CRC Report No. RW-105

ROADSIDE MEASUREMENT OF EVAPORATIVE AND PM EMISSIONS

Final Report

April 2023

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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REVECORP

ENGINEERING AND DATA SOLUTIONS

Final Report for:

CRC PROJECT NO. RW-105

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APRIL 5, 2023

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CRC Project # RW-105

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Forward/Preface

Remote Sensing Devices (RSDs) are open path spectrometers which measure the emissions of a large number of in-use vehicles in a short period of time on-road as the vehicles pass through the beam of the spectrometer. In addition to measuring gaseous pollutants emitted from the tailpipe (hydrocarbons, carbon monoxide, oxides of nitrogen, etc.), RSDs are attempting to add capability to measure particle matter emissions and evaporative emissions of hydrocarbons.

The goal of this study was to take nearly simultaneous measurements with Remote Sensing Devices from three vendors:

- The University of Denver "FEAT" device
- The Opus Inspections RSD 5300 (two devices were used)
- The Hagar Environmental & Atmospheric Technologies "EDAR" device

Four data sets were collected by the Remote Sensing Devices which were co-located on an interchange ramp between two freeways for five days in Phoenix AZ from April 12th -16th 2021:

- Two vehicles, operated at selected speeds, were used to simulate evaporative emissions measured at various flow rates and made by intentionally releasing butane from various locations on the vehicles known to be common sources of vapor leaks
- Two vehicles were equipped with a Portable Emissions Measurement System to measure tailpipe emissions, including particulate matter, in real time at various vehicle speeds
- An electric vehicle was driven past all three RSDs releasing one of two known gas mixtures simulating vehicle exhaust
- Tailpipe and evaporative emissions from all vehicles passing through the interchange over five days were measured (these data were reported to CRC directly under CRC E-119-3 by each vendor and are not included or analyzed in this document)

The goal of this report is to document the study and provide an analysis of the data from the first three data sets noted above.

Acknowledgements

The authors acknowledge the immense technical support, input, many hours of preparation, and funding for the study by the Coordinating Research Council (CRC). The CRC Committee Members on this project and subject matter experts from the United States Council for Automotive Research (USCAR) are the most knowledgeable engineers in the automotive industry related to tailpipe and evaporative emissions control systems in vehicles. They provided technical direction on study design due to the many variables impacting this highly unique study. The study was originally planned to take place in March 2019. CRC twice delayed the start date of the study due to COVID concerns and made everyone's safety and comfort with working together in the field a priority.

Gary Bishop of Denver University, Niranjan Vescio of Opus Inspections (and his team), and Stewart Hager of HEAT (and his team) conducted the remote sensing measurements. All three Remote Sensing Device (RSD) vendors spent considerable time working to obtain (and change) the permits required by the State of Arizona to work at roadside, started work early each day during the study and then met every evening to review status and results. Niranjan Vescio of Opus was very generous with his time and expertise assisting with site selection, obtaining required simulated exhaust gases and the input on the simulated exhaust configuration.

Brent Schuchmann, Dan Lund and Robert Michael of SGS installed and operated the Portable Emissions Measurement System (PEMS) used to collect real time tailpipe emissions data. The system is immensely complex, and they installed it in a vehicle and had it operational in a short period of time, then removed it and reinstalled in in another in less than a day. They quickly processed the data to provide results in near real time.

Gordon-Darby provided the use of two inspection lanes in a vehicle inspection station in Phoenix for preparing the vehicles with evap leaks, installation of the PEMS in the research vehicles, configuring the electric vehicle with the gas cylinders to simulate exhaust, and the use their constant volume sampling system (CVS) to measure flow rates of the simulated exhaust. Allan Martin of Gordon-Darby was critical in getting us anything needed, at any time of the day or night, for seven long days in a row, from a jack and jack stands, to building a simulated exhaust pipe, to finding a person to cut and weld stainless steel in under an hour. The study could not have been accomplished without his assistance. Craig Pierson, Alfred Rodriguez, James Bentley and Arturo Leyva of Gordon-Darby assisted with equipment installation at the start of the study. During the entire study, the Gordon-Darby staff were a tremendous help, without their assistance, we could not have conducted the experiments, and they did this at no cost to the project.

Disclaimer:

The statements and conclusions in this report are those of the Principal Investigators and not necessarily those of the Coordinating Research Council or other participants in this project. The mention of commercial products, their source, or their use in conjunction with material reported herein is not to be construed as actual or implied endorsement of such products.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF PICTURES

ABBREVIATIONS AND ACRONYMS

AZ DOT	Arizona Department of Transportation
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COA	Certificate of Analysis
CRC	Coordinating Research Council
DU	Denver University
FID	Flame Ionization Detector
FEAT	Fuel Efficiency Automobile Test (the DU remote sensor)
E10	Fuel with 10% Ethanol
EDAR	Emissions Detection and Reporting (the HEAT remote sensor)
EPA	Environmental Protection Agency
EV	Electric Vehicle
G	Gram
G/MI	Grams Per Mile
GDI	Gasoline Direct Injection
HC	Hydrocarbons
HEAT	Hager Environmental & Atmospheric Technologies
HR	Hour
IM	Vehicle Inspection and Maintenance Programs
IR	Infrared
KM	Kilometer
KG	Kilogram
µG	Microgram
LIDAR	Light Detection And Ranging
MG/MI	Milligram Per Mile
MPH	Miles Per Hour
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NDIR	Non-dispersive Infrared
NMHC	Non-methane Hydrocarbons
NMOG	Non-methane Organic Gas
NO_x	Oxides of Nitrogen ($NO + NO_2$)
OBDII	On-board Diagnostics, Second Generation
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
Public Vehicles	Non-study vehicles passing the remote sensors
RSD	Remote Sensing Device
RVP	Reid Vapor Pressure
S	Second
SDM	Opus Remote Sensor Source/Detector Module
SLPM	Standard Liters Per Minute
UV	Ultraviolet
VIN	Vehicle Identification Number

1 EXECUTIVE SUMMARY

CRC designed this study to compare the tailpipe and evaporative emissions measurements of the Denver University (DU), Hager Environmental & Atmospheric Technologies (HEAT) and Opus remote sensing devices nearly simultaneously for intercomparison. The data were collected on-road from April 12th to the 16th 2021 at a freeway interchange in Phoenix AZ. Tailpipe emissions (HC, CO, NO_x, CO_2, and PM) and evaporative emissions were measured from vehicles passing the Remote Sensing Devices (RSDs). The accuracy of the RSDs for measuring tailpipe emissions was evaluated with the use of an Electric Vehicle (EV) equipped to release simulated exhaust at two selected concentrations. The accuracy of the RSDs for measuring tailpipe emissions including PM was also evaluated by comparing RSD emissions measurements of two research vehicles to emissions measurements of the vehicles with a Portable Emissions Measurement System (PEMS). The capability of the RSDs to measure evaporative emission was evaluated by driving past the RSDs with two research vehicles simulating evaporative leaks at four common leak locations. The vehicles were driven at various selected speeds with known flow rates of butane simulating the evaporative system leaks.

The data for the simulated vehicle exhaust, PEMS and research vehicle runs past the RSDs is available in a single spreadsheet for further analysis: https://s3-revecorp-static.s3.us-west-2.amazonaws.com/Revecorp+RW-105+Data+Summary+-+FINAL.xlsx. The RSDs also collected data on all vehicles passing through the freeway interchange over the five days, and those data were reported by each remote sensing vendor and in a statistical analysis by Charles Blanchard under separate contracts to CRC, available on the CRC website (www.CRCAO.org).

Measurement of Evaporative Leaks

To determine the flow rate of a completely open leak in a vehicle evaporative emissions control system as a function of temperature, a fuel tank was filled to 40% full and heated while measuring the fuel vapor flow rate. Using EPA Tier 3 EEE Certification Emissions Fuel with an RVP of 9 and E10 (10% ethanol), the flow rate of the fuel vapor (when corrected for the air in the tank) was approximately 1 slpm at 95˚F and 4 slpm at 117˚F[1]. Therefore, the simulated evaporative leaks were performed with leak rates of butane at 1, 2.5 and 4 lpm. Because the concentration of hydrocarbons is a function of dilution due to mass of air passing a vehicle at a given vehicle speed, each flow rate was leaked from research vehicles traveling at approximately 25, 35 and 45 mph. The simulated leaks were designed to represent common leaks (top of the fuel tank, at the canister, at the fuel cap, and at the canister vent. Control boards were used to allow the driver to flow butane to simulate the evaporative leaks to the desired locations at the desired flow rates in both research vehicles (a 2014 Mazda6 and a 2013 Ford F-150).

The results from the simulated evaporative system leak experiments indicated:

- The FEAT/DU RSD is not optimized for measuring evaporative emissions
- The HEAT and Opus identified many vehicles with no leaks as having leaks
- The HEAT and Opus did not differentiate vehicles with small leaks leak from those with significant leaks (15 g/mi)
- An advantage to the HEAT measurement system is that it looks down on the road, making it easier to identify higher evaporative leaks high on a vehicle (such as a missing fuel cap) than Opus which measures 12 inches off the road surface
- Measurement of the same vehicle and leak rate between the HEAT and Opus did not correlate

[1] During the on-road experiments, the highest ambient temperature recorded was 99.8°F and the highest liquid fuel temperature was 106°F indicating the temperature range chosen by CRC was appropriate to represent most on-road fuel temperature and potential evaporative leak rates.

- Using remote sensing measurements estimate the rate which vehicles have evaporative leaks is most likely overestimated
- It may be possible to use the measurements to determine fleet average evaporative emissions of a large sample, but not reliably identify individual vehicle evaporative emissions rates

Measurement of Tailpipe Emissions

The accuracy of the RSDs was evaluated in two experiments: 1) by outfitting an EV with a tailpipe and releasing two calibration gases through it to simulate vehicle exhaust, and 2) by measuring the emissions in real time from two research vehicles using an on-board Portable Emissions Monitoring System (PEMS). In general, both HEAT and Opus had good correlation to the simulated exhaust with the vehicle operating between 25 and 45 mph flowing gas at a constant rate prior to passing the RSDs.

Results from Driving EV Past Remote Sensors Releasing Simulated Exhaust									
Simulated Exhaust		"Low" Gas (15 Passes)				"High" Gas (16 Passes)			
		NO ppm	HC ppm	CO ppm	CO2 %	NO ppm	HC ppm	CO ppm	CO2 %
Gas Concentration		249.8	255.2	498.7	14.9	773.2	756.4	15,030	14.1
DU	Average	390.9	383.5	188.2	15.0	1,104.4	520.0	16,303	13.8
HEAT		249.0	259.0	492.0	15.0	746.5	770.3	14,466	14.0
Opus		192.5	242.7	462.3	15.0	715.0	717.4	15,742	13.9
DU	Delta %	56.5	50.3	(62.3)	0.5	42.8	(31.3)	8	(1.9)
HEAT		(0.3)	1.5	(1.3)	0.5	(3.5)	1.8	(4)	(0.7)
Opus		(22.9)	(4.9)	(7.3)	0.6	(7.5)	(5.2)	5	(1.3)
DU	Std Dev	74.4	340.9	1,628.0	0.1	230.9	324.5	2,285	0.1
HEAT		4.9	41.4	16.4	0.0	7.1	42.1	1,101	0.1
Opus		69.1	69.9	211.7	0.0	70.6	53.3	732	0.1

Data from the PEMS measurement of tailpipe emissions for the two research vehicles were compared to those reported by the RSDs to also assess accuracy. The research vehicles were model year 2013 and 2014 and were in proper operating condition, with low miles, therefore their emission rates were low. The RSDs had difficulty measuring the emissions from these vehicles and the correlation to the PEMs measurement was poor.

- Neither HEAT nor Opus correlated with the measurements from DU
- Moving from DU measurements of fleet tailpipe emissions to HEAT or Opus measurements needs more consideration

Measurement of Particulate Matter (PM) Emissions

The accuracy of the RSDs for measuring PM was also done by comparing the RSD measurements to PM measurements by PEMS installed in both research vehicles. Comparison of the PEMS emission rates to the measurements by HEAT and OPUS showed no correlation between the measurements for either research vehicle. Based on the PEMS measurements, the PM of the Mazda6 was an order of magnitude lower than the F-150 and the Mazda6 emissions were also lower based on the HEAT and Opus measurements. This evaluation was limited due to the low PM emission rates of the two research vehicles which are still much higher than current technology vehicle PM emission rates.

- RSDs would not be able to identify a current technology vehicle with PM emissions over the standard to which they were certified

2 BACKGROUND

Remote Sensing Devices (RSDs) were developed by the University of Denver (DU) and have been in operation since 1997 measuring the tailpipe emissions of public vehicles operating on-road including hydrocarbons (HC), oxides of nitrogen (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2) and other chemicals on various sites in the US. CRC, EPA and other researchers have used these time series data sets to evaluate changes in vehicle emissions over time as vehicle emissions control technology has improved and to identify the portion of the fleet not operating as designed (high emitters). Two commercial RSDs (HEAT and Opus) have improved on the DU remote sensing concept using newer measurement technology and have recently made advancements to potentially identify hydrocarbons from evaporative control system leaks versus hydrocarbons from the tailpipe, and measure particulate matter. The DU measurement system is about to be retired, and therefore CRC wanted a comparison between the three RSDs so that future comparisons of emissions trends (if provided by HEAT or Opus), produce a consistent, continuous view of fleet tailpipe emissions trends over time.

An RFP for Project No. RW-105 "Roadside Measurement of Evaporative and PM Emissions" was released by CRC December 18, 2018[2]. Revecorp and Engineered Testing Solutions (ETS) were awarded this project and functioned as the Principal Investigators for the study, working with CRC to develop the test methods, experiments, instrumenting the research vehicles and coordinating all aspects of the experimental field work. The second portion of the project was coordinating with the three Remote Sensing Device vendors, a portable emissions monitoring system (PEMS) team, and CRC to measure tailpipe emissions (including PM), simulated exhaust, simulated and actual evaporative emissions and a large sample of public vehicles, in one place, over the course of five days.

The specific goals of the project were:

- Evaluate the ability of Remote Sensing Devices to measure evaporative emissions from vehicles using two instrumented research vehicles by:
  - Simulating evaporative leaks of hydrocarbons by releasing butane from various locations on the vehicles while the vehicles were traveling at 25 to 45 mph
  - Leaking fuel vapor by disconnecting evaporative emissions controls at various locations and driving past the RSDs at 25 to 45 mph
- Evaluate the ability of Remote Sensing Devices to measure particulate matter emissions from two direct injection vehicles by comparing the Remote Sensing Device measurements to on-board PEMS measurements
- Evaluate the relative accuracy of the Remote Sensing Devices to measure tailpipe emissions by:
  - Releasing known concentrations of HC, NO_x, CO and CO_2 gases from an electric vehicle and measuring these with roadside Remote Sensing Devices
  - Measuring tailpipe emission from two vehicles with PEMS and comparing the results to measurements with roadside Remote Sensing Devices
  - Comparing tailpipe emissions measurements for the same vehicle between the three collocated Remote Sensing Vendors for each public vehicle measured

The measurements for this project (CRC RW-105) were obtained from three RSDs Device vendors using four RSDs:

[2] RFP for "CRC Project No. RW-105 – Roadside Measurement of Evaporative and PM Emissions", Coordinating Research Council,5755 North Point Parkway, Suite 265. Alpharetta GA 30022

- University of Denver Operating the Fuel Efficiency Automobile Test (FEAT) remote sensor
- Opus Inspections Operating two RSD5300 remote sensors
- Hager Environmental & Atmospheric Technologies (HEAT) operating the Emissions Detection and Reporting (EDAR) remote sensor

The RSDs were set up in series at the side of the road at an interchange ramp between two freeways (Interstate 60 eastbound and Highway 101 northbound) in Phoenix AZ April 12th to the 16th, 2021. Public fleet passing the Remote Sensing Devices were also measured during this time as part of the complimentary CRC Project E-119-3, "Evaluation of Remote Sensing Devices and Technology - Phase 2". Approximately 9,700 public vehicles were measured during the five days by all three RSDs for tailpipe, evaporative and PM emissions. The data were to be used for intercomparison of the three Remote Sensing Devices. Each Remote Sensing Device vendor evaluated and presented their measurements from their systems in separate reports to CRC.

This report is focused on describing the reasoning for the experimental design of this study, the methods used to collect data, and presenting analysis of the data from the research vehicles in the study. CRC had an additional project where the data from this study and CRC E-119-3 (measurement of the public vehicles passing the RSDs during the study) was evaluated in further detail[3].

[3] Blanchard, C. L., 2022. Draft Final Report for CRC Project No. E-119-3a, Remote Sensing Device (RSD) Statistical Analysis. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022.

3 APPROACH

The project required coordination of several discrete steps which are detailed below. Preparation for a week of data collection on site occurred over more than a year, due to changes in the expected start date because of the Covid-19 (Covid) pandemic. The preparation included choosing a location for the on-road testing, choosing the vehicles to be used for simulated and actual evaporative emissions leaks, determining the best method to simulate evaporative leaks, determining appropriate simulated evaporative leak rates, determining the best method to simulate vehicle exhaust, instrumenting the research vehicles, use of PEMS to measure PM emissions and finally how the vehicles would be operated on site (speeds and acceleration rates). The test site had to safely accommodate the RSDs collocated at the side of an operating freeway.

3.1 Data Collection

The operation of the roadside simultaneous measurements by the RSDs was designed to collect the following data sets on a freeway interchange ramp from April 12th to April 16th, 2021:

- Simulated evaporative emissions (butane) from two vehicles, driven at approximately three speeds (25, 35 and 45 mph) with leaks from four locations and blanks
- Actual evaporative emissions from two vehicles, driven at approximately three speeds (25, 35 and 45 mph) with leaks from three locations
- Simulated exhaust (propane, NO, CO, and CO_2), at two concentrations plus blanks from an electric vehicle
- Tailpipe emissions (hydrocarbons, NO_x, CO, CO_2 and particulate matter) from two vehicles driven at approximately three speeds (25, 35 and 45 mph) which were equipped with a portable emissions monitoring system (PEMS) to measure the emission rates at the tailpipe
- Outside the scope of this project (RW-105) was for the RSDs to also capture emissions measurements (tailpipe NO_x, CO, CO_2 and particulate matter, and evaporative emissions) on the fleet of public vehicles passing the RSDs during the five days of the study for CRC Project No. E-119-3.

Nearly simultaneous data collection by the RSDs allowed for intercomparison of results for the measurement of the same vehicle at nearly the same operating conditions.

3.2 Test Site

CRC had several criteria for the testing location. How each of these might have impacted the collected data and results were discussed over months of group calls.

- The desired ambient temperature range between night and day is 60 to 80 degrees F
- The location should ensure vehicles are warmed up
- Vehicle average speeds should be 35 mph with a range from 25 to 45 mph
- The location should ensure vehicles are slightly speeding up and under load (accelerating gently and/or going uphill) when measured
- The location had to accommodate three RSDs very near to each other
- The location had to be safe for staff to be near the roadside while the testing was occurring
- Sufficient test volume to support measuring approximately 25,000 vehicles in five days – which was lowered to 15,000 vehicles in five days due to Covid-induced traffic volume reductions
- The location had to have nearby facilities to store and configure the test and calibration vehicles
- Measurements should be at vehicle speeds similar to other large RSD data collection activities in the past, RSD data collection for vehicle inspection and maintenance (IM) program purposes and at speeds appropriate for measuring evaporative emissions

Vehicle speeds were a balance between higher speeds which lead to more vehicles sampled in a period of time and lower speeds which cause evaporative emissions concentrations to be higher, improving the ability to read these emissions. All three of the RSD vendors said that speeds up to 50 mph are acceptable to measure tailpipe emissions, and they noted that during operation in IM programs, measurements at roadside generally occur between 35 to 45 mph. The RSD vendors confirmed that in their experience, higher speeds result in more vehicles sampled in a given period of time. However, evaporative emissions produce lower ambient concentrations of hydrocarbons the higher the speed (given a constant leak rate). EPA[4] noted that in their experiments, the best speed for measuring evaporative emission rates was 25 mph. To gather as much information as possible about the relative accuracy of the different RSDs at various speeds, it was decided to target an average speed of 35 mph for vehicles passing the RSDs, but operate the research vehicles at 25, 35 and 45 mph to allow for improved evaluation of accuracy.

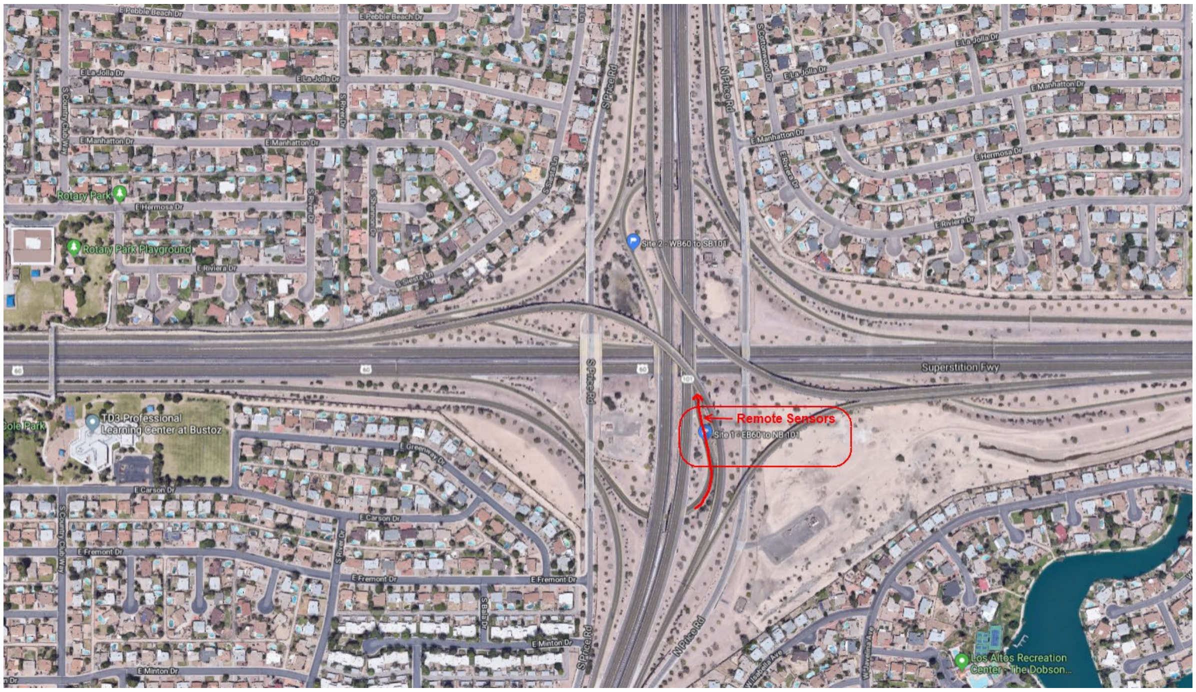
Several potential sites were proposed by the RSD vendors based on the given criteria and their experience which were reviewed by the group. The consensus was that Phoenix Arizona had several locations meeting the criteria where the RSD vendors had previously set up their instruments and collected large data sets. At the time of year, the study was initially planned to be performed (March), the temperature range in Phoenix was between 60 at night and 80 during the day, usually avoiding temperature extremes and rain. In addition, Gordon-Darby operates the light duty vehicle IM program in Phoenix and has inspection facilities all around the city. Gordon-Darby has always been gracious and willing to allow research to be conducted at or from their facilities which could be used to stage the research vehicles and equipment.

Based on the RSD vendors experience, the potential test sites were narrowed to two locations in Phoenix: one an on-ramp to a freeway with an uphill incline and one a connector between two freeways. Initial evaluation looking at statistics for vehicle volumes and speeds from AZ DOT indicated both locations had high vehicle volumes. For the on-ramp, since vehicles were starting from a low speed and accelerating onto a freeway, the placement of the RSDs could be adjusted to achieve measurements close to the desired average target speed of 35 mph. However, this site also had two lanes merging into one lane and limited space on the side of the road to place the RSDs.

It was decided to investigate the connector between Interstate 60 eastbound and Highway 101 northbound in Tempe AZ (a suburb of Phoenix, Picture 1). Revecorp visited the site with Niranjan Vescio from Opus and observed vehicles at the location. The interchange leaves Interstate 60, goes downhill to where the road passes under Highway 101, makes a sharp left and then goes uphill as the road comes up to meet Highway 101. The entrance to the interchange has blinking warning lights with signs noting the curve speed is 25 mph (Picture 2). There were indications on the outside of the curve that vehicles had struck the outside barricade in the past, and that the low speed was warranted (Picture 3).

[4] Carl Fulper, US EPA, personal communication as part of a CRC RW-105 Committee conference call, Oct 8, 2019.

Picture 1 - Overview of Remote Sensing Location EB 60 to NB 101 in Phoenix AZ



Picture 2 - Off Ramp from EB 60 Showing 25 MPH Warning Signs

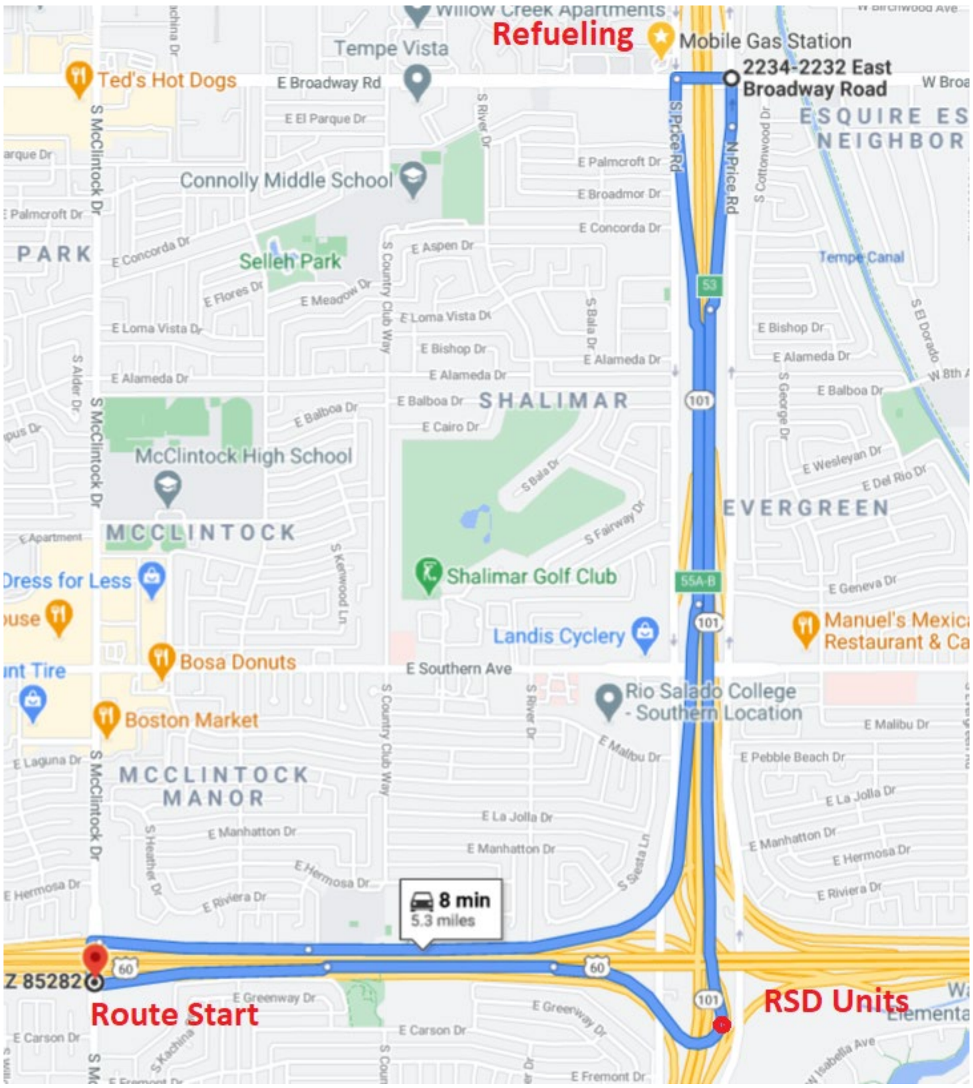
Picture 3 – Curve Under Highway 101 Showing Warning Arrows and Impact Indications Just Prior to RSD Location (RSDs Not Yet Visible)

An advantage of the low speed was that just after passing under the overpass, vehicles began to accelerate as they also started up an approximate 2% grade causing the vehicles to operate in the desired loaded condition. An additional criterion for the site was that there was sufficient space to locate the three RSDs on the inside (left) of the curve. There was approximately 8 feet which was relatively level inside the curve for the RSDs to set up, and enough space so they could move closer or further form the exit under the bridge as might be necessary to capture the appropriate speed. It was also noted that at the top of the hill behind where the RSD were to be located there was a traffic control box. HEAT requested and was granted access by AZ DOT to the box during the study to obtain power for their instrument and shared the power with others to obviate the need for generators to power the equipment on the inside of the curve.

To evaluate the site, Niranjan Vescio and Revecorp drove a loop starting on I-60, through the proposed site, exiting at the first exit from Highway 101 and returning to the potential testing location Figure 1. Vehicles were followed at their natural speeds through the loop and most vehicles which were unimpeded travelled at approximately 35 mph where we intended to locate the RSDs. We did notice that some motorists accelerated heavily after exiting from under the overpass as the merge onto the freeway ahead started to come into view and exceeded 45 mph. At the exit from the freeway is a Mobil refueling station, which was conveniently located for when the research vehicles required refueling and would allow for the research vehicles to use consistent fuel for the entire study.

The potential location for data collection was presented to CRC and the RSD vendors and they all agreed that the location would be ideal for the study data collection. The route was driven repeatedly to determine average time to complete the loop (approximately 10 minutes) so including expected stops or breaks and estimated 50 runs could be completed per day.

Figure 1 - Route For Research Vehicles to Pass RSDs and Return



The test route is detailed on Google Maps (https://goo.gl/maps/bp8fBZjw7XRPEG2e6):

1. Start on S McClintock Drive at entrance to E 60
2. Turn Left onto E 60, as entering freeway, start gas flow
3. Transition – from E 60 to N 101 exit 176B – through test site
4. Turn off gas at top of ramp past remote sensors
5. Merge to the right to exit at W Broadway/Apache Blvd Road exit 53, be in the left lane
6. Turn left onto Broadway, keep left, turn left onto S 101
7. If refueling or a bathroom break is needed, exit in the second from the left lane, move to the right after turning, go to Mobil just through light, return to freeway
8. Keep right and transition to W 60 exit 55A-B
9. Keep right, exit S McClintock Drive, be in the left lane
10. Enter the left-hand turn lane to entrance to E60 again

The three RSDs were to be located as close as possible to each other to attempt to measure vehicles in as close to the same condition as possible. The HEAT RSD is mounted on a trailer which is 16 feet long with the instrument located on a boom coming up from the center of the trailer. The DU RSD is operated from a class-C recreational vehicle (“the Winnie”), which takes up significant space. The power for the instrument IR source was from a generator (installed on the far side of the road from the RSDs). It was decided the DU RSD should be the last RSD in line, allowing any emissions from the generator to be pushed away from the test site. With these considerations, it was decided that the Opus RSDs would be located first after the curve at one end of the HEAT trailer, and the DU RSD after the HEAT trailer as shown in Figure 2.

Figure 2 - RSD Locations On Interior of Interchange

Another significant advantage to the chosen site was that the Gordon-Darby vehicle inspection site M6[5] is located approximately five miles from the test location. The site was used extensively during the study for preparation of the vehicles for on-road data collection, vehicle testing, storage and staging of auxiliary equipment. Gordon-Darby allowed the use of their IM pressure decay test systems[6] which were used to ensure the integrity of the research vehicles evaporative emissions control systems prior to passing the RSDs. The facility was used to configure the two research vehicles with the simulated leak equipment and to prepare the vehicles for induced leaks, install the PEMS units in the vehicles, and prepare the electric vehicle to release gas from two gas cylinders via a simulated tailpipe to simulate vehicle exhaust. Gordon-Darby also allowed us to use their constant volume sampling system (part of their IM-147 testing equipment used to perform emissions tests on public vehicles) to determine the pressure at which the simulated exhaust gas should be set so the flow rate simulated vehicle exhaust.

[5] Gordon-Darby AZ State Vehicle Inspection Facility M6, 4949 E Madison St, Phoenix, AZ 85034

[6] These are IM240 (EPA420-R-00-007, §85.2227) compliant vehicle evaporative system integrity test systems

3.3 Research Vehicles

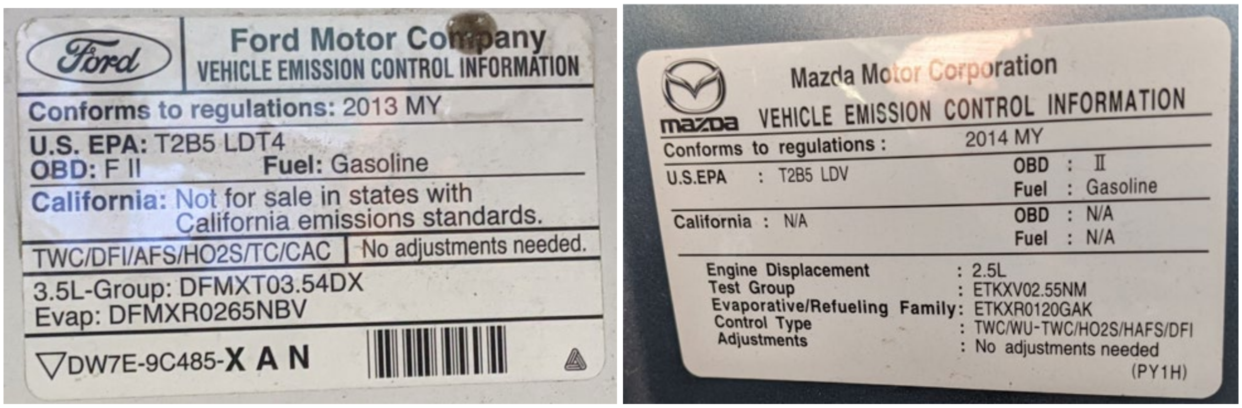
Two vehicles were needed for the study to be driven past the RSDs with simulated evaporative leaks and with some components in the evaporative emissions control system disconnected to simulate actual evaporative leaks. Considerations in choosing the vehicles included the difficultly in accessing the vehicle canister, difficulty in disconnecting the canister (clamps, line types, etc.), location and access to the fuel sending unit, as well as the vehicle physical layout to accommodate installation of the PEMS – for instance, the inclusion of a trailer hitch was desirable to mount the PEMS exhaust collection system and the vehicle had to have enough space in the trunk and backseat to accommodate the PEMS. Vehicles of different shapes and heights which would influence the mixing of the leaked evap emissions were also desired. In addition, slightly older direct injection vehicles with higher than current technology PM emissions were desired so measurement of PM by the RSDs could be evaluated.

CRC chose to use two vehicles which were part of previous CRC studies. One was a mid-sized sedan which could accommodate the PEMS, and second vehicle was a pickup truck. Because of the previous test programs these vehicles participated in, their emission rates were well characterized. Both were certified to the Tier 2, Bin 5 (Picture 5), 10 mg PM standard, so their PM emissions would be significantly higher than a well-functioning current technology (2021) production vehicle. The vehicles were:

- 2014 Mazda6 (JM1GJ1U50E1113049) – odometer was 15,667, certified at 1.4 mg/mi PM
- 2013 Ford F-150 (1FTNF1CT9DKE35075) – odometer was 9,923, certified at 5.7 mg/mi PM

Picture 4 - Research Vehicles

Picture 5 - Research vehicle Emissions Control Information Labels



The research vehicles were shipped from Southwest Research Institute to the ETC lab in Grass Lake MI. After the required modifications were completed (described below), the research vehicles were shipped to Arizona and leak checked using the pressure decay method as described in the IM240 guidance document[7] for IM evaporative emissions systems tests (fuel inlet pressure test) with the fuel at ambient temperature using pressure test equipment Gordon-Darby currently uses in their IM240 test lanes. No decay in pressure was observed indicating the systems had no leaks.

3.4 Implanted Vehicle Leaks and Data Collected

CRC, in conjunction with input from evaporative emissions control systems experts at USCAR, chose representative leak locations to be simulated during the study and what leak rates should be used to simulate a failed evaporative emissions control system. Several alternative methods to simulate evaporative system leaks were discussed and what data should be collected with the various simulations. Simulating the leaks required some modifications to the research vehicles, development of leak simulation hardware and techniques for collection of additional data on the test conditions. The vehicle configurations and the reasoning for the chosen methodologies are described below.

3.4.1 Leak Locations

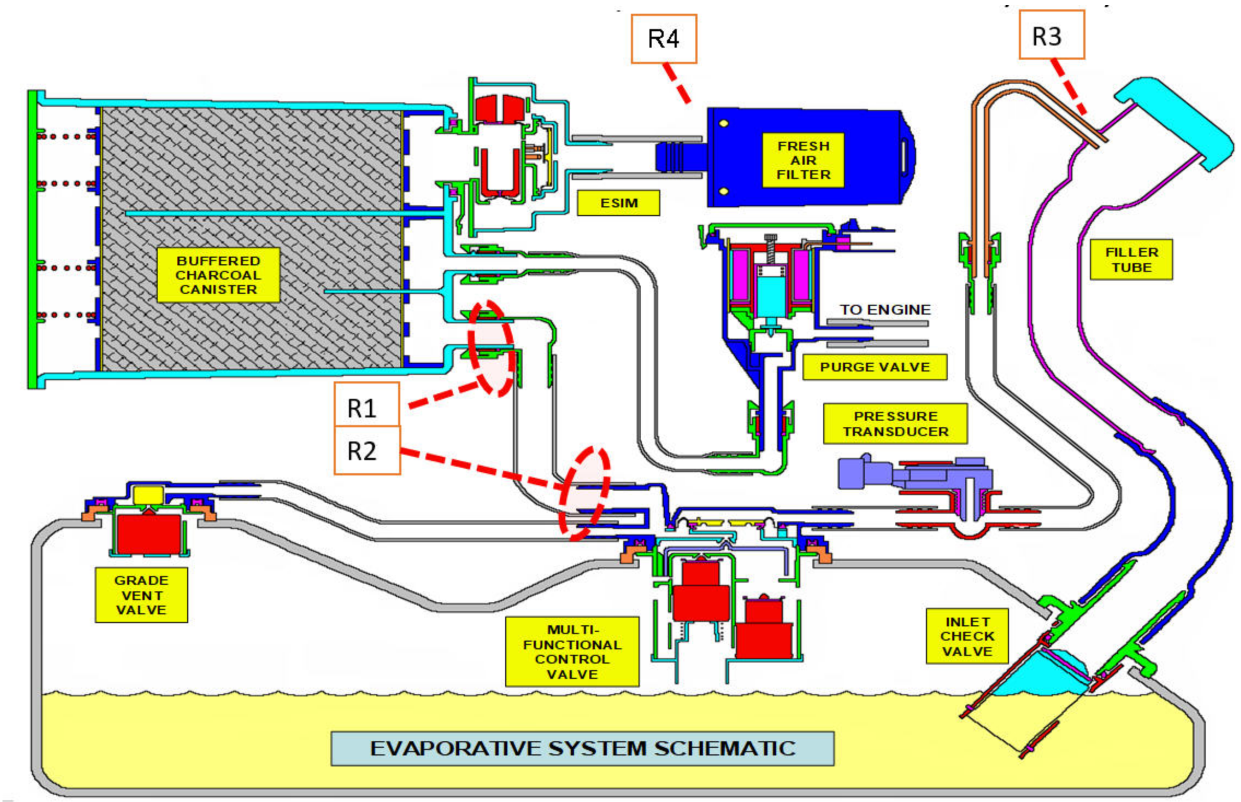
CRC and USCAR chose leak locations to be simulated which represented common failure modes. There were five cases simulated:

1. Properly functioning (no leaks or "blanks")
2. Vapor line from fuel tank to canister disconnected at the canister (R1)
3. Vapor line from fuel tank to canister disconnected at the fuel tank (R2)
4. Fuel cap off (R3)
5. Simulated purge valve failure, canister overflows fuel vapors out of the vent (R4), however this was simulated at the purge valve (since the canister was never saturated)

The locations of each are shown in the evaporative system diagram below (Figure 3).

[7] IM240 & Evap Technical Guidance, US EPA, April 20\00, EPA420-R-00-007, §85.2222.

Figure 3 - Evaporative System Diagram With Leak Locations Indicated



3.4.2 Leak Rates and Hydrocarbons to Leak

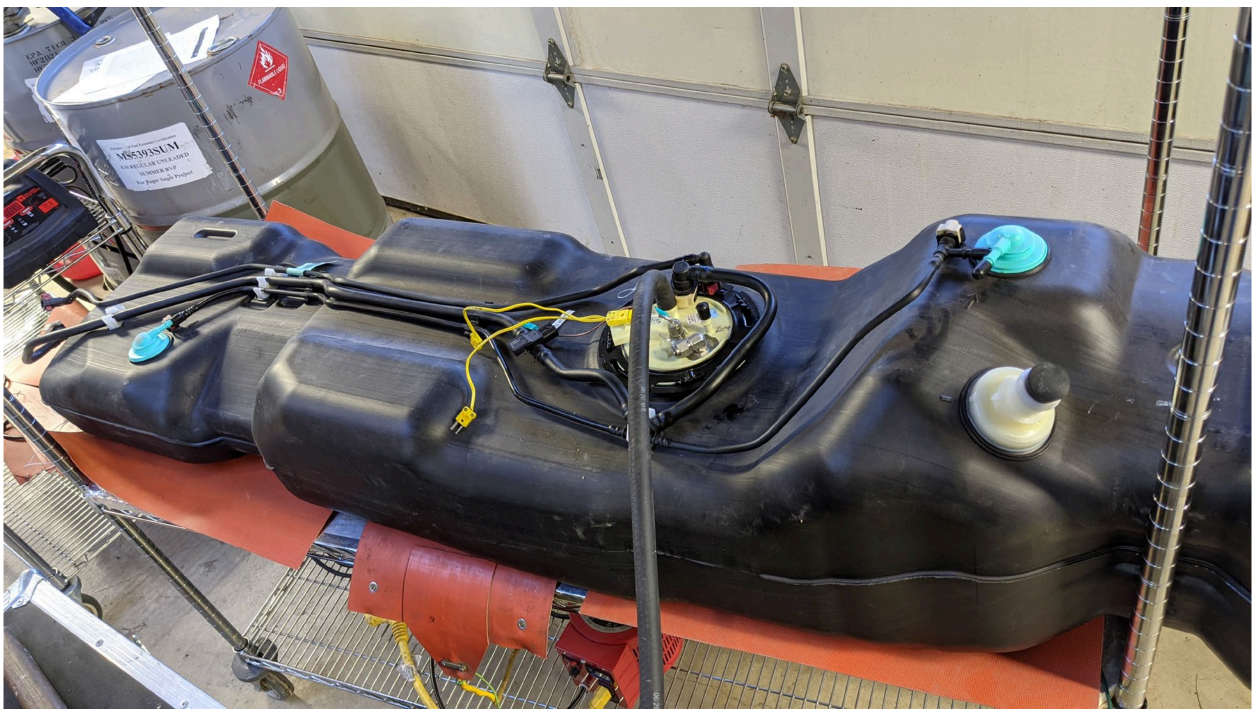
CRC, in conjunction with USCAR and with some input from US EPA, discussed representative evaporative leak rates and representative hydrocarbons to leak. EPA noted that evaporative measurements by RSDs generally improve in accuracy the slower the vehicle speed. This is because for a given leak rate of hydrocarbon (for example 1 gram per minute), at a slow speed there is less air passing the vehicle to dilute the mass of hydrocarbons released, therefore the concentration is higher the slower the vehicle speed. EPA indicated that a commonly used speed for their previous experiments was 25 mph. RSDs which are set up in I&M programs typically are positioned at locations with higher vehicle volumes, and to achieve these higher volumes, the measurements are taken at locations with higher vehicle speeds such at freeway on or off ramps, larger arterial roads or transitions between highways, etc. The RSD vendors indicated the common speeds for their measurements were in the range of 35 to 45 mph. After further discussion, CRC decided that the study would attempt to take measurements over a range of speeds from 25 to 45 mph, with varying simulated leak rates. This would add to the robustness of the data and allow a comparison of measurements between the RSDs at various conditions.

For the hydrocarbon to be measured, the initial plan was to simply disconnect the evaporative emissions control system at the chosen locations and let naturally forming vapors leak from the vehicles. However, it was decided that this was not controlled enough, and it was desired by CRC to know the mass of hydrocarbons leaking from the vehicle, so when combined with the known speed and approximation of the mass emission rate of hydrocarbons the RSDs should have reported could be calculated. Revecorp and ETS proposed heating fuel using various techniques or bubbling nitrogen through the fuel in the tank to achieve a mass of fuel vapor and then controlling the flow, however this was still not considered accurate enough (and raised potential safety concerns) because the mixture of hydrocarbons would still not be known. CRC and USCAR agreed that most of the hydrocarbons which leak from a vehicle are generally butane, and if the goal is to determine if the RSDs can measure a hydrocarbon from locations other than the tailpipe, then using butane, released at controlled flow rates would be the most accurate, repeatable method to simulate evaporative emissions.

The next issue was to determine the representative flow rate of evaporative vapors over the course of expected fuel tank temperatures. The US vehicle manufacturers use a fixed route, referred to as the Davis Dam drive profile, which represents accelerating from a stop to 55 mph, and maintaining 55 mph up a constant 5% grade in a hot ambient environment. In this experiment, the vehicle manufactures can get the fuel to warm. The experiment is done with 9 psi RVP fuel which warms to 120F (with no purge), and they measure the flow rate from the tank to help with sizing of the evaporative emissions control system components.

The committee decided the best way to determine the flow rate from a fuel tank when being heated was to conduct an experiment using a real fuel tank and heating it slowly while measuring the flow rate of the gas generated. The fuel tank from the F-150 research vehicle was removed and used as the test bed for the experiment. The ports on the tank were closed with the exception of one to allow generated fuel vapor to exit (Picture 6). The tank was instrumented with thermocouples to allow for measurement of the liquid fuel temperature and the fuel vapor temperature, and with a flow meter on the line exiting the tank to measure the fuel vapor flow rate as a function of temperature. Stellantis (Fiat Chrysler Automobiles at the time) provided two drums of EPA Tier 3 EEE Certification Emissions Fuel[8] with an RVP of 9 psi and E10 (10% ethanol).

Picture 6 - Fuel Tank for Flow Experiment from F-150, All Ports Closed, Instrumented with Thermocouples Through Sender Unit



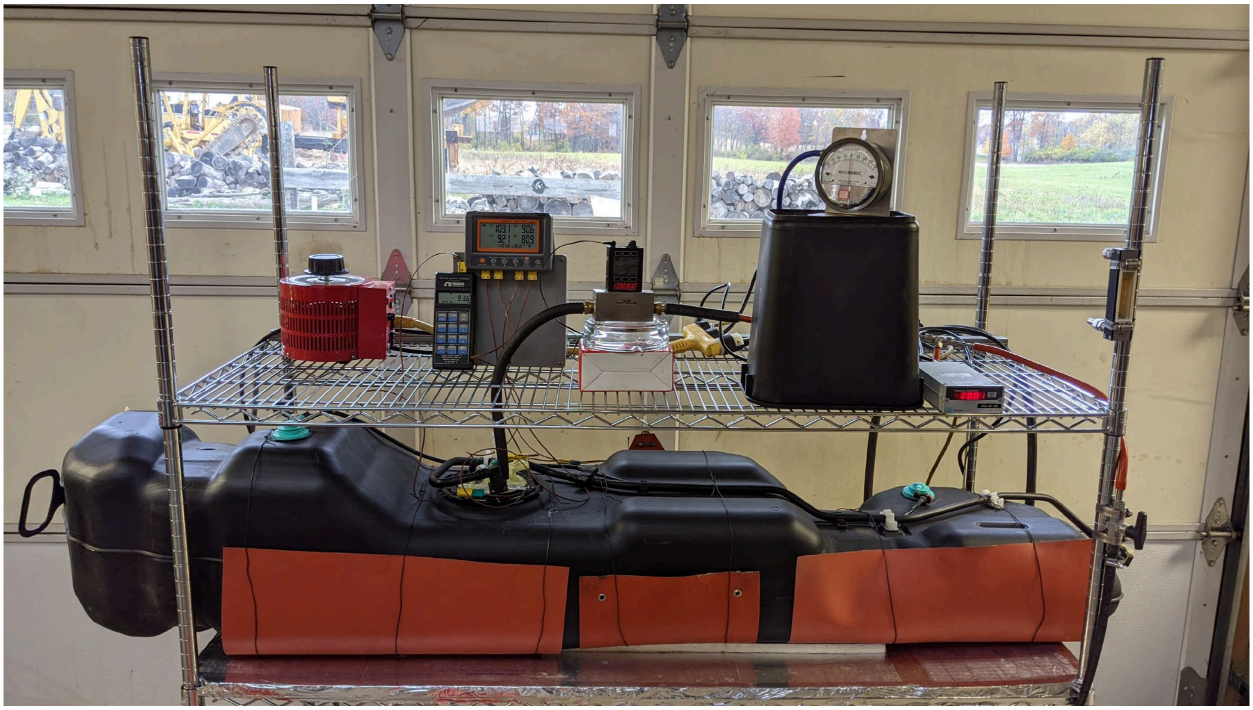
The fuel tank was installed on a metal rack on top of three heating elements to allow the temperature to be raised. Thermocouples were installed between each of the three heating pads and the fuel tank to monitor their temperature to ensure the heating pads did not get hot enough to melt the plastic fuel tank. A Variac was used to control the current through the heating pads. The flow was measured using a Alicat[9] flow meter which was calibrated for butane. A pressure transducer was also installed in line as a safety measure to ensure pressure was not generated in the fuel tank while it was heated. Because of the cold ambient conditions at the time of the experiment, the fuel was condensing in the output line, so backpressure from the line getting filled

[8] https://www.haltermannsolutions.com/products?id=128401&category_id=124000

[9] Model M-250SLPM-D-1/5M, Serial number 131000 calibrated by and provided by Stellantis

with liquid was also a concern. The entire configuration can be seen in Picture 7.

Picture 7 - Fuel Tank on Rack For Flow Experiment



During the experiment the fuel tank was wrapped in a blanket to keep the temperature around the tank constant (simulating an on-road environment), and the entire setup, which was installed on a metal rack on wheels, was gently moved back and forth every five minutes to ensure good mixing and constant heat distribution through the fuel as it would in an actual vehicle on-road in use.

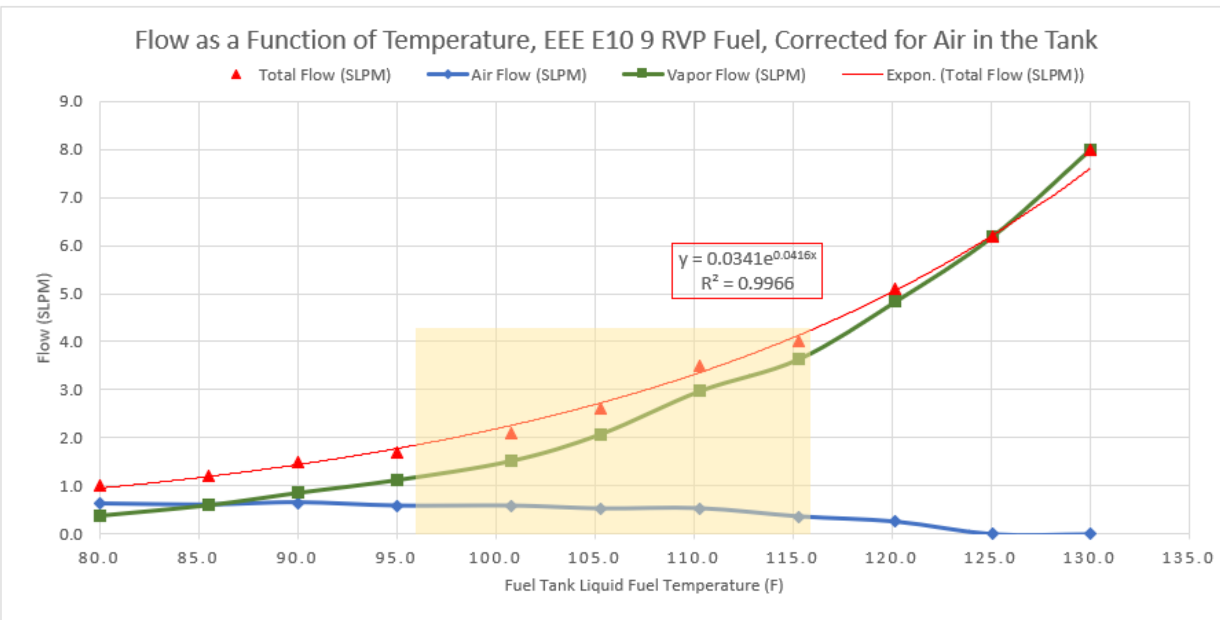
The tank was flushed twice with the test fuel prior to the experiment. The tank volume was 26 gallons, the experiment was to be done with the tank 40% full (as in certification), so 10.4 gallons of test fuel were used for the experiment (measured by weight). The density of the fuel was 6.037 pounds per gallon, so 63.2 pounds of fuel were added to the tank to achieve the 40% fill. The fuel was brought to 80 degrees F using the heating elements to start the test. A test run varying the fuel from 80 to 130 degrees F was performed on October 25th 2020 to ensure that the measurement equipment was working properly. The next day, with representatives from CRC present, the tank was again flushed twice, refilled and the actual experiment was conducted. The experiment started at 8:47 am with the fuel at 80 degrees F. The temperature was slowly raised by increasing the current through the heating elements using the Variac. The flow rate and temperature were logged at approximately 5-degree increments in fuel temperature from 80 to 130 degrees F until 12:31 PM.

From discussions with the USCAR staff, they indicated that the results should compensate for the air which will be in the tank at the start, and only account for the fuel vapor which is released. USCAR had previously done experiments looking at this effect and supplied data to allow for the correction of the fuel vapor flow rate data to account for the air versus fuel flow. The data collected are given in Table 1 below and plotted in Figure 4 below showing the total observed flow rate as a function of the liquid fuel temperature (in red), with an exponential curve fit to the data. The coefficient of determination (r^2) for the experimental data was 0.996. The adjustments for the mass air / fuel ratio in the tank are shown in Table 1 below and are represented in blue in the plot. The adjust flow rate from the tank after the mass of air in the tank was removed are shown in green representing the mass flow rate of fuel vapor.

Table 1 - Flow (SLPM) Versus Temperature (°F) From Flow Experiment

CRC RW-105 Fuel Tank Temperature Verus Flow Experiment						
Measurements				Adjustment for Air / Fuel In The Tank		
Time	Vapor Temp (F)	Liquid Fuel Temp (F)	Total Flow (SLPM)	Mass Air / Fuel Ratio	Air Flow (SLPM)	Vapor Flow (SLPM)
8:47	78.7	80.0	1.0	0.62	0.62	0.4
9:25	80.8	85.5	1.2	0.50	0.60	0.6
9:41	85.8	90.0	1.5	0.43	0.65	0.9
10.02	96.0	95.0	1.7	0.34	0.58	1.1
10:24	100.4	100.8	2.1	0.28	0.58	1.5
10:42	100.4	105.3	2.6	0.20	0.52	2.1
11:01	104.8	110.3	3.5	0.15	0.53	3.0
11:18	109.2	115.3	4.0	0.09	0.36	3.6
11:38	114.4	120.2	5.1	0.05	0.26	4.8
12:01	120.0	125.1	6.2	0.00	0.00	6.2
12:31	125.0	130.0	8.0	0.00	0.00	8.0

Figure 4 - Flow (SLPM) Versus Temperature (°F) For Flow Experiment Showing Correction for Air and Resulting Fuel Vapor Flow (Green Squares)



CRC indicated that the maximum temperature of the fuel in the tank on-road would most likely not exceed 117 degrees F. Based on this upper limit, the maximum flow rate to be tested was set to 4 LPM. The committee discussed performing experiments at a single flow rate or various flow rates to increase the representativeness of the results. It was decided that the flow rates to be used would be 1.0, 2.5 and 4.0 LPM covering the range of temperatures which are of concern on-road (shown in the shaded area in the plot). These flow rates were combined with a mixture of speeds (25, 35 and 45 MPH) allowing for 9 overall evaporative leak cases to be simulated. Each combination of speed and flow rate was to be simulated from each of the four leak locations leading to a total of 45 total leak scenarios to be performed (included blanks) for each of the two research vehicles.

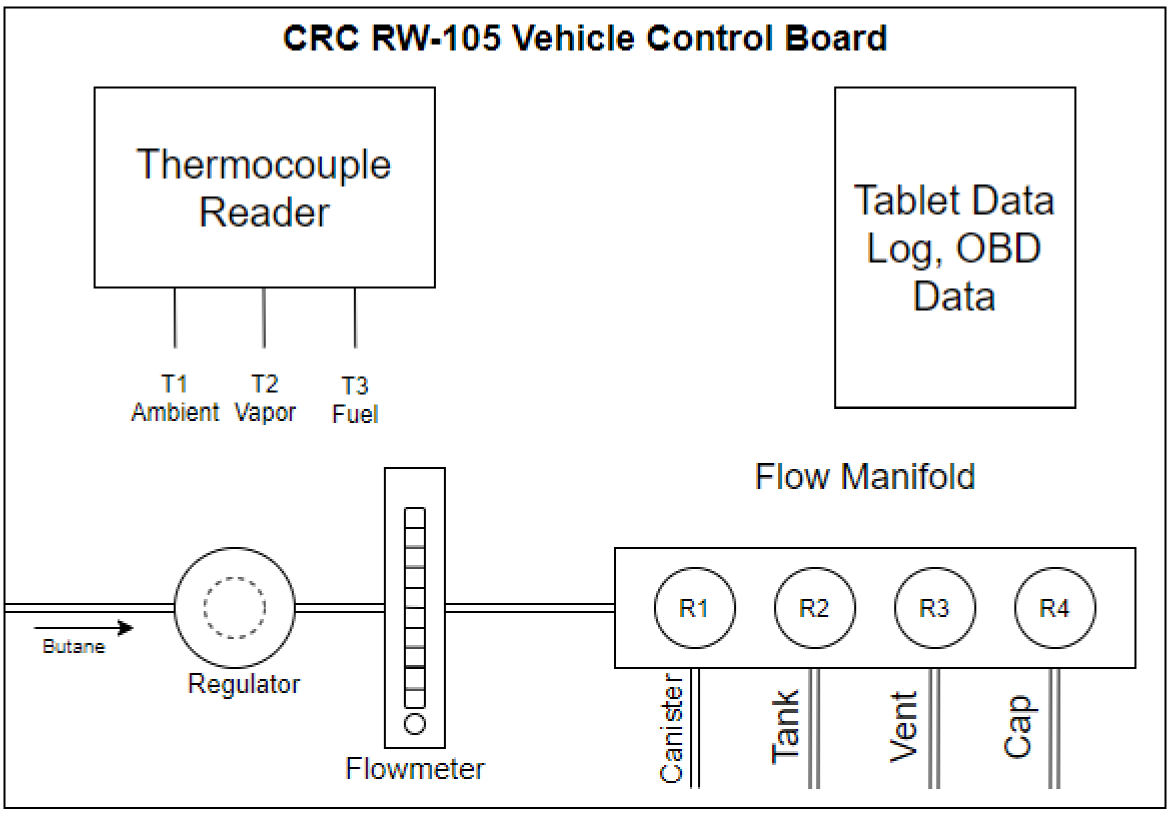
Therefore, for simulated evaporative leaks, the matrix of tests was:

- Two vehicles (the Ford F-150 truck and the Mazda6)
- Three speeds (25, 35 and 45 MPH)
- Three leak rates (1.0, 2.5 and 4.0 LPM)
- Four leak locations and blanks

3.4.3 Simulating Leaks and Data Collection

To allow a vehicle operator to control the release of butane to simulate leaks at various flow rates from four locations, a control system was developed. Butane was provided in a 20-pound cylinder which was placed on the floor in front of the passenger seat. This allowed for the vehicle heat to be turned on to the floor of the vehicle to heat the cylinder slightly to ensure the butane was volatizing from a liquid to a gas fast enough to supply the desired flow rate needed for the experiment. The butane was connected to a Masterflex variable-area flow meter (EW-32003-12) with a range of zero to 5 LPM and a flow controller at the input. The output was connected to a manifold which had valves allowing the driver to turn on and off the flow to each of the four leak locations on the vehicle. The layout of the control board is shown in Figure 5 below:

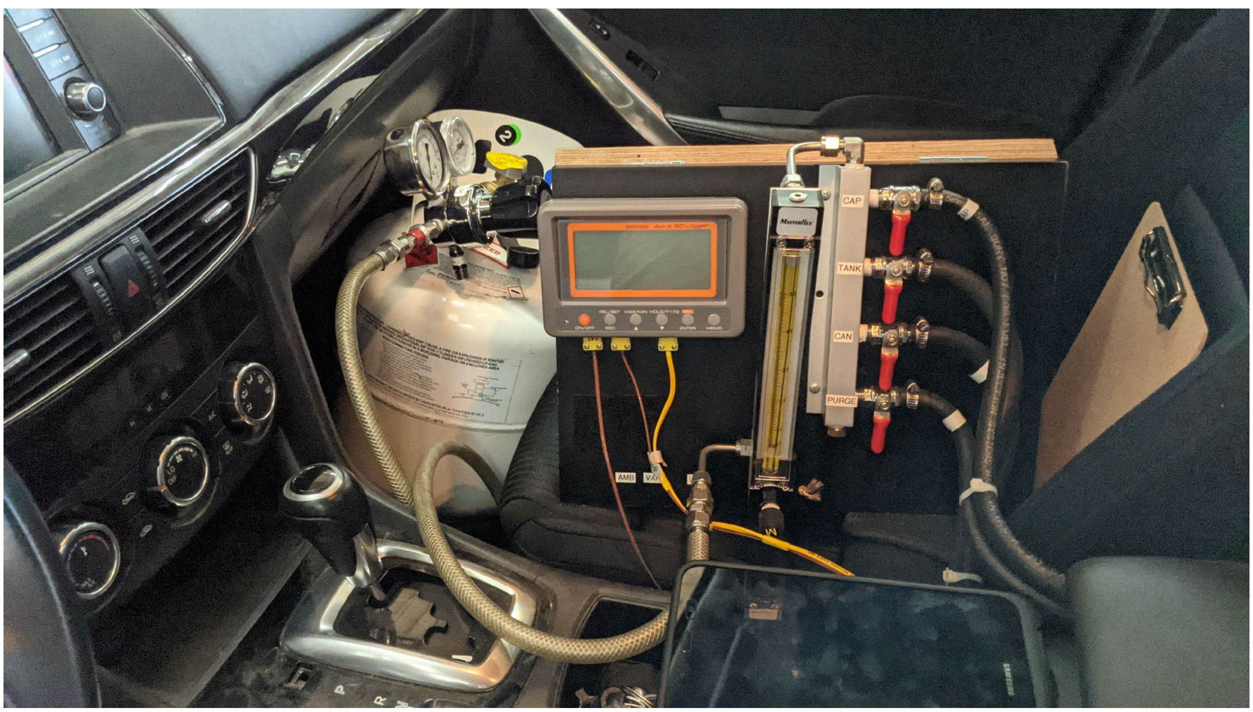
Figure 5 - Driver Simulated Evaporative Emissions Release Control Board Layout



A control board was constructed for each of the research vehicle and placed on the passenger seat shown in Picture 8 and Picture 9 below. During the experiments, a tablet (shown on the center console in the pictures) was used with a ScanTool.Net OBDLink MX scan tool connected to the OBD port of the vehicles to log the amount of purge which was commanded by the engine as well as other vehicle operating parameters such as throttle position. The ScanTool.Net software allows for configurable data logging, with time stamps which allowed the vehicle parameters at the time of passing the RSDs to be identified.

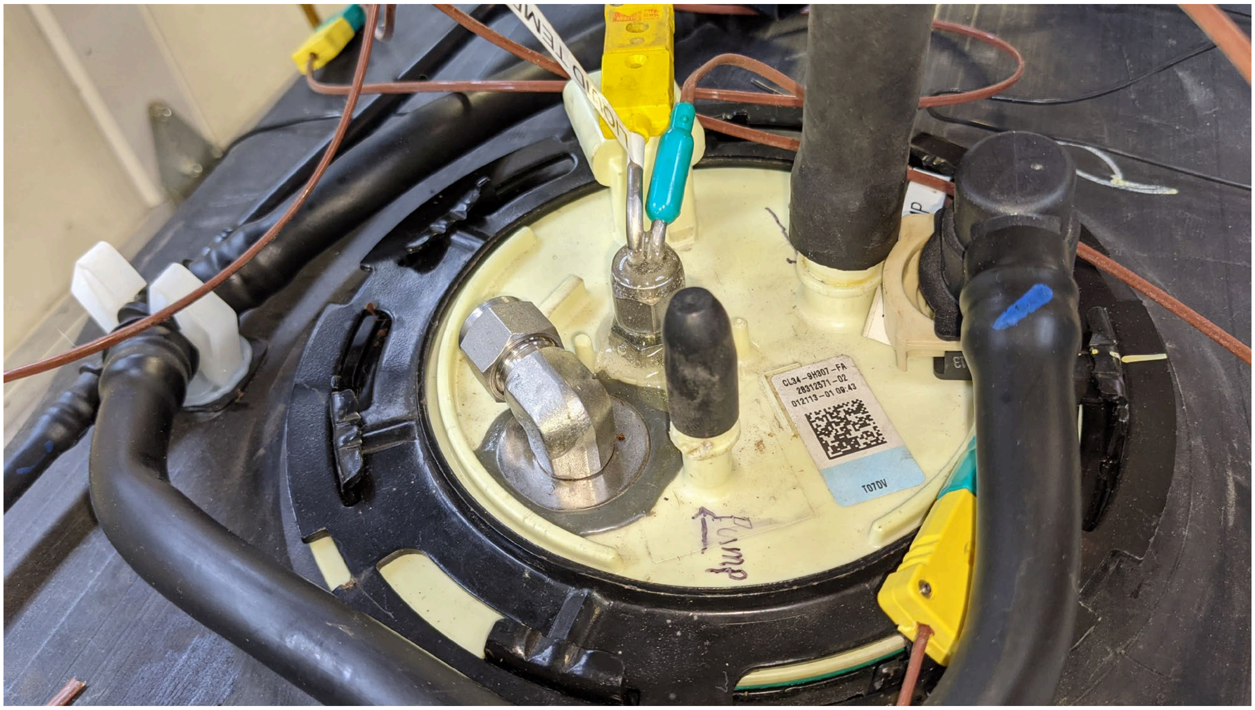
Picture 8 - Control Board in F-150, Butane Tank Not Installed

Picture 9 - Control Board in Mazda6 with Butane Tank



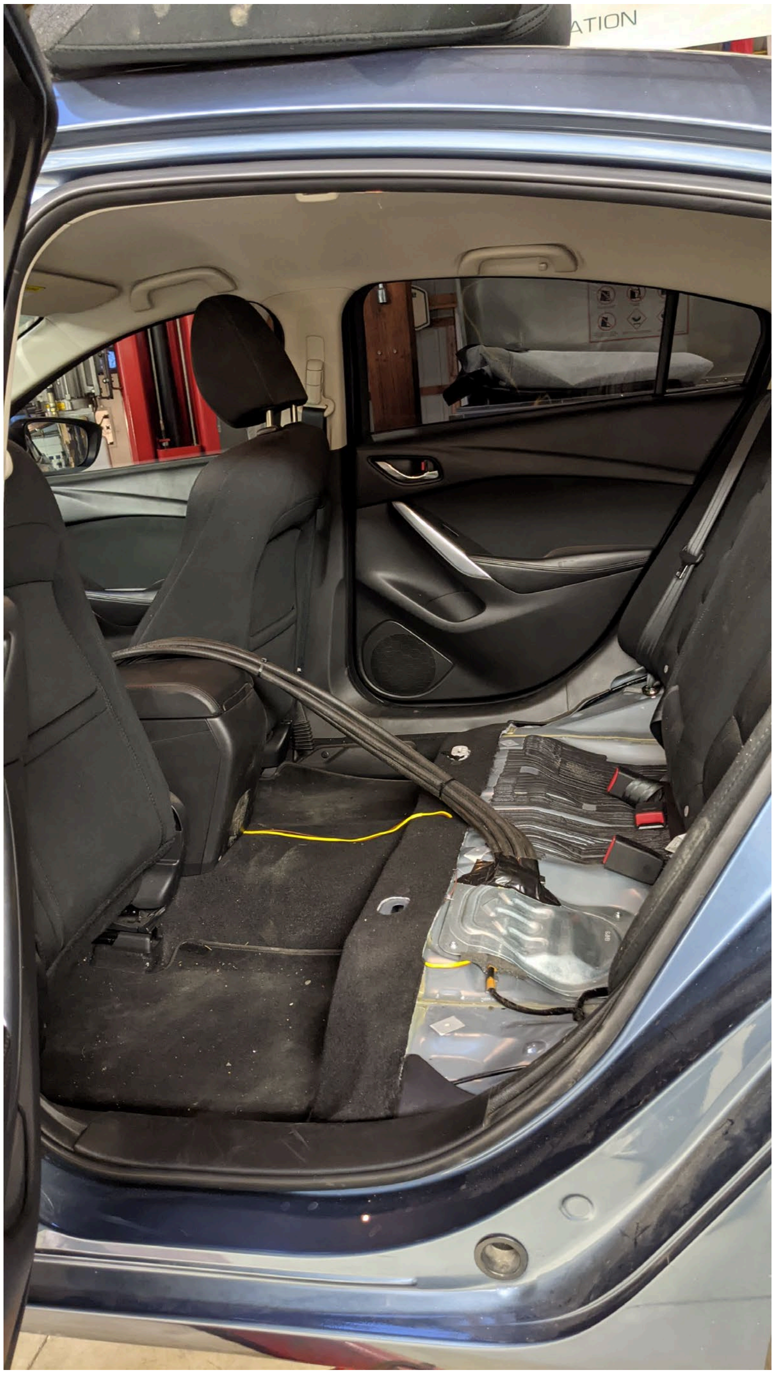
The control board also had a thermocouple reader installed do display the temperatures of the fuel vapor in the tank, the liquid fuel in the tank and the ambient temperature. For both the F-150 and the Mazda6, the fuel sender units were modified by installing a fitting through the sender unit, and then installing thermocouples which reached to the bottom of the tank without touching it to measure liquid fuel temperature and into the top of the tank to measure fuel vapor temperature (Picture 10). The ambient temperature was measured with a thermocouple mounted on the roof of the vehicles in a plastic cage to protect it from direct wind.

Picture 10 - Modified Fuel Sender Unit with Thermocouples Installed



3/8" evaporative emissions control system hose was routed from the control board to the four leak locations on the vehicle with the end of the hose at the leak location left open. The hoses were routed through an opening covered by a plate under the back seat in the Mazda6 (Picture 11), and through rubber knockouts in the front and back of the cab of the F-150 to the appropriate locations. The ends of the hoses were attached in place using zip ties to prevent their movement.

Picture 11 - Hoses to Distribute Butane for Simulate Evaporative Leaks



3.4.4 Actual Disconnected Evaporative System Leaks

For experiments with actual evaporative leaks, leaks were caused by disconnecting components at three locations:

- Removing the load line from the tank to the canister at the canister
- Opening the purge line from the canister at the purge valve
- Removing the fuel cap

An actual leak on top of the fuel tank, such as by loosening the fuel sender unit, was not performed as it was considered too dangerous due to the potential for fuel to slosh out of the tank near potential ignition sources. The physical disconnections were done on-road in the parking lot of a Mobil gas station at the north end of the route (Picture 12).

Picture 12 - Purge Leak Being Implanted at Mobil Gas Station in Mazda6

The actual leaks were implanted in the order noted above. Six runs in each condition (two each at 25, 35 and 45 mph) were conducted with the vehicle operating on the fuel which it had in the tank from the prior day. After collecting the first 18 data points, regular fuel from the Mobil brand gas station was added to the fuel tank to return it to 40% full. After fueling, another six runs in each condition were conducted.

The F-150 fuel system was a capless design, so it was not possible to remove the fuel cap for the experiments. Instead, a funnel which is supplied with the truck and opens the interior seals in the filler neck was installed. This had the same effect of opening the system to the atmosphere and allowing fuel vapors to leak.

There was concern that if the purge line was simply disconnected on top of the engine the open end of the purge valve could still pull in the fuel vapors leaked from the purge line. There was also a concern that if the purge line were disconnected from the purge valve, the On-Board Diagnostic system would sense a leak, turn on the check engine light and cause the emissions control system to operate differently. For this reason, a "T" was installed in the purge line from the canister to the purge valve which allowed the canister to be vented to atmosphere. A second purge valve was installed so the electronic connection to the factory purge valve could be removed, preventing a vacuum to the engine (Picture 13). The electrical connection was moved from the factory purge valve to the secondary purge valve to allow a purge valve to operate and preventing the setting of a diagnostic trouble code. Therefore, for the runs with the canister line to the purge valve disconnected, the three-way valve was turned, and the electrical connector was moved from the factory purge valve to the secondary purge valve and replaced back to the original condition after the six runs.

Picture 13 - Mazda6 With Second Purge Valve and "T" Installed in Purge Line

3.5 Fuels and Gases Used For Experiments

3.5.1 Butane Used for Simulated Evaporative Releases

Two 20-pound cylinders of 99.8% butane were purchased from Ann Arbor Welding Supply for use as the gas simulating the evaporative leaks. The tanks can be used for both liquid and gas delivery, however they were fitted to only deliver gas which necessitated making sure the tank was warm enough to produce enough gaseous butane from the liquid as it was released to simulate the evaporative leaks. For this reason, the tanks were installed at the floor in the front seat so that the floor heater could be turned on to heat the tank if the flow rate dropped. During the experiments, since the ambient temperature was approximately 70 degrees F when we started the experiments each day and the gas was only flowed for short periods of time, the generation of butane gas without heating was sufficient.

3.5.2 Fuel Used For Research Vehicles

Local AZ market fuel was used by the two research vehicles (the F-150 and Mazda6). Vehicles were refilled at the end of each testing each day a local Mobil brand gas station located at 2180 E Broadway Rd, Tempe, AZ 85282. The exception of the day before the actual evaporative emissions tests were conducted, the vehicles were not refueled at the end of that day. The local fuel was "Phoenix April Fuel" which as per regulation had an RVP of 10 psi.

3.6 PEMS Use and PM Emissions

3.6.1 PEMS Equipment

Real-time on-board emissions data was collected from both research vehicles with a Portable Emissions Monitoring System (PEMS) owned and operated by SGS. The PEMS was an AVL PEMS 493/494 which together measured CO, CO2, NO, NO2, THC and PM. The PEMS also collected position data via GPS which allowed the alignment of the emissions measurements to the point in time the vehicle was passing the RSDs.

The PEMS gaseous analyzers unit and flow meter received their annual calibration at AVL several months prior to the study and had monthly linearity verifications according to the CFR. The gas analyzers also received a zero/span adjustment before every set of on-road data collection during the study. The gas analyzer calibrations were performed using two calibration gases:

- A quad mixture of CO/CO2/NO/Propane. Propane is measured/reported as C1
- NO2

CO2 and CO were measured via Non-Dispersive Infrared (NDIR) spectroscopy. NO and NO2 were measured using UV. Hydrocarbon emissions were measured using a Flame Ionization Detector (FID). The reported values were calculated from the total hydrocarbon measurements (THC) using 0.98*THC based on the method in the CFR. The THC analyzer is only a single FID and therefore did not speciate out methane to determine non-methane hydrocarbons.

PM was measured with a microsoot analyzer which had linearity checks every month for the microphone and laser, and also is calibrated annually by AVL against their soot standard instrument. The flow measurement for the PEMs was accomplished using an AVL 495 flowmeter that uses a pitot tube to calculate exhaust flow.

The PEMS emissions values are reported in grams of pollutant per kg of fuel consumed from carbon balance using the EPA calculation method. This is not the same as the units which are used by all the RSDs which makes direct comparison more complex.

3.6.2 PEMS Measurements

SGS arrived Saturday April 10th and on Sunday installed the PEMS in the F-150, calibrated the system and reviewed the calibration data with the CRC staff on site for approval to start testing. After completion of data collection from the F-150, the PEMS was removed and installed in the Mazda6, calibrated again and the data provided to CRC for approval.

There was a concern that the PM emissions of new technology DI vehicles would be near or below the detection limits of the PEMS and RSDs since the research vehicles were operating properly. This would not allow the experiment to determine if the RSDs could identify a current technology "slightly broken" gasoline powered direct injection vehicle. The research vehicles were model year 2013 and 2014 which were certified to a 10 mg/mi standard, and had PM emissions, as measured in prior CRC studies of 5.7 and 1.4 mg/mi. Since these are significantly above current vehicle PM standards, they could be considered a "slightly broken" new vehicle, therefore evaluating the capabilities of the RSDs in the range desired.

Installation of the PEMS in the F-150 was easier since the PEMS analyzers, batteries, gases, etc. could be placed in the bed of the vehicle (Picture 14). A luggage carrier was installed in the trailer hitch to hold the exhaust sampling and flow measurement system and to protect it from traffic in case of an accident (Picture 15). The full configuration is shown in Picture 16. The testing started on April 12th at 9:00 am until noon when the F-150 quit running and would not start again. At this point the vehicle had passed the RSDs 9 times (the goal was 25). The team had the vehicle towed to the Gordon-Darby inspection facility, diagnosed the problem (a fuel pump controller), got the part from a local Ford dealership and got the vehicle back on the road. Testing resumed three hours later at 3:00 pm and continued until 5:00 pm, for a total of 17 passes of the RSDs that day. Because of the delay, 14 more PEMS runs were conducted on Tuesday April 13th for three hours in the morning to achieve a total of 31 measurements of the F-150 tailpipe emissions with the PEMS. The remainder of the day was used to retrieve the data from the PEMS and ensure it was okay before removing the PEMS from the F-150.

Picture 14 - F-150 with PEMS in Bed

Picture 15 - Exhaust Sampling and Flow Measurement For F-150 PEMS

Picture 16 - F-150 with PEMS Installed Ready for Data Collection

On Wednesday April 14th, the PEMS was removed from the F-150 and installed in the Mazda6. Because of the size and weight of the PEMS analyzers and ancillary equipment, the back seat of the Mazda6 was removed, and a platform was constructed to support the equipment (Picture 17). The vehicle has dual exhausts, so the sampling system had to be modified to keep the exhaust from the vehicle exiting at the side of the vehicle near where the RSDs are designed to measure exhaust, but higher than a typical exhaust (Picture 18). A local shop was used to cut and reweld the stainless tubing to get the exhaust to exit at the side of the vehicle as shown in Picture 19. The PEMS calibration was checked again, and then four runs were achieved before the end of the testing day to ensure the system was working properly. On Tuesday April 15th, another 21 runs were conducted for a total of 25 measurements passing the RSDs while also measuring the exhaust with the PEMS. The evening of April 15th the data was retrieved and checked for the Mazda6 and then the PEMS was removed that evening.

Picture 17 - Mazda6 with PEMS Analyzers Installed in Backseat

Picture 18 - Mazda6 with PEMS Sampling System Being Installed

Picture 19 - Mazda6 with PEMS Installed Ready for Data Collection

3.7 Remote Sensing Devices (RSDs)

The RSDs from Opus, HEAT and DU were set up on the inside (left) of the curve on the freeway interchange. Each of the vendors obtained permits from AZ DOT which had specific requirements for orange highway signage and cones which can be seen in Picture 20, Picture 21 and Picture 22 below.

Picture 20 - Approach to RSDs

Picture 21 - Opus RSD Setup, HEAT EDAR Sensor Seen Above the Road

Picture 22 - HEAT Trailer front, and DU RSD and Data Collection Van ("The Winnie")

A video was collected driving the route from the start on Interstate 60 to past the RSDs in the Chevy Bolt calibration gas vehicle from a motorists point of view (https://s3-revecorp-static.s3.us-west-2.amazonaws.com/CRC_RW105_Test_Route.mp4). The video shows the permanent 25 mph caution signs and lights when entering the offramp, the view a driver would see when they come out from under the overpass and see the cones, equipment, and staff right next to the lanes, and the incline of the ramp. The noise in the background when approaching the first RSD is the calibration gas flowing to simulate exhaust from the electric vehicle. As the vehicle drives over the HEAT retroreflector across the road, there is an audible "bump".

Because of the A pillar of the vehicle blocking some of the video on the left, it is difficult to see how close the equipment is set to the edge of the lane, including that some staff are sitting just a few feet from the edge of the lane. Note that motorists see signs indicating “Shoulder Closed Ahead”, but motorists are not expecting to come around the blind corner, on an interchange between two freeways and see all this equipment and staff sitting so close to the edge of the road. On several occasions motorists slowed down to ask what we were doing (”Are you filming a movie?”, etc.) and staff encouraged the motorists to keep moving as they were on a freeway and around a blind corner.

3.7.1 Overview of Remote Sensing Device Placement and Operation

Because the HEAT trailer is 16 feet long and the goal was to have the RSDs as close together as possible, the HEAT trailer was set up between the other two RSDs. This allowed the RSDs to initially be set up with approximately 9 feet between each. As noted, because the DU IR source needed power and was on the opposite side of the road from the RSDs, DU was last in the order so that wind from vehicles as they drove past the RSDs would pull the generator emissions away from the RSDs.

After the first day, Opus moved their RSDs further from the HEAT RSD (for reasons described below) so the distance from Opus to DU was approximately 18 and 23 feet. At 25 miles per hour, A vehicle passed from the Opus RSD to the DU RSD in 0.44 seconds on the first day and 0.66 seconds on the other days when the RSDs were further apart.

Both the Opus and DU RSDs use sealed cells to calibrate their instruments. However, because both Opus and DU release gas in front of their sensors to perform audits, there was a concern that this gas could travel into the path of other sensors, potentially causing errors in measurements. For the readings of the public vehicles passing the RSDs, only data where all three RSDs reported data was used in the analysis – and when an RSD was flowing calibration gas it did not report data – so measurements with interference should have been automatically excluded. For experiments using the PEMS, simulating evaporative leaks or actual evaporative leaks, driving a research vehicle past the RSDs was coordinated with the RSD operators via text to ensure they were not calibrating when experimental runs were conducted.

3.7.2 HEAT

The Hager Environmental & Atmospheric Technologies’ (HEAT) remote sensing technology is referred to as EDAR (Emissions Detection and Reporting). The EDAR sensor unit which includes measurement of emissions using infrared lasers and differential absorption light detection and ranging to measure the entire vehicle plume, vehicle speed, vehicle acceleration, license plate reader, and a weather sensor. The system is described in detail in HEATs report on the study[10]. The EDAR system collected vehicle emissions, entirely unmanned during operation, including CO, CO2, NO, NO2, HC (excluding methane – NMHC), speciated HC, and PM. Measurements of HC, NO, NO2, NOx and CO were all reported in ppm and CO2 was reported in percentage for the calibration measurements. Because NO and NO2 were measured separately, to calculate the mass of NOx emissions for comparison to the other RSDs in the analysis, the NO values were multiplied by 46/32 (to adjust or the difference in mass) and added to the NO2 emissions. For comparison to the PEMs measurements, NMHC, NO, NO2 and NOx were reported in g/kg of fuel.

The sensor system is mounted on a pole held over the road at 16 feet above the road surface (Pictures 24). For this experiment, the sensor system was mounted on a 16-foot-long portable trailer which allowed the sensor system to be deployed up and over the road. Placing the sensor over the road allows EDAR to measure the exhaust plume of a vehicle regardless of the location of

[10] J. Hager. March 2022. On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Spring 2021. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022. https://crcao.org/wp-content/uploads/2022/08/Arizona_2021_CRC_final.pdf

the exhaust pipe(s). The infrared lasers emitted above the road are scattered off a retroreflective tape installed on the road surface for this study), and the back-scattered light is then collected by EDAR. In a more permanent application, the retroreflector is embedded in a groove in the pavement. However, due to the short-term nature of this experiment, the retroreflector was applied to the road surface and a temporary small "ramp" approximately one inch high was built up on either side of the reflector to protect it from vehicle wheels damaging it (Picture 23). A side effect of the small rise on the road was that some larger vehicle trailers bounced as they went over the slight rise in the road. This caused vibrations which necessitated Opus to move further away from the EDAR sensor as described below.

Pictures 23 - HEAT EDAR System With Trailer Shown, Retroreflector on-road, Retroreflector

Pictures 24 - HEAT EDAR System, Retroreflector on-road and Opus Sensor Approximately 9 Feet Away (Day 1 Of Study)


The EDAR system had several differences compared to RSDs which measure across the road (DU and Opus) due to the methodology used:

- EDAR was operated in completely automated and unattended manner
- Due to its measurement technology EDAR does not require calibration
- The EDAR measurement method captures the entire vehicle plume allowing for calculation of the entire mass of pollutants released by vehicles (it could therefore report emissions rates in mass per unit travelled)
- EDAR measured both vehicles with low tailpipes and heavy-duty vehicles with high exhaust pipes since it was looking down on the road
- Because EDAR looks down on the vehicle it can identify the location of the emissions. This allows the system to identify the emissions exiting the tailpipe separately from emissions due to an evaporative hydrocarbon leak from a separate location.

3.7.3 Opus

Opus used two RSD5300 model remote sensors for the study. The Opus RSDs use horizontal dual beams of infrared (IR) and ultraviolet (UV) light projected from one side of the road to a corner cube mirror module on the other side of the road which returns the beam to the sensor. The system is described in detail in Opus' report on the study[11]. These systems have automatic checks on the alignment of the beams. If there is movement which would impact measurements, the operator is notified. The sensor is connected to a detector unit which processes the data and combines the emissions data with a picture of the vehicle license plate, vehicle speed and acceleration data. These units which contain the source, the detector and the audit setup are referred to as Sensor/Detector Units (SDMs). The two Opus RSD5300s were operated at 12 inches (which is traditionally used by Opus for remote sensing) and 18 inches off the ground to allow for comparison of the effectiveness of capturing evaporative emissions and tailpipe emissions at different heights. The comparison of the two RSDs was not part of this study and the analysis included in this report only used the data collected at 12 inches. Just prior to the RSDs were strips with a set of lights to measure vehicle speed and cameras to capture the vehicle license plate. The equipment setup is shown in Picture 25, Picture 26 and Picture 27.

Picture 25 - Two Opus RSDs (Near Left) two Retroreflectors (Across Road), and Two Speed Sensors (Bottom Right with Reflector Top Middle)

[11] R. Klausmeier, N Vesico. August 2022. On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Spring 2021. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022. https://crcao.org/wp-content/uploads/2022/08/E-119-3-Final-Report-OPUSv3.pdf

Picture 26 - Two Opus RSD Detection and Data Processing Units (On Table)

Picture 27 - Opus License Plate Camera Is In Large Orange Traffic Barrel Viewing Through The Hole And Second Camera Is Mounted On The Tripod Behind Bollard

The Opus RSDs measured and reported CO_2, CO, NO, NO_2, HC (as propane), PM (reported as UV opacity), and evaporative hydrocarbons. For this study, HC, NO_x and CO were all reported in ppm and CO_2 was reported in percentage. Evaporative hydrocarbons were reported in values of three unitless indices ("Opus Score", "ERG evaporative index 23" and "ERG Bin") which indicated the relative magnitude of the evaporative emissions. For many of the experiments, the Opus score was one or zero. During the analysis of the data, it was clear that the ERG index was best correlated to the actual evaporative emissions during the simulated evaporative emissions experiments and was used in comparisons in the analysis.

On the first day of the study, the closest RSD5300 remote sensor to the HEAT RSD was at 12 inches off the ground was approximately 9 feet from the center location of the HEAT RSD. As noted above, the HEAT RSD uses a retroreflector on the ground to reflect their measurement beam back up to the detector which in this application was raised approximately 1 inch. This caused empty truck trailers to "bounce" after going over the strip across the road. The bounce caused a vibration of the ground which caused the Opus RSDs to move slightly. As the Opus RSDs moved, the alignment of the beams across the road and returning moved slightly each time and eventually caused the systems to be unaligned. The Opus SDMs automatically report this to the on-site technicians who would realign the beams, but some measurements were lost during this time. Opus tried adding weight to the RSDs and other techniques to keep them from moving, however the vibrations still caused the RSDs to lose alignment. On the second and following days of the study, the Opus RSD 12 inches off the ground which was 9 feet from the HEAT trailer center was moved to be 18 feet prior to the HEAT RSD center and the second RSD5300 at 18 inches off the ground was 23 feet from the HEAT RSD.

3.7.4 Denver University FEAT

The University of Denver's Fuel Efficiency Automobile Test (FEAT) remote sensor has been used for over 30 years to measure vehicle emissions in various locations over time to study changes in vehicle tailpipe emissions. The instrument consists of a non-dispersive infrared (NDIR) spectrometer for detecting CO, CO2, and HC and twin dispersive ultraviolet (UV) spectrometers for measuring oxides of nitrogen (NO and NO2). The sources were positioned on the far (right) side of the road powered by a generator and focused across the road to the detector units (Picture 28). The system also includes a video capture system and a speed measurement system to identify the vehicle and its mode of operation when passing the RSD via a computer in the control vehicle (Picture 29).

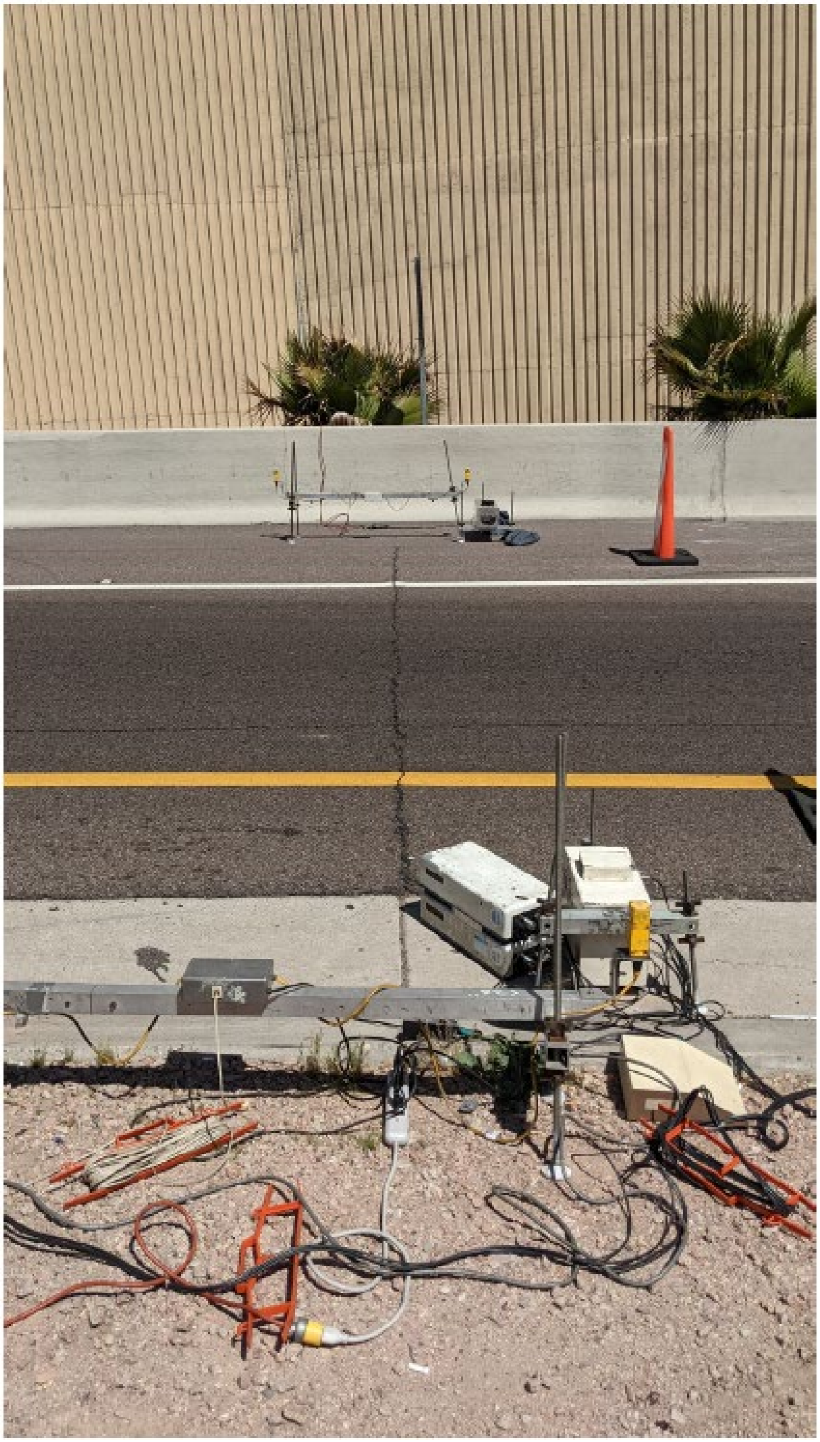
The DU FEAT measures pollutants as a molar ratio to CO2 and are therefore unitless. Those ratios can be converted to a molar percentage by making a number of assumptions as described in the Denver University report[12] on the study. The molar ratios are converted into grams of species/kilogram of fuel depending on the purpose of the data. For this study, HC, NO, NO2, NOx were all reported in ppm and CO and CO2 were reported in percentage. The DU HC measurements included methane, but the instrumental response to methane is limited so the reported HC concentrations are not equivalent to methane plus NMHC. HC concentrations were corrected for the instrument's different response to a HC mix rather than to the propane calibration standard and the data also include HC measurements that have been offset to better represent total HC.

FEAT reports PM as the percent IR opacity which is generally related to PM. It is the percent transmittance similar to tailpipe opacity which is measured with visible light. Since it is only measuring in the IR region, it does not measure oil smoke but does see black carbon.

FEAT evaporative measurements use a statistical technique developed by Eastern Research Group and the State of Colorado called running loss index version 23. The technique identified vehicles that exceed the Tier II evap running loss SHED standard of 3 grams of VOC's/15 minutes in terms of standard deviations from this value (values ranges from -3 to +3 in the DU data).

[12] Bishop, G. A. 2022. On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Spring 2021. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022. https://crcao.org/wp-content/uploads/2022/04/DU-Phoenix-2021-Final-report-v1.pdf

Picture 28 - DU FEAT RSD with Speed Measurement and Source For Emissions Measurements on Far Side, Detector and Video Capture in the Foreground



Picture 29 - DU FEAT Data Capture, License Plate Picture and Analysis Computer

3.8 RSD "Simulated Exhaust Calibration Vehicle" Setup and Use

Revecorp rented a 2017 Chevy Bolt electric vehicle to drive past the RSDs releasing one of two mixtures of gas designed to simulate vehicle exhaust. The concentrations of the gases chosen were from a set developed by the California Bureau of Automotive Repair that were used previously for evaluation of RSDs simulate a lower emitter and a medium emitter. All three RSD vendors and CRC agreed to the chosen simulated exhaust gas concentrations. The gas certifications are provided in Appendix 1 and the concentrations were:

Gases Used to Simulate Exhaust (Balance Nitrogen)				
Gas	NO ppm	Propane ppm	CO ppm	CO2 %
Low	249.8	255.2	498.7	14.93
High	773.2	756.4	15030	14.07

The vehicle was configured to carry the low and high gas cylinders in the passenger seat of the vehicle. For safety, the cylinders had locking split caps installed which allowed regulators to be used while protecting the valves. The cylinders were strapped to the front passenger seat and retained using the seat belt (Picture 30). Lines from the cylinders were run from each to a tailpipe simulator. The tailpipe simulator was made from 2" PVC and was designed so the middle of the opening was 12 inches off the ground behind the vehicle (Picture 31).

Picture 30 - Gas Cylinders Filled With Simulated Exhaust Installed In Electric Vehicle

Picture 31 - Electric Vehicle With Simulated Tailpipe Installed

Using the IM240 constant volume sampling system and hydrocarbon analyzer in the Gordon-Darby vehicle inspection lanes, we were able to determine the appropriate pressure to release the gases at 30 cubic feet a minute, simulating typical light duty vehicle exhaust flow. Since the RSDs only use ratios of the gases to determine mass, the exact flow rate just needed to be similar to vehicle exhaust. With this high of a flow rate and flowing gas for approximately 30 seconds for each run, it was determined that there was enough volume of gas in the cylinders for approximately 25 releases of gas and we planned for 15 runs releasing each gas.

Prior to on-road operation, the pressures for each gas were pre-set and the flow shutoffs were closed. For each run, the calibration gas flow was initiated just prior to driving under the overpass (approximately 150 feet from the first RSD) and was turned off after the last RSD. The calibration vehicle target speed was 35 MPH, however, due to traffic the runs varied from 17 to 35 MPH. The time of the runs and data collected included:

- Date
- Time
- Speed
- Ambient temperature
- Gas concentrations
- Pressure of the gas released

The calibration vehicle was driven past the RSDs each day of the study approximately one hour after testing began, mid-day and approximately an hour prior to ending testing for the day. Each time, three passes were performed, one releasing low gas, one releasing high gas and one releasing no gas (a blank). This achieved 15 passes with each gas and 15 blanks for a total of 45 passed over the course of the week.

For the blank runs, unfortunately the RSDs are set to trigger and perform their calculations for measured gases when CO_2 is observed. CO_2 measurement is necessary to calculate a ratio of CO_2 to the gases of concern. Without the release of CO_2, the RSDs were not able to provide data for the blanks.

3.9 Schedule and On-Road Testing

As noted, the study was delayed a year due to the COVID virus from spring 2020 to spring 2021. Springtime was chosen because the expected temperatures were 65 to 80 in Phoenix AZ at that time. The on-road data collection occurred from April 12th to 16th, 2021 with days prior and after on site for setup and teardown. The goal for the testing was to perform test runs driving past the RSDs to collect tailpipe and evaporative emissions measurements with the prepared research vehicles and calibration vehicle and to collect data on the public's vehicles emissions 9 to 10 hours a day.

The on-road data collection included the following:

1. Simulated Evaporative Leaks using Butane (F-150 and Mazda6) – 45 Runs per Vehicle
   1.1. 3 flow rates (1, 2.5, 4 lpm); at 25, 35 and 45 mph; 4 leak locations and blanks
   1.2. Log fuel, vapor and ambient temperatures, speed, and purge status via OBDII

2. Actual Evaporative Leaks (F-150 and Mazda6) – 36 Runs per Vehicle
   2.1. 3 samples at 25, 35, 45 mph with blank, fuel cap off, vapor line disconnected at canister, purge valve disconnected
   2.2. Log fuel, vapor, ambient temperatures, speed, and purge status via OBDII
   2.3. F-150 is cap less so a pipe was inserted in the filler neck for cap off test

3. Simulated Evaporative Leaks with Butane Driving Aggressively (F-150) – 36 Runs
   3.1. 4 flow rates (0.5, 1, 2.5, 4 lpm); at variable speeds; leak on top of canister and blanks
   3.2. Log fuel, vapor and ambient temperatures, speed, acceleration rate and purge status via OBDII

4. Exhaust Measurement with PEMS (F-150 and Mazda6) – 31 and 25 Runs
   4.1. Speeds with the flow of traffic, from 23.7 to 42.9 mph
   4.2. Log ambient temperature, speed, and emissions from the PEMS (HC, NO_x, CO, CO_2, PM)

5. Simulated Exhaust Released from an Electric Vehicle (Chevy Bolt)- 45 Runs
    5.1. Runs at approximately 9:00 am, noon and 4:00 pm all five days of the study
    5.2. Low and high concentration gases and blank runs
    5.3. Approximately 35 mph
    5.4. Log ambient temperature, speed, gas release pressure and gas released

To accomplish all the testing described above, a schedule shown in Figure 6 was developed to maximize the use of testing time.

On Saturday April 10th, Revecorp completed the configuration of the simulated evaporative leaks on the Ford F-150 and Mazda6. Both vehicles were leak tested using the IM240 leak systems in the IM lanes. On Sunday April 11th, the vehicle exhaust simulation vehicle (the Chevy Bolt) was configured with the gas cylinders and the simulated tailpipe. The appropriate pressure to achieve the desired flow was determined using the Gordon-Darby constant volume sampling system and IM240 analyzers and knowing the concentration of gas released. SGS also started the installation and calibration of the PEMS in the F-150. Both research vehicles were taken on-road and all systems for simulating evaporative emissions and driving by the RSDs were checked. Revecorp, ETS, CRC staff and the RSD vendors visited the test site where staff were setting up the RSDs and preparing for testing the next morning. Sunday evening, CRC staff, Revecorp, ETS, representatives from HEAT, Opus and DU, and the SGS PEMS team all met to coordinate testing for the next day starting at 8:00 am.

Testing began on Monday April 12th with preparation of the vehicles for use on-road. The Mazda6 was to be driven all day simulating evaporative leaks and the F-150 was to be driven with the PEMs operating. As noted earlier, the F-150 had a fuel pump relay failure and testing was stopped mid-day and had to continue the next day. In general, however, the testing was conducted each day as per the outlined schedule with few issues. Because the testing went as planned without any need to re-perform planned testing, on the last day the F-150 was used to assess the impact of higher tailpipe HC emissions (by driving aggressively) on the ability of the RSDs to discern tailpipe HC from evaporative HC.

Sunday evening, both vehicles were filled with the local market summer fuel from the Mobil station to 40% in preparation for testing the next day. On days prior to the actual evaporative leak tests, the vehicles were no refueled at the end of the prior day so there was a large amount of headspace in the tank for the first set of tests. However, mid-day during the actual evaporative testing, the vehicles were filled with the local market summer fuel from the Mobil station to 40% for the second half of the testing.

Each night Monday through Thursday the entire team met in a conference room at the hotel and with some CRC staff connected remotely to discuss the data collected that day, study design, issues which occurred, desired changes, and additional parameters to collect. After the first day, it was decided to add collection of throttle position on the research vehicles after concern about the research vehicles operating in wide open throttle and releasing a higher level of hydrocarbons possibly making it more difficult for the RSDs to discern which hydrocarbons came from the tailpipe and which were evaporative emissions. As noted, Opus moved their two RSD units further from HEAT to accommodate vibration issues.

Figure 6 - Testing Schedule

CRC RW-105 Testing Schedule

Monday April 12th

9:00 to 17:00	RSD vendors operational on site
	Mazda does 45 passes with butane evaporative leaks
	F-150 does 25, 35 and 45 mph runs all day, as many as possible with PEMS
10:00, 13:00 and 16:00	Calibration EV does two passes, one with each calibration gas
17:00 to 21:00	SGS removes PEMS from F-150
19:00 to 21:00	Revecorp, ETS, RSD vendors and CRC meet in conference room at hotel to review data from the day, coordinate activities for Tuesday

Tuesday April 13th

9:00 to 17:00	RSD vendors operational on site
	Mazda does 36 passes with "natural" evaporative leaks
9:00 to 12:00	F-150 does 25, 35 and 45 mph runs with PEMS
13:00 to 17:00	PEMS removed from F-150, evap butane equipment reinstalled
10:00, 13:00 and 16:00	Calibration EV does two passes, one with each calibration gas
19:00	Revecorp, ETS, RSD vendors and CRC meet in conference room at hotel to review Monday evap data

Wednesday April 14th

9:00 to 17:00	RSD vendors operational on site
	F-150 does 45 passes with butane evaporative leaks
8:00 to 13:00	Remove evap equipment from Mazda, install PEMS
14:00 to 17:00	Mazda does 25, 35 and 45 mph runs with PEMS
10:00, 13:00 and 16:00	Calibration EV does two passes, one with each calibration gas
19:00	Revecorp, ETS, RSD vendors and CRC meet in conference room

Thursday April 14th

9:00 to 17:00	RSD vendors operational on site
	F-150 does 36 passes with "natural" evaporative leaks
	Mazda does 25, 35 and 45 mph runs with PEMS
10:00, 13:00 and 16:00	Calibration EV does two passes, one with each calibration gas
19:00	Revecorp, ETS, RSD vendors and CRC meet in conference room

Friday April 15th

9:00 to 17:00	RSD vendors operational on site
	F-150 does passes with butane evaporative leaks, possibly different speeds, flow rates
17:00 to 18:00	SGS removes PEMS from Mazda
10:00, 13:00 and 16:00	Calibration EV does two passes, one with each calibration gas

3.10 Data Collected

3.10.1 Data Collected for Evaporative Measurement Experiments

When starting to use a research vehicle to simulate evaporative emissions, the operator would turn on the butane tank and the output from the regulator. Prior to starting a simulated evaporative run, the operator would open the appropriate flow position valve (such as "Cap") and set the desired flow rate using the valve at the bottom of the flow meter. The flow position valve would then be turned off, and approximately 10 seconds prior to passing the RSDs, the appropriate flow position valve would be turned on to flow butane and the correct flow rate form the correct location. For actual evaporative system disconnection runs, the vehicle was modified with the leak location disconnected and open to the atmosphere.

For all runs, the data logged included:

- Vehicle
- Date
- Time
- Time between consecutive passes of the RSDs
- Leak position
- Flow rate (not recorded for actual leak runs)
- Actual speed
- Longitude and latitude when RPM and Purge % were collected
- Engine RPM
- Purge %
- Relative throttle position
- Absolute throttle position
- If the vehicle was operated at wide open throttle while passing the RSDs
- Ambient temperature
- Fuel liquid temperature
- Fuel vapor temperatures
- If the vehicle was purging
- The relative butane concentration for simulate leak runs

For each run, the relative butane concentration, taking into account the vehicle speed and flow rate was calculated, using the highest flow rate (4 LPM) and the slowest speed (25 MPH) as the highest concentration releases while passing the RSDs. Therefore, at a speed of 35 MPH and a flow rate of 2.5 LPM, the relative concentration was 45%. For the actual evaporative leak experiments, the vehicles began the day with the fuel remaining from the day prior (approximately 40%) and were driven until midday. The time of refueling between runs when the vehicles were refueled was also recorded with the run data.

For the evaporative emissions rates, the manner in which the data was reported by each RSD vendor is described in their individual reports to CRC which are referenced and described in short detail earlier in this report. HEAT reported the data in grams per mile, Opus reported evaporative emissions in units of an index created by Eastern Research Group (ERG Index) and DU reported evaporative emissions in units of standard deviation.

3.10.2 Data Collected for Public Vehicles

For all public vehicles, RSD vendors were requested to record:

- Date
- Time
- Vehicle license plate
- Evaporative emissions rate (varied by vendor)
- Gaseous pollutants measured (NO_x ppm, hydrocarbons ppm hexane, CO ppm, CO_2%)
- PM measured (varied by vendor)
- Vehicle speed and acceleration rate

3.10.3 Data Collected for Tailpipe Measurement Experiments

For the simulated exhaust vehicle, the RSDs were requested to record:

- Date
- Time
- Vehicle license plate
- Gaseous pollutants measured (NO_x ppm, hydrocarbons ppm hexane, CO ppm, CO_2%)
- Vehicle speed and acceleration rate

For the research vehicles when the PEMS was installed, the RSDs were requested to record:

- Date
- Time
- Vehicle license plate
- Gaseous pollutants measured (NOx, hydrocarbons C1, CO, CO2 in g/kg fuel consumed)
- PM measured (varied by vendor)
- Vehicle speed and acceleration rate

The PEMS unit reported the emissions of HC, NOx, CO, CO2 and PM in grams per kilogram of fuel (g/kg fuel). For measurements of the research vehicles when the PEMS was installed, HEAT reported their results in g/kg fuel as well. For the particulate matter from Opus, the measurements were reported in PM UV and for DU the measurements were reported in opacity.

4 RESULTS

Nine data sets were generated as part of the study:

- Mazda6 Simulated Evaporative Leak Tests (45 runs, 4/12/2021)
- Mazda6 Simulated Evaporative Leak Tests (45 runs, 4/16/2021)
- Mazda6 Actual Evaporative Leak Tests (36 runs, 4/13/2021)
- Mazda6 PEMS Tests (25 runs, 4/15/2021)
- Ford F-150 Simulated Evaporative Leak Tests (45 runs, 4/14/2021)
- Ford F-150 Simulated Evaporative Leak Tests with aggressive driving (36 runs, 4/14/2021)
- Ford F-150 Actual Evaporative Leak Tests (36 runs, 4/15/2021)
- Ford F-150 PEMS Tests (31 runs, 4/13/2021)
- Simulated Tailpipe Emissions with Calibration Gas (45 runs, 4/12 to 4/16/2021)

All of the data is available in a single spreadsheet for further analysis:

https://s3-revecorp-static.s3.us-west-2.amazonaws.com/Revecorp+RW-105+Data+Summary+-+FINAL.xlsx

The data from this study and measurements of public vehicles were evaluated by Charles Blanchard for CRC and that analysis is available in a separate report[13].

The description of the experiments and analysis of the results below provide a review of each of the data sets described above and evaluation of some of the varied conditions during the testing. An overview of the amount of data collected on public vehicles is also provided, however the results from measurement of public vehicles is only included in the Blanchard report cited above and were not available to Revecorp.

4.1 Experimental Conditions and Fuel Temperatures

The ambient temperatures during on-road data collection varied from 72.8 to 99.8°F with higher ambient temperatures and higher winds later in the day at the start of the week. Overall, the weather was generally calm with clear skies. The test site setting was slightly below grade with the highway 20 feet above and behind the RSDs and a 20-foot-high wall directly across from the RSDs which helped to block the limited wind. This also created a slight venturi effect by the cars passing - pulling ambient air from under the bridge up towards the final RSD (DU), clearing out lingering vehicle exhaust.

4.1.1 Simulated Evaporative Experiment Temperatures

For the simulated evaporative experiments with the F-150, only intermittent ambient temperature data was collected during normal driving (the experiment on 4/14) due to a loose connection on the thermocouple and no temperature data was collected (ambient, fuel tank vapor or fuel tank liquid) for the F-150 aggressive driving due to an instrument malfunction. The highest recorded fuel tank vapor temperature during the simulated evaporative leak experiments was 104.2°F with the liquid fuel temperature of 106.3°F.

For the simulated evaporative experiments with the Mazda6, the high ambient temperature was 94.5°F during the first day. Driving the vehicle simulating evaporative leaks for eight hours, the fuel ambient temperature increased to 119.3°F and the liquid fuel temperature was 120.6°F. These are nearly exactly the suggested high fuel and fuel vapor temperatures predicted by USCAR indicating the flow rates chosen were appropriate.

[13] Blanchard, C. L., 2022. Draft Final Report for CRC Project No. E-119-3a, Remote Sensing Device (RSD) Statistical Analysis. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022.

4.1.2 Actual Evaporative Experiment Temperatures

During the actual evap leak experiments, the vehicles were refueled with local fuel from the Mobil gas station at mid-day, which caused a reduction in the fuel vapor and liquid temperatures.

For the F-150, the ambient temperature for the leak experiment ranged from a low of 72.8°F in the morning to a high of 84.0°F. The fuel tank vapor and liquid temperatures were:

- Fuel vapor temperature – 77.8 to 94.3°F, refueled, 87.4 to 97.0°F
- Fuel liquid temperature – 78.3 to 96.8°F, refueled, 87.5 to 97.4°F

For the Mazda6, the test day ambient temperature that day ranged from a low of 79.5°F in the morning to a high of 92.0°F. The fuel tank vapor and liquid temperatures were:

- Fuel vapor temperature – 83.0 to 105.9°F, refueled, 94.1 to 112.7°F
- Fuel liquid temperature – 84.3 to 111.4°F, refueled, 94.1 to 113.1°F

Note that the F-150 sits higher off the ground than the Mazda6, and the Mazda6 has much tighter packaging of the fuel tank against the bottom of the vehicle and is closer to the tailpipe than the fuel tank in the in the F-150.

4.2 Simulated and Actual Evaporative Leak Experiments

4.2.1 Simulated Evaporative Leak Experiments

As noted previously, the F-150 and Mazda6 were instrumented to allow for evaporative leaks to be simulated occurring at the canister, the top of the fuel tank, at the purge valve and at the fuel cap. The instrumentation allowed the driver of the research vehicle to adjust the location and flow rate (0.5, 1, 2.5 or 4 lpm) of the leaked hydrocarbon (butane) prior to approaching the RSDs. The experiments targeted passing the RSDs at 25, 35 and 45 mph.

For evaporative leaks of hydrocarbons, it is easier for the RSDs to detect the leak if the concentration of hydrocarbons in the air behind the leaking vehicle as it passes the RSD is higher. Therefore, both the flow rate of the hydrocarbons released and the speed at which the vehicle passed the RSD (higher speeds cause more dilution) impacted the concentration. Since the experiments were run at various speeds and flow rates, we needed to represent the leak rate from the vehicle in a manner similar to the way that other emissions are expressed, and which also provides for changes in the relative concentration (grams per mile).

For the experiment, the highest mass per mile would occur at the lowest speed (25 mph) and highest flow rate (4.0 lpm). At a butane leak rate of 4 lpm at 25 miles/hr, the mass emission rate is equivalent to 22.4 g/mi of butane.

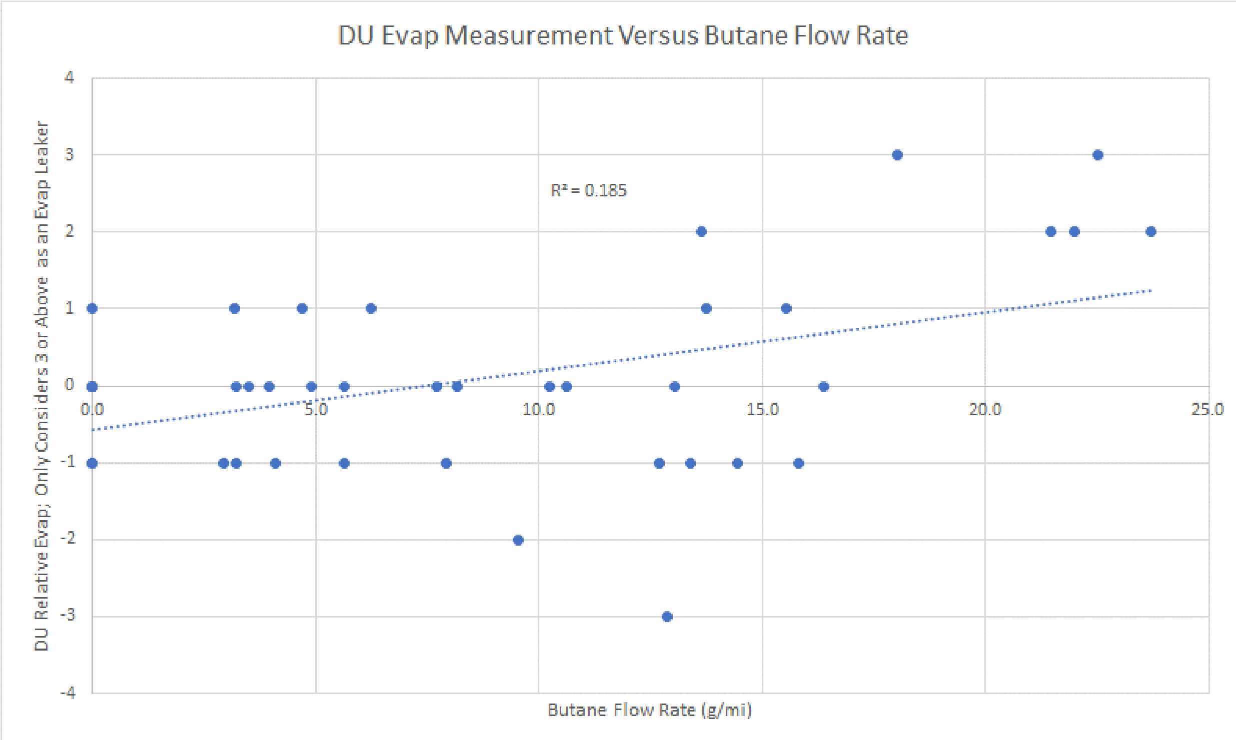
Table 2 - Evaporative Leak Rate Calculation in Grams per Mile

Calculation of Evap Leak in g/mi as a Function of Flow Rate and Vehicle Speed		
Description	Value	Units
Leak rate (variable)	4	L/min
Vehicle speed (variable)	25	miles/hr
Moles per unit volume	0.040178571	mol/L
Moles per minute	0.160714286	mol/min
Butane density	58.12	g/mol
Mass per minute	9	g/min
Minutes to hours	60	min/hr
Mass per hour at given speed	560	g/hr
Evap leak rate mass per mile	22.4	g/mile

DU Measurements of Evaporative Emissions

As noted in the description of the DU FEAT device, the evaporative emissions are reported as a standard deviation, with a higher value representing a higher probably of the vehicle being an evaporative leaker above the Tier II evaporative running loss SHED standard of 3 grams of VOC's/15 minutes. Evaluation of the DU Evaporative Emissions estimates versus the butane emission rate showed they were not well correlated (Figure 7).

Figure 7 - DU Evaporative Estimates, Simulated Evaporative Experiments, Mazda6



Based on the correlation shown above, it was decided not to include the DU evaporative emissions measurements in further analysis of the evaporative experiment results.

HEAT and Opus Measurements of Simulated Evaporative Emissions

The evaporative measurements from both HEAT and Opus were combined for both vehicles in Figure 8. Because HEAT reports their results in terms of mass (g/mi) and Opus reports their results in terms of an ERG developed unitless "Evaporative Index", they are plotted on separate y-axes. For both sets of data, the equation of a straight line, forced through zero is shown along with coefficient of determination (r-squared).

The results need to be viewed in terms of the use of the data. If the data are used to estimate the average evaporative emissions of a fleet, the data are limited due to the large evaporative emissions reported for experiments where there were no evaporative emissions ("blanks"). This can be seen at zero on the x-axis and the spread of evaporative emissions rates data reported on the y-axis for both HEAT and Opus. For HEAT, reported evaporative emissions measurements for the blank runs ranged from 0.1 to 35.4 g/mi with an average over 20 data points reported for 27 total runs (7 were missing data) was 8.5 g/mi. For the Opus readings, they were converted from "index" readings into g/mi values for evaluation of the size of the readings in g/mi of butane. Data from both vehicles during the simulated runs as measured by Opus shown below in Figure 8 were used to convert the Opus measurements to g/mi leak rates:

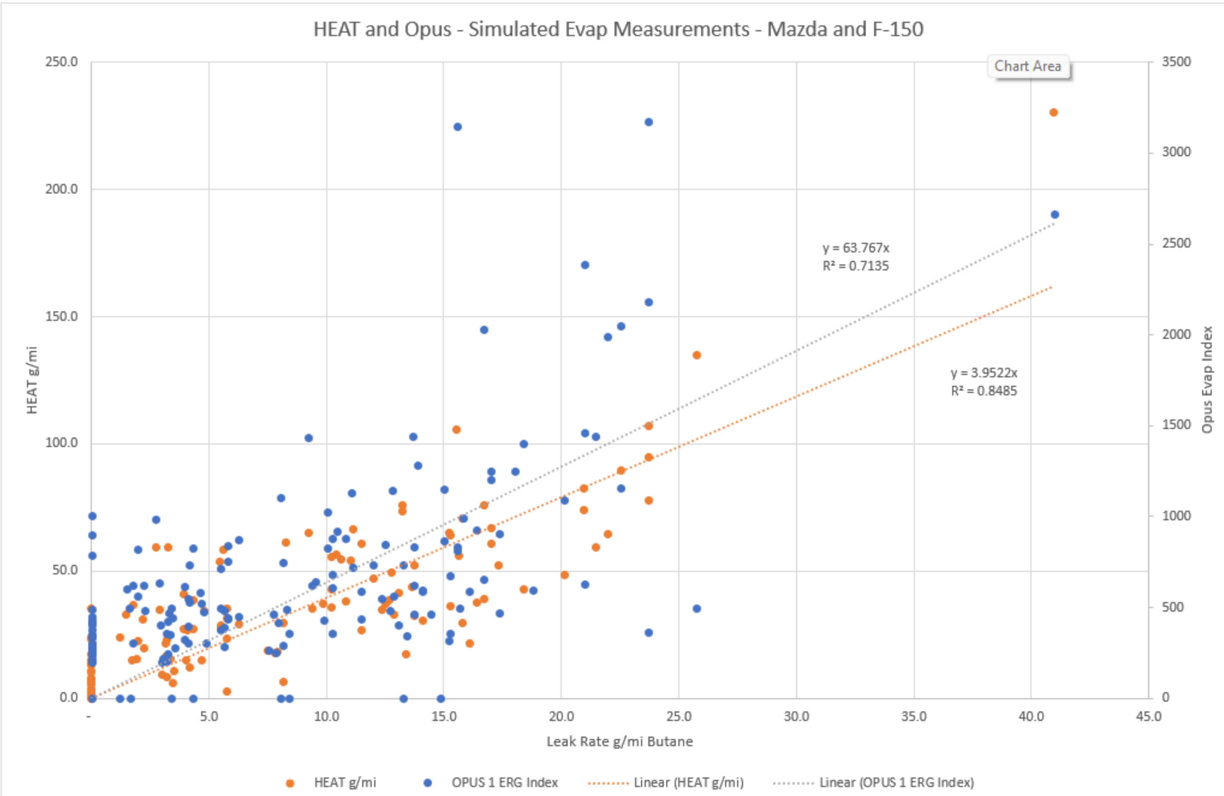
Opus index / 63.767 = butane emission rate g/mi

For Opus, reported evaporative emissions measurements for the blank runs ranged from 3.1 to 15.7 g/mi with an average over 24 data points reported for 27 total runs (3 were missing data) was 6.0 g/mi.

If RSD data were used to identify individual high emitting vehicles, then based on the noise in the data as seen at zero, the threshold would need to be at high to avoid false failures. However, a high threshold may miss a substantial portion of the actual leaking vehicles. For this reason, it seems

RSD for determining evaporative emissions is not practical. This also indicates that the RSD measurements cannot be used to estimate fleet wide emissions.

Figure 8 - HEAT and OPUS Simulated Evap Measurements Mazda6 and F-150



Looking at the results for the individual vehicles which have different shapes, for results from the Mazda6 only, the agreement between the HEAT and Opus measurements was worse as can be seen in Figure 9, however the Opus coefficient of determination improved. The maximum error for reading a blank was by HEAT and was 23 g/mi. Using the correlation between the Opus Index and the simulated evaporative emission rate, the maximum error for reading a blank was 7.2 g/mi.

For results from the F-150 only, the HEAT and Opus average measurements were in better agreement, however the Opus coefficient of determination was worse Figure 10. The maximum error for reading a blank was by HEAT was 35.4 g/mi and again using the correlation between the Opus Index and the simulated evaporative emission rate, the maximum error for reading for Opus was 14.5 g/mi.

The error reading blanks by both the HEAT and Opus RSDs makes it difficult to identify passing or failing vehicles without false failures. Applying this knowledge that actual evaporative leaks could not be differentiated from the blanks, if readings from either RSD were used to determine the fraction of evaporative emissions from the fleet, those emissions would be over-estimated since vehicles with no evaporative emissions would be identified as having evaporative leaks.

A difference between the vehicles which may have impacted the measurements was that the Mazda6 is closer to the ground and the air movement around the vehicle would be expected to be unified and trail closer to the ground. For the F-150, the vehicle has a high ground clearance and a more open sub structure for mixing and larger air flow under the vehicle. This difference could have pushed the evaporative emissions from the F-150 higher off the ground than the evaporative emissions leaking from the Mazda6. Only data from the Opus RSD at 12 inches off the ground was evaluated, but it is possible that the RSD which was 18 inches off the ground may have had better correlation. Compared to the HEAT remote sensing technique which looked down on the vehicle as it passed underneath, the height of the leak and the mixing were not a factor in their measurements.

Figure 9 - HEAT and OPUS Simulated Evap Measurements Mazda6 Only

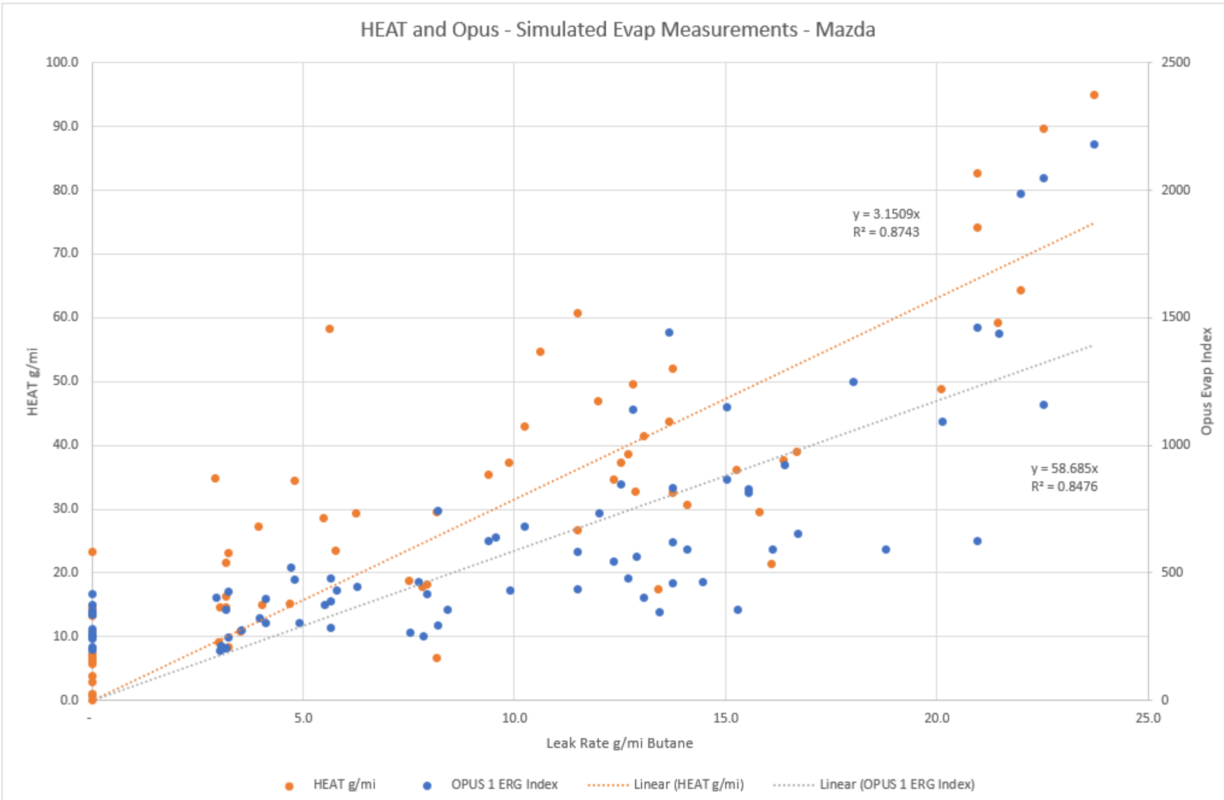
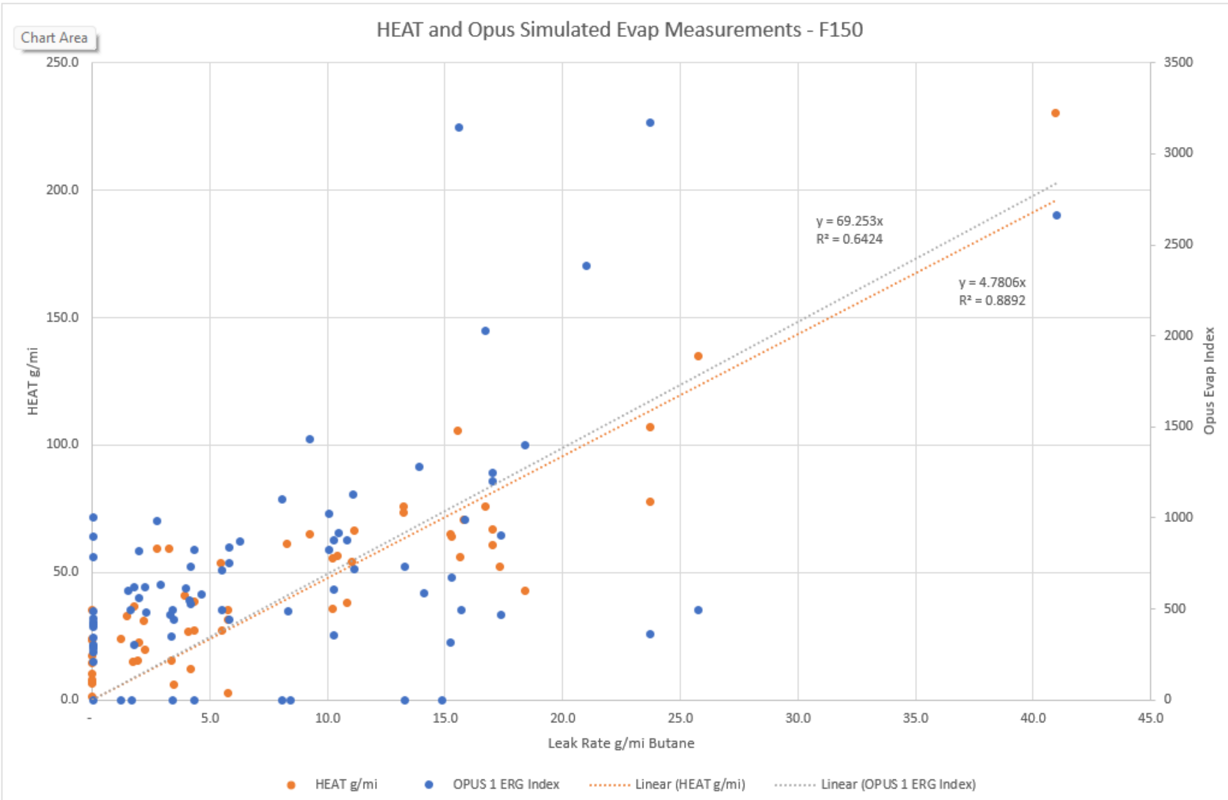


Figure 10 - HEAT and OPUS Simulated Evap Measurements F-150 Only



Evaluation of Speed on Measurement Accuracy

To determine if vehicle speed impacts the measurement of evaporative leaks, the evaporative measurements from HEAT and Opus were evaluated as a function of vehicle speed. The results were broken into three speed ranges – under 30 mph, between 30 and 40 mph and over 40 mph. Plots for each speed range for both vehicles are shown in Figure 11, Figure 12 and Figure 13.

It does not appear speed by itself impacts the accuracy of the evaporative emissions measurements. This is likely because the rate of evaporative emissions was varied at each speed, so the total evaporative emissions flow rate was a function of both flow rate and speed changing the overall concentration of evaporative emissions in the air behind the vehicle as it passed the remote sensors.

For this reason, the results were next analyzed by the overall evaporative emissions released by the vehicles.

Figure 11 – Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Measurements with the Vehicles Under 30 MPH

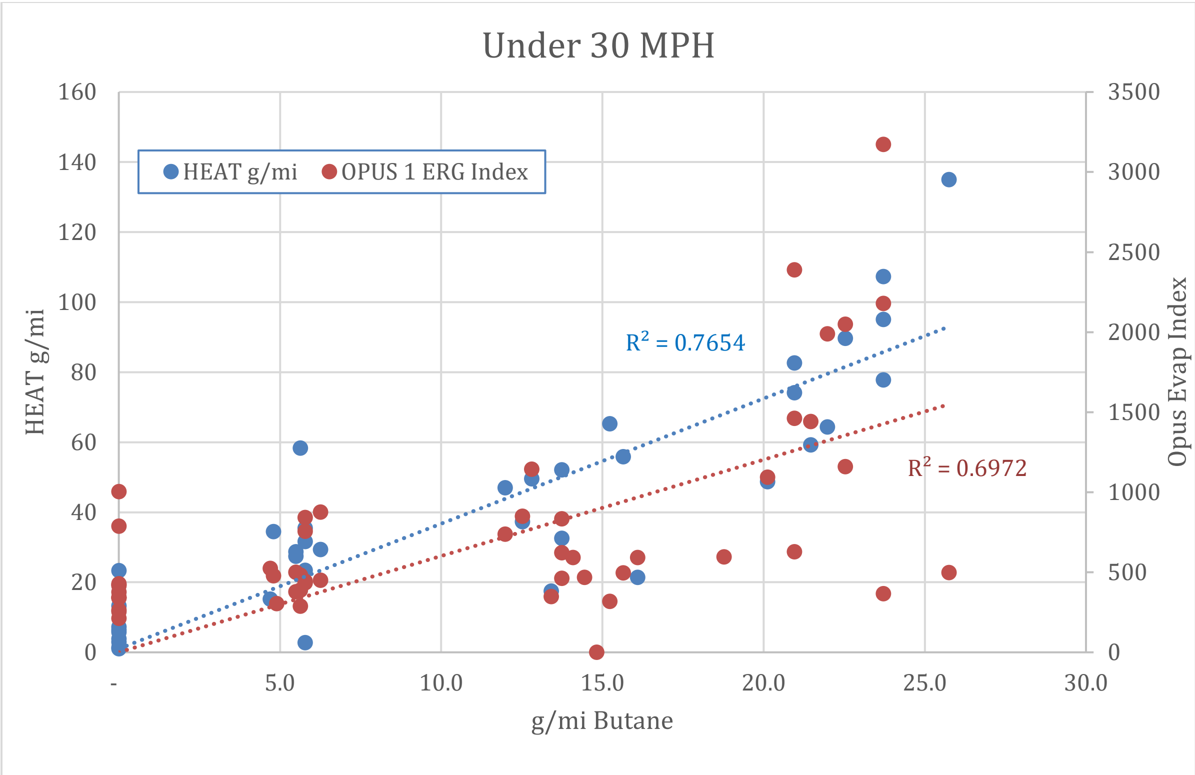


Figure 12 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Measurements with the Vehicles 30 to 40 MPH

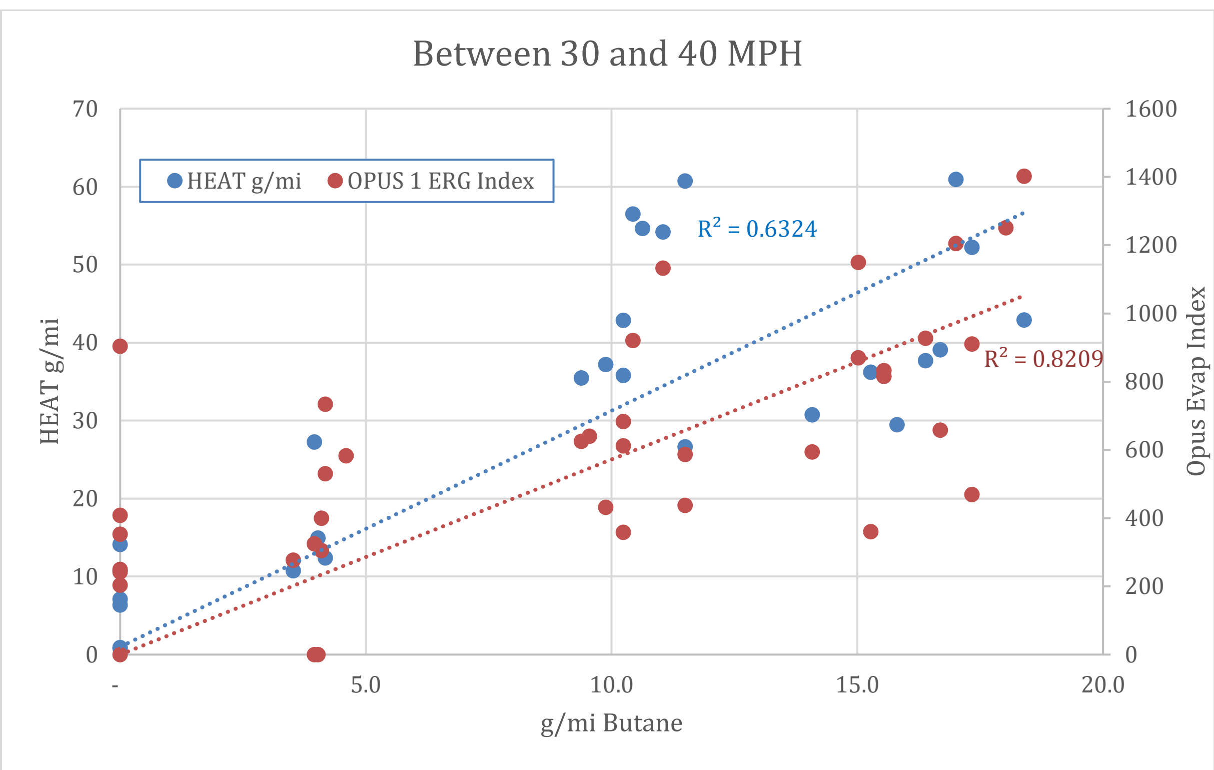
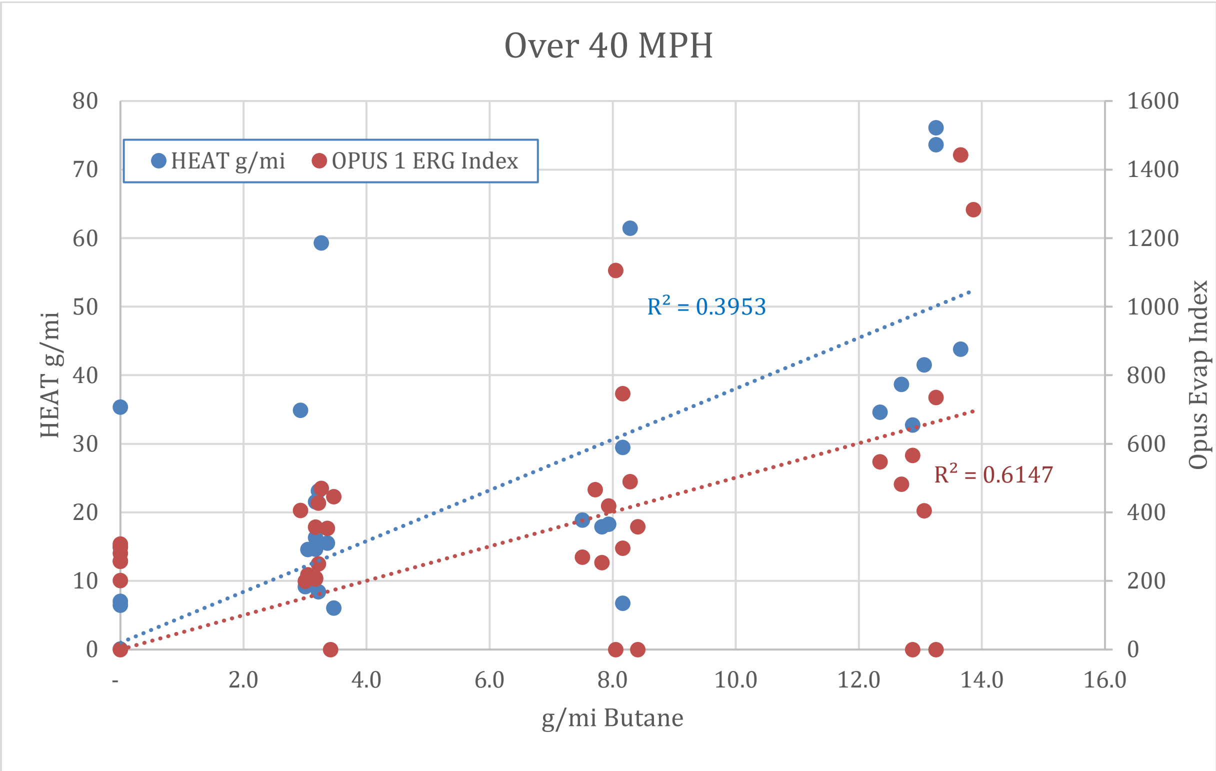


Figure 13 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Measurements with the Vehicles Over 40 MPH



Evaluation of Evaporative Emissions Concentration on Measurement Accuracy

To determine if the accuracy of the RSDs change based on the concentration of evaporative emissions, the measurements from the 108 passes of the RSDs by the Mazda6 and F150 while simulating evaporative emissions were broken into four groups of 27 passes each:

1. lowest quarter of emission rates - 2.9 to 5.5 g/mi butane
2. second lowest quarter of emission rates - 5.6 to 10.4 g/mi butane
3. second highest quarter of emission rates - 10.6 to 15.2 g/mi butane
4. highest quarter of emission rates – 15.3 to 25.7 g/mi butane

The data were identified by the RSD vendor, and correlations for each were generated. The data are show in Figure 14, Figure 15, Figure 16 and Figure 17.

The data show that the accuracy of the remote sensors to measure evaporative emissions was poor in the first three groups, with concentrations below 15.2 g/mi, with coefficients of determination for both remote sensors below 0.15. Only in the group with the highest concentrations (over 15.3 g/mi) had improved coefficients of determination. The r^2 for HEAT was 0.776 and for Opus the r^2 had only improved slight to 0.237.

The results indicate that the remote sensors would have difficulty identifying properly working vehicles from broken vehicles unless those vehicles were severely broken and had very high emission rates. If the RSDs cannot differentiate between evap emissions unless vehicles are significantly high, the data from RSDs can not be used to estimate fleet wide evaporative emissions.

Figure 14 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Lowest Emission Rate

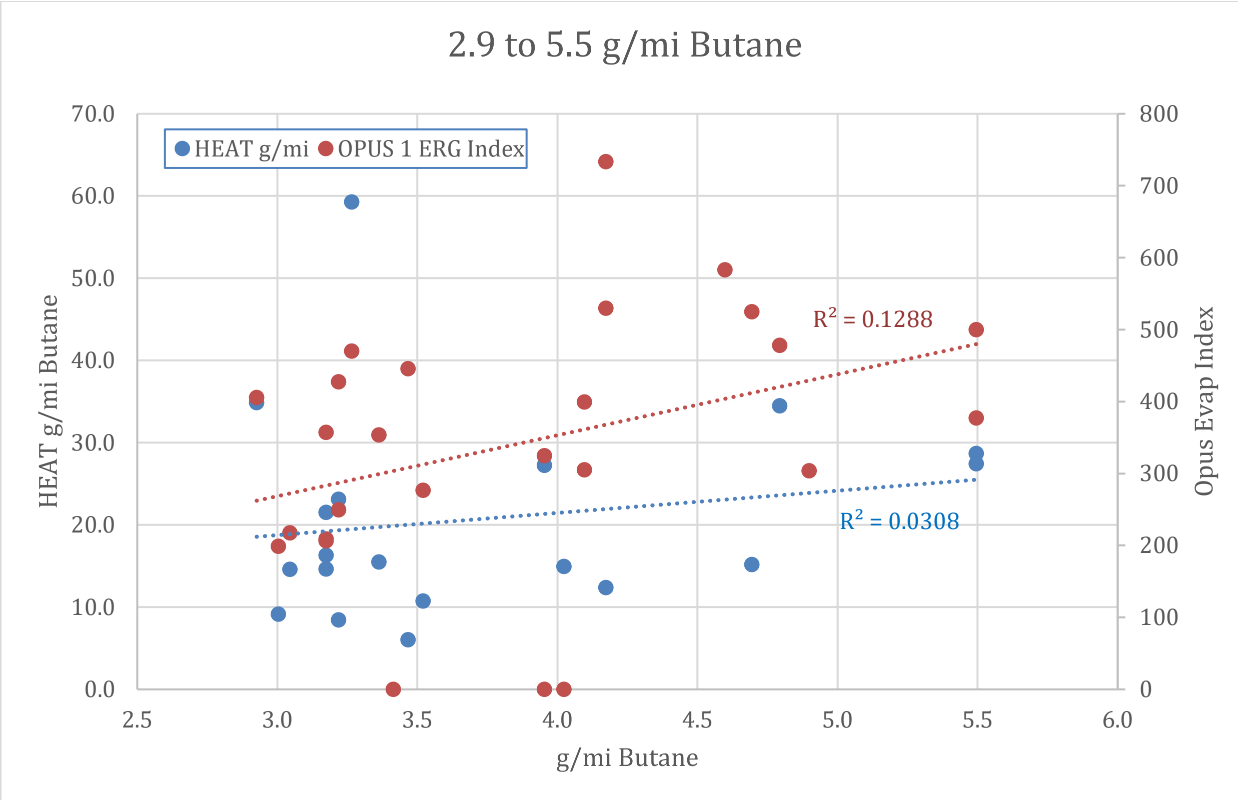


Figure 15 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Second Lowest Emission Rate

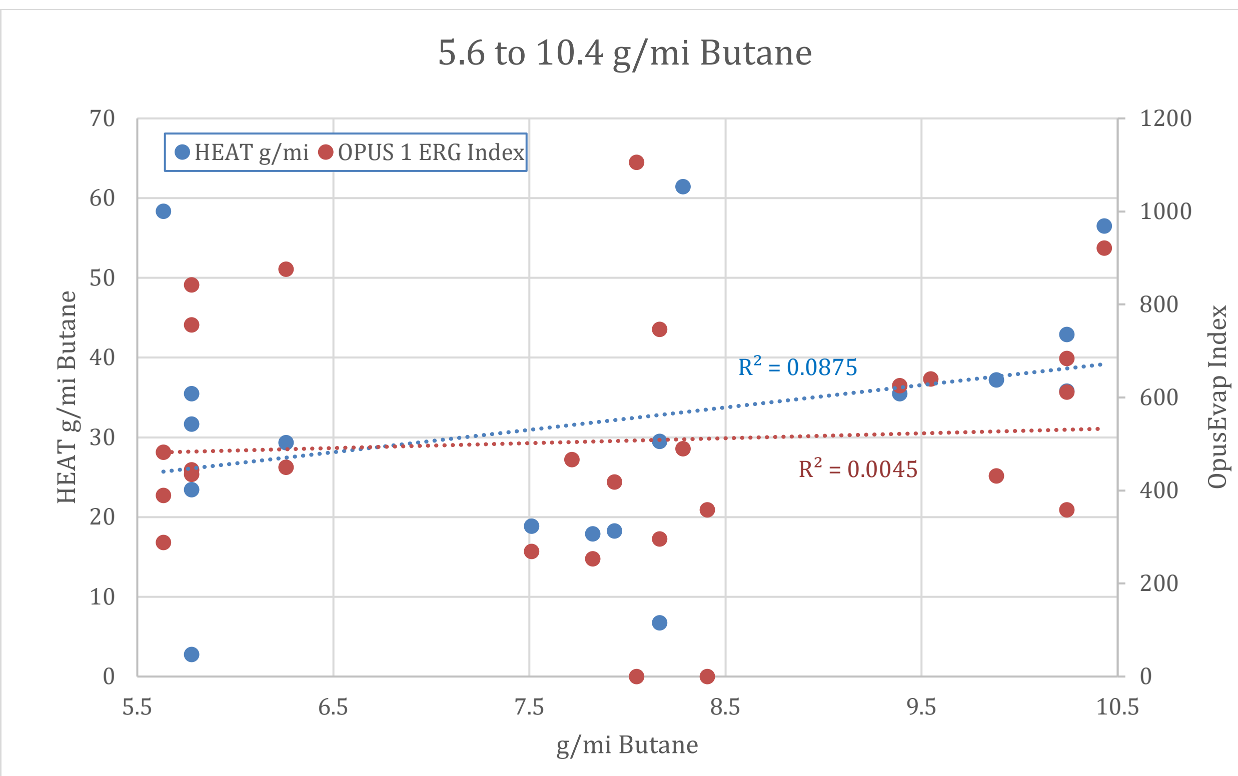


Figure 16 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Second Highest Emission Rate

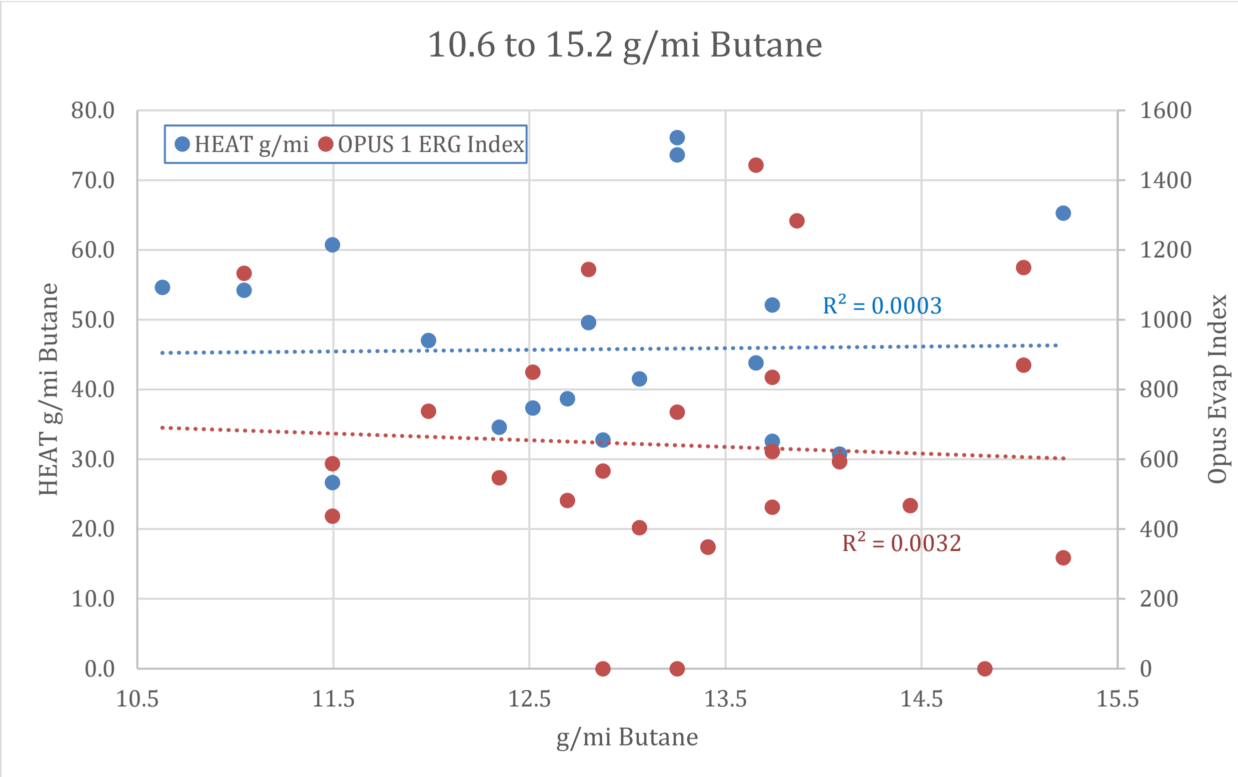
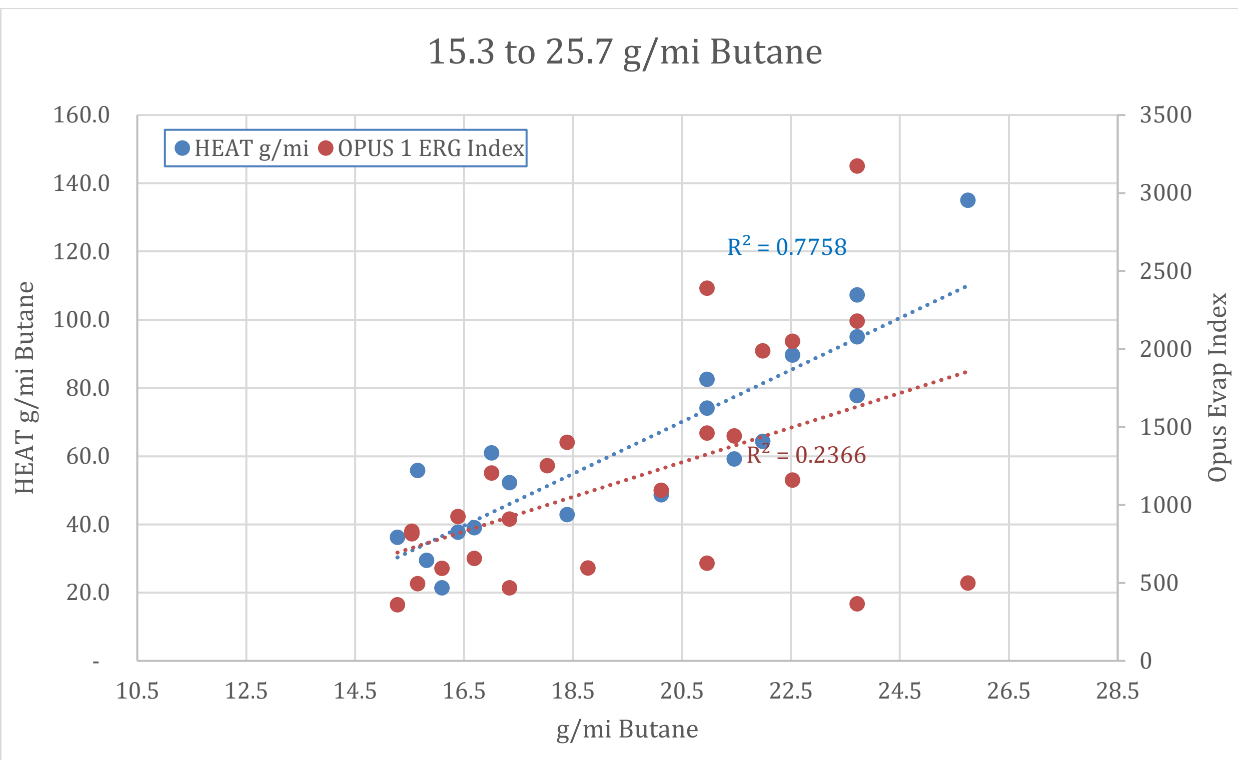


Figure 17 - Evaporative Measurements for HEAT and Opus, Mazda6 and F150 with Simulated Evaporative Emissions, Highest Emission Rate



Evaluation of Leak Location on HEAT and Opus Evaporative Emissions Measurements

To determine if the location of the leak had an impact on HEAT or Opus' ability to measure a simulated evaporative emissions leak, the results of the simulated evaporative experiments for both sensors were plotted by leak location. Separate plots were created for both the Mazda6 and F150, since the vehicles have significantly different shapes which could impact the RSD measurements. Plots for each leak location on the Mazda6 are shown in Figure 18 and Figure 19. Plots for each leak location on the F150 are shown in Figure 20 and Figure 21.

Figure 18 - HEAT, Mazda6 Evaporative Emissions Measurements by Leak Location

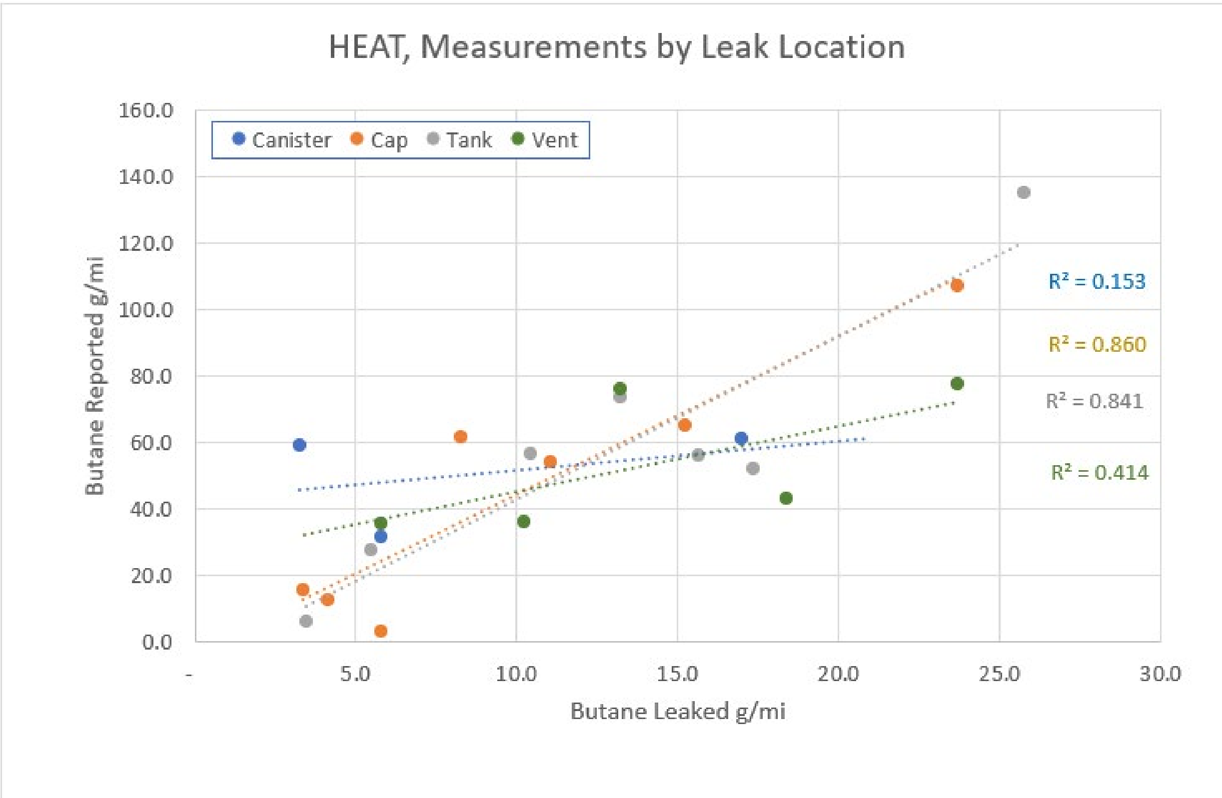


Figure 19 - HEAT, Mazda6 Evaporative Emissions Measurements by Leak Location

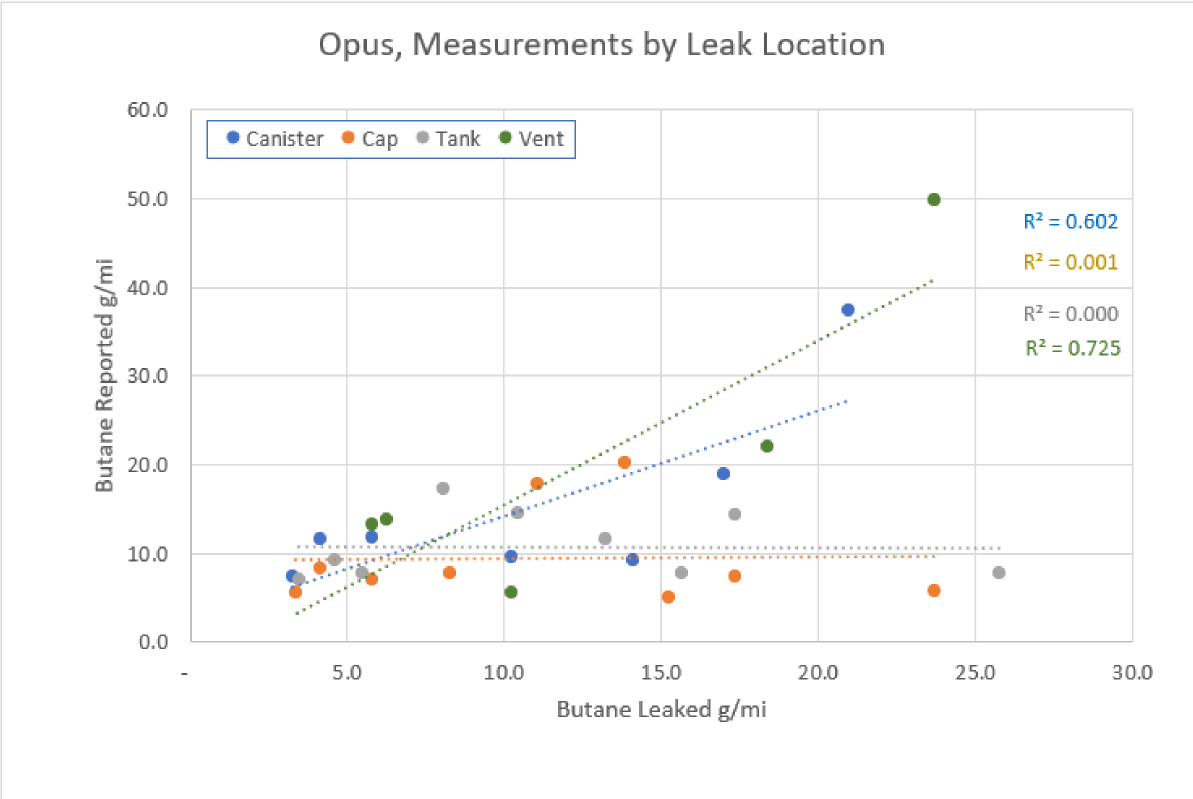


Figure 20 – HEAT, F150 Evaporative Emissions Measurements by Leak Location

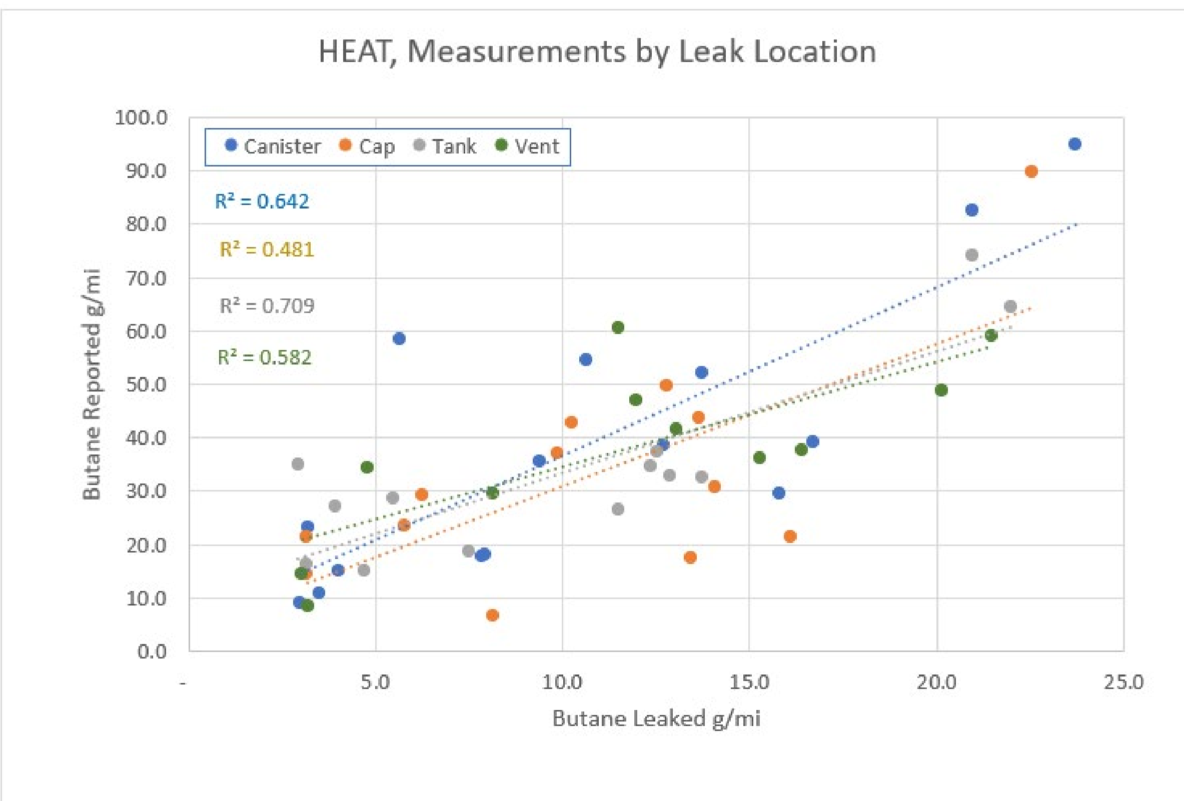
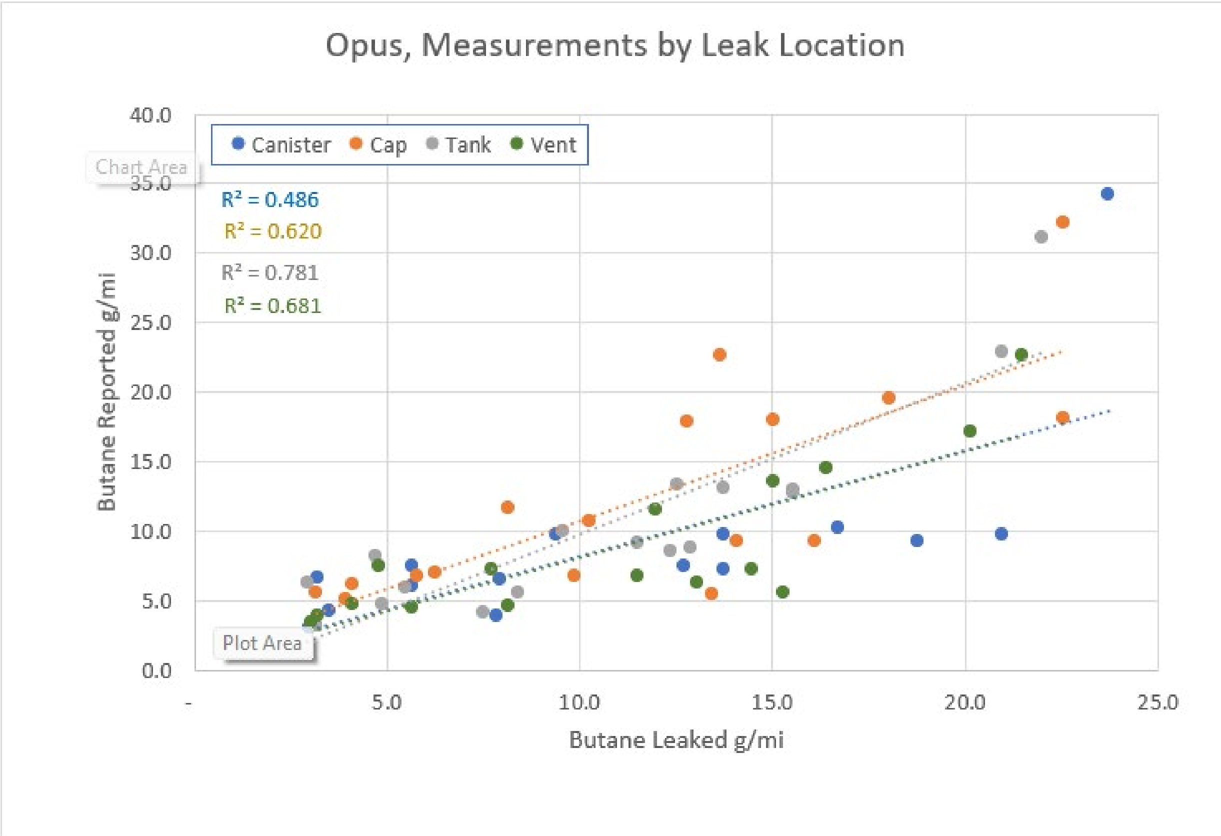


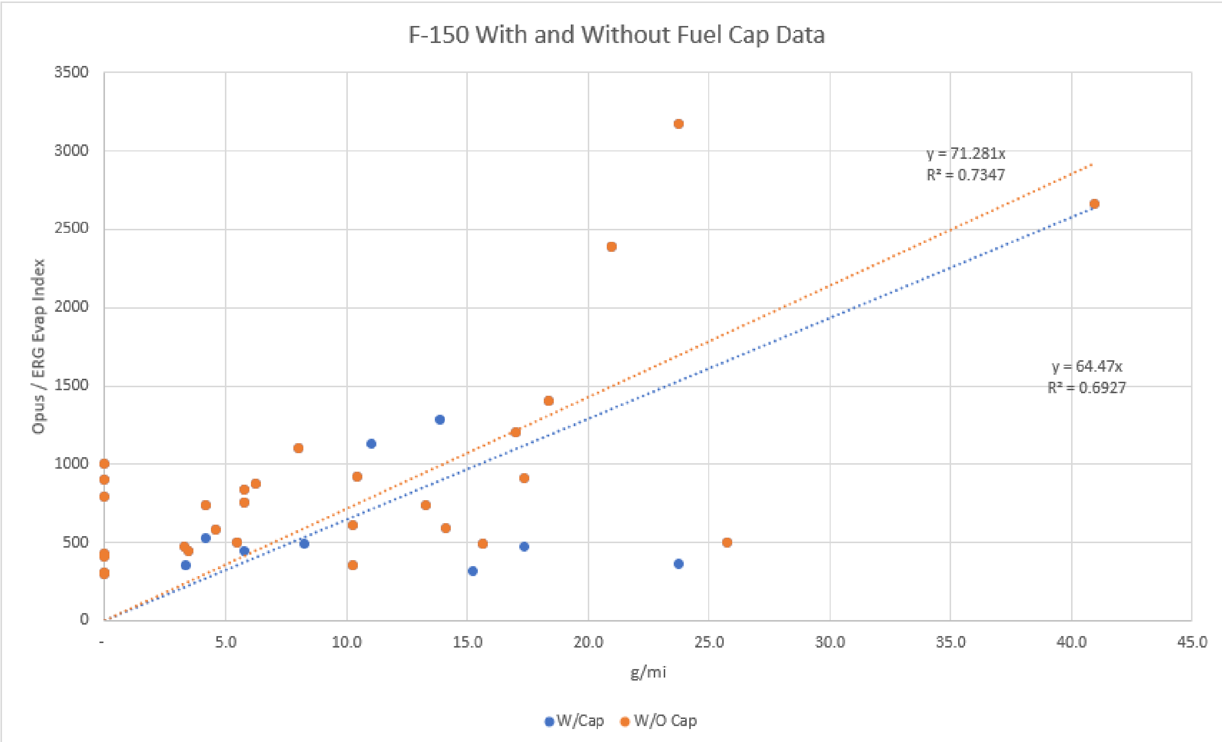
Figure 21 – Opus, F150 Evaporative Emissions Measurements by Leak Location



Evaluation of Cap Location on Opus Evaporative Emissions Measurement Capability

To determine if the height of the evaporative leak was impacting the measurements reported by Opus, the measurements from simulated evaporative emissions testing with and without the test with the fuel cap leak data were compared. The fuel cap leak location was at the location of the fuel cap, 50 inches above the ground and therefore 38 inches above the Opus RSD. As can be seen in Figure 22, the coefficient of determination does improve slightly when the measurements with the fuel cap leak are removed.

Figure 22 - Opus Evaporative Emissions for the F-150 With and Without Fuel Cap



Evaluation of High Tailpipe HC Emissions Masking Evaporative Emissions

To determine if high hydrocarbons emitted from the tailpipe could mask evaporative emissions, on the last day of testing the F-150 was driven in an aggressive manner (wide open throttle if possible) just prior to and while passing the RSDs to increase tailpipe hydrocarbon emissions. The data from the experiment for HEAT are shown in Figure 23 and for Opus in Figure 24. The coefficients of determination for both HEAT and Opus did not change with or without the aggressive driving data included. This may indicate that the RSDs measurements of evaporative emissions were not impacted by high tailpipe hydrocarbon emissions.

Figure 23 - HEAT Evaporative Emissions Data for the F-150 With and Without Aggressive Driving

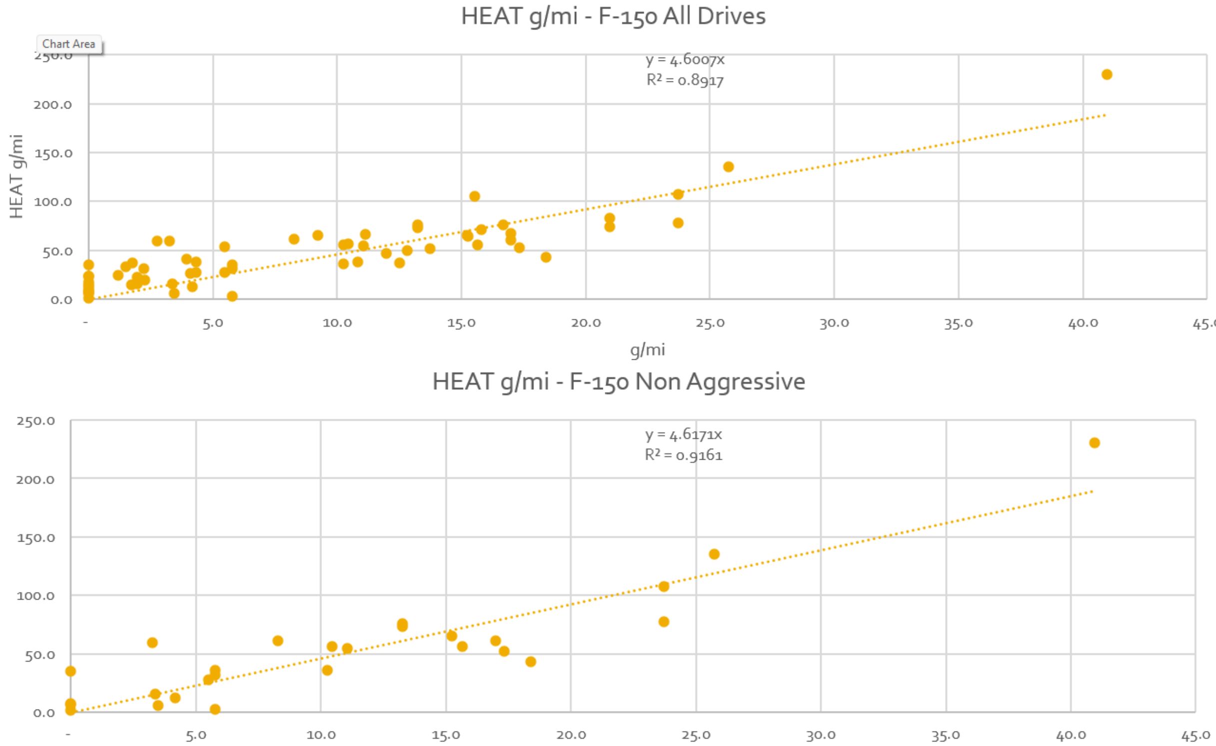
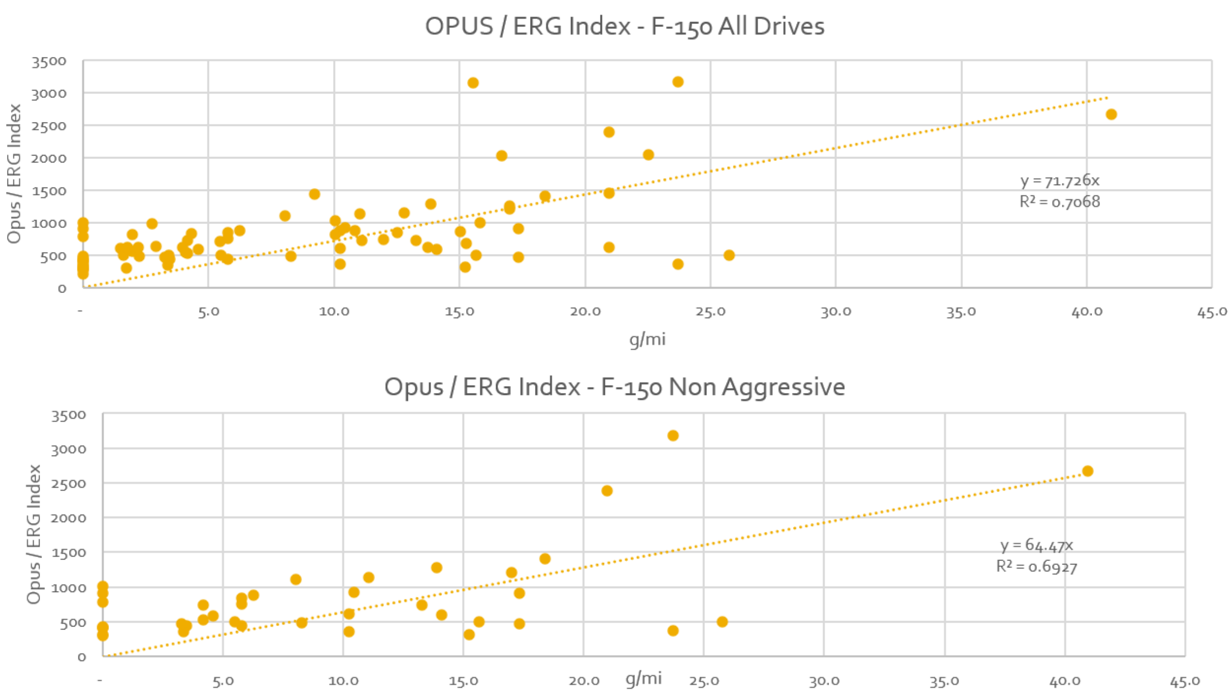


Figure 24 - Opus Evaporative Emissions Data for the F-150 With and Without Aggressive Driving



4.2.2 Actual Evaporative Leak Experiments

For the actual evaporative emissions testing, the vehicles were driven past the RSDs with actual evaporative system components disconnected including disconnection of the load line from the fuel tank to the canister at the canister, removing the purge line at the engine or removing the fuel cap. The F-150 and Mazda6 used in the experiment drove past the RSDs the first half of the day with the fuel which remained in the tank from the prior day and was allowed to soak overnight prior to use on-road (which was less than 40%). A total of 18 runs past the RSDs (6 runs with each of the three disconnections implanted at the side of the road), the vehicle was then refueled (changing the fuel vapor and liquid temperatures as described in Section 4.1.2 above) and then another 18 runs were conducted.

There was no way to know what the actual leak rates were for any location for either vehicle. For instance, even with the cap removed from the vehicles, if the vehicle was purging, it would not be expected that there would be fuel vapor escaping from the fuel filler neck. To evaluate the data, the correlations for the Opus "ERG Index" to g/mi shown in Figure 8 as noted earlier.

As can be seen in Figure 25, for the Mazda6 and the F-150, there was poor correlation between the measurements by HEAT and Opus for the same vehicles at the same time. For the Mazda6, the measurements above the background (measurements of evaporative emissions during the simulated leak experiment blanks) for each RSD were:

- Heat – 5 of 25 runs, max was 45.3 g/mi
- Opus – 3 of 33 runs, max was 7.7 g/mi

One vehicle was measured above background by both HEAT and Opus:

- Heat 34.8 and Opus 7.7 g/mi

For the F-150, the measurements above the background for each RSD were:

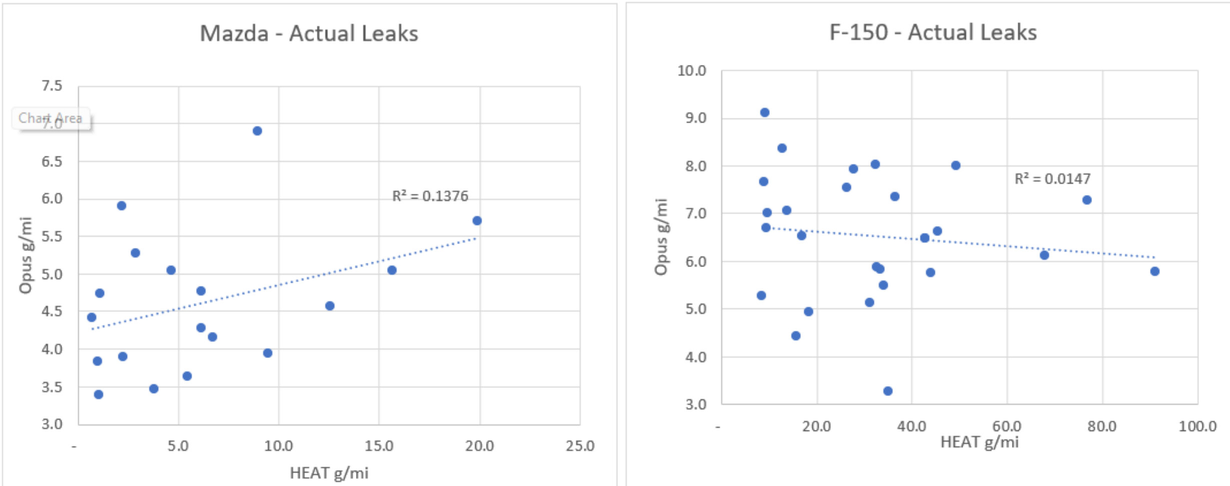
- Heat – 17 of 29 runs, max was 91.2 g/mi (cap off)
- Opus – 14 of 32 runs, max was 10.1 g/mi (cap off)

Of measurements above background:

- HEAT identified 17 and of those Opus identified 10 of the same vehicles being above background
- Opus identified 14 and of those HEAT identified 7 of the same vehicles being above background

As shown, the Mazda6 was measured to have lower actual evap emissions than the F-150 by both RSDs.

Figure 25 - HEAT Versus OPUS Measurements for The Same Run



4.3 Particulate Matter (PM) Measurements

Although the PM emission rates during certification testing of the F-150 and Mazda6 were higher than current technology vehicle standards, they were near the detection limit for the PEMs.

- 2014 Mazda6 - certified at 1.4 mg/mi PM
- 2013 Ford F-150 - certified at 5.7 mg/mi PM

The DU RSD used visible light extinction (opacity) to determine PM, and at the low emission rates, the DU instrument did not detect any PM.

Comparison of the PEMS emission rates to the measurements by HEAT and OPUS showed no correlation between the measurements for either vehicle (Figure 26 and Figure 27). Based on the PEMS measurements, the PM of the Mazda6 was an order of magnitude lower than the F-150 and was lower based on the HEAT and Opus measurements. Given the results, it would not be possible for HEAT or Opus to identify a current technology vehicle manufactured in the last 10 years which is operating at 1.5 times the standard to which it was certified, which is the standard typically applied in vehicle inspection programs for failing an in-use test.

Figure 26 - PEMS versus HEAT and Opus Reported PM Measurements For The Mazda6

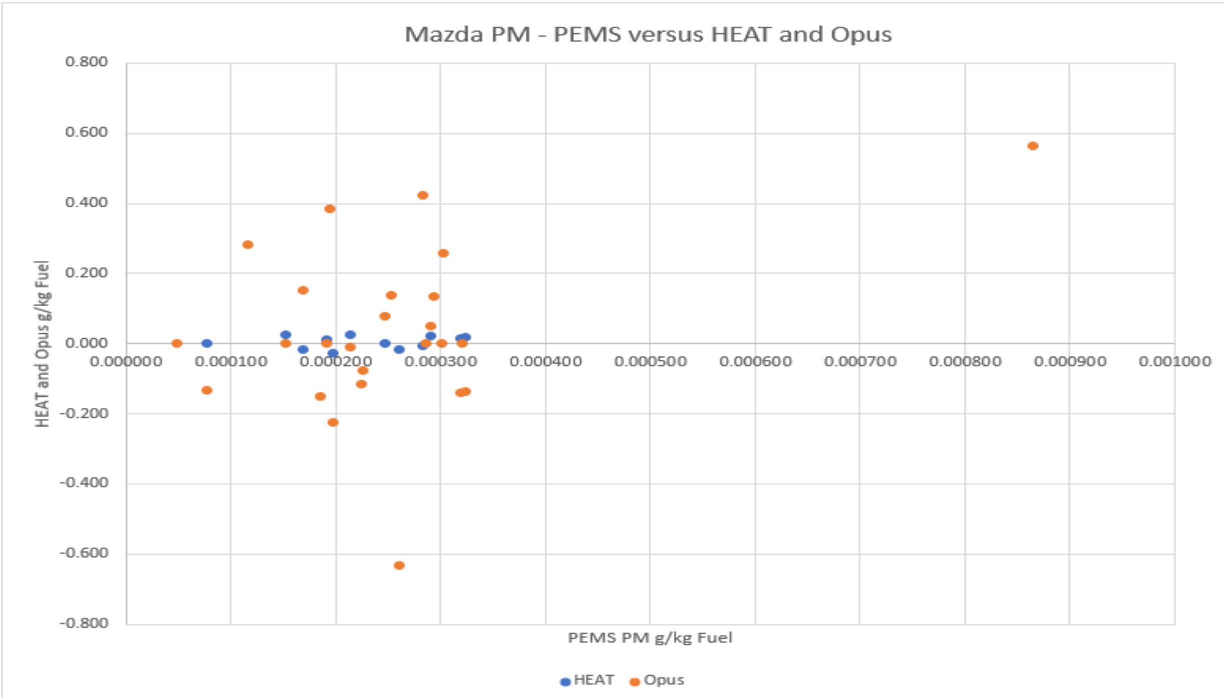
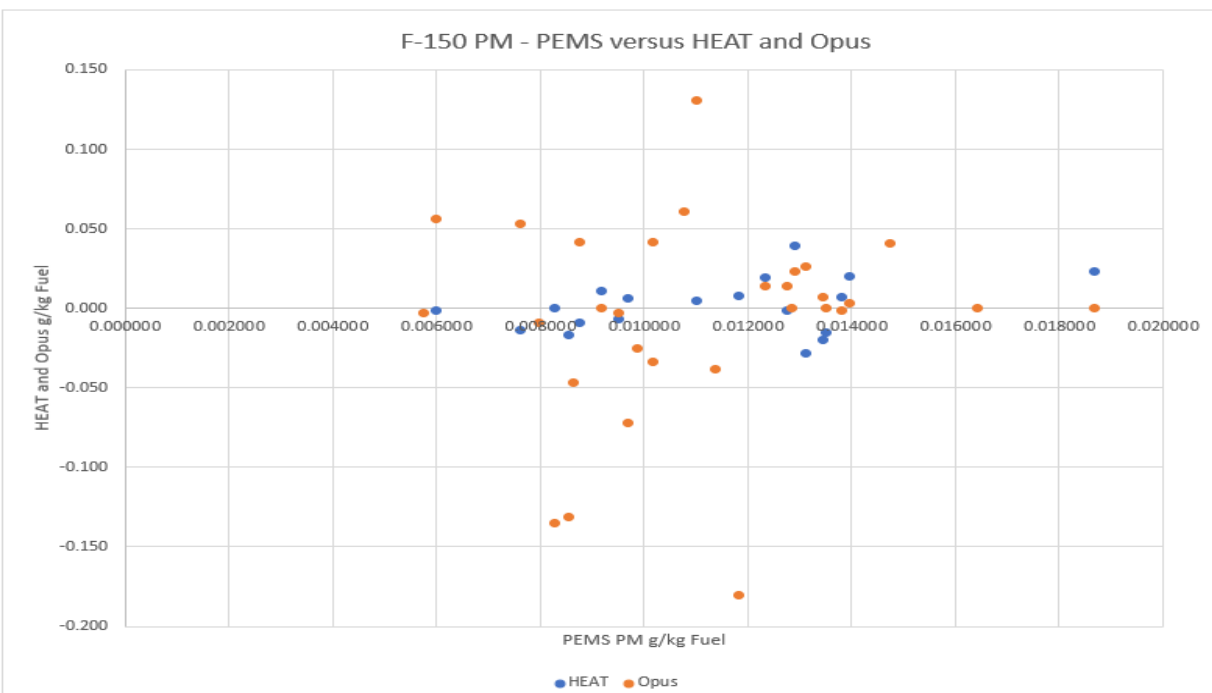


Figure 27 - PEMS versus HEAT and Opus Reported PM Measurements For The F-150



4.4 Accuracy Measuring Tailpipe Emissions

4.4.1 Simulated Tailpipe Emissions

An electric Chevy Bolt was driven past the RSDs three times a day - morning, afternoon and late in the day – all five days of the study. For each timeframe, the vehicle was driven past the RSDs three times, once releasing low concentration gas, once releasing high concentration gas, and once releasing no gas (simulating a blank) exhaust for a total of nine passes a day. On one day at the end of the study, an extra run with high gas was conducted. Therefore, over the five days of the study a total of 15 passes of the sensors while releasing low gas and 16 while releasing high gas were conducted. As noted previously, the blank runs did not emit any CO_2, therefore the RSDs did not report results for these runs.

The results of the measurements of the gases by all three RSDs are shown in Table 3. Included in the table is the average for all similar concentration gas passes (high or low) by RSD vendor, the percent difference between the average reading by the RSD and the known concentration, and the standard deviation by gas.

Table 3 - RSD Measurements of Simulated Exhaust

Results from Driving EV Past Remote Sensors Releasing Simulated Exhaust									
Simulated Exhuast		"Low" Gas (15 Passes)				"High" Gas (16 Passes)			
		NO ppm	HC ppm	CO ppm	CO2 %	NO ppm	HC ppm	CO ppm	CO2 %
Gas Concentration		249.8	255.2	498.7	14.9	773.2	756.4	15,030	14.1
DU	Average	390.9	383.5	188.2	15.0	1,104.4	520.0	16,303	13.8
HEAT		249.0	259.0	492.0	15.0	746.5	770.3	14,466	14.0
Opus		192.5	242.7	462.3	15.0	715.0	717.4	15,742	13.9
DU	Delta %	56.5	50.3	(62.3)	0.5	42.8	(31.3)	8	(1.9)
HEAT		(0.3)	1.5	(1.3)	0.5	(3.5)	1.8	(4)	(0.7)
Opus		(22.9)	(4.9)	(7.3)	0.6	(7.5)	(5.2)	5	(1.3)
DU	Std Dev	74.4	340.9	1,628.0	0.1	230.9	324.5	2,285	0.1
HEAT		4.9	41.4	16.4	0.0	7.1	42.1	1,101	0.1
Opus		69.1	69.9	211.7	0.0	70.6	53.3	732	0.1

The accuracy of the HEAT and Opus RSDs is better than that of DU. A concern is that the measurements of HEAT and Opus do not correlate well with the values reported by DU. One of the goals of the study was to determine if reading by HEAT or Opus RSDs could supplant time series measurements by DU. These results indicate that further investigation is necessary.

4.4.2 Tailpipe Emissions Measured via PEMS

The Mazda6 and the F150 had very low emission rates for HC, CO and NOx when the vehicle was operating under steady state conditions. The tailpipe emission rates measured by the PEMS were reported in both g/mi and g/kg of fuel consumed for comparison to the RSD measurements. However, only HEAT reported the RSD measurements in g/kg of fuel, both Opus and DU reported the PEMs measurements in PPM or % for HC, CO and NOx.

HEAT

Of the 56 passes for the Mazed6 and F150 combined, HEAT reported measurements for 31 of the passes. For 25 of the measurements HEAT listed “Opus Cal”, “Low CO2”, “ Interference” (an interfering plume) and “Adj. EDAR” in place of measurements.

Plots showing the relationship between the HEAT measurements and the measurements reported by the PEMS for HC, NOx and CO are shown in Figure 28, Figure 29 and Figure 30. The plots show little correlation between the HEAT reported emission rates and the PEMS reported emission rates.

Figure 28 – HEAT HC Measurements Versus PEMS, Mazda6 and F150

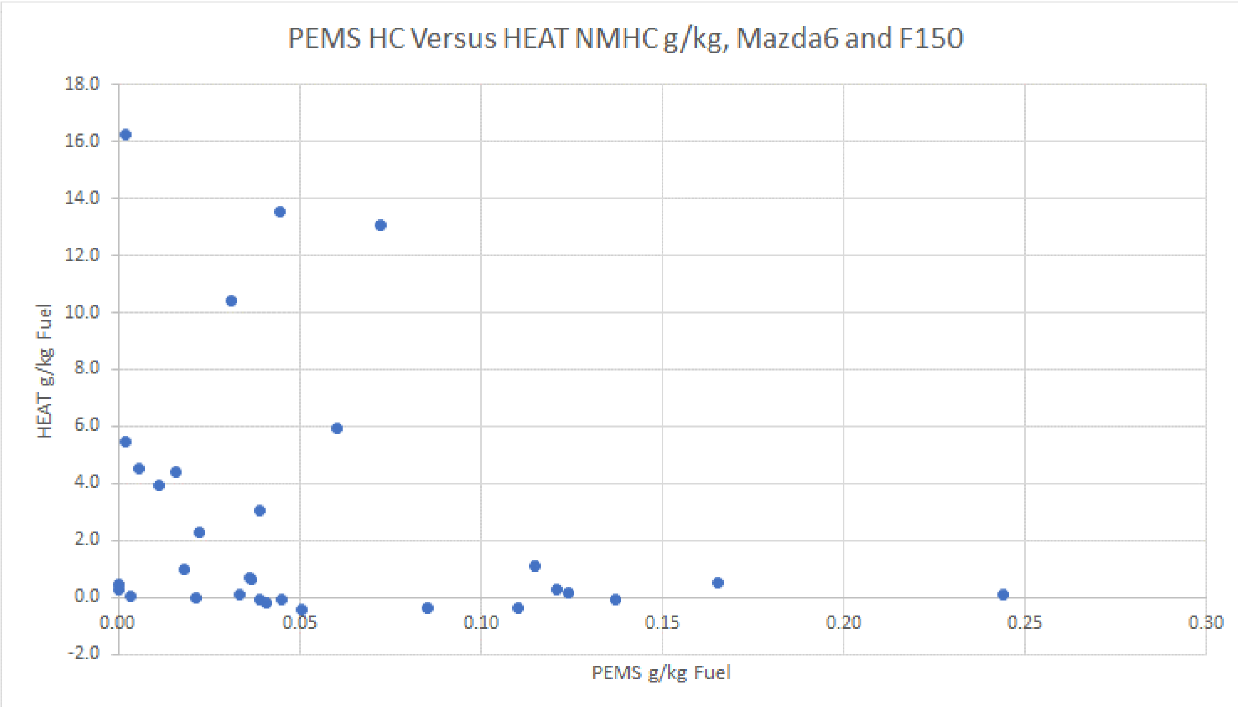


Figure 29 - HEAT NOx Measurements Versus PEMS, Mazda6 and F150

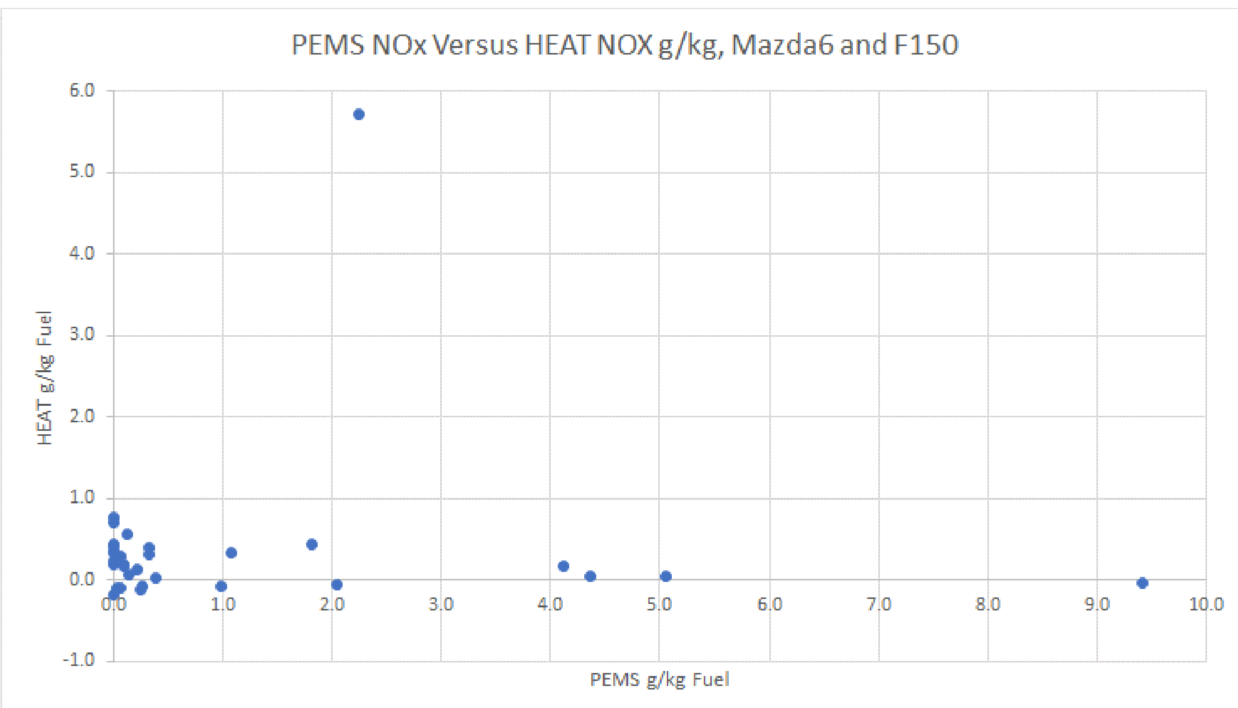
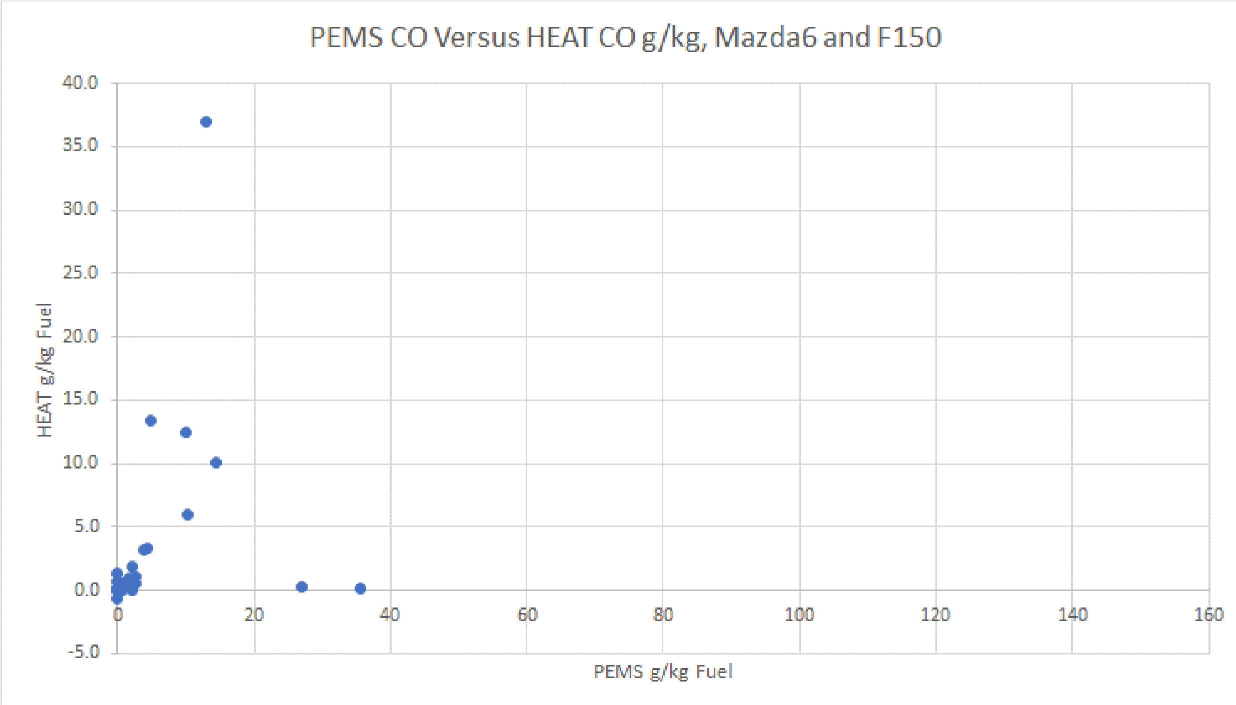


Figure 30 - HEAT CO Measurements Versus PEMS, Mazda6 and F150



Opus and DU

Opus and DU reported their emission rates in percent or parts per million (PPM)which do not correlate to the way the PEMs reported the emission rates (g/mi or g/kg fuel), therefore direct comparison of them was not possible. They were plotted against each other using percentage for CO and PPM for HC and NOx, but there was no correlation.

Opus reported 45 measurements for the 56 passes, and DU reported 48 measurements for the 56 passes.

4.5 Common License Plates

The RSD teams reported the number of valid measurements and license plates for those vehicles during the operating times of the study over five days when all three RSDs were on site operating. The total number of valid measurements for each of the RSDs is shown below.

Table 4 - Valid Emissions and License Plate Readings By RSD

Valid Readings Over Five Days	
HEAT	24,343
Opus	20,946
DU	17,245

The RSD teams provided their license plates to Revecorp and then the data were compared by license plate to determine the total number of unique license plates observed (35,299) by any RSD, and the number of times one, two or all three RSDs read the license plate of a passing vehicle.

Table 5 - Number of Measurements read by One, Two Or All Three RSDs

Vehicles with Measurements by HEAT, Opus and DU		
Measurements	# Vehicles	Fraction
1	17,763	50.3%
2	7,837	22.2%
3	9,699	27.5%
Total	35,299	

As can be seen, in the five days of data collection, 9,699 vehicles were measured by all three RSDs nearly simultaneously. There were 14,133 vehicles which were measured by HEAT and OPUS. The 9,699 measurements were used in the E-119 evaluation portion of the study to evaluate fleet tailpipe emissions and the 14,133 measurements for comparison of evaporative and PM emissions[14]. The data were also to be used for comparative analysis of measurements of tailpipe, evaporative and PM emissions between the RSDs for the same vehicle to determine how the RSDs compared.

[14] Blanchard, C. L., 2022. Draft Final Report for CRC Project No. E-119-3a, Remote Sensing Device (RSD) Statistical Analysis. Coordinating Research Council, Inc., 5755 North Point Parkway, Suite 265, Alpharetta, Georgia 30022.

5 DISCUSSION

The DU remote sensor has been the benchmark over the years collecting time series emissions measurements of vehicle tailpipe emissions. The DU RSD is going to be retired soon, and CRC needs to know if measurements taken by HEAT and Opus RSDs are comparable to measurements taken by the DU RSD. In addition, the HEAT and Opus instruments claim to have new capability to measure evaporative emissions from vehicles separately from tailpipe emissions and measure particulate matter (PM) emissions.

Therefore, the five days of testing in this study included several experiments conducted simultaneously with the following goals:

- Evaluation of the ability of the RSDs to measure evaporative emissions
- Evaluation of the ability of the RSDs to measure tailpipe particulate matter
- Evaluation of the relative accuracy and comparability of the DU, HEAT and Opus RSDs for measuring tailpipe HC, NO_x, CO and PM
- Gather data on public vehicles for evaluation of fleet tailpipe, evaporative and PM emissions and intercomparison of measurements for the same vehicles by all RSDs

The first of these three goals were analyzed in this report and the results are discussed below. The large data set from this well controlled experiment is available from CRC if further analysis is desired. Revecorp did not analyze the data form public vehicles, those data were analyzed by the RSD vendors and a statistician for CRC. Those reports are available at www.CRCAO.org.

5.1 Ability of RSDs to Measure Evaporative Emissions

The ability of the HEAT and Opus RSDs to measure evaporative emissions separately from tailpipe emissions was evaluated by releasing known quantities of butane from various locations on two research vehicles with different shapes (a car and a light duty truck). The gas was released at four locations where evaporative leaks are commonly occur, at emissions rates which were determined by experiment to be representative of large uncontrolled leaks, as a function of expected on-road temperatures.

The overall correlations of released butane to measured evaporative emissions were better for the Mazda6 car (r^2 = 0.8476) than for the F-150 truck (r^2 = 0.6424) for Opus, but the correlations were similar for HEAT and Opus for the car and truck data combined (r^2 = 0.8743 and 0.8892). This may be a function of the manner the measurements are physically taken - looking across the road at 12 inches off the ground (Opus) versus looking down on the vehicle from above (HEAT). Note that the results were determined with forcing the correlations through zero (RSD measurements were forced to zero when a blank was run when analyzing the data), however as can be seen in the plots, both RSDs reported large measurements even when there were evaporative emissions were not released by our research vehicles and the correlations between the emission rate and the RSD reported emissions were poor except at high emission rates (above 15.4 g/mi).

When comparing individual measurements by the RSDs to leak rates and considering the large amount of noise in the measurements near zero, using remote sensing to determine individual vehicle passing or failing, unless the standards are set significantly high, will cause false failures. Setting the standards high have the consequence of potentially missing a substantial portion of the evaporative leaking vehicles.

Due to the high false readings when there were no evaporative emissions from the research vehicles, the RSDs will overestimate fleet average evaporative emissions. This is a critical consideration when considering the relative contribution of evaporative emissions to overall vehicle emissions.

The simulated leaks in this study were from actual vehicles, at expected emissions rates for vehicles with completely broken evaporative emissions control system, on-road, intermixed with other on-road vehicles, in real world conditions. HEAT and Opus had quite different measurements for the same vehicles. This indicates that on a vehicle-by-vehicle basis, the measurements methods need improvement for use in the real world.

5.2 Ability of RSDs to Measure Particulate Matter (PM) Tailpipe Emissions

The PM emission rates reported by the RSDs for the two test vehicles were not correlated to the PEMs calculated emission rates and appeared to be below the detection limit of the RSDs. The PM emission rates from the two research vehicles are higher than new vehicle PM emission rates because the research vehicles are model year 2013 and 2014 and since then the emissions standards have been lowered. Given that the RSDs could not measure the test vehicles, the RSDs would not be able to identify if mid-2010 or newer vehicles are functioning properly for in-use (IM) testing. Since the majority of vehicles on-road are mid-2010 and newer which have emission rates below the RSD detection limits, RSDs cannot be used to estimate fleet average emission rates of PM.

5.3 Accuracy of RSDs to Measure Tailpipe Emissions

The overall accuracy of the HEAT and Opus RSDs when measuring consistently flowing simulated exhaust (lower and higher concentrations of calibration gas with HC, CO, CO_2, and NO_x) was good. If the goal of the RSDs is to identify the vehicles which have significantly high emissions, then the level of accuracy of the RSDs may be sufficient. It always needs to be considered that they RSDs are only measuring a moment in time in the entire vehicles operation and does not measure emissions from other operating modes such as cold start, etc. A comparison of the measurements of each individual public vehicle that passed the RSDs during the study (which was performed separately) should provide more robust results compared to the tests in this study where only two concentrations of gas were tested, under ideal conditions.

The results indicated significant differences, for the same gases, in the measurements between DU and the HEAT and Opus RSDs. Since a main goal of this research was to evaluate moving form DU measurements of fleet emissions over time to using the HEAT or Opus instruments for these measurements, the differences in results needs further investigation.

5.4 Lessons Learned

5.4.1 Study On-Road Design

The setting for the RSDs and driving research vehicles on-road with the public added complexity to the study. The RSDs were set up around a curve which prevented the public from seeing the equipment until they were very near the testing location. The first RSD, Opus, at times had staff sitting at the edge of the road at a table operating the equipment – just feet from the passing vehicles on a freeway interchange ramp. Because the road went uphill from under the bridge, it was difficult for tractor-trailers to estimate the height of the HEAT RSD hanging over the middle of the road. Some of the public slowed down due to seeing people, the equipment and all the cones. The public was naturally very curious. In a few cases vehicles actually came to a stop which was dangerous since more vehicles (sometimes our research vehicles trying to achieve a particular speed) were coming around the blind curve behind these slowed or stopped vehicles.

Although there was permanent 25 mph warning signs and blinking lights at the entry to the off ramp, and the RSD vendors erected “Shoulder Closed Ahead” signs just before vehicles passed under the bridge, this did not seem to slow the traffic. We most likely should have had "Watch for Stopped Traffic" signs, or other signs such as "Survey Team Ahead" so the motorists would know there could be slow or stopped vehicles, staff and equipment ahead.

We did not anticipate that HEAT would temporarily locate their reflective strip above the road surface and that it would cause vehicles to bounce and then this impacted Opus's equipment alignment. The final solution was to move the Opus equipment further from the HEAT equipment, but one of the goals of the study was to have the equipment as close as possible. This should be considered if more studies with both RSDs are conducted in the future.

For the measurement of the simulated exhaust gas, we did not anticipate the RSDs required some CO_2 to trigger the RSD measurement systems and allow for their calculations. The blanks were run with no gas being emitted from the electric vehicle. A blank gas with 14.5% CO_2 should have been used as the blank.

5.4.2 Study Experimental Design

The limitation of the RSD measurements when there were no evaporative emissions simulated (the blanks) made it difficult to determine the lower limit for the RSDs to measure evaporative emissions. The reason for this difficulty was unclear, was it due to interference from the tailpipe emissions or other causes. It would have been helpful to perform simulated evaporative emissions runs with lower emissions rates and with more highly variable vehicle tailpipe pollutant concentrations. It would have been useful to measure both the tailpipe HC and know the simulated evaporative HC emission rates, so that total HC emissions from the vehicles could be evaluated to see how they impacted the attribution of HC to evaporative or tailpipe emissions.

The exhaust from the PEMS was located at the right edge of the vehicles, directed toward the side of the vehicles. This may have been pushing some of the exhaust out of the measurement paths, past the RSDs view.

It would have been useful to have a research vehicle with the PEMS installed where the PM level generated by the engine could be caused to vary, allowing for differing levels of PM to be measured. The low levels of PM emissions from the two research vehicles did not exercise the dynamic ranges of any of the RSDs, so the experiments provided limited information.

5.5 Future Suggested Research

The study evaluated data from controlled experiments, however there were some limitations or findings which should be investigated further that may be useful. These include:

- The correlation of HEAT and Opus to the simulated exhaust gases was much better than DU, and neither HEAT nor Opus had similar measurements to DU for any gas. This should be investigated further.
- If more is desired to be known about the ability of the RSDs to measure PM emissions, this needs to be done with a research vehicle that allows the mass of PM emissions to be varied to levels above those of the two research vehicles used in this experiment
- Both HEAT and Opus operate on-road sampling programs in various locations, some outside of IM areas. It may be useful to use apply correlations factors developed in this study (RSD reported evaporative emissions in g/mi rates) to the RSD on-road data collected to re-evaluate on-road evaporative emissions, and to determine which vehicles are the largest contributors.

- The noise levels in the evaporative measurements was large. Reports which use RSD measurements to determine vehicle evaporative emission rates which are then used to estimate fleet evaporative emissions should be reviewed to determine if the noise in the RSD evaporative emissions measurements is taken into consideration.
- It would be useful to know for vehicles which do have high evaporative emissions, if the Malfunction Indicator Light (MIL) is illuminated. If it were possible to use the RSDs to measure vehicles on-road and as soon as possible after a vehicle is identified with high emissions on-road, contact the owner and find out if the MIL is illuminated.

6 APPENDICIES

6.1 Appendix 1 – Simulated Exhaust Gases Certification Data

Airgas
an Air Liquide company

Airgas Specialty Gases
Airgas USA, LLC
11711 S. Alameda Street
Los Angeles, CA 90059
Airgas.com

CERTIFICATE OF ANALYSIS

Grade of Product: TRACEABILITY STANDARD

Part Number:	X05NI84T15A0005	Reference Number:	48-401998557-1
Cylinder Number:	AAL069462	Cylinder Volume:	152.6 CF
Laboratory:	124 - Los Angeles (SAP) - CA	Cylinder Pressure:	2015 PSIG
		Valve Outlet:	660
		Certification Date:	Jan 21, 2021

Expiration Date: Jan 21, 2029

This cylinder has been analytically certified as directly traceable to NIST with a total analytical uncertainty as stated below with a confidence level of 95%, in accordance with Airgas ISO procedures. There are no significant impurities which affect the use of this calibration mixture. All concentrations are on a mole/mole basis unless otherwise noted.

Do Not Use This Cylinder Below 100 psig.

ANALYTICAL RESULTS

Component	Requested Concentration	Actual Concentration	Total Relative Uncertainty
NOX	750.0 PPM	773.2 PPM	+/- 1% NIST Traceable
NITRIC OXIDE	750.0 PPM	771.5 PPM	+/- 1% NIST Traceable
PROPANE	750.0 PPM	756.4 PPM	+/- 1% NIST Traceable
CARBON MONOXIDE	1.500 %	1.503 %	+/- 1% NIST Traceable
CARBON DIOXIDE	13.99 %	14.07 %	+/- 1% NIST Traceable
NITROGEN	Balance		

CALIBRATION STANDARDS

Type	Lot ID	Cylinder No	Concentration	Uncertainty	Expiration Date
NTRM	15010320	KAL003769	980.7 PPM NITRIC OXIDE/NITROGEN	+/- 0.5%	Aug 21, 2021
GMIS	401203436104	CC513876	4.653 PPM NITROGEN DIOXIDE/NITROGEN	+/- 2.1%	May 02, 2022
NTRM	15060803	CC462447	992.3 PPM PROPANE/NITROGEN	+/- 0.6%	Jul 22, 2021
NTRM	97010912	ALM-066197	1.984 % CARBON MONOXIDE/NITROGEN	+/- 1.0%	Mar 12, 2024
NTRM	08010611	K005428	13.94 % CARBON DIOXIDE/NITROGEN	+/- 0.6%	Jan 30, 2024

ANALYTICAL EQUIPMENT

Instrument/Make/Model	Analytical Principle	Last Multipoint Calibration
SIEMENS 6E CO2	NDIR	Jan 15, 2021
SIEMENS 6E CO HIGH	NDIR	Jan 14, 2021
Nicolet 6700 AHR0801551 NO	FTIR	Jan 15, 2021
Nicolet 6700 AHR0801551 NO2	FTIR	Jan 15, 2021
Nicolet 6700 AHR0801551 C3H8	FTIR	Jan 13, 2021

Triad Data Available Upon Request

PERMANENT NOTES:-NA-

Michael

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Page 1 of 48-401998557-1

Airgas
an Air Liquide company

Airgas Specialty Gases
Airgas USA, LLC
11711 S. Alameda Street
Los Angeles, CA 90059
Airgas.com

CERTIFICATE OF ANALYSIS

Grade of Product: TRACEABILITY STANDARD

Part Number:	X05NI84T15A0006	Reference Number:	48-401998558-1
Cylinder Number:	CC76567	Cylinder Volume:	153.2 CF
Laboratory:	124 - Los Angeles (SAP) - CA	Cylinder Pressure:	2015 PSIG
		Valve Outlet:	660
		Certification Date:	Jan 05, 2021

Expiration Date: Jan 05, 2029

This cylinder has been analytically certified as directly traceable to NIST with a total analytical uncertainty as stated below with a confidence level of 95%, in accordance with Airgas ISO procedures. There are no significant impurities which affect the use of this calibration mixture. All concentrations are on a mole/mole basis unless otherwise noted.

Do Not Use This Cylinder Below 100 psig.

ANALYTICAL RESULTS

Component	Requested Concentration	Actual Concentration	Total Relative Uncertainty
NOX	250.0 PPM	249.8 PPM	+/- 1% NIST Traceable
NITRIC OXIDE	250.0 PPM	249.3 PPM	+/- 1% NIST Traceable
PROPANE	250.0 PPM	255.2 PPM	+/- 1% NIST Traceable
CARBON MONOXIDE	500.0 PPM	498.7 PPM	+/- 1% NIST Traceable
CARBON DIOXIDE	15.01 %	14.93 %	+/- 1% NIST Traceable
NITROGEN	Balance		

CALIBRATION STANDARDS

Type	Lot ID	Cylinder No	Concentration	Uncertainty	Expiration Date
NTRM	18060133	KAL004370	249.9 PPM NITRIC OXIDE/NITROGEN	+/- 0.4%	Nov 08, 2023
GMIS	401203436104	CC513876	4.653 PPM NITROGEN DIOXIDE/NITROGEN	+/- 2.1%	May 02, 2022
NTRM	10060508	CC281242	495.3 PPM PROPANE/AIR	+/- 0.5%	Jan 06, 2022
NTRM	15060524	CC450548	491.9 PPM CARBON MONOXIDE/NITROGEN	+/- 0.6%	Jan 08, 2021
NTRM	08010615	K011262	13.94 % CARBON DIOXIDE/NITROGEN	+/- 0.6%	Jan 30, 2024

ANALYTICAL EQUIPMENT

Instrument/Make/Model	Analytical Principle	Last Multipoint Calibration
Nicolet 6700 AHR0801551 CO2 HIGH	FTIR	Dec 18, 2020
SIEMENS 6E CO LOW	NDIR	Dec 11, 2020
Nicolet 6700 AHR0801551 NO	FTIR	Dec 14, 2020
Nicolet 6700 AHR0801551 NO2	FTIR	Dec 14, 2020
Nicolet 6700 AHR0801551 C3H8	FTIR	Dec 09, 2020

Triad Data Available Upon Request

PERMANENT NOTES:-NA-

Approved for Release

Page 1 of 48-401998558-1