ORVR vehicles. A study such as this one can effectively identify those vehicles by using the infrared camera to screen many vehicles as they refuel. With a gas station

owner's assistance, the owners of identified vehicles might be approached to participate in a follow-on study of laboratory measurement of evaporative emissions and vehicle examination. Vehicle owners might be offered a substantial incentive and use of a rental car for the few days while their vehicle is being tested.

4) In a liquid-spill study like at Thornton, the size of spills should be more accurately measured. This could be simply done by estimating the diameter or area of the spilled gasoline on the pavement. Also, in this study, gasoline leaking from vehicles was determined by examining the pavement where vehicles were sitting after they drove away. Since many vehicles were dripping water from a nearby car wash, technicians had a difficult time determining whether drips were gasoline or water without touching or smelling he drips. A handheld electronic HC detector could easily solve that problem.

5) Fuel pump nozzle manufacturers have developed new "dripless" nozzles to help reduce liquid gasoline spills. Since a single technician with a clipboard or iPad is all that is needed to collect gas station behavior data, a comparative study to quantify the benefits of such nozzles vs. conventional nozzles could be inexpensively done at a participating station if different pump nozzles types were installed on different fuel pumps.

Appendix A
Arvada: Reference Vehicle Test Conditions and Results[40]

[40] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Data QC\RefVehicleTests/RefVehLogsheets-190802.xlsx

Date	Release Start Time	Video Start Time	Video Filename (*.mp4)	Pump	Test Condition Number	Test Condition Name	Plume Seen?
07/10/2019	14:19	14:19:14	viewer_1562789954316	9	1	GAS 100 L DOOR	1
07/08/2019	17:48	17:48:24	viewer_1562629703976	7	1	GAS 100 L DOOR	1
07/12/2019	08:06	08:06:32	viewer_1562940392482	11	1	GAS 100 L DOOR	1
07/16/2019	15:17	15:17:15	viewer_1563311834967	11	1	GAS 100 L DOOR	1
07/17/2019	08:06	08:05:56	viewer_1563372356322	6	1	GAS 100 L DOOR	1
07/10/2019	14:26	14:26:38	viewer_1562790397771	9	4	GAS 030 L DOOR	1
07/08/2019	17:54	17:54:30	viewer_1562630069759	7	4	GAS 030 L DOOR	1
07/12/2019	08:11	08:11:46	viewer_1562940706278	11	4	GAS 030 L DOOR	1
07/15/2019	19:45	19:45:40	viewer_1563241540391	9	4	GAS 030 L DOOR	1
07/16/2019	15:25	15:25:35	viewer_1563312335081	11	4	GAS 030 L DOOR	1
07/17/2019	08:10	08:10:43	viewer_1563372642877	6	4	GAS 030 L DOOR	1
07/10/2019	14:31	14:30:58	viewer_1562790658301	9	7	GAS 010 L DOOR	1
07/08/2019	17:59	17:59:50	viewer_1562630390229	7	7	GAS 010 L DOOR	1
07/12/2019	08:16	08:16:31	viewer_1562940990695	11	7	GAS 010 L DOOR	0
07/15/2019	19:37	19:37:36	viewer_1563241056222	9	7	GAS 010 L DOOR	0
07/16/2019	15:33	15:33:43	viewer_1563312822739	11	7	GAS 010 L DOOR	1
07/17/2019	08:15	08:15:39	viewer_1563372938525	6	7	GAS 010 L DOOR	1
07/10/2019	13:47	13:47:57	viewer_1562788077434	9	10	BUT 100 L DOOR	1
07/08/2019	17:28	17:28:04	viewer_1562628483786	7	10	BUT 100 L DOOR	1
07/12/2019	07:44	07:44:33	viewer_1562939072840	11	10	BUT 100 L DOOR	1
07/15/2019	19:06	19:05:55	viewer_1563239155450	9	10	BUT 100 L DOOR	1
07/16/2019	15:01	15:01:17	viewer_1563310877302	11	10	BUT 100 L DOOR	1
07/17/2019	07:47	07:47:22	viewer_1563371241757	6	10	BUT 100 L DOOR	1
07/10/2019	14:01	14:00:57	viewer_1562788857493	9	13	BUT 030 L DOOR	1
07/12/2019	07:54	07:54:04	viewer_1562939644496	11	13	BUT 030 L DOOR	1
07/15/2019	19:21	19:21:13	viewer_1563240072669	9	13	BUT 030 L DOOR	1
07/16/2019	15:06	15:05:53	viewer_1563311152661	11	13	BUT 030 L DOOR	1
07/17/2019	07:36	07:36:44	viewer_1563370604099	8	13	BUT 030 L DOOR	1
07/17/2019	07:52	07:52:46	viewer_1563371566031	6	13	BUT 030 L DOOR	1
07/10/2019	14:06	14:06:19	viewer_1562789178766	9	16	BUT 010 L DOOR	0
07/12/2019	07:59	07:59:14	viewer_1562939954357	11	16	BUT 010 L DOOR	1
07/15/2019	19:27	19:27:04	viewer_1563240423955	9	16	BUT 010 L DOOR	1
07/16/2019	15:10	15:10:36	viewer_1563311435617	11	16	BUT 010 L DOOR	1
07/17/2019	07:42	07:41:54	viewer_1563370913961	8	16	BUT 010 L DOOR	1
07/17/2019	07:57	07:57:48	viewer_1563371867750	6	16	BUT 010 L DOOR	1

Date	Release Start Time	Video Start Time	Video Filename (*.mp4)	Pump	Test Condition Number	Test Condition Name	Plume Seen?
07/10/2019	14:21	14:21:23	viewer_1562790083372	9	2	GAS 100 TANK	1
07/08/2019	17:49	17:49:40	viewer_1562629780385	7	2	GAS 100 TANK	1
07/12/2019	08:08	08:07:58	viewer_1562940477564	11	2	GAS 100 TANK	1
07/16/2019	15:19	15:18:56	viewer_1563311936402	11	2	GAS 100 TANK	1
07/17/2019	08:07	08:07:17	viewer_1563372436538	6	2	GAS 100 TANK	1
07/08/2019	17:55	17:55:50	viewer_1562630150107	7	5	GAS 030 TANK	1
07/12/2019	08:13	08:13:19	viewer_1562940799371	11	5	GAS 030 TANK	1
07/15/2019	19:50	19:50:33	viewer_1563241833284	9	5	GAS 030 TANK	1
07/10/2019	14:28	14:28:11	viewer_1562790491332	9	5	GAS 030 TANK	0
07/16/2019	15:29	15:29:13	viewer_1563312553068	11	5	GAS 030 TANK	1
07/17/2019	08:12	08:12:13	viewer_1563372732501	6	5	GAS 030 TANK	1
07/08/2019	18:01	18:01:10	viewer_1562630469908	7	8	GAS 010 TANK	0
07/10/2019	14:32	14:32:16	viewer_1562790736246	9	8	GAS 010 TANK	0
07/12/2019	08:19	08:19:49	viewer_1562941189372	11	8	GAS 010 TANK	0
07/15/2019	19:41	19:41:40	viewer_1563241299668	9	8	GAS 010 TANK	0
07/16/2019	15:37	15:37:03	viewer_1563313022556	11	8	GAS 010 TANK	0
07/17/2019	08:17	08:17:02	viewer_1563373022474	6	8	GAS 010 TANK	1
07/10/2019	13:52	13:52:39	viewer_1562788358582	9	10	BUT 100 TANK	1
07/10/2019	14:14	14:13:58	viewer_1562789638113	9	11	BUT 100 TANK	1
07/12/2019	07:49	07:49:05	viewer_1562939344997	11	11	BUT 100 TANK	1
07/15/2019	19:08	19:08:00	viewer_1563239279843	9	11	BUT 100 TANK	1
07/16/2019	15:02	15:02:45	viewer_1563310965389	11	11	BUT 100 TANK	1
07/17/2019	07:49	07:49:47	viewer_1563371387319	6	11	BUT 100 TANK	1
07/10/2019	14:02	14:02:51	viewer_1562788970757	9	14	BUT 030 TANK	1
07/08/2019	17:38	17:38:36	viewer_1562629116104	7	14	BUT 030 TANK	1
07/12/2019	07:56	07:55:59	viewer_1562939758962	11	14	BUT 030 TANK	1
07/15/2019	19:23	19:23:19	viewer_1563240198529	9	14	BUT 030 TANK	1
07/16/2019	15:07	15:07:18	viewer_1563311238282	11	14	BUT 030 TANK	1
07/17/2019	07:38	07:38:07	viewer_1563370686983	8	14	BUT 030 TANK	1
07/17/2019	07:54	07:54:28	viewer_1563371667869	6	14	BUT 030 TANK	1
07/10/2019	14:07	14:07:48	viewer_1562789267991	9	16	BUT 010 TANK	0
07/12/2019	08:00	08:00:38	viewer_1562940038239	11	17	BUT 010 TANK	0
07/17/2019	07:43	07:43:02	viewer_1563370982363	8	17	BUT 010 TANK	0
07/17/2019	07:59	07:59:19	viewer_1563371958843	6	17	BUT 010 TANK	0
07/15/2019	19:29	19:29:26	viewer_1563240566114	9	17	BUT 010 TANK	1
07/16/2019	15:12	15:12:43	viewer_1563311563361	11	17	BUT 010 TANK	1

Date	Release Start Time	Video Start Time	Video Filename (*.mp4)	Pump	Test Condition Number	Test Condition Name	Plume Seen?
07/10/2019	14:23	14:22:58	viewer_1562790177999	9	3	GAS 100 R DOOR	1
07/08/2019	17:51	17:51:47	viewer_1562629906863	7	3	GAS 100 R DOOR	1
07/12/2019	08:09	08:09:17	viewer_1562940557110	11	3	GAS 100 R DOOR	1
07/16/2019	15:20	15:20:49	viewer_1563312048931	11	3	GAS 100 R DOOR	1
07/17/2019	08:08	08:08:43	viewer_1563372523491	6	3	GAS 100 R DOOR	1
07/10/2019	14:29	14:29:28	viewer_1562790568210	9	6	GAS 030 R DOOR	1
07/08/2019	17:57	17:57:07	viewer_1562630226650	7	6	GAS 030 R DOOR	1
07/12/2019	08:14	08:14:48	viewer_1562940888125	11	6	GAS 030 R DOOR	1
07/15/2019	20:03	20:02:30	viewer_1563242549876	9	6	GAS 030 R DOOR	1
07/16/2019	15:31	15:31:14	viewer_1563312673922	11	6	GAS 030 R DOOR	1
07/17/2019	08:14	08:13:56	viewer_1563372835553	6	6	GAS 030 R DOOR	1
07/10/2019	14:35	14:35:35	viewer_1562790934930	9	9	GAS 010 R DOOR	1
07/08/2019	18:02	18:02:30	viewer_1562630550322	7	9	GAS 010 R DOOR	1
07/12/2019	08:21	08:21:12	viewer_1562941272057	11	9	GAS 010 R DOOR	1
07/15/2019	19:43	19:43:36	viewer_1563241415717	9	9	GAS 010 R DOOR	1
07/16/2019	15:40	15:40:49	viewer_1563313248914	11	9	GAS 010 R DOOR	1
07/17/2019	08:18	08:18:28	viewer_1563373108493	6	9	GAS 010 R DOOR	1
07/10/2019	13:56	13:56:35	viewer_1562788595369	9	12	BUT 100 R DOOR	1
07/08/2019	17:31	17:31:46	viewer_1562628705810	7	12	BUT 100 R DOOR	1
07/12/2019	07:52	07:51:57	viewer_1562939516569	11	12	BUT 100 R DOOR	1
07/15/2019	19:19	19:18:43	viewer_1563239923303	9	12	BUT 100 R DOOR	1
07/16/2019	15:04	15:04:30	viewer_1563311070179	11	12	BUT 100 R DOOR	1
07/17/2019	07:34	07:34:37	viewer_1563370476637	8	12	BUT 100 R DOOR	1
07/17/2019	07:51	07:51:23	viewer_1563371482749	6	12	BUT 100 R DOOR	1
07/10/2019	14:04	14:04:38	viewer_1562789078266	9	15	BUT 030 R DOOR	1
07/08/2019	17:39	17:39:47	viewer_1562629186708	7	15	BUT 030 R DOOR	1
07/12/2019	07:57	07:57:37	viewer_1562939856526	11	15	BUT 030 R DOOR	1
07/15/2019	19:25	19:25:19	viewer_1563240319384	9	15	BUT 030 R DOOR	1
07/16/2019	15:09	15:08:57	viewer_1563311336784	11	15	BUT 030 R DOOR	1
07/17/2019	07:39	07:39:31	viewer_1563370771134	8	15	BUT 030 R DOOR	1
07/17/2019	07:56	07:55:46	viewer_1563371746211	6	15	BUT 030 R DOOR	1
07/17/2019	08:00	08:00:45	viewer_1563372045396	6	18	BUT 010 R DOOR	0
07/10/2019	14:10	14:10:28	viewer_1562789427901	9	18	BUT 010 R DOOR	1
07/12/2019	08:02	08:02:07	viewer_1562940127463	11	18	BUT 010 R DOOR	1
07/15/2019	19:34	19:33:46	viewer_1563240825974	9	18	BUT 010 R DOOR	1
07/16/2019	15:14	15:14:27	viewer_1563311667002	11	18	BUT 010 R DOOR	1
07/17/2019	07:44	07:44:24	viewer_1563371063711	8	18	BUT 010 R DOOR	1

Appendix B
Arvada: Phase 1 Enhanced MidWave Video Viewing Instructions[41]

[41] C:\Documents\EPA CanisterDegradation\WA2-23 (GasStnRebellion_MAR2019)\Data QC/VideoQCingInstr-190918.docx

Overview of the SharePoint QC Database

Each row in the SharePoint database contains information for one refueling event for one vehicle including:

Variables (sortable) on the main screen:

Title: A code that is unique to each vehicle.
Year: Vehicle model year according to Colorado registration database via license plate.
Make: Vehicle make according to Colorado registration database via license plate.
Model: Vehicle model according to Colorado registration database via license plate.
EmptyWt: Vehicle empty weight according to Colorado registration database via license plate.
PumpID: The identifier of the pump at the Costco Arvada gas station.
Gallons: The volume of gasoline dispensed.
Arrive_MTN: DateTime that the vehicle arrived at the pump.

Additional variables on the drop-down list (accessed by clicking on a Title on the main screen):

VehicleShort: Concatenation of Year, Make, Model, EmptyWt.
ShortVehicle_Match: An indicator of the match between appearance/description of the vehicle.
EnhMW_#_Video: A hyperlink to a 30-second video. Up to 6 videos per refueling event.
***_VidDefect:** Technician's evaluation of video quality.
***_PlumeChar:** Technician's evaluation of plume presence and other qualities.
***_PlumeTime:** Technician's evaluation of when plume is first seen in the video.
***_Vehicle:** Technician's evaluation of vehicle motion.
***_HoseDistance:** Technician's evaluation of gas pump hose placement.

Abridged Phase 1 Instructions Used by Technicians to Evaluate Videos:

Each row in the SharePoint database contains information for one refueling event for one vehicle including: a variable telling if the observation's videos should be watched (Target), a pump identifier (i_PumpID), a vehicle description (i_VehicleShort), multiple EnhMW video hyperlinks (r_EnhMW_#). The rows should be sorted by the datetime of the credit card authorization timestamp (c_CCStart).

View only videos on rows that are marked as Targets. If Target is blank, do not watch any videos on that row. Either the videos have already been watched or some portion of the vehicle description is unknown.

To allow recording of EnhMW information, the SharePoint database has initially empty variables for each of a row's EnhMW videos for the following five major categories with a drop-down menu for each to allow selection of just one of the values within each category:

Video Defects
Refueling plume characteristics
Video Second that the plume is first seen in the video
Vehicle Action
Hose Distance

Specific Phase 1 Instructions

1. Starting at the top of the SharePoint database, find the line with the first Target.

2. Note the i_PumpID value:
   If i_PumpID = 5, 6, or 9, the target vehicle is the front pump.
   If i_PumpID = 7, 8, or 11, the target vehicle is the rear pump.

3. View r_EnhMW_1, which is the first video for the refueling event, by clicking on the video filename.

4. As the video plays and looking only at the vehicle at the correct pump, select a single response to the five categories using the drop-down menus corresponding to the video number (1 to 5). Watch the video multiple times if necessary.

5. Repeat the same procedure for all EnhMW videos on the line.

6. Go to the next line that is marked by Target and repeat the procedure.

Guidelines Used by Technicians to Evaluate Videos:

i_ShortVehicle_Match: Verify that the vehicle on the camera matches the short vehicle description. Use google images to help identify cars. Use this primarily if you think that there is no way that the vehicle in the video can match the registration database description. Usually leave this field "Can't tell."

Match = Vehicle matches the description
Doesn't Match = Vehicle is very clearly different from the vehicle in description.
Can't Tell = If it is unclear (Default)

Video Defects:
+ = Good EnhMW video for entire 30s

- Video is black and white.
- Video is noisy. (Look for salt and pepper)
- Entire video is in motion, no still frames.
- No white screen present during video.

\- = Not an EnhMW video for some part of video

- Video is in color, not black and white.
- Video is not in enhanced infrared. The video is black and white but appears almost like it's a video in negative light and isn't noisy.

F = Frozen video

- Video freezes (still frame).

W = White screen for some part of video.

- Video cuts to a white screen.
- This occurs when the Rebellion IR camera is calibrating, which occurred every 8 minutes.

X = Video is completely useless since it has no plume info.

- If any of the video defects persist for more than 2/3 (20 seconds) of the video.

Refueling plume characteristics:

0 = No plume visible
L = Light plume
H = Heavy plume
P = Puddle on pavement after vehicle leaves with plume coming from it. (Takes priority.)
X = Not possible to review for plume. (If video defect is X)
G = Fueled something that isn't a car (Gas can, Boat, Jet ski, etc.)
S = Plume is blown on-screen from an off-screen source.

Video Second that the plume is first seen in the video:

0 = no plume is ever seen in this video
# = (a number between 1 and 30) The second that a plume is first visible in the video.

Vehicle Action:

0 = No vehicle is at this pump in this video.
A = The targeted vehicle arrives at the pump in this video.
R = The targeted vehicle is at the pump for the entire video.
D = The targeted vehicle drives away from the pump in this video.
X = The video has a vehicle different from the vehicle in the other videos assigned to this refueling event.

Hose Distance:

N = Near (the fuel fill door is close to the pump)
F = Far (the pump hose is stretched across the vehicle to get to the fuel fill door)

Appendix C
Arvada: Phase 2 Enhanced MidWave Video Viewing Instructions

The Phase 1 video viewing found that some refueling events showed refueling plumes. About 455 refueling events of confirmed ORVR vehicles had overall Phase 1 viewing results of L, H, or P (low-density, high-density, or puddle). We need to re-view the Enhanced MidWave videos of those events to determine the time trends of when plumes appeared. The reason is that in many cases with plumes present, plumes appeared only briefly when the gas cap was removed and/or when the fuel pump nozzle clicked off. We want to distinguish instances of that behavior from the behavior when plumes are being produced during fuel-dispensing periods.

Each Enhanced MidWave video is 30s long. We divide each video into six 5s blocks and evaluate each of the blocks in each video to produce a 6-digit string of characters. Assign a single character to each 5s block.

During the Phase 1 video examination, we typically saw two types of refueling emissions: 1) continuous plumes, and 2) puffs of emissions. Each type of emission can produce codes, but use only one code for each 5s block, as described below.

Puff Codes – We define a “puff” as a short-duration plume that seems to be associated with a specific activity - especially gas cap removal, beginning of fuel flow, end of fuel flow at gas pump nozzle click-off. If you see a puff during these activities, use these codes for the 5s block that they occur in:

R = puff at gas cap Removal.

B = puff at Beginning of fuel flow, i.e., when the customer pulls the nozzle handle. If you see a puff in a block when both gas cap removal and beginning of fuel flow happen, and if you cannot tell whether the puff comes from R or B, then record a B.

E = puff at End of fuel flow, i.e., when the nozzle clicks off.

For blocks other than those where a puff occurs, use the continuous plume codes described below.

Continuous Plume Codes – As described above, during gas cap removal and nozzle insertion and during and after nozzle click-off, if you see a puff of vapor, record the puff for the 5s block. But if a puff associated with those activities does not occur, use the codes for continuous plumes – keeping in mind that continuous plumes can occur before and/or after those three puff-associated activities. Here are the characters to be used to characterize a continuous plume in each 5s block:

0 = no plume can be seen

1 = a low-contrast plume can be seen.

2 = a high-contrast plume can be seen.

X = the entire video screen is white, which indicates that the GCI camera is calibrating.

P = a plume is coming from a puddle of gasoline on the pavement. This might occur at any time in the video. P takes priority over 1 and 2.

Record the continuous plume character that makes up the most time of the 5s block. For example, if there are about 4 seconds of 0 and 1 second of 1, record 0 for the block.

A note about continuous plume evaluation. Contrast refers to the variation of light to dark within the plume. Areas of very white and very black within the plume are high contrast and would be assigned a 2. Areas with slight differences of gray indicate low contrast and would be assigned a 2 – unless the plume is large – in which case it would be assigned a 2. In the Phase 1 viewing, we did not look so much at plume contrast but considered mainly plume size. The problem is that the contrast is affected by the distance from the emission point, the speed and direction of air movement, and the camera's view of the target vehicle and its surroundings. Sometimes the view shows only a small portion of the surroundings, which means that large plumes may not be in the video even if they exist off-screen. So, if a large, billowing plume is seen over a large screen area, it can be a 2 even if the contrast within the plume is low. Also, if a large, billowing plume cannot be seen because the vehicle is near the edge of the screen, but a small, high-contrast stream of vapor is seen coming from the fuel fill door, this result can also be a 2. If you are watching the video and you say to yourself: "Is that a plume? I think there MIGHT be a plume there." That is a 1. A small wispy plume will also be a 1.

General Guidance – You can use the Phase 1 viewing results of a refueling event as guidance, but do not think and do not try to make the Phase 2 time profile string to somehow match the Phase 1 viewing results. The Phase 2 evaluation criteria are different from the Phase 1 viewing criteria.

Do not evaluate (just ignore) plumes from off-screen (formerly S), gas cans and off-road equipment (formerly G). Evaluate only plumes that you judge are from the target vehicle.

Record a digit even though you can clearly see that the customer has not yet lifted the nozzle from the pump or that he has already hung up the nozzle. We must have a 6-digit string for every video.

You need to be reasonably certain that the plume you are evaluating is from the targeted vehicle – not the other vehicle at the island. If you are not certain, use a ? as the character.

Appendix D
Thornton: Clicks, Spills, Spitback Data Collection Instructions

For the WHITE datasheets

Goal: Collect data to find out the fraction of refueling events that produce liquid gasoline spills.

Rule 1: Use your best printing when making these data entries. If you make a printing error or you think that the entry may not be clear to someone else, correct it immediately. Make the correction by carefully drawing a single horizontal line through the entry and re-writing the entry above, below, or near the crossed-out entry. Never write over an erroneous character. Never scribble over an erroneous entry. Never use an X to cross out an erroneous entry.

Step 1. Use the logsheet CSS_logsheet-190704.xlsx.

Step 2. Enter the Day of Week (Sun, Mon, Tue, …) in the first cell of the data row.

Step 3. The next vehicle to be picked will be from any one of the 12 pumps at the station. Pick the first vehicle where the driver gets out.

Step 4. Enter the Pump Number.

Step 5. Enter the license plate State using the rear license plate.

Step 6. Enter the rear Plate. Be very careful to clearly print the Plate. The license Plate is a critical variable in this study. Clearly distinguish characters that are easily confused:

5 vs. S
2 vs. Z
D vs. Q vs. O vs. 0
I vs. 1
B vs. 8
U vs. V
G vs. C
7 vs. 9

If the plate is missing, enter the word “missing”. If the plate is a paper temporary plate, enter the word “temp”.

Step 7. Enter the vehicle Make and Model. Sometimes it is not clear what the vehicle model is. Some labels tell trim package. So, enter all of the labels on the vehicle that might tell the model.

Step 8. Most times, people pull up to a gas pump so that their vehicle’s fuel fill door is on the same side of the vehicle as the gas pump. If they do that, enter Fueling Side = Near. Occasionally, people stretch the pump hose across, behind, or under their vehicle because their fuel fill door is on the far side of their vehicle from the pump. If they do that, enter Fueling Side = Far.

Step 9. Look at how they put the nozzle in their fuel fill pipe. Enter RSU for RightSideUp, USD for UpSideDown. Or SW for SideWays.

Step 10. The typical fueling event ends with the nozzle automatically clicking off and the customer puts the nozzle back on the pump without further pulling the nozzle handle. If that happens, enter the Number of Extra Clicks=0. If the customer does not accept the automatic shut-off, he will attempt to put more gasoline into the tank and each attempt will produce "extra clicks" as the nozzle automatically turns off again. Count the number of extra clicks and enter the count on the logsheet.

Sometimes nozzles falsely click off at the beginning of a refueling. Do not count these clicks.

Step 11. Using your personal timepiece, enter the Nozzle Hang-Up Time (hh:mm:ss) when the customer puts the nozzle back on the pump.

Step 12. Sometimes during fueling the pump nozzle seems to fail to automatically shut-off the fuel flow, and there can be a violent gushing of fuel from the vehicle's fill pipe. This is called a spitback. If a spitback happens for any reason, enter Spitback=Yes, otherwise enter Spitback=No.

Step 13. Occasionally, a liquid fuel spill can occur during fueling. The spill could be caused by a spitback, or by repeated clicks as the customer tries to maximize the amount of fuel in the tank, or by something else. If there is a spill and it comes from the fuel fillpipe, enter the Spill Source=F. Also, estimate and enter Spill Size as N, T, G, or B.

Step 14. Occasionally, a vehicle will leak gasoline under the vehicle. So, after the vehicle drives away, look for gasoline puddles under where the vehicle was sitting. Puddles under vehicles can be from things other than gasoline, such as A/C condensate (water), green or orange antifreeze coolant, blue windshield washer fluid, engine oil, pink transmission fluid, brake fluid, or power steering fluid. The smell, color, and viscosity of gasoline ought to be a giveaway. The other thing is to try to be sure that the gasoline puddle is from the vehicle that was just there and not an earlier vehicle. If there is a gasoline puddle under and attributed to the vehicle, enter the Spill Source=U. Also, estimate and enter Spill Size as N, T, G, or B.

Step 15. Record the action that the station attendant takes in response to spills or spitbacks by entering N, K, S, and/or C under Attendant Action for none, kitty litter, spray, or orange cones.

Step 16. Text. If something unusual happens – like spills or spitbacks, please describe what happened in the full width of the data form lines under the line for the vehicle. Use complete sentences, so we can tell what happened. Use a lot of words. Don't try to squeeze a couple of words into the little box provided at the end of the line. For typical refueling events with no spills or spitbacks, no text description is needed.

Step 17. After the vehicle drives away and after all data entries and any text has been written, have been made, go back to Steps 2 and 3 and pick the next vehicle to follow.

Figure D-1. Logsheet for Observations of Randomly Selected Vehicles

Day of Week	Pump Number	License		Make	Model	Fueling Side (**N**ear, **F**ar)	Nozzle Orientation: **R**ight**S**ide**U**p **U**p**S**ide**D**own **S**ide**W**ays	Number of Extra Clicks (0=auto shut-off only)	Nozzle Hang-Up Time (hh:mm:ss)	Spitback ? (**Y**es, **N**o)	Spills		Attendant Action (**N**one, **K**itty, **S**pray, **C**one)	**Text:** If there was an event, tell about it in lines under the car's data.
		State	Plate (very clear)								Source: **F**ill neck **U**nder car	Size: **N**ickel **T**ennis **G**rapefruit **B**ucket		

Select next customer who exits car, follow until departure (Look on ground): <u>Record all selected customers whether there is an event or not.</u>
Extra Click = The number of times that the automatic nozzle shut-off is not accepted by the customer.
Spills are caused by the customer clicking the nozzle excessively.
Spitback is a violent gushing of fuel from the fillpipe.

Appendix E
Estimation of Headspace Vapor Properties for Denver Summer Conditions

The total flow of the artificial releases was 10 gallons/minute, which is a typical fuel dispensing flow of gas station fuel pumps on their highest pump nozzle setting. According to our ReddyEvap 2010 calculations (see Table 1), headspace vapor in Denver at summer temperatures is approximately 50 vol% HC vapor.

We made ReddyEvap 2010 headspace calculations using the following inputs: 8.7 psi RVP, 10 vol% ethanol, 88 F ambient temperature, 0.83 atm barometric pressure. The partial pressures were: ethanol 62.53 mmHg, non-ethanol HC 289.96 mmHg. The barometric pressure was 631 mmHg (=0.83 * 760 mmHg). Therefore, the headspace composition was: ethanol 10 vol%, non-ethanol HC 46 vol%, and air 44 vol%.

The results shown at the bottom of Table E-1 show that the estimated headspace vapor concentration is 4.6 g HC per gallon of headspace vapor.

Table E-1. Reddy Evap 2010 Inputs and Outputs to Estimate Summer Fuel and Headspace Properties in Denver

```
**** INPUT DATA ****
Test Fuel RVP              =    8.7psi
Tank Volume                =   18.0gal
Tank Capacity              =   16.0gal
Volume Percent Fill        =   50
Tank Orifice Diameter (inch)=    0.500
Fuel Cap Blow off Pressure  =    0.0 inch H2O
Tank Pressure Control Valve =    0.0inch H2O
Atmospheric Pressure       =    0.83atm
Vapor Pressure of 8.7 psi RVP gasoline at 88.0F = 6.82 psia
```

Component	MW	Liquid Fuel (mass%)	Vapor Pressure (mmHg)	Partial Pressure (mmHg)	HeadSpace Vapor (mass%)
Propane	44.1	0.044	8244.51	7.44	1.411
2M-Propane	58.1	0.472	3102.92	25.42	6.354
Butane	58.1	2.133	2194.44	81.47	20.364
t-2-Butene	56.1	0.052	2117.36	1.78	0.430
Ethanol	46.1	10.528	83.43	62.53	12.390
Isobutanol	74.1	0.002	15.82	0.00	0.000
2M-Butane	72.2	4.375	849.11	55.65	17.267
1-Pentene	70.1	0.642	787.39	6.97	2.102
Pentane	72.2	3.917	639.62	37.58	11.661
2,3-DM-2-Butene	84.2	0.095	163.39	0.21	0.075
2M-2-Butene	70.1	0.789	584.53	6.71	2.023
Cyclopentane	70.1	0.344	401.53	2.03	0.612
2,3-DM-Butane	86.1	2.094	297.81	8.13	3.011
2M-Pentane	86.2	5.218	270.92	18.42	6.828
1-Hexene	84.2	0.505	239.23	1.44	0.523
Hexane	86.2	3.048	195.94	7.80	2.889
M-Cyclopentane	84.2	1.497	178.03	3.49	1.262
2,4-DM-Pentane	100.2	2.056	128.71	3.02	1.300
Benzene	78.1	2.368	125.30	4.10	1.378
2,3-DM-Pentane	100.2	2.572	90.94	2.67	1.149
3M-Hexane	100.2	3.587	81.73	3.35	1.442
2,2,4-TM-Pentane	114.2	4.731	65.69	3.14	1.541
Heptane	100.2	1.383	61.54	0.97	0.419
M-Cyclohexane	98.2	1.313	61.76	0.94	0.399
Toluene	92.1	8.363	38.73	3.92	1.554
2,3-DM-Hexane	114.2	1.738	32.10	0.56	0.275
3M-Heptane	114.2	1.317	27.01	0.36	0.175
2,2,5-TM-Hexane	128.3	1.420	22.95	0.29	0.159
Octane	114.2	0.697	19.59	0.14	0.067
E-Benzene	106.2	2.230	13.40	0.31	0.142
m&p-Xylene	106.2	9.390	11.74	1.12	0.511
Nonane	128.3	0.617	6.25	0.03	0.019
n-Propylbenzene	120.2	2.636	4.92	0.12	0.061
1M-3E-Benzene	120.2	3.425	4.29	0.13	0.068
Decane	142.3	7.406	1.99	0.12	0.071
1,2,3-TM-Benzene	120.2	5.658	2.42	0.11	0.059
1,3-DE-Benzene	134.2	1.338	1.64	0.02	0.010

```
Stoichiometric air/fuel ratio of 8.7 psi RVP gasoline vapors at 88.0F =14.45
Air/fuel ratio of 8.7 psi RVP gasoline vapors at  88.0F = 0.35
RVP =   8.7 psi T =  88.0 gHC/gal vapor =  4.639
 8.7 psi RVP gasoline vapors at  88.0F contain 55.88 percent HC
Lower flammability of  8.7 psi RVP gasoline vapors at  88.0F = 2.01
Upper flammability of  8.7 psi RVP gasoline vapors at  88.0F =10.12
Molecular Weight of Vapor  66.0
Boiling point of  8.7 psi RVP gasoline at 12.20 psia pressure = 117.4F
```