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Is That Route Really the Most Fuel-Efficient?

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NATIONAL INSTITUTE FOR CONGESTION REDUCTION

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16. Abstract

Many travelers use Google Maps to select the route for their trip and the Google recommendation can have a significant impact on traffic congestion. Google recently added a new route option: the most fuel-efficient route. In theory, the algorithm behind this route selection (Route E) examines the current travel conditions on the available routes and estimates typical fuel consumption based on those conditions. This should include acceleration/deceleration events as these change of speed events significantly impact fuel consumption and are a critical aspect of selecting the most fuel-efficient route, especially when comparing freeway general purpose lanes (GPLs) to Express Lanes/Managed Lanes (MLs). Initial testing of the Google Maps algorithm indicates it may not account for these speed changes.

This study examines if the new route guidance from Google Maps is accurately identifying the most fuel-efficient routes and tests the RouteE API models. Researchers examined typical travel conditions on GPLs and MLs on two Dallas freeways with MLs. Several vehicles equipped with on-board diagnostic (OBD) data loggers recorded key aspects of the vehicle operations while driving in real-world traffic conditions. These vehicles were driven on the Dallas freeways (both GPLs and MLs) during various traffic conditions, which allowed for detailed fuel consumption to be estimated based on the OBD data collected. The data collected from OBD devices were then compared with RouteE and MOVES for their accuracy on the fuel usage estimation.

RouteE and MOVES were both found to miss the actual fuel consumption by a significant amount and do not appear to accurately incorporate speed changes of vehicles in real-world situations. Thus, it was not surprising that Google would usually identify the GPLs as the most fuel-efficient route when comparing GPLs and MLs. Using the real-world fuel consumption data along with detailed speed profiles, researchers developed equations that could be used to estimate fuel consumption based on microscopic traffic data on vehicle speeds. Unlike Google, our real-world based fuel consumption equations, along with detailed Wejo traffic data, found the MLs to be more likely to be the most fuel-efficient, but this varied based on the exact traffic conditions. This was based on a small set of fuel consumption data and can only be used as proof of concept. It does show the importance of including speed changes in the analysis. There needs to be considerably more data collected in real-world conditions to further refine these models of fuel consumption and possibly incorporate these models into route recommendation algorithms. This research shows that this proof of concept model can prove helpful in estimating route-specific emissions when combined with either high-resolution data like that from Wejo or lower-resolution data like that from Google to provide a more accurate estimate of which route really is more fuel-efficient.

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Executive Summary

Google recently introduced the most fuel-efficient route feature to its mapping software (see Figure 1). This feature uses the US Department of Energy's National Renewable Energy Laboratory RouteE and FASTSim technologies to estimate fuel consumption (https://www.nrel.gov/news/program/2021/google-taps-nrel-expertise-to-incorporate-energy-optimization-into-google-maps-route-guidance.html). The NREL model indicated it included factors such as fuel consumption for vehicles in that area, road grade, speed profiles, and road type (https://www.nrel.gov/docs/fy22osti/81097.pdf). The software examined potential routes and provided guidance on the fastest and the most fuel-efficient route based on the user's selected origin and destination. Google estimated this feature could reduce carbon emissions by over 1 million tons per year (https://www.autoblog.com/2021/10/18/google-maps-eco-friendly-routes/). However, in some cases, this fuel-efficient routing algorithm may be moving travelers to a less fuel-efficient route or misestimating the actual benefit. This is particularly relevant in the case of congested freeways, most saliently represented by freeways with an express lane/managed lane (ML) option. This would reduce the impact of the Google Maps feature and would likely be encouraging additional use of the more congested General Purpose Lanes (GPLs) over the free-flowing MLs, adding to congestion as well as fuel consumption and emissions. Our research examines this issue and helps companies like Google and MapUP identify the most fuel-efficient route. This will also help to reduce traffic congestion as the algorithm may be misrouting people onto congested GPLs now.

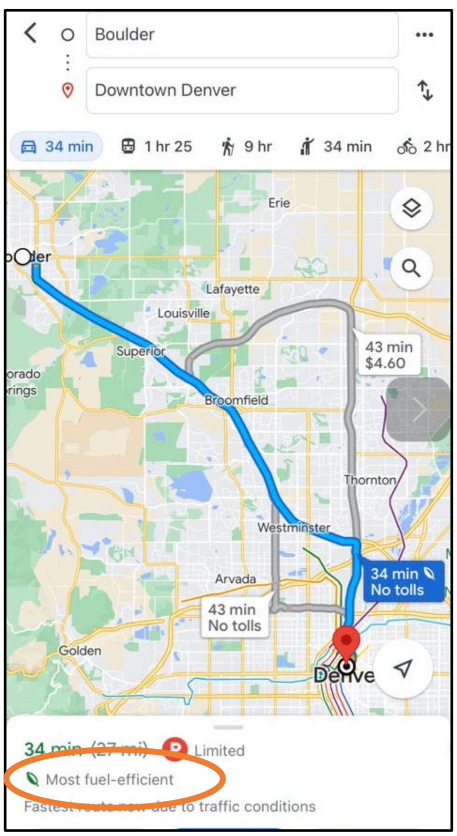

Figure 1: Google Map's recommendation on fuel-efficient route

The goal of this study was to develop an accurate method for determining vehicle fuel consumption particularly in real world situation that includes changes in speed. This was done by performing several vehicle runs on Dallas highways using 4 different categories of vehicles: SUVs, sedans, a hybrid vehicle, and pick-up trucks. The study location was selected for freeways with MLs and GPLs running parallel to each other. The freeways were I-35W and I-820/SH183/SH121 in the Dallas–Fort Worth area. Nearly 100 vehicle runs were performed for data collection using two OBD data loggers (HEM Data and VEEPEAK). These devices recorded the precise time-of-the-day, corresponding speed, engine parameters (engine speed, load, mass air flow), and geographic coordinates. Mass air flow provides a direct correlation to fuel consumption. Both data loggers were then evaluated for their accuracy with respect to fuel consumption. This was done by comparing the results from the OBD data with that of the U.S. EPA's Motor Vehicle Emissions Simulator (MOVES) estimations and how much fuel the vehicle actually used (ground truth). After multiple evaluations, the HEM Data OBD Mini Logger (https://hemdata.com/products/dawn/obd-mini-logger/) was found to be the best-performing data logger, and VEEPEAK was not used, primarily due to gaps in the second-by-second data needed for accurate estimations.

In the second step, the vehicle fuel consumption by speed results from the HEM OBD device and MOVES were compared. After multiple tests, it was found that HEM better captured the fuel consumption changes with the vehicle's acceleration or deceleration.

In the third step, the accuracy of NREL's RouteE model was tested by comparing it with ODB results and MOVES estimates and it was concluded that the algorithm had a problem. The RouteE model did not take congestion and speed fluctuations into consideration and therefore the fluctuations in fuel consumption were not accurate. Thus, it was not surprising that Google Maps would often identify the GPLs as the most fuel-efficient route when comparing GPLs and MLs.

Finally, researchers developed models of fuel consumption based on speed change over 0.2-mile increments. OBD data was split into 0.2-mile segments and fuel consumption and speed change over that segment was determined. Regression models were estimated by examining the change in fuel consumption versus the speed change over that 0.2-mile segment. This was done for multiple speed brackets. The result is a model of fuel consumption based on average speed and change in speed over a 0.2-mile segment of freeway. Combining these models with disaggregate vehicle speed data, such as Wejo, could result in an extremely accurate estimate of fuel consumption on a section of freeway. This was tested for our Dallas freeways and showed promising results.

Unlike Google, our real-world based fuel consumption equations along with detailed Wejo traffic data found the MLs to be more likely to be the most fuel efficient, but this varied based on the exact traffic conditions. Also note this was based on a very small set of fuel consumption data and can only be used for proof of concept. There needs to be considerably more data collected in real world conditions to further refine these models of fuel consumption. Then combine these models with Wejo or Google data on traffic speeds to provide a more accurate estimate of which route really is more fuel efficient.

1.0 Introduction

In 2020, the transportation industry produced 12 billion metric tons of greenhouse gas (GHG) emissions globally, including CO_2, N_2O, and methane. This is expected to increase to 21 billion metric tons by 2050, producing environmental and human health problems [1]. Governments across the world are now striving for more environmentally friendly modes of transportation. However, achieving a 100% sustainable transportation system is not possible soon. Therefore, measures are undertaken to mitigate emissions. In this regard, Google Maps has recently added a new feature that recommends the most fuel-efficient route to its users. This new feature was added after researchers from Colorado showed a significant association between the energy consumed and the elevation change along the route. NREL studied this further and developed the RouteEnergy Prediction Model (RouteE) to predict a vehicle's energy use along a route. This got them a partnership with Google and we can now see the model running in the Google Maps [2]. The model accounts for factors like traffic speed, traffic congestion, and road elevation change. It uses the Future Automotive Systems Technology Simulator (FASTSim), which is based on powertrain modeling, in combination with real-world data from the Transportation Secure Data Center to determine the energy consumed by a vehicle.

Google estimates the use of their fuel-efficient routing could reduce carbon emissions by 1 million tons per year [3]. However, initial investigation of the results from this routing software found problems calculating fuel consumption on Managed Lanes (MLs) versus General Purpose Lanes (GPLs). If their fuel-efficient routing algorithm has does not accurately predict fuel consumption then it may be moving travelers to a less fuel-efficient route in some cases, or misestimating the actual benefit that is possible from the technology. This would reduce the impact of the Google Maps feature and would likely be encouraging additional use of the more congested General-Purpose Lanes (GPLs) over the free-flowing Managed Lanes (MLs), adding to congestion as well as fuel consumption and emissions.

This study examines if the new route guidance from Google Maps using Route E is accurately identifying the most fuel-efficient routes by testing the RouteE API models. To do this, researchers examined typical travel conditions on GPLs and MLs on two Dallas freeways with MLs. Several vehicles equipped with onboard diagnostic (OBD) data loggers record key aspects of the vehicle operations while driving in real-world traffic conditions. These vehicles were driven on the Dallas freeways (both GPLs and MLs) during various traffic conditions, which allowed for detailed fuel consumption to be estimated based on the OBD data collected. The data collected from OBD devices were then compared with RouteE and MOVES for their accuracy on the fuel usage estimation.

Therefore, the main objectives of this study were:

1. To examine if the new route guidance from Google Maps is accurately identifying the most fuel-efficient routes by testing the RouteE API models.
2. Collection of real-world fuel consumption data from 4 different categories of vehicles (SUV, Sedan, Hybrid and Pick-up trucks).
3. Testing and identifying the most accurate on-board diagnostic (OBD) data loggers.
4. Comparing the fuel consumption data from the most accurate OBD with MOVES.
5. Estimating the change in fuel consumption with change in speed for all 4 categories the vehicles.

2.0 Initial Investigation of RouteE API

To begin, the research team testing the open-source RouteE API models. The website (https://developer.nrel.gov/docs/transportation/routee-v1/) allows for three different analyses:

1. /route: Which estimates energy consumption for a single route
2. /network: Predicts the energy consumption on a network level
3. /compass/beta: For giving the shortest path

2.1 Energy consumption estimates

This research began by testing the /route API which gives an estimate of the energy consumption on a particular route. 3 scenarios were tried:

1. The car travels at 70mph for 6 miles, then 30 mph for 6 miles.
2. The car travels at 70mph for 1 mile and then 30 mph for 1 mile, repeating this cycle six times.
3. The car travels 70mph for 0.5 miles and then 30mph for 0.5 miles, repeating this cycle 12 times.

For all three scenarios, the same energy use was reported (see Figure 2). This indicates that the software was not accounting for at least some speed fluctuations.

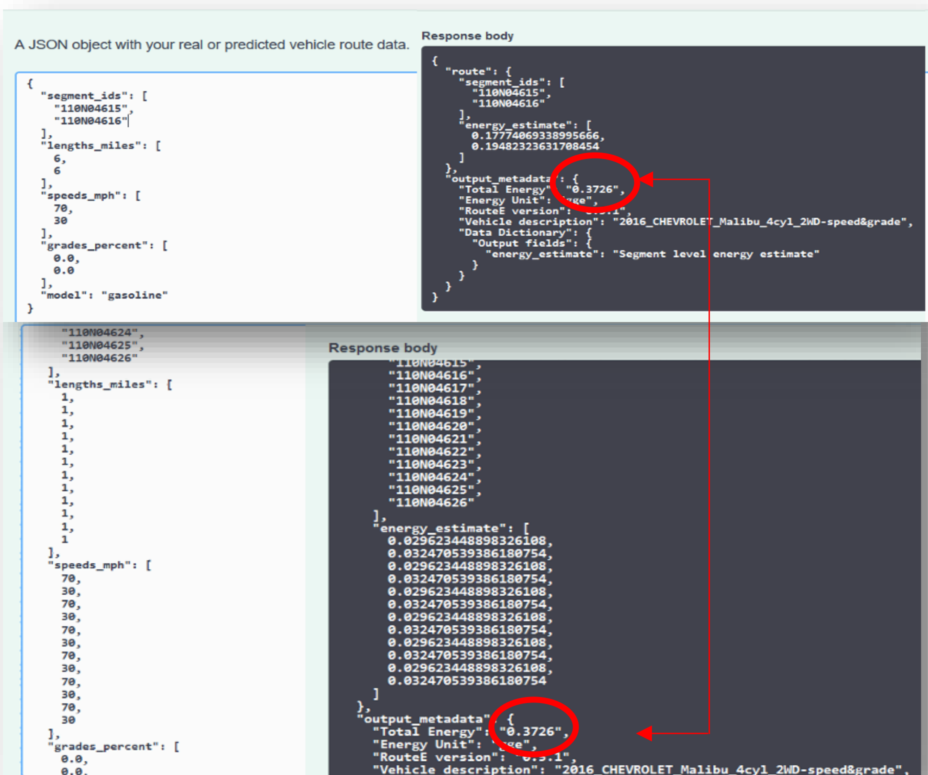

Figure 2: RouteE results on fuel usage

The three scenarios mentioned above were then tested in MOVES (see Figure 3). Comparing the NREL results with MOVES in Figure 3 it can be seen that MOVES gives more accurate results and the fuel usage changes with a change in speed. MOVES estimates the fuel usage of 0.20 gal, 0.25 gal, and 0.32 gal for scenarios 1, 2, and 3 respectively. All of these are lower than the NREL estimate of 0.37 gal.

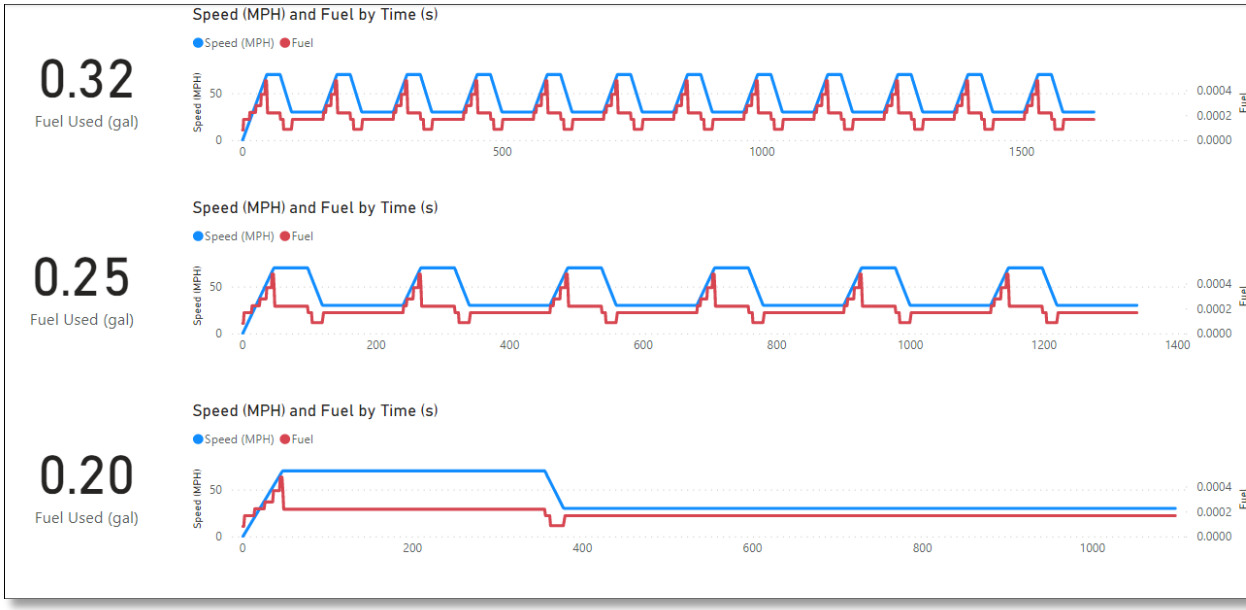

Figure 3: Fuel usage with change in speed using MOVES

The /network API on the NREL website (the second option) was then tested by adding the AADT of the different vehicles (gas, diesel, electric, hybrid). It estimates fuel consumption for a variety of vehicles over all links in a transportation network. It takes inputs on segment _id, miles, speed, grade, volume, and ratios on gasoline, diesel, hybrid, and electric. However, it simply multiplies the fuel consumption estimate found by the /route API by the number of that vehicle type. Thereby, multiplying any error from the single-vehicle analysis found above.

2.2 Fuel-Efficient Route

The NREL also provides an API for identifying the most fuel-efficient route between the OD pairs (the third option called /compass/beta). Currently, the algorithm has been developed only for the Denver region. So, the team selected two routes to examine: (1) downtown Denver to Douglas County and (2) Boulder to downtown Denver. The team used the NREL API to identify the most fuel-efficient route during different times of the day.

RouteE always returned the same results on the shortest path regardless of the time of day. Comparing the RouteE results with Google Maps as shown in Figure 4 and Figure 5, it was found that the API results are far from accurate. Considering a particular origin and destination (ODs) and comparing the results for fuel-efficient route, NREL's API recommended route with travel time almost double Google's recommended route. Doing this for multiple ODs and at different times of the day NRELs API returned same results that were very different from Google's recommended routes. These results tell us that the shortest path API of NREL does not necessarily use real-time data to determine the shortest path.

In talking with NREL staff, the research team was informed that RouteE is developed to be a macroscopic model and does not consider some of the important variables like congestion level and lane type and therefore does not necessarily provide accurate results on the fuel usage and the shortest route.

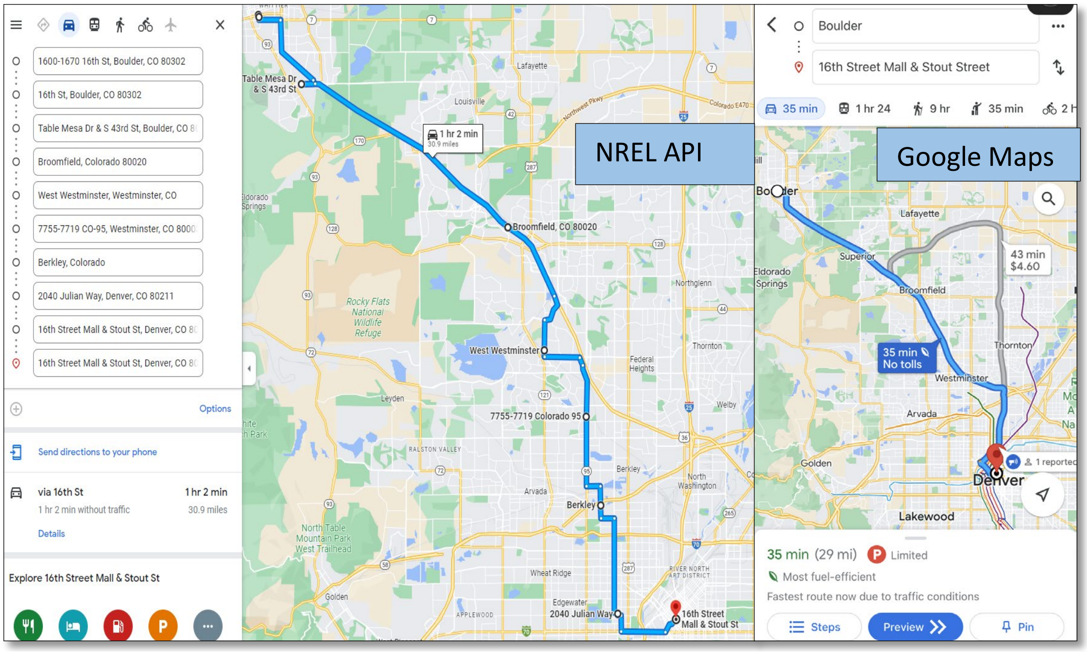

Figure 4: Comparison of the fuel-efficient route from Downtown Denver to Douglas County by the NREL API and Google Maps

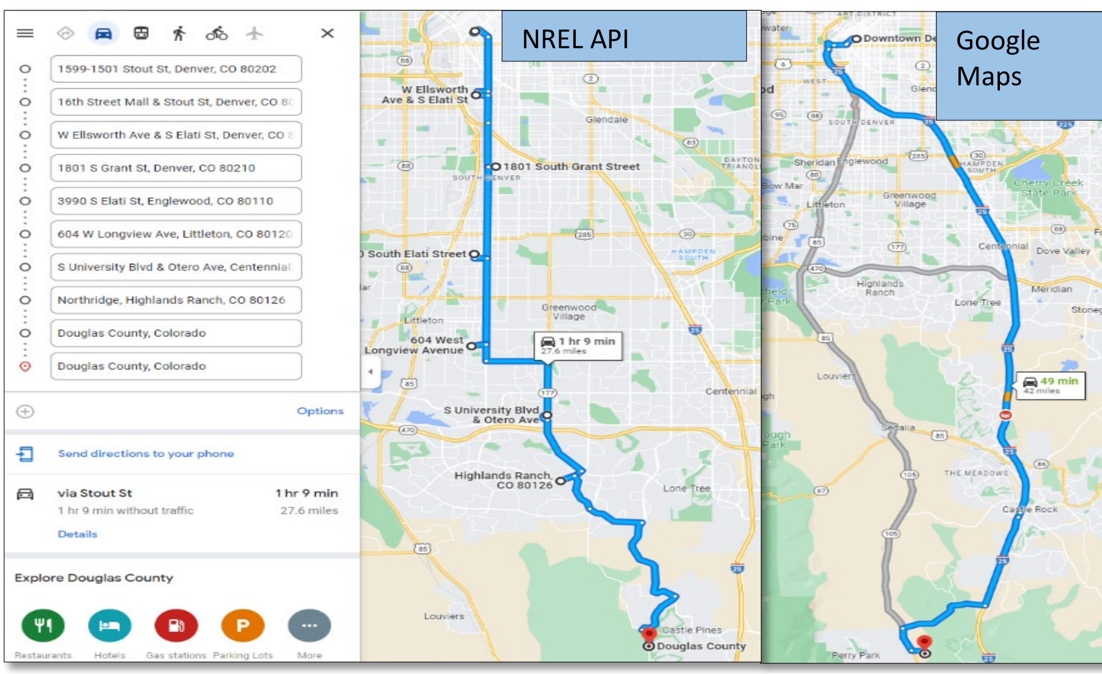

Figure 5: Comparison of the fuel-efficient route from Boulder to Downtown Denver by the NREL API and Google Maps

3.0 Google Maps Recommendation

A traveler can now enable the most fuel-efficient route option in Google Maps. It makes use of a sizable NREL database to find the route that uses the least amount of fuel and is supposed to take into account any variables that may have an impact on CO_2 emissions and fuel consumption. The variables include the typical fuel consumption for cars in the area, the gradient of the route, congestion level, and type of road. If this feature is turned off, then the app will always recommend the fastest route showing the fuel-efficient route as an alternative route. However, it is unclear how well the app takes speed fluctuations into account.

The research team studied the trends on the route recommendations suggested by Google Maps. This was done by first enabling the fuel-efficient feature in the app and then by choosing an origin and destination (Melody Hills to Euless, Dallas) at many times of the day and recording the route suggestions by Google along with the travel time and the lane type. The alternate route recommendations by Google and the respective travel time and lane type were also recorded and shown in Table 1. The origin and destination were chosen to have both an express (toll) lane and non-toll option in Dallas.

It was found that Google generally provides 3 different types of recommendations: fuel-efficient route, best route, and fastest route.

1. **Fuel-efficient route**: Google recommended the most fuel-efficient route 58% of the time. The freeway (non-toll lanes) was the more fuel-efficient route 79% of the time. The toll lanes were only found to be more fuel efficient if they were at least 9 minutes faster.
2. **Best route due to congestion**: Recommended mostly due to road closure as shown in Figure 6.
3. **Fastest route due to congestion:** The fuel-efficient route was not shown even as an alternative. The toll lanes were recommended 71% of the time.

Table 1: Google Maps Recommended Routes

DATE	TOD	ORIGIN	DESTINATION	RECOMMENDED	RECOMMENDED _TT	RECOM_ROUTE_TYPE	ALTERNATE	ALT-TT
24-Jun	10:58 AM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	34 mins	Freeway	Toll lane	38 mins
24-Jun	12:21 PM	Richland Hills, Texas	Parkland Mem Hospital	best route due to congestion	35 mins	Freeway	fuel eff route	34 mins
27-Jun	12:02 PM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	33 mins	Freeway	Toll lane	37 mins
27-Jun	1:20 PM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	33 mins	Freeway	Toll lane	37 mins
27-Jun	4:17 PM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	40 mins	Freeway	Toll lane	37 mins
27-Jun	6:09 PM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	33 mins	Freeway	Toll lane	37 mins
27-Jun	7:59 PM	Richland Hills, Texas	Parkland Mem Hospital	best route due to congestion	30 mins	Freeway	Toll lane	34 mins
23-Aug	11:57 AM	Richland Hills, Texas	Parkland Mem Hospital	fuel-efficient	33 mins	Freeway	Toll lane	32 mins
23-Aug	2:08 PM	Richland Hills, Texas	Parkland Mem Hospital	Fastest route due to congestion	35 mins	Toll lane		
24-Aug	1:59 PM	Richland Hills, Texas	Parkland Mem Hospital	Fastest route due to road closure	35 mins	Freeway		
24-Jun	10:59 AM	Parkland Mem Hospital	Richland Hills, Texas	fuel-efficient	27 mins	Toll lane	Freeway	36 mins
24-Jun	12:24 PM	Parkland Mem Hospital	Richland Hills, Texas	fuel-efficient	28 mins	Toll lane	Freeway	38 mins
27-Jun	12:03 PM	Parkland Mem Hospital	Richland Hills, Texas	Fastest route due to congestion	27 mins	Toll lane	Toll lane	35 mins
27-Jun	1:20 PM	Parkland Mem Hospital	Richland Hills, Texas	fuel-efficient	30 mins	Freeway	-	-
27-Jun	4:18 PM	Parkland Mem Hospital	Richland Hills, Texas	Fastest route due to congestion	30 mins	Toll lane	Toll lane	43 mins
27-Jun	6:08 PM	Parkland Mem Hospital	Richland Hills, Texas	Fastest route due to congestion	27 mins	Toll lane	Toll lane	37 mins
27-Jun	7:58 PM	Parkland Mem Hospital	Richland Hills, Texas	fuel-efficient	27 mins	Freeway	-	
23-Aug	11:59 AM	Parkland Mem Hospital	Richland Hills, Texas	Best route due to road closure	36 mins	Toll lane	TOOLS - FUEL EFFICIENT	27 mins
23-Aug	2:09 PM	Parkland Mem Hospital	Richland Hills, Texas	fuel-efficient	30 mins	Toll lane	Freeway	43 mins
24-Aug	2:01 PM	Parkland Mem Hospital	Richland Hills, Texas	Fastest route due to congestion	27 mins	Freeway	Toll lane	35 mins
24-Aug	2:04 PM	Parkland Mem Hospital	Melody hills	Fastest route due to traffic condition	32 MINS	Toll lane		
23-Aug	2:12 PM	Fort Worth	Hawaiian Brothers Tarrant County	fuel-efficient	14 mins	Freeway	Toll lane	16 mins
23-Aug	3:29 PM	Melody hills	Euless	fuel-efficient	20 mins	Freeway	Toll lane	23 mins
24-Aug	2:04 PM	Melody hills	Parkland Mem Hospital	fuel-efficient	38 mins	Freeway	Toll lane	42 mins

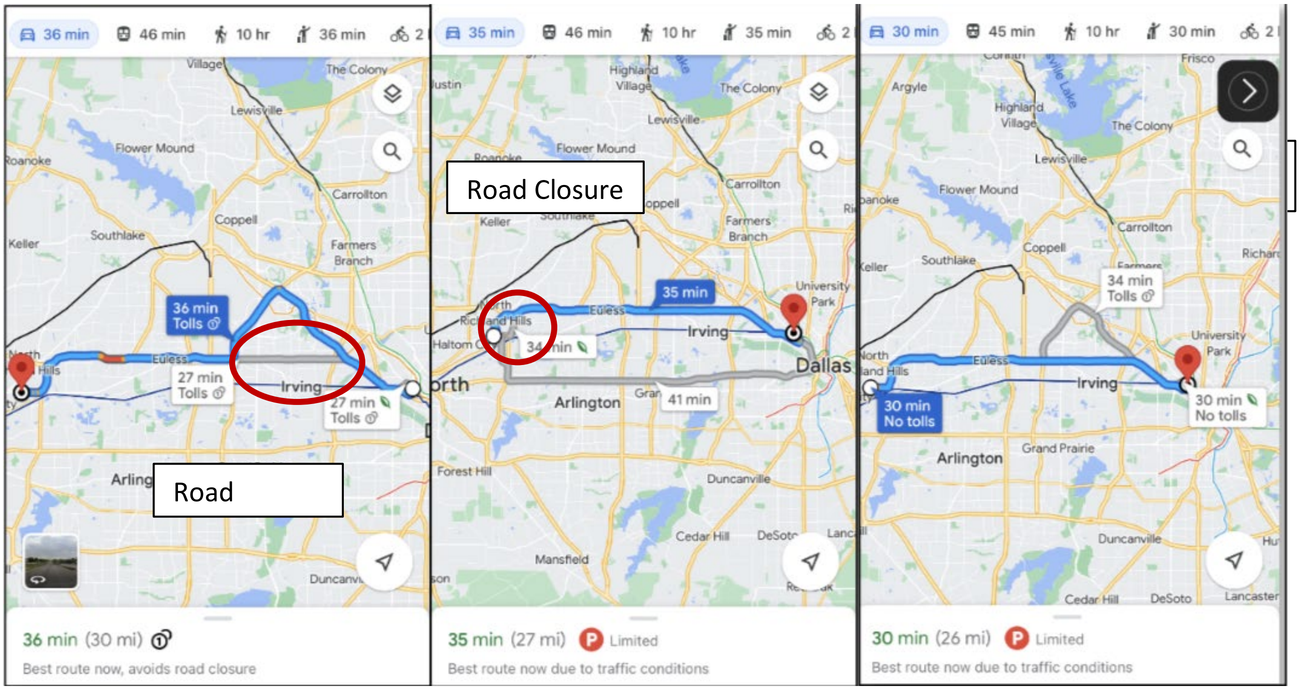

Figure 6: Best route recommended by Google

The recommendations provided by Google Maps varied by day and did not recommend the most fuel-efficient route every time. It was also found that Google might no longer be using NREL's RouteE models. Google Maps recommends the freeway as the most fuel-efficient route most of the time over the free-flowing toll lanes (MLs). Its fuel-efficient routing algorithm may be moving travelers to a less fuel-efficient route in some cases. This would reduce the impact of the Google Maps feature and would likely be encouraging additional use of the more congested GPLs over the free-flowing MLs, adding to congestion as well as fuel consumption and emissions. Therefore, there is a need to develop a framework for identifying the most fuel-efficient route more accurately - an algorithm that will incorporate vehicle type and speed fluctuations before recommending the most fuel-efficient route to the user.

4.0 Collecting Fuel Consumption Data

4.1 Field Trial One

Next, the fuel consumption measured by the OBD units was compared with that of MOVES. MOVES has been widely used in estimating emission rates. It is found to be superior to the previous MOBILE series models which did not consider acceleration in their emission model. Therefore, taking MOVES as our benchmark, two different OBD devices were tested: VEEPEAK (Figure 7) and HEM Data OBD Mini Logger (Figure 8). The HEM data logger is an expensive, high quality OBD device that connects to the vehicle's CAN bus and collects the engine data, along with the GPS data via an integrated GPS chip, on a second-by-second basis. The amount, and specifics, of data that is being reported by the CAN bus varied by the vehicle manufacturer and resulted in thousands of parameters. For this project, the data loggers were configured to only record a set number of available parameters, which were chosen based on previous data collection efforts conducted by the research team. There were 9 potential parameters that were recorded as part of the project, including information such as engine speed, engine load, engine temperatures, vehicle distance, vehicle speed, and mass air flow (MAF). The MAF data was especially important in this project as it was used to estimate fuel usage from the vehicles.

Conversely, VEEPEAK is an inexpensive OBD data logger that pairs with a user's phone to collect data. The Android version uses Bluetooth, while the iPhone option uses wi-fi for communicating with the phone. It requires the user to download an OBD reader application and select the parameters needed to be recorded by the VEEPEAK OBD unit (For example Car Scammer ELM shown in Figure 7). Similar to the HEM, key data included vehicle speed, location (based on the user's phone's GPS), and mass air flow.

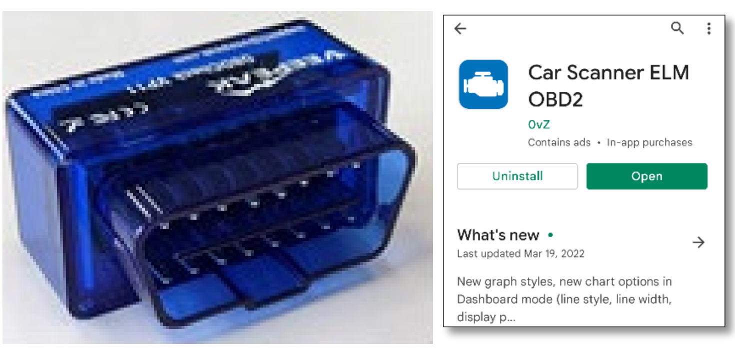

Figure 7: VEEPEAK OBD and application

Figure 8: HEM OBD

Two different vehicles were used for the initial investigation: a 2021 Chevy Equinox and a 2018 Ford Fusion. For the speed data, the MLs and GPLs of Texas State Highway 183–East (183-E) road segments in Dallas were considered. The peak-hour and off-peak data were then extracted from the Regional Integrated Transportation Information System (RITIS), which is shown in Table 2. The team then performed seven different vehicle runs for 5.5 miles traveling at a speed similar to what was found on 183-E. These runs were done from RELLIS campus to County Rd 221 on Highway 21 in Bryan, Texas, as shown in Table 3.

Table 2: Speed Profile of GPL and ML Taken from RITIS

Travel Distance (miles)	General Purpose Lane Speed (MPH)	Managed Lane Speed (MPH)
0	66	71
0.5	66	71
1	70	71
1.5	50	71
2	50	70
2.5	49	69
3	61	66
3.5	70	69
4	68	67
4.5	69	71
5	68	71

Table 3: Vehicle Runs

Trial	Device	Start Time	Start Location	End Time	End Location	Vehicle	Lane Type Replicated
1	VEEPEAK	11:53:08	Rellis	11:58:18	Co Rd 221	Chevy Equinox, 2021	ML
2	VEEPEAK	11:59:58	Co Rd 221	12:05:20	Rellis	Chevy Equinox, 2021	GPL
3	HEM	12:14:01	Rellis	12:18:46	Co Rd 221	Chevy Equinox, 2021	ML
4	HEM	12:19:38	Co Rd 221	12:24:57	Rellis	Chevy Equinox, 2021	GPL
5	HEM	12:47:56	Rellis	12:52:56	Co Rd 221	Ford Fusion, 2018	ML
6	HEM	12:53:49	Co Rd 221	12:59:20	Rellis	Ford Fusion, 2018	GPL
7	VEEPEAK	13:02:44	Rellis	13:07:36	Co Rd 221	Ford Fusion, 2018	ML
8	VEEPEAK	13:09:54	Co Rd 221	13:15:23	Rellis	Ford Fusion, 2018	GPL

Comparing the speed from both devices in Figure 9, it can be seen that the speed data matches quite well between the two units. However, the VEEPEAK data (VP) had many missing values which were imputed before performing any analysis or developing this figure.

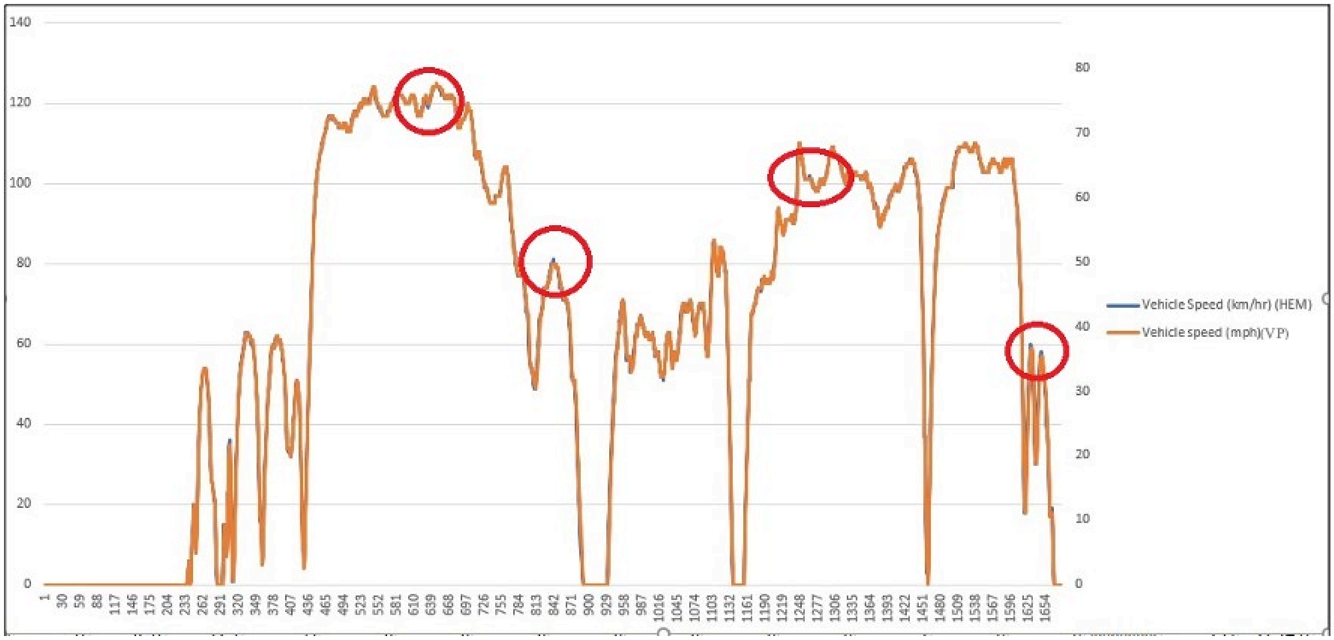

Figure 9: Speed comparison from two OBD devices

The VEEPEAK data logger records the MAF multiple times per second which was used to estimate fuel usage. The VEEPEAK also reports fuel consumption directly, however, the reported fuel consumption was much larger than the estimates from the MAF. To estimate the fuel consumption from the MAF the following equation was used [4]:

Fuel consumption (gallons/second) = ((MAF/14.7)/454)/6.07

1. Divide the MAF by 14.7 to get grams of fuel per second. The oxygen sensors in modern automobiles are used to send data to the vehicle's electronic control module (ECM) and adjust the air-fuel ratio. For a modern engine with a catalytic converter to operate with virtually perfect combustion, 1 gram of gasoline must be combined with 14.7 grams of air. Modern vehicles are able to match this ratio precisely.
2. Divide the result by 454 to get pounds of fuel per second.
3. Divide the result by 6.07, the weight in pounds of one gallon of fuel. This was measured locally by filling a gas can and weighing it at different fill amounts (Table 4). For instance, the weight for 1.253 gallons will be 7.6 pounds which will give 6.065 pounds/gallon.

Therefore, instead of the reported fuel consumption, the MAF was converted to an equivalent fuel consumption and the results were then compared with MOVES as shown in Figure 10. It is evident from Figure 10 that VEEPEAK is missing some of the peaks and MOVES shows a flat trend where there are small fluctuations in fuel consumption. Unfortunately, the team was unable to get all data from the HEM data loggers during these tests because of the installation mistakes. The HEM OBD often did not record data on the first vehicle run after installing it. By the end of this study, it was concluded that there is a need to use splitters while making vehicle runs. The splitters will help in installing both OBD devices and collect data at the same time.

Table 4: Fuel Consumption Estimation

Weight (pounds)	Gallons	Weight/Gallon (pounds)
6.07	1	6.07
7.6	1.253	6.065
9.11	1.5	6.073
10.63	1.752	6.067
12.19	2.008	6.070
13.66	2.257	6.052
15.18	2.502	6.067

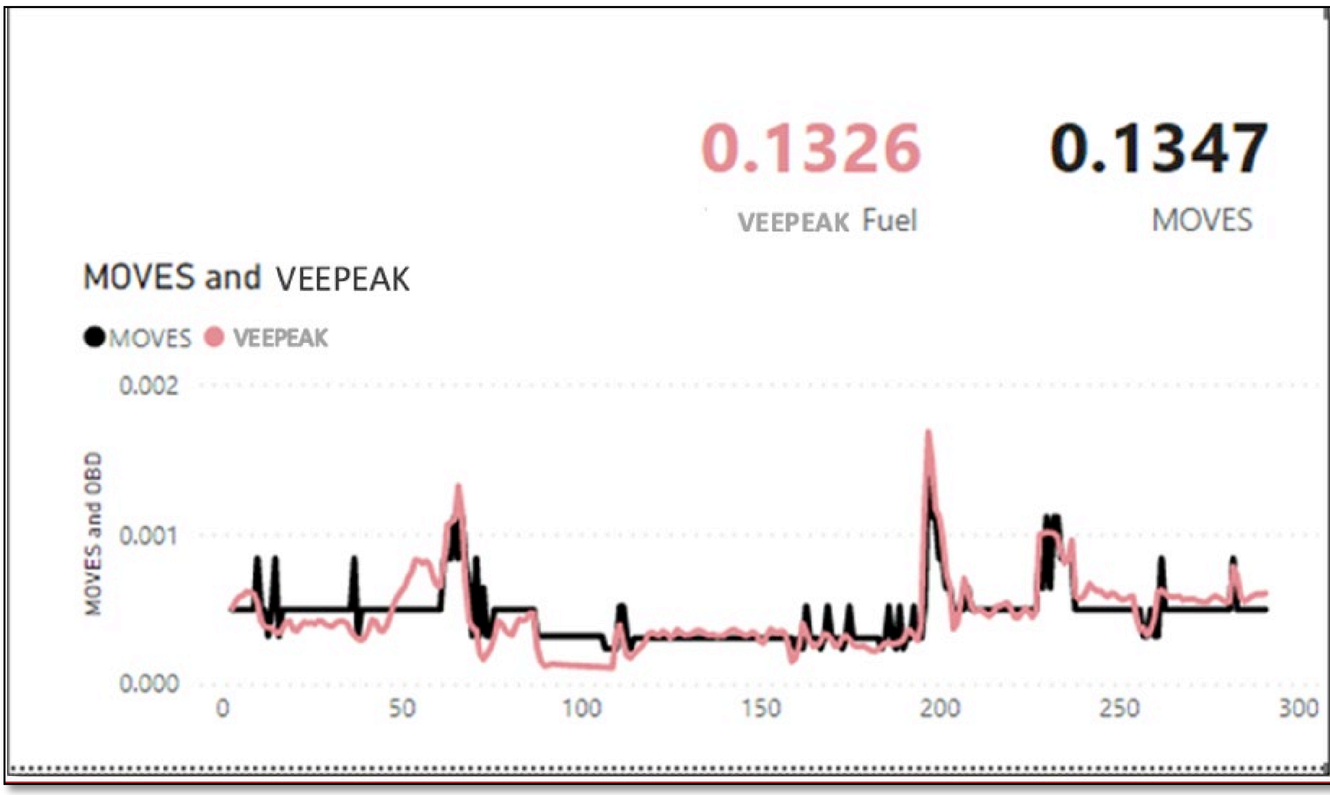

Figure 10: Comparing the fuel usage from VEEPEAK and MOVES

4.2 Field Trial Two: Local Travel in a 2021 Chevy Equinox

The team continued collecting more data by making vehicle runs locally using 2021 chevy Equinox utilizing both OBD devices and comparing the findings from the two devices with MOVES. Figure 11 shows that the reported fuel consumption from the VEEPEAK device is far from being accurate but the calculated fuel consumption from VEEPEAK using MAF and speed closely matches data from the HEM data logger. The description of the labels in Figure 11 is as follows:

1. VP Est Fuel (MAF): Fuel estimation from VEEPEAK using the MAF
2. reportedFuel: Fuel estimations recorded by the VEEPEAK and reported in the exported data
3. HD Est Fuel (MAF): HEM Data fuel estimations using the MAF
4. VP MOVES: Fuel estimation from MOVES using VEEPEAK data
5. HemData MOVES: Fuel estimation from MOVES using HEM data

The speed comparisons indicate that there are few differences between the HEM and VEEPEAK data. This is due to the anomalies and missing data in the VEEPEAK datasets. VEEPEAK records multiple data per second which is then aggregated per second. The data is also seen to skip a few seconds at random instances and did not give accurate results even after addressing the missing data. Table 13 in Appendix A shows some of these patterns of missing data. The research team tried to address these anomalies in our python code as shown in Appendix A. However, the results still had many inconsistencies. HEM was found to have more accurate data on fuel consumption, distance, GPS, and speed compared to the VEEPEAK device. The research team still did not want to give up on the VEEPEAK and decided to use both OBD's and perform vehicle runs in Dallas. However, eventually, the VEEPEAK data was too inconsistent and was not used.

Figure 11: Comparing speed and fuel consumption

4.3 Field Study

For the field investigation, the team selected I-820 (Northwest loop), SH 183/SH 121(Airport freeway), and I-35 W interstate highway corridors. The study location was selected for freeways with MLs and GPLs running parallel to each other. These are known as the North Tarrant Express (NTE) lanes. The selection of these segments was influenced by the ease of access and granularity of the RITIS (Regional Integrated Transportation Information System) data for each of these corridors. The probe data analytics (PDA) suite was used to gather the speed information for the NTE lanes from the RITIS website (https://pda.ritis.org/suite/). The probe data analytics suite offers real-time and historical speed data for a variety of roadway networks. Additionally, CINTRA had comparable data on these corridors, which was used to confirm our findings from the RITIS. The speeds were taken between fixed origin and destination points as marked in Figure 12 and Figure 13.

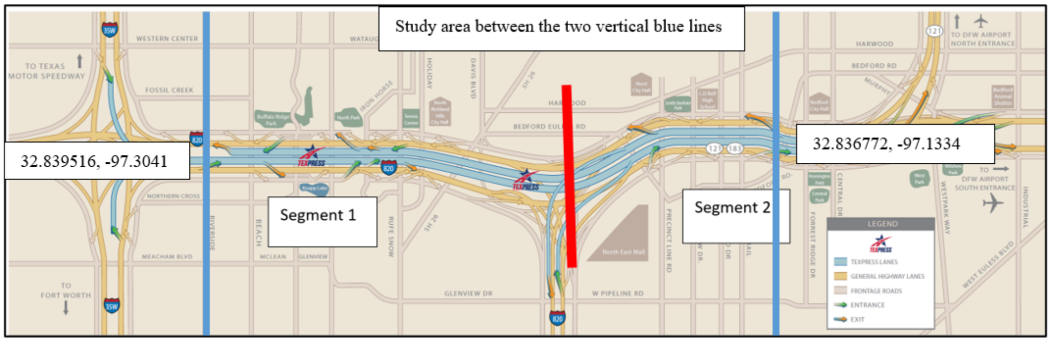

Figure 12: Segments 1 and 2 along the I-820 loop and SH 183/SH 121 freeway

Figure 13: Segment 3 along I-35 W

The research team first identified the typical speed fluctuations of traffic on the chosen freeway in the general-purpose lanes and the express lanes. This was done to identify typical peak and off-peak hours at these respective road segments. To establish the daily speed trend over time, speed data were gathered from RITIS (Regional Integrated Transportation Information System) website to create the speed distribution plots over time. The I-820 (Northwest loop), SH 183/SH 121(Airport freeway), and I-35 W interstate highway corridors were examined. Speeds were calculated throughout the day and utilized to generate boxplots displaying the speed's distributional characteristics. From these boxplots the research team identified the speeds on MLs and GPLs at peak and off-peak hours. Figure 14 is an example of the boxplots. The procedure of downloading the data from RITIS is given in Appendix B.

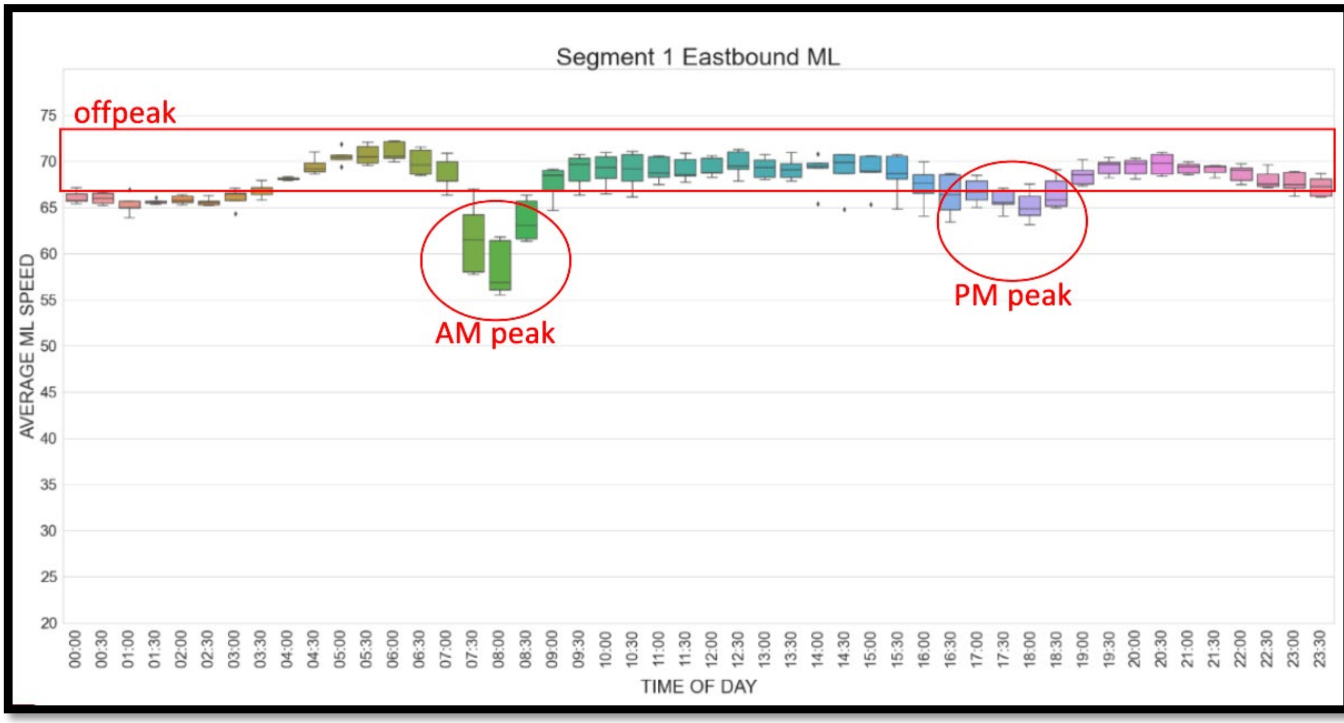

Figure 14: Speed profile along the eastbound of segment 1: ML

The boxplot (Figure 14) shows how speed fluctuates throughout the day and helps us decide when to make the vehicle run and collect the fuel consumption data. Peak and off-peak periods were identified from the plots and fuel consumption data were collected for those times for all the road segments: segments 1 and 2 for travel in the EB and WB directions and segment 3 for travel in the NB and SB direction. The remaining charts of travel speeds are found in Appendix B.

One vehicle on the ML and two vehicles on the GPLs were equipped with OBD devices and simultaneously collected data during the period of severe congestion during the morning and evening peak hours. Vehicle 1 used was a Chevy Equinox 2021 (SUV), vehicle 2 was a Toyota Camry 2018 (sedan), and vehicle 3 was a Nissan Sentra 2019 (sedan). Table 5 shows the information on these initial vehicle runs done in Dallas.

Table 5: Initial Vehicle Runs in Dallas

Date	Trip Number	Start Time	Road	Direction	End Time
7/21/2022	1	11:25 AM	I35 W	NB	11:57 AM
7/21/2022	2	12:37 PM	I35 W	SB	1:00 PM
7/21/2022	3	1:03 PM	I35 W	NB	1:23 PM
7/21/2022	4	1:39 PM	Riverside Dr/Sylvania Ave	SB	2:14 PM
7/21/2022	5	2:46 PM	Glenview Dr/Pipeline Rd	EB	3:26 PM
7/21/2022	6	4:45 PM	183/820/Airport Freeway and ML	WB	5:29 PM
7/21/2022	7	6:27 PM	I35 W	SB	6:42 PM
7/21/2022	8	8:37 PM	I35 W	SB	8:58 PM
7/21/2022	9	9:01 PM	I35 W	NB	9:18 PM
7/22/2022	10	8:06 AM	I35 W	SB then NB (Round Trip)	8:50 AM
7/22/2022	11	9:19 AM	183/820/Airport Freeway and ML	EB	9:44 AM
7/22/2022	12	9:45 AM	183/820/Airport Freeway and ML	WB	10:03 AM

4.3.1 OBD Data Versus MOVES

VEEPEAK continued showing some critical anomalies such as missing speed data, unreliable data on distance per second, inaccurate coordinate points, and inaccurate fuel data. When the fuel consumption estimations from the OBD data loggers were compared to those from MOVES, it was found that VEEPEAK significantly overstated the fuel consumption as shown in Figure 15 and Figure 17. Data from the HEM data logger closely matched MOVES (Figure 15 and Figure 16) and therefore HEM was concluded to be the best OBD data logger for our research and further data collection used only the HEM devices. These figures show results from an 8.96-mile section of I-35W.

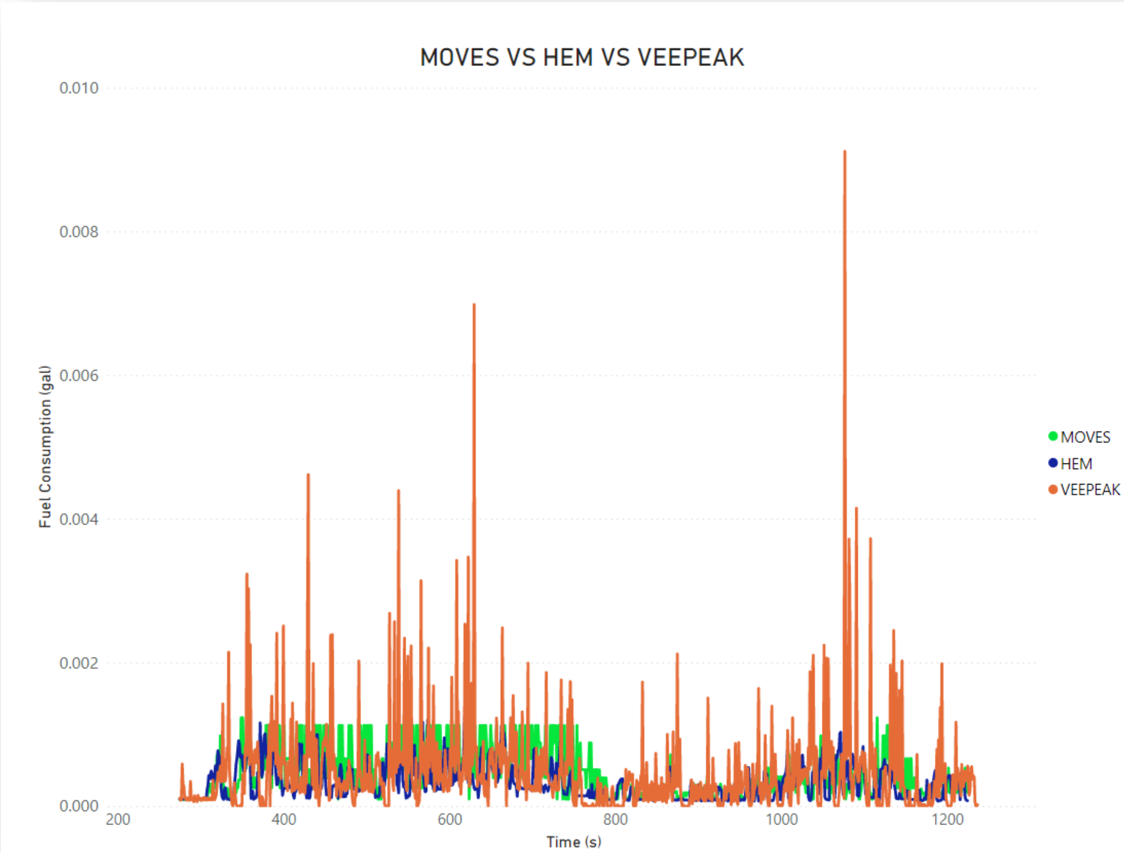

Figure 15: Comparison of fuel consumption estimates from MOVES, HEM, and VEEPEAK

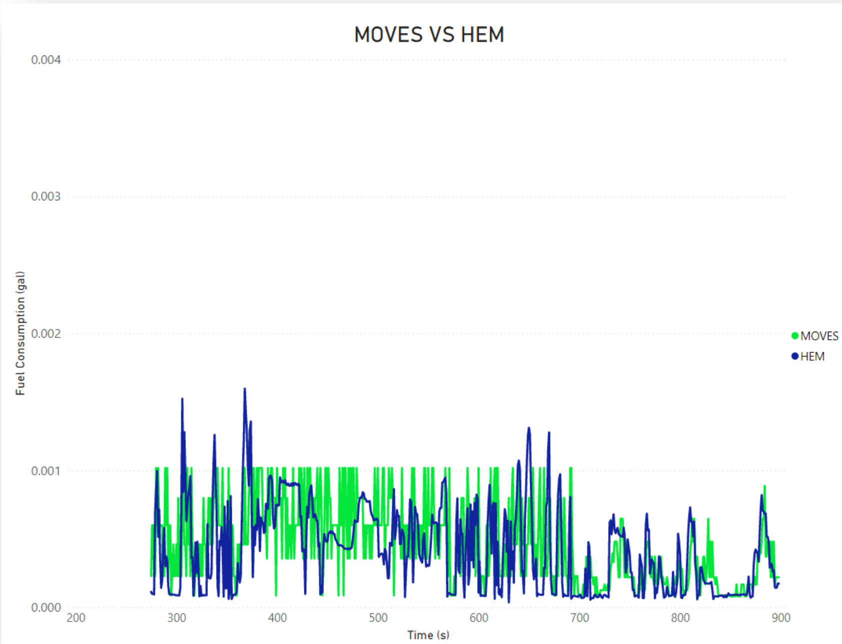

Figure 16: Comparison of fuel consumption estimates from MOVES and HEM

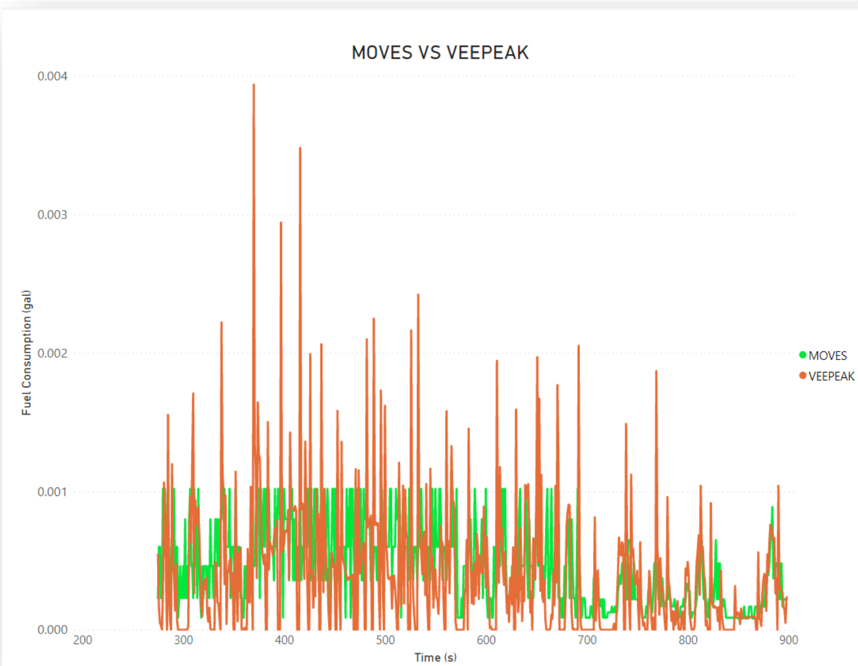

Figure 17: Comparison of fuel consumption estimates from MOVES and VEEPEAK

Figure 18 compares the fuel consumption estimations from HEM OBD and MOVES for 8.96 miles on I-35W. The MOVES fuel estimates were calculated using the variables from default vehicle physics based on the type of vehicles (passenger car, truck, etc.) for each data set. The default physics used may not be representative of the exact vehicles used in the data collection efforts, and therefore the calculated values can be expected to have some variation based on the actual physics of the vehicle. In addition, the MOVES estimates are based on average rates from all instances of operating modes over extended periods of operation. Therefore, the second-by-second based fuel estimates may have differences compared to actual fuel consumption. So, while some differences in the actual value versus the MOVES estimates may include some expected error, using MOVES in this manner allows for the estimation of fuel usage from larger data sets that may not be otherwise usable for these scenarios.

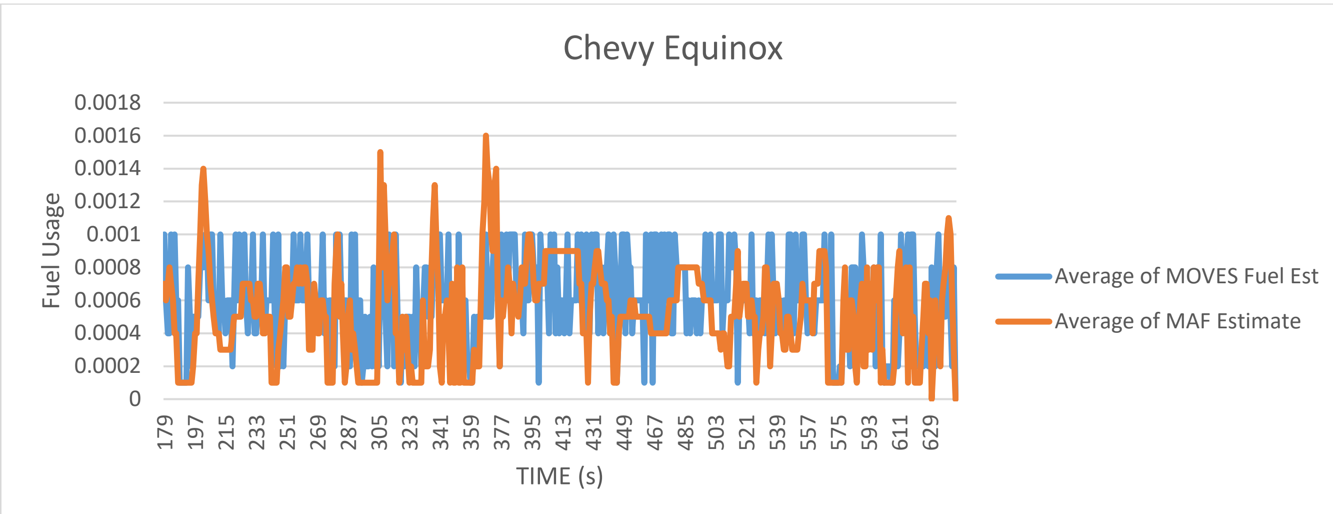

Figure 18: Comparing fuel consumption estimates from HEM and MOVES

4.3.2 Accuracy Test of the HEM OBD (Ground–Truth Analysis)

To further test the accuracy of HEM and MOVES, a vehicle's fuel consumption was carefully monitored for a large number of local trips and one long distance trip. The vehicle was the 2021 Chevy Equinox that also did vehicle runs in Dallas. For the local trips, the vehicle made 106 short trips totaling 308.2 miles on the odometer using 12.10 gallons of gas based on the gas pump reading while filling the tank. Those values were considered ground truth and HEM OBD readings along with the MOVES estimate were compared to the ground truth. The HEM measured 11.90 gallons of fuel used and 305.4 miles traveled, both less than 2% different from ground truth. MOVES estimated 10.58 gallons of fuel used, 12.6% lower than ground truth (see Table 6).

The long-distance trip was from Texas to Florida and back. This included refueling the vehicle 8 times and those data were compared between the amount of gas pumped into the vehicle (assumed to be ground truth) and the HEM OBD measurement and MOVES estimate (see Table 6). Combining these trips with the local trip, it could be seen that MOVES underestimated fuel consumed by 15.2% while HEM underestimated fuel consumed by only 5.1%. In this case, the HEM did better for the many local trips than on the long-distance trip. Also, the HEM performed better than MOVES. However, as this is only one vehicle and a very limited test very little can be concluded. This test does provide additional confidence that the HEM OBD is providing reasonable results for our research.

Table 6: Comparing HEM OBD and MOVES Estimates to Actual Fuel Consumption

Trials	Distance (miles, odometer)	HEM Fuel Consumption (Gal)	MOVES Fuel Consumption (Gal)	Actual Fuel Consumption (Gal)	HEM Error (%)	MOVES Error (%)
Local	308.2	11.902	10.593	12.10	-1.6	-12.5
LD 1	342.0	10.999	9.087	12.334	-10.8	-26.3
LD 2	335.7	10.777	8.819	11.538	-6.6	-23.6
LD 3	356.3	11.899	12.259	12.714	-6.4	-3.6
LD 4	342.8	11.704	11.911	12.174	-3.9	-2.2
LD 5	193.5	6.007	5.164	6.752	-11.0	-23.5
LD 6	355.5	11.374	9.89	11.795	-3.6	-16.2
LD 7	349.5	11.109	9.431	11.279	-1.5	-16.4
LD 8	249.0	8.038	6.672	8.191	-1.9	-18.5
Total	2864.3	81.907	73.2	86.8	-5.1	-15.2

LD = Long Distance Trip

5.0 Data Collection and Analysis

The research team continued collecting real-world fuel consumption data from vehicle runs on I-35 W and I-820/SH 183/SH 121 using the HEM OBD. The data was collected from 4 different categories of vehicles: SUV, sedan, hybrid, and pick-up trucks (see Table 7). The data from the HEM OBD was first exported to an Excel file and then geofenced from fixed origin to destination as shown in Figure 12 and Figure 13, taking 8.94 miles on I-35 W and 10.7 miles on 820/183/121.

Table 7: Vehicles Used for the Study

Vehicle Type	Vehicles
SUV	2007 Ford Explorer
	2021 Chevy Equinox
Sedan	2018 Toyota Camry
	2019 Nissan Sentra
	2021 - Hyundai Elantra and KIA Forte
Hybrid	2012 Ford Escape Hybrid
Pick-up Truck	2007 Ford F-250
	2017 FORD F-350
	2015 FORD F-650
	2011 FORD F-250

5.1 Aggregated Data Analysis

The geofenced data were then summarized in tabular form (Appendix D) with all the information on start and end time, travel time, distance, average speed, lane type, road, direction of the trip, and fuel consumption estimates. The average fuel consumption from HEM and MOVES was then calculated for all the categories of vehicles as shown in Table 8 and Table 9. The average fuel consumption was calculated for seven different times of day based on lane type and traffic conditions. The first four columns represent the average fuel consumption estimates from the GPLs during morning peak (AMP), mid-day (MD), evening peak (PMP), and off-peak (OP). The next three columns represent the average fuel estimates from the MLs during the morning peak (AMP), evening peak (PMP), and off-peak (OP). For instance, the average fuel consumption on I-35 W (8.96 miles) by the SUV on the GPLs during the morning peak hour is 0.40 gal according to the OBD data and 0.31 gal according to the MOVES estimates. The sedans were consistently the most fuel-efficient vehicle both on the MLs and GPLs. This may be due to the hybrid being an older vehicle and the high speeds on the freeway during most times of day.

Table 8: Average Fuel Consumption on I35W

Vehicle	GPL-AMP	GPL-MD	GPL-PMP	GPL-OP	ML-AMP	ML-PMP	ML-OP
SUV – HEM	0.40	0.35	0.41	0.26	0.26	0.44	0.29
- MOVES	0.31	0.29	0.34	0.23	0.23	0.34	0.23
Sedan - HEM	0.22	0.23	0.21	0.23	0.23	0.23	0.23
- MOVES	0.27	0.26	0.22	0.26	0.26	0.26	0.26
Pickup - HEM							
- MOVES	0.25		0.25		0.19	0.22	0.19
Hybrid - HEM	0.24		0.22		0.29	0.29	0.29
- MOVES	0.24		0.25		0.27	0.27	0.27

Table 9: Average Fuel Consumption on 820/183

Vehicle	GPL-AMP	GPL-MD	GPL-PMP	GPL-OP	ML-AMP	ML-PMP	ML-OP
SUV – HEM	0.47		0.52	0.31	0.31	0.33	0.31
- MOVES	0.40		0.44	0.27	0.27	0.28	0.27
Sedan - HEM	0.24	0.26	0.24	0.21	0.21	0.21	0.21
- MOVES	0.09	0.29	0.10	0.25	0.25	0.25	0.25
Pickup - HEM							
- MOVES	0.33		0.33		0.22		0.22
Hybrid - HEM	0.23	0.22	0.23		0.33	0.33	0.33
- MOVES	0.27	0.27	0.27		0.30	0.30	0.30

Overall, the average fuel consumption estimates from ODB data closely matched MOVES estimates. Figure 19 to Figure 25 illustrate the fuel consumption across ML and GPL at various speeds. Travel on the GPLs more often consumed more fuel than on the MLs (see Figure 19). This is understandable given that there are more stop-and-go situations on GPLs. Comparing different categories of vehicles, it can be seen that SUVs consume more fuel than sedans and hybrids on both the GPL and ML. However, this is a very limited sample size.

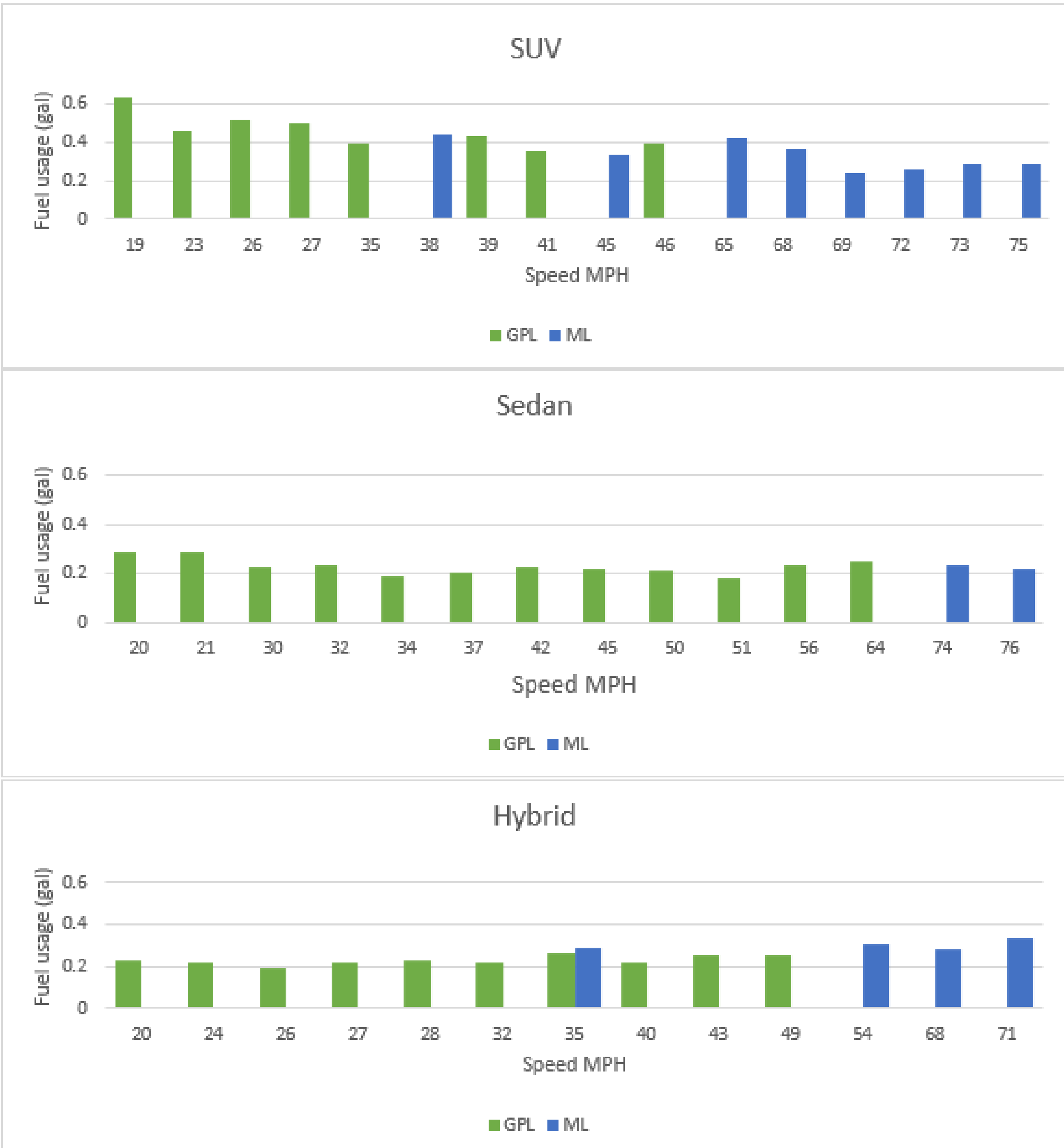

Figure 19: Comparing the fuel usage of the Sedan, SUV, and Hybrid on the GPLs and MLs using HEM

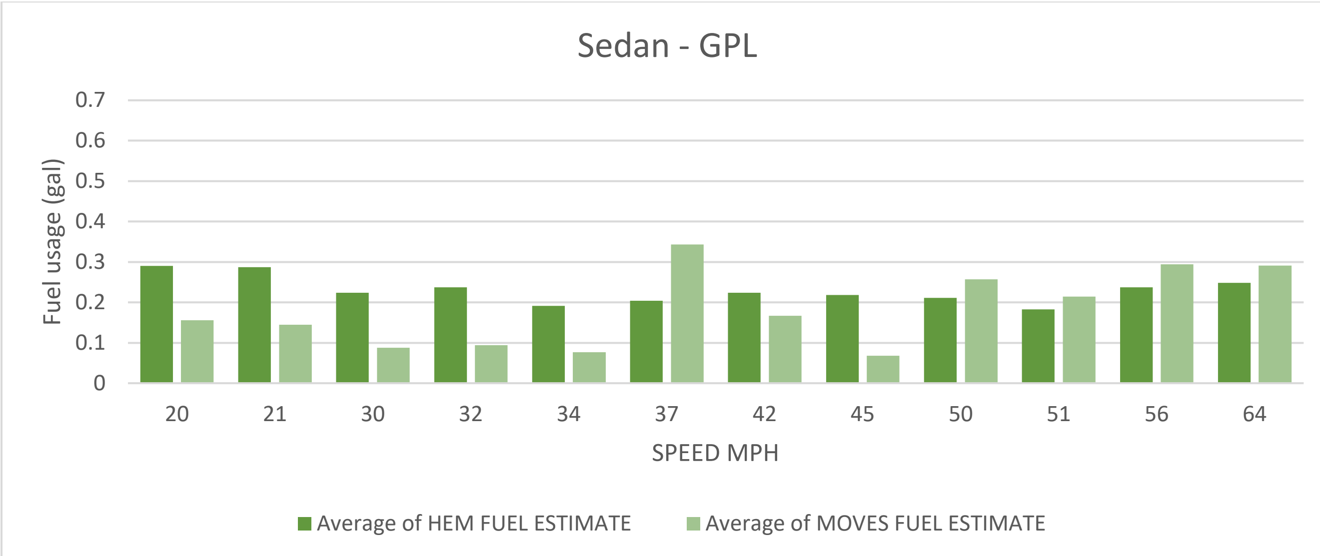

Figure 20: Comparison of fuel consumption estimates for a sedan on the GPLs

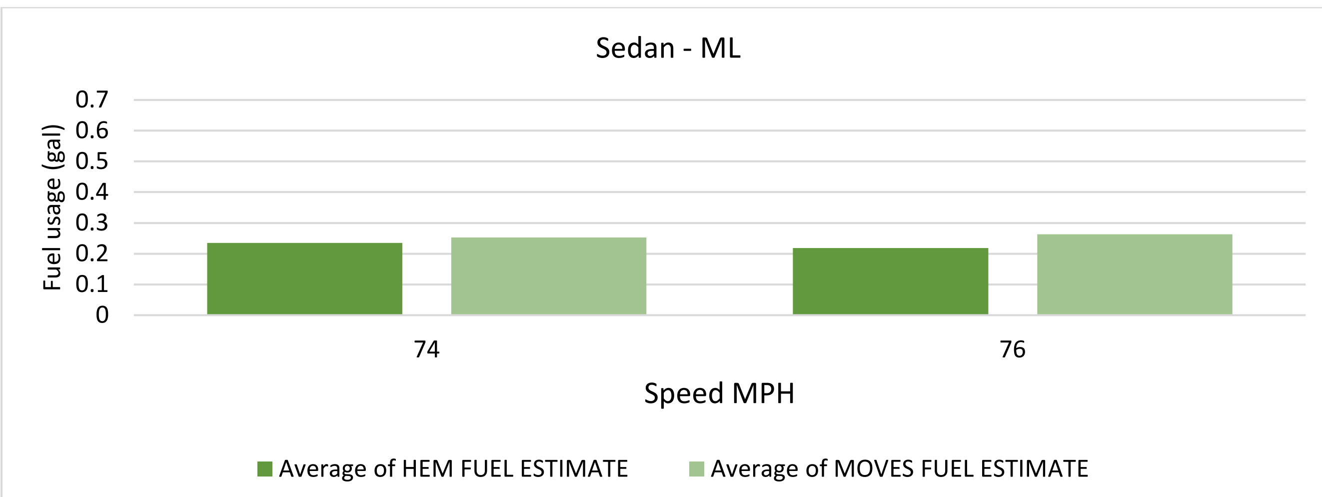

Figure 21: Comparison of fuel consumption estimates for a sedan on the MLs

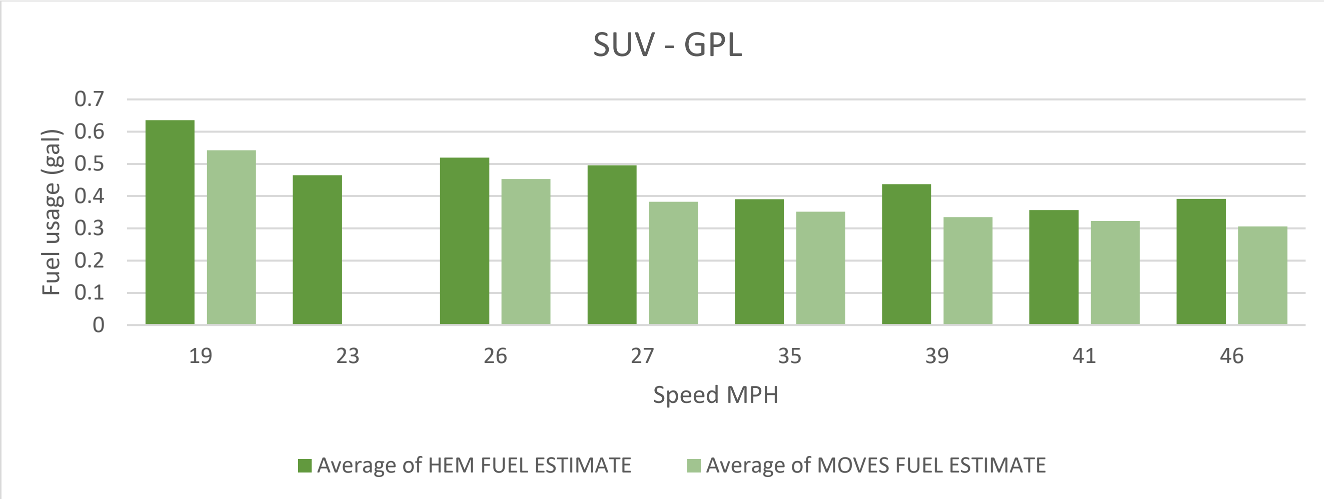

Figure 22: Comparison of fuel consumption estimates for a SUV on the GPLs

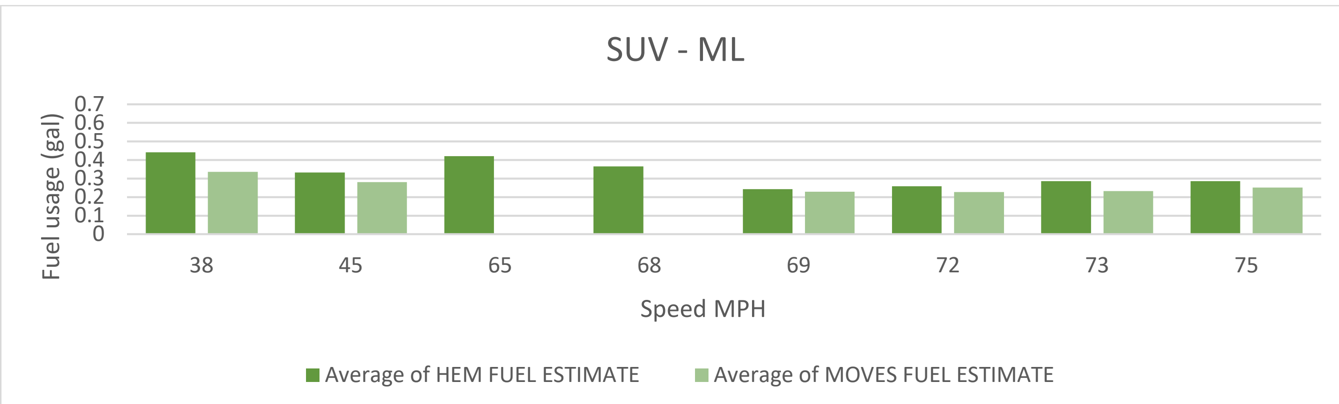

Figure 23: Comparison of fuel consumption estimates for a SUV on the MLs

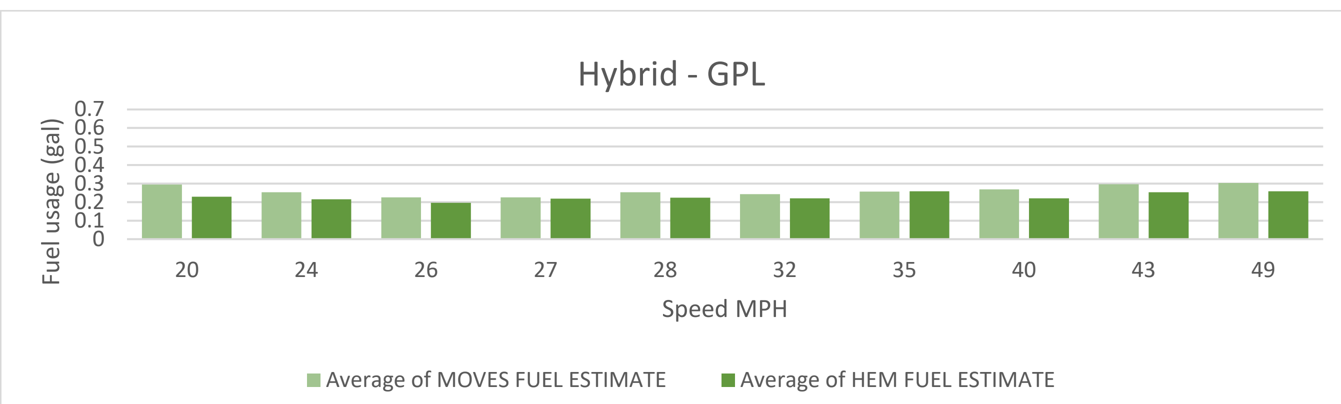

Figure 24: Comparison of fuel consumption estimates for a hybrid on the GPLs

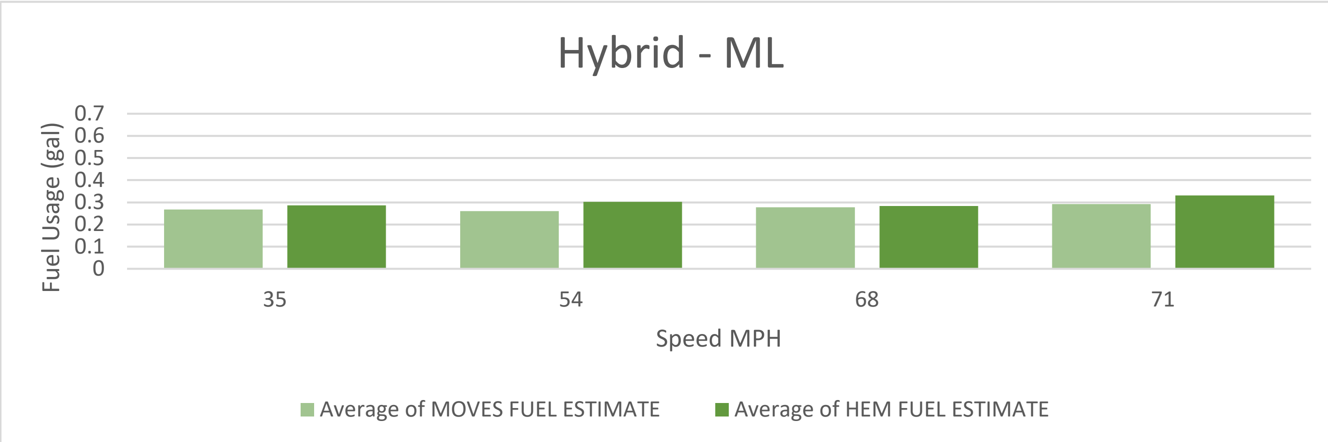

Figure 25: Comparison of fuel consumption estimates for a hybrid on the MLs

The research team rented a pick-up truck and made many vehicle runs on I-35W and the I-820 loop and SH 183/SH 121 freeway. Unfortunately, the HEM data logger did not record the most critical piece of information, the MAF. Thus, these runs did not yield useful data. Cintra then volunteered their trucks to collect data and a majority of this pick-up truck data was collected on the Lyndon B Johnson Freeway. Once again the HEM OBD did not record MAF data on 2021 Ford Ranger and the 2021 Ford F-350. We assume this is a late model Ford pick-up truck issue as our rental pick-up was also a relatively new Ford. Older Ford pick-up trucks that Cintra used did collect MAF. However, these pick-up trucks were frequently found switching lanes from service lanes to the freeway and sometimes from service lanes to the freeway to MLs and back to freeway. This limited the useful data to the two geofenced areas of 2.57 miles of GPL trips. The data used for further analysis was mostly from off-peak hours. Figure 26 and Figure 27 show the 2.57-mile segments from where data was collected and used for further analysis.

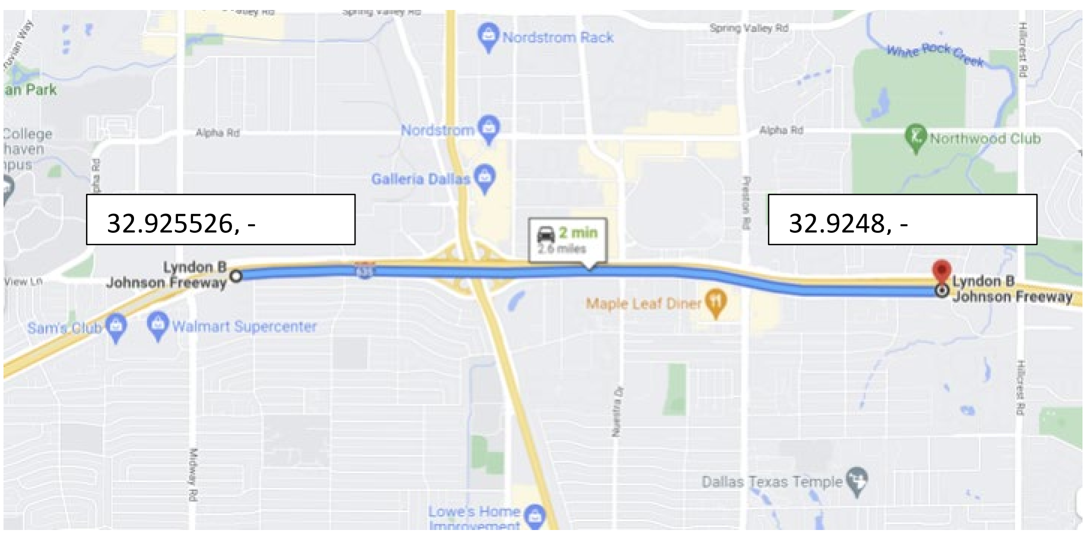

Figure 26: Segment 4 on Lyndon B Johnson Freeway

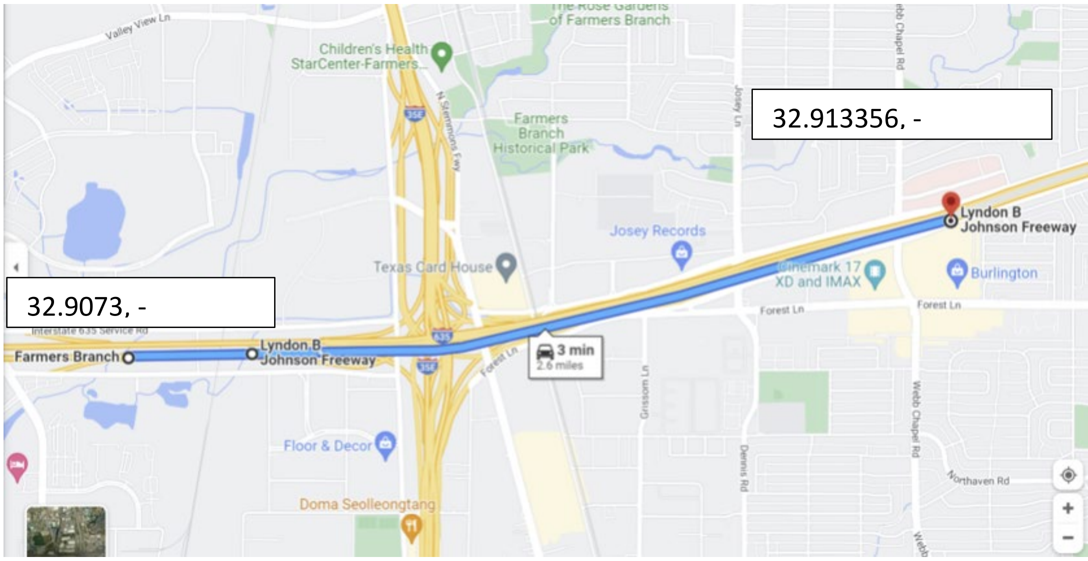

Figure 27: Segment 5 on Lyndon B Johnson Freeway

Figure 28 shows the comparison of HEM OBD and MOVES for pick-up truck data. The trips were completed at off-peak hours, hence the speed across GPL varied from 52 mph to 74 mph. The fuel consumed based on OBD and MOVES was considerably different at speeds above 60 mph. The OBD data reported considerably more fuel consumed than MOVES estimated. These pick-up trucks were extremely large (such as the F650) and not the common size usually observed in traffic. This may have caused some of the discrepancy. Overall, we encountered too many problems attempting to get quality data from pick-up trucks and we will focus on the other three vehicle types (SUV, sedan, hybrid) when exploring the detailed relationship between speed, speed change, and fuel consumption at a disaggregate level in the next section.

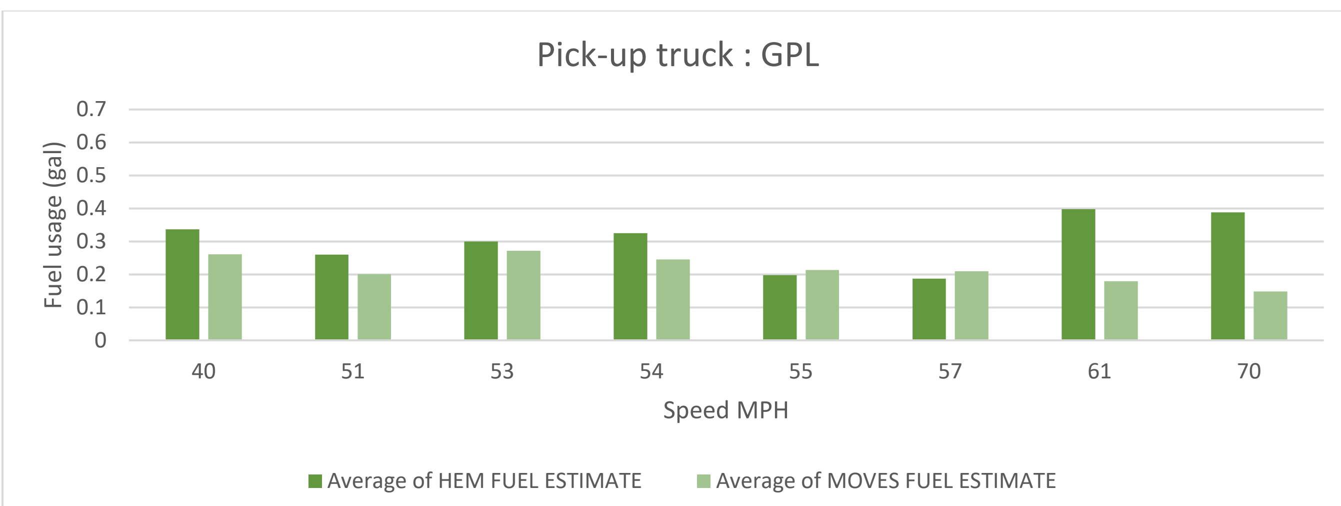

Figure 28: Comparison of fuel consumption estimates for pick-up trucks

5.2 Disaggregated Data Analysis

Next, the fuel consumption data for both HEM OBD and RouteE was examined at a more disaggregate level. The team first requested access to the RouteE API from NREL, which would enable the research team to add features—such as road type, gradient, and congestion level—crucial for accurate estimation of fuel consumption. The team was able to use the RouteE fuel estimates based on the speed and lane type. However, the RouteE model does not account for the congestion level. Also, the RouteE model estimates the fuel consumed for every 0.2 miles. Therefore, to compare RouteE with the OBD results, 0.2-mile links were created in the Dallas datasets and the corresponding fuel consumption was estimated for each link.

The change in speed over this 0.2-mile length and average speed on the link were also calculated. The change in speed was based on the difference between the average speed of the last one-third of speeds minus the average speed of the first one-third of speeds. This difference gives an indication if vehicles were generally accelerating, slowing, or maintaining a constant speed through the link. Additionally, these results were separated based on the average speed over that 0.2-mile segment. Thus, there would be different results for different average speeds, for example 45-50 mph, 50-55 mph, etc. This was due to those different speeds using different amounts of fuel. Figure 29 is one example of the comparison in which RouteE can be seen as overestimating fuel consumption and is more or less constant, implying that it does not account for acceleration/deceleration situations. Similar patterns were found for all vehicles as shown in Appendix C. It was thus concluded that the RouteE models used by NREL are not fully accounting for speed changes.

Figure 29: Fuel consumption from RouteE and HEM: SUV-GPL

Regression plots were created to assess the relationship between the change in speed over the 0.2-mile link and the fuel consumption measured by the HEM OBD for each speed range. Figures 30 to 33 show the regression plots for SUV, Sedan, Hybrid, and pick-up trucks, respectively. As expected, fuel consumption increased with greater increases in speed, and fuel consumption decreased with greater decreases in speed. The exact relationship is shown in Tables 10 and 11. The “x” stands for “Speed Difference” and the “y” predicts the fuel consumption over 0.2 miles. Unlike RouteE, these equations account for congestion and may be used to calculate the fuel consumption with a change in speed. The amount of data points used to build the equation is shown by “Data pts,” and the goodness of fit of the mode is indicated by the "R-sq.” value.

For example, while comparing the change in fuel consumption for the speed range of 60 to 65 mph, it can be seen that when the SUV, sedan, and hybrid accelerate, the fuel consumption changes by 0.0002 gal /mph speed change, 0.0005 gal /mph speed change, and 0.0004 gal /mph speed change, respectively. Assuming x (the speed) change to be an increase of 10 mph, the fuel consumption would increase by 0.002 gal, 0.005 gal, 0.004 gal over 0.2 miles for SUV, sedan and hybrid respectively. For the sedan without any speed change we found approximately 0.0037 gallons of fuel used in 0.2 miles for a fuel economy of 54.1 mpg. If the speed change is +10 mph that would increase to 0.0087 gallons used or 23.0 mpg.

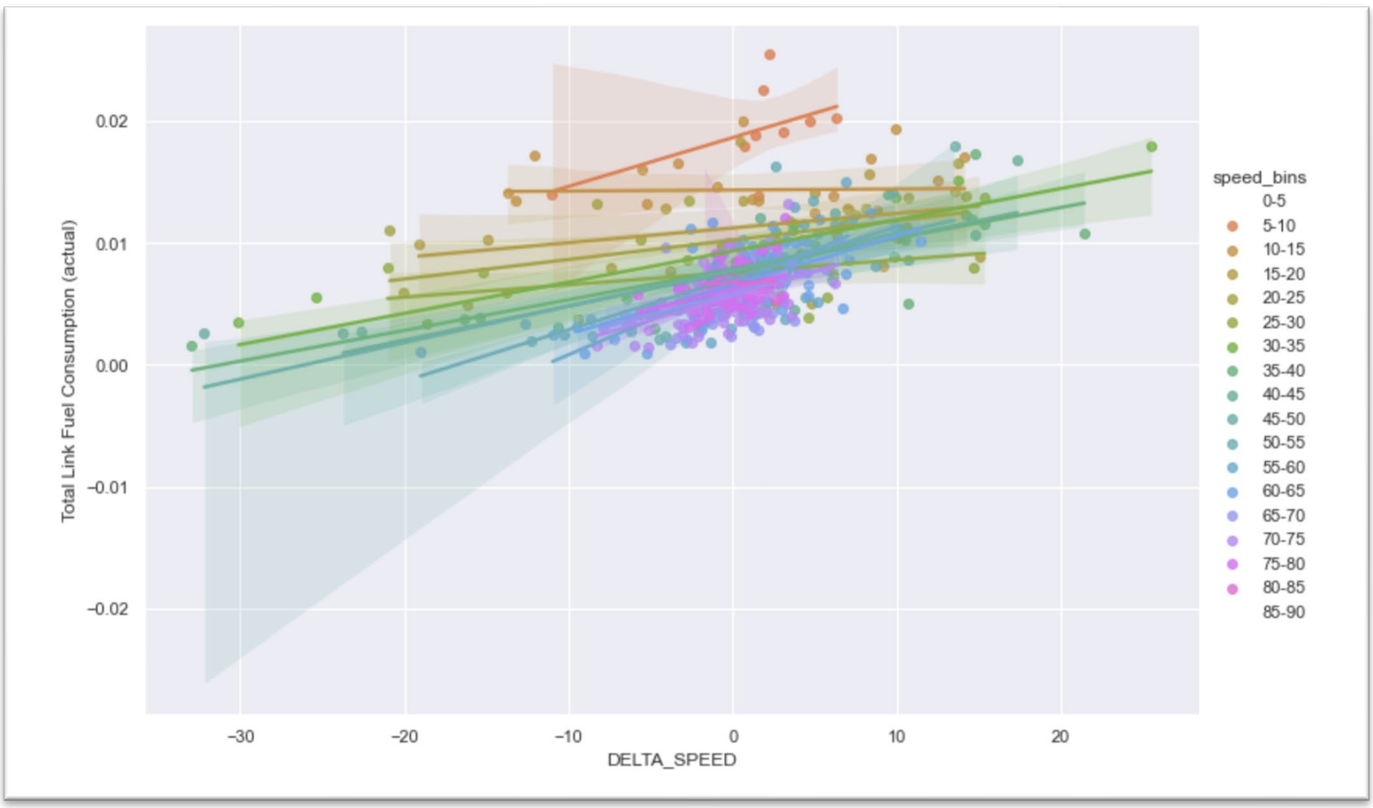

Figure 30: Fuel consumption by speed change regression lines – SUVs

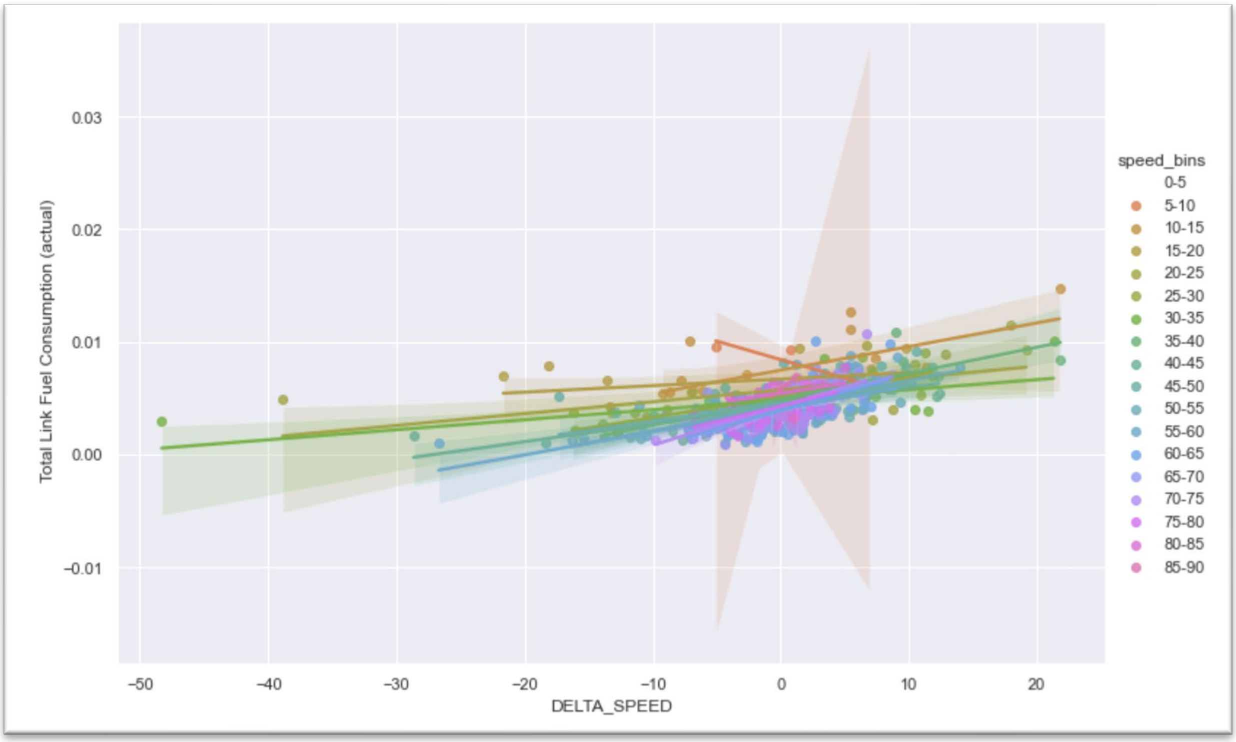

Figure 31: Fuel consumption by speed change regression lines – sedans

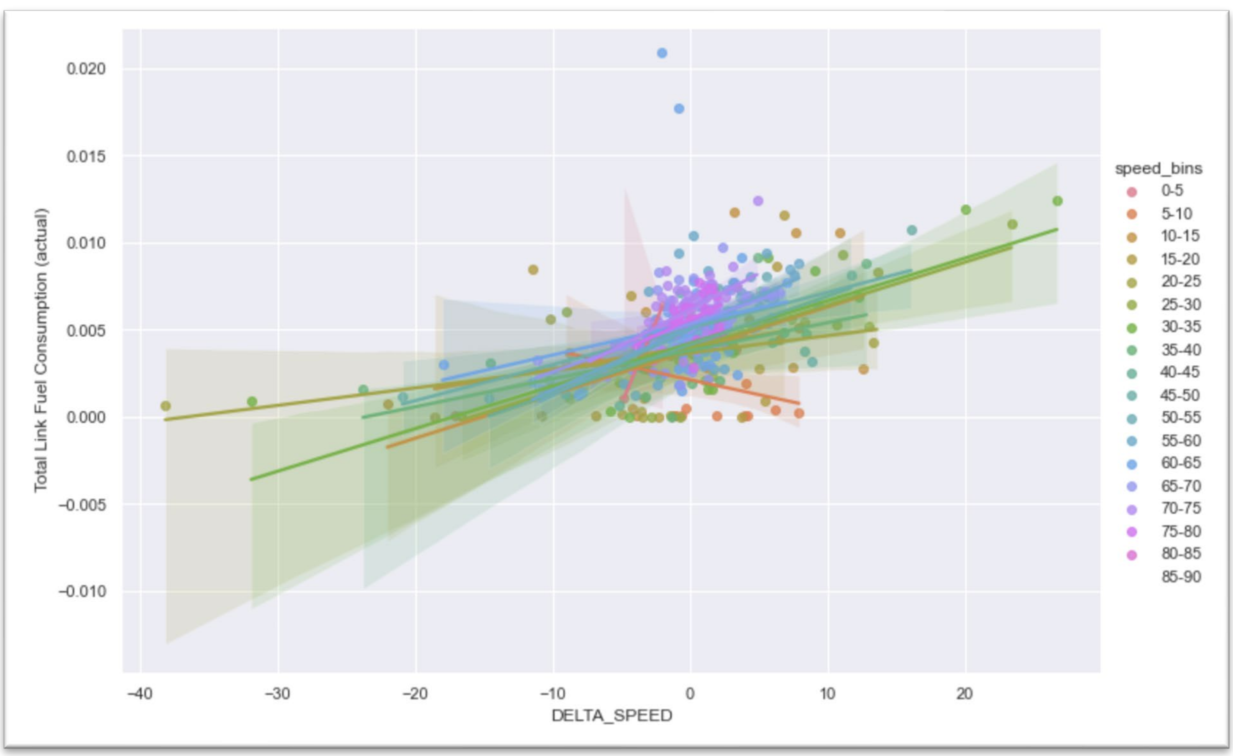

Figure 32: Fuel consumption by speed change regression lines – hybrid

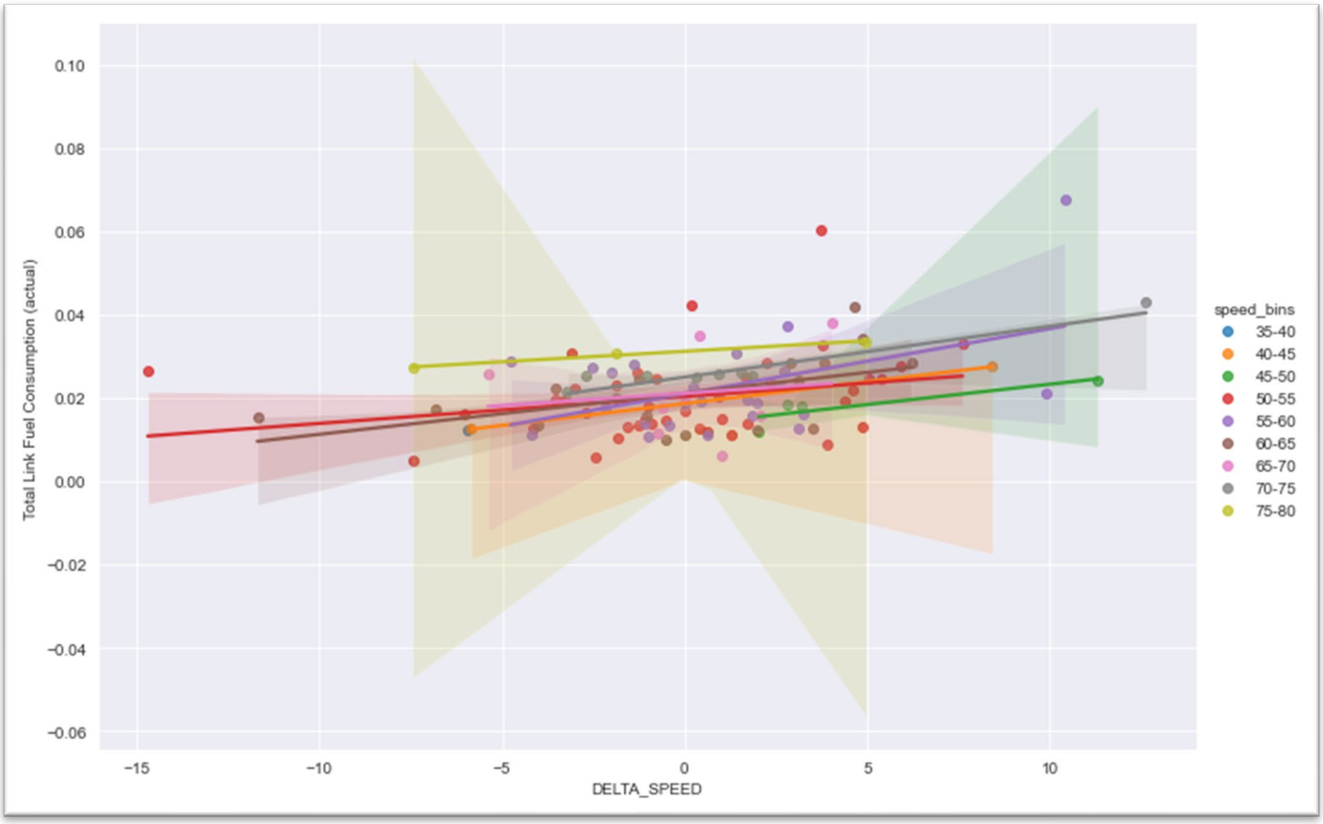

Figure 33: Fuel consumption by speed change regression lines – pick-up trucks

Table 10: Fuel Consumption by Vehicle Type and Speed – Speed Increases

Vehicle type	Speed	Data-points	Fuel Consumption (Gallons/0.2 miles)	R-Sq
SUV	5 - 10 MPH	7	y = 0.0005x + 0.0177	0.1226
	10 - 15 MPH	12	y = 3E-05x + 0.0143	0.0011
	15 - 20 MPH	12	y = -0.0004x + 0.0153	0.3715
	20 - 25 MPH	12	y = 0.0007x + 0.0052	0.7037
	25 - 30 MPH	10	y = 0.0003x + 0.0057	0.3311
	30 - 35 MPH	7	y = 0.0005x + 0.007	0.8051
	35 - 40 MPH	14	y = 0.0001x + 0.0094	0.0847
	40 - 45 MPH	8	y = 0.0006x + 0.0056	0.656
	45 - 50 MPH	7	y = 0.0009x + 0.0046	0.6531
	50 - 55 MPH	15	y = 0.0005x + 0.0069	0.1956
	55 - 60 MPH	27	y = 0.0005x + 0.0068	0.1353
	60 - 65 MPH	38	y = 0.0002x + 0.0072	0.0582
	65 - 70 MPH	28	y = 8E-05x + 0.0061	0.0036
	70 - 75 MPH	33	y = 0.0003x + 0.0058	0.0358
	75 - 80 MPH	25	y = 0.0007x + 0.0058	0.1396
	80 - 85 MPH	4	y = -0.0008x + 0.0081	0.5307
Sedan	10 - 15 MPH	9	y = 0.0005x + 0.0051	0.4637
	15 - 20 MPH	6	y = 9E-05x + 0.0065	0.0704
	20 - 25 MPH	11	y = 0.0003x + 0.0042	0.3724
	25 - 30 MPH	8	y = 0.0002x + 0.0051	0.6957
	30 - 35 MPH	9	y = -0.0002x + 0.0066	0.1428
	35 - 40 MPH	8	y = 0.0002x + 0.0054	0.1524
	40 - 45 MPH	8	y = -3E-05x + 0.0072	0.0047
	45 - 50 MPH	20	y = 0.0003x + 0.004	0.2082
	50 - 55 MPH	24	y = 0.0003x + 0.0041	0.2398
	55 - 60 MPH	39	y = 0.0004x + 0.0036	0.3056
	60 - 65 MPH	48	y = 0.0005x + 0.0037	0.3277
	65 - 70 MPH	29	y = 0.0005x + 0.0038	0.3795
	70 - 75 MPH	17	y = 0.0003x + 0.0039	0.1153
	75 - 80 MPH	14	y = 0.0002x + 0.0046	0.0583
	80 - 85 mph	4	y = 0.0011x + 0.0022	0.9696
Hybrid	5 - 10 MPH	10	y = -0.0003x + 0.0035	0.1127
	10 - 15 MPH	6	y = -0.0006x + 0.0123	0.2257
	15 - 20 MPH	7	y = 0.0009x + 0.0006	0.2319
	20 - 25 MPH	6	y = 0.0002x + 0.0036	0.234
	25 - 30 MPH	7	y = 0.0004x + 0.0037	0.7953
	30 - 35 MPH	8	y = 0.0004x + 0.0027	0.7409
	35 - 40 MPH	7	y = 0.0005x + 0.0023	0.4876
	40 - 45 MPH	7	y = 0.0002x + 0.0056	0.2939
	45 - 50 MPH	10	y = -0.0001x + 0.0062	0.0801
	50 - 55 MPH	14	y = 0.0002x + 0.0057	0.1553
	55 - 60 MPH	26	y = 0.0004x + 0.0048	0.2369
	60 - 65 MPH	27	y = 0.0004x + 0.005	0.1359
	65 - 70 MPH	25	y = 0.0003x + 0.0053	0.1502
	70 - 75 MPH	22	y = 0.001x + 0.0053	0.4287
	75 - 80 MPH	11	y = 0.0004x + 0.0052	0.0319
Pick-up Truck	50 - 55 MPH	24	y = 0.0006x + 0.0194	0.0808
	55 - 60 MPH	10	y = 0.0002x + 0.0212	0.0053
	60 - 65 MPH	9	y = 0.0032x + 0.0089	0.515

Table 11: Fuel Consumption by Vehicle Type and Speed – Speed Decreases

Vehicle type	SPEED	Data-points	Fuel Consumption (Gallons/0.2 miles)	R-Sq
SUV	10 - 15 MPH	7	y = -1E-05x + 0.0136	0.0004
	15 - 20 MPH	7	y = -8E-06x + 0.0092	0.0003
	20 - 25 MPH	6	y = 0.0002x + 0.0112	0.2455
	25 - 30 MPH	7	y = 2E-05x + 0.0073	0.0062
	30 - 35 MPH	7	y = -3E-05x + 0.0034	0.1117
	35 - 40 MPH	5	y = 0.0001x + 0.0057	0.7431
	40 - 45 MPH	4	y = 6E-05x + 0.004	0.9455
	45 - 50 MPH	5	y = 6E-05x + 0.0043	0.1423
	50 - 55 MPH	8	y = 8E-05x + 0.0033	0.1862
	55 - 60 MPH	26	y = 0.0003x + 0.0058	0.1836
	60 - 65 MPH	25	y = 0.0007x + 0.0071	0.274
	65 - 70 MPH	23	y = 0.0003x + 0.0057	0.0945
	70 - 75 MPH	37	y = 0.0007x + 0.0066	0.3414
	75 - 80 MPH	28	y = 0.0001x + 0.0058	0.0117
Sedan	10 - 15 MPH	8	y = -3E-05x + 0.0062	0.0132
	15 - 20 MPH	8	y = -3E-06x + 0.0055	0.0009
	20 - 25 MPH	7	y = 7E-05x + 0.0044	0.3657
	25 - 30 MPH	7	y = 5E-05x + 0.0036	0.1548
	30 - 35 MPH	9	y = 4E-05x + 0.0039	0.204
	35 - 40 MPH	11	y = 0.0001x + 0.0039	0.4156
	40 - 45 MPH	10	y = 7E-05x + 0.0032	0.1883
	45 - 50 MPH	16	y = -4E-05x + 0.0031	0.0133
	50 - 55 MPH	20	y = 0.0001x + 0.0036	0.3947
	55 - 60 MPH	50	y = 7E-05x + 0.0033	0.0427
	60 - 65 MPH	46	y = 0.0001x + 0.0033	0.0364
	65 - 70 MPH	29	y = 0.0003x + 0.0044	0.3141
	70 - 75 MPH	19	y = 0.0003x + 0.0042	0.3109
	75 - 80 MPH	13	y = 0.0003x + 0.0043	0.2281
	80 - 85 mph	5	y = 7E-05x + 0.0058	0.0093
Hybrid	5 - 10 MPH	7	y = -2E-05x + 0.0012	0.0028
	10 - 15 MPH	9	y = 7E-05x + 0.0018	0.0659
	15 - 20 MPH	10	y = -2E-05x + 0.0029	0.0012
	20 - 25 MPH	8	y = 2E-05x + 0.0017	0.0125
	25 - 30 MPH	7	y = 0.0001x + 0.0037	0.0225
	30 - 35 MPH	6	y = 5E-05x + 0.0023	0.1065
	35 - 40 MPH	6	y = -5E-05x + 0.0011	0.1377
	40 - 45 MPH	5	y = 0.0002x + 0.0041	0.351
	45 - 50 MPH	6	y = 0.0002x + 0.0054	0.8412
	50 - 55 MPH	10	y = 0.0003x + 0.0043	0.6903
	55 - 60 MPH	19	y = 0.0003x + 0.0053	0.2822
	60 - 65 MPH	29	y = 0.0002x + 0.0056	0.0287
	65 - 70 MPH	30	y = 0.0003x + 0.0053	0.1939
	70 - 75 MPH	20	y = 0.0003x + 0.0066	0.0881
	75 - 80 MPH	11	y = 0.0006x + 0.0058	0.4886
Pick-up Truck	50 - 55 MPH	22	y = -8E-05x + 0.0205	0.0026
	55 - 60 MPH	8	y = -0.0027x + 0.0357	0.2083
	60 - 65 MPH	11	y = -0.0003x + 0.0198	0.0308

Using equations like these it will be possible to accurately estimate fuel usage on a roadway segment based on travel speeds and traffic volumes. This should prove more accurate than current methods since this uses a disaggregate approach with extremely accurate fuel usage measurements. An example of this, on a very small scale, is presented in section 5.3. The challenge will be to use a much larger sample size in developing the fuel consumption equations to better represent all vehicles on the road. Table 12 shows the example of how these regression equations could be used for the fuel estimation and calculates equivalent miles/gallon (MPG) for different values of x (acceleration/deceleration).

Table 12: Fuel Estimation Using Regression Equations

Vehicle_type	Speed	x = Delta_speed	y = Fuel Consumption (gal/0.2miles)	y (gal/0.2miles)	MPG
Sedan	50 - 55 MPH	-10	y = 0.0001x + 0.0036	0.0026	76.9
		-8		0.0028	71.4
		-6		0.0030	66.7
		-4		0.0032	62.5
		-2		0.0034	58.8
		0		0.0036	55.6
		0	y = 0.0003x + 0.0041	0.0041	48.8
		2		0.0047	42.6
		4		0.0053	37.7
		6		0.0059	33.9
		8		0.0065	30.8
		10		0.0071	28.2
	55 - 60 MPH	-10	y = 7E-05x + 0.0033	0.0026	76.9
		-8		0.0027	73.0
		-6		0.0029	69.4
		-4		0.0030	66.2
		-2		0.0032	63.3
		0		0.0033	60.6
		0	y = 0.0004x + 0.0036	0.0036	55.6
		2		0.0044	45.5
		4		0.0052	38.5
		6		0.0060	33.3
		8		0.0068	29.4
		10		0.0076	26.3
	60 - 65 MPH	-10	y = 0.0001x + 0.0033	0.0023	87.0
		-8		0.0025	80.0
		-6		0.0027	74.1
		-4		0.0029	69.0
		-2		0.0031	64.5
		0		0.0033	60.6
		0	y = 0.0005x + 0.0037	0.0037	54.1
		2		0.0047	42.6
		4		0.0057	35.1
		6		0.0067	29.9
		8		0.0077	26.0
		10		0.0087	23.0

5.2.1 Fuel Consumption on MLs Versus GPLs Using Disaggregate Data

Next, the research team took the models of fuel consumption developed in section 5.2 and applied them to NTE (SH121/183) data provided by Wejo. The Wejo data contains detailed speed information on approximately

3% to 7% of the vehicles in the traffic stream, but no fuel consumption information. Therefore, the Wejo speed data can be used along with our disaggregate models to estimate fuel consumption. Note that since these results are based on our relatively limited dataset it can only be considered an example of how this could be done.

Figure 34 compares fuel consumption on the MLs and GPLs along SH 183/121 in both the eastbound and westbound directions. Looking at the red box marked number 1, the GPL was operating in an ideal speed range for fuel consumption during the middle of the day (speeds in the high 50s to low 60s mph). However, GPL vehicle fuel consumption was similar to that of ML vehicle fuel consumption (at suboptimal speeds in the high 70s mph) because the GPL vehicles experienced more acceleration and deceleration events. Box number 2 illustrates that the fuel consumption is less on the MLs during the PM peak period when average speeds on GPLs are below 50 mph and ML speeds are above 75 mph. Again, since this is based on limited fuel consumption data we cannot make any conclusions regarding which lanes are the most fuel-efficient, but the procedure developed here has strong potential.

Figure 34: Demonstration of disaggregate approach to estimating fuel consumption

6.0 Conclusion

This study first examined methods to estimate vehicle fuel consumption in real-world freeway travel with changes in speed. To begin, NREL's RouteE API models were examined and found that they did not account for speed fluctuations which resulted in inaccurate fuel consumption estimates. The team then tested the shortest path API of NREL and learned that the API can be used only for Denver region. Comparing the NREL results with Google Maps routing algorithm, NREL's API recommended routes with travel time much larger than Google's recommended routes.

The research team then performed several field trials where vehicles were driven and fuel consumption was measured using two different OBD data loggers (HEM Data and VEEPEAK). Both data loggers were evaluated for their accuracy with respect to measuring vehicle fuel consumption. The OBD data was compared with that of the U.S. EPA's Motor Vehicle Emissions Simulator (MOVES) estimations on how much fuel the vehicle used and ground truth (actual fuel purchased). After multiple evaluations, the HEM Data OBD Mini Logger was found to perform extremely well while the VEEPEAK was rejected due primarily to gaps in the second-by-second data needed for accurate estimations. The HEM OBD was found to be performing even better than MOVES by giving more accurate fuel consumption results that better followed actual vehicle speed and acceleration/deceleration events.

The research team then collected data using the HEM OBD through almost 100 vehicle trips on Dallas highways using four different categories of vehicles: SUVs, sedans, a hybrid vehicle, and pick-up trucks. The study location was selected for freeways with MLs and GPLs running parallel to each other. The freeways were I-35W and I-820/SH183/SH121 in the Dallas–Fort Worth area. The most fuel efficient route between the MLs and the GPLs varied with traffic and vehicle type. MLs showed a lower fuel consumption than the GPLs over half of the time, much more often than Google Maps indicated the MLs were the more fuel efficient route. However, all of these results are based on a relatively small set of data.

Finally, researchers looked for a potential path forward to develop a new method of accurately predicting the most fuel-efficient route using the models developed here. To begin, models of fuel consumption based on speed and speed change over 0.2-mile freeway segments were developed. Regression models of fuel consumption were estimated by examining the fuel consumption versus the speed change over that 0.2-mile segment. This was done for multiple brackets of average speed. The result is a model of fuel consumption based on average speed and change in speed over a 0.2-mile segment of freeway. With detailed traffic data, such as from Wejo, equations like these would make it possible to precisely estimate fuel consumption on a roadway segment.

Researchers applied these models to a one day sample of Wejo data along SH 183/121. For this small test we found the ML travel required less fuel more than half of the time, but there were many periods of the day where the GPL travel required less fuel. We feel this is a successful test of a significantly improved algorithm for determining the most fuel efficient route. However, before it can be used to definitely identify the most fuel efficient route it will require a great deal more data to be collected using a larger variety of vehicles to improve on these regression models of fuel consumption.

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Appendix A: Algorithm for Cleaning VEEPEAK Data

Table 13: Patterns of Missing Data in the VEEPEAK Datasets

TIME	Speed	CUMSUM Distance	Distance per_sec	CUMSUM FuelUsed	MAF (GPS)	Vehicle acceleration (g)	Latitude	Longitude
0:18:12	1.242742	0.000828	0.000828	0.001895	5.76	0.003373	30.60692	-96.2792
0:18:13		0.000828	0	0.00211	6.2	0.006745	30.60692	-96.2792
0:18:14	1.864114	0.001744	0.000916	0.00211	6.213333	0.00925	30.60703	-96.2792
0:18:15	2.485485	0.002596	0.000852	0.002363	6.24	0.012019	30.60703	-96.2792
0:18:16		0.002596	0	0.002568	6.13	0.013536	30.60703	-96.2792
0:19:42	42.25324	0.494876	0.014222	0.030781	22.82	0.009366	30.60305	-96.2851
0:19:43		0.494876	0	0.031537	23.31	0.009434	30.60301	-96.2853
0:19:44	42.87461	0.515052	0.020176	0.031537	23.45	0.01322	30.6029	-96.2855
0:19:45	42.87461	0.53179	0.016738	0.03248	23.66	0.012545	30.603	-96.2859
0:19:46		0.53179	0	0.032897	15.2825	0.009302	30.60298	-96.286
0:19:47	42.87461	0.550448	0.018658	0.032897	9.89	0.009554	30.60302	-96.286
0:19:48	42.87461	0.566314	0.015866	0.033207	7.29	0.00718	30.60302	-96.286
0:25:04	7.456454	3.830608	0	0.116294	3.77	0	30.62321	-96.3295
0:25:05		3.830608	0	0.116294	3.77	0	30.62321	-96.3295
0:25:06		3.830608	0	0.116437	3.77	0	30.62321	-96.3295
0:25:07		3.830608	0	0.116554	3.7	0	30.62321	-96.3295
0:25:08		3.830608	0	0.116554	3.693333	0	30.62321	-96.3295
0:25:09		3.830608	0	0.116698	3.69	0	30.62321	-96.3295
0:25:10		3.830608	0	0.116815	3.64	0	30.62321	-96.3295
0:25:11		3.830608	0	0.116815	3.646667	0	30.62321	-96.3295
0:25:12		3.830608	0	0.116945	3.65	0	30.62321	-96.3295

1. Data cleaning

   DROP ROWS: If no data (blanks) on:
   1. Speed
   2. Distance
   3. Fuel consumption

      If a row has no information on all three of these variables, then we remove that row

2. Data imputation

   1. Missing fuel consumption: we have been given cumulative fuel consumption and we forward fill on blanks
   2. We did the same for cumulative distance
   3. We then added one more column to the dataset calculating the “Distance_per_row” by simply calculating the difference between two consecutive rows
   4. For MAF and acceleration we forward fill on missing values

SPEED

- There are three columns on speed in the VEEPEAK data and for this analysis we considered the vehicle speed (mph) column

3. Converting the data to "Per Second"

To resample the above data, we considered the following values for each variable:

1. "Speed": "max", (since there are many missing values and we assume that a vehicle will not change its speed by large margin within a second)

2. "CUMSUM-Distance": "max",
3. "Dist-per-row": "sum"
4. "CUMSUM-Fuel-Used": "sum"
5. "MAF (GPS)": "mean"
6. "Vehicle acceleration (g)": "mean"
7. SPEED
   - After considering the max speed for each second, we wanted to make sure to address the rows with "0" speed (if any) as we had found it in few datasets (Austin).
   - For this we did not want to simply forward fill as we do not want speed values when vehicle is at stop positions (e.g., red light). We therefore must differentiate between TRUE zero values (stop position) and anomalies zero speed entries. We did this in following steps:
   - 1. Converting all zero speed rows to blanks.
   - 2. If speed = blank and distance per second is 0, then return zero or else the given speed value (doing this will make sure that we have zero speeds at the stop positions).
   - 3. If speed = blank then forward fill.

Appendix B: Procedure for Gathering and Analyzing Speed Data from RITIS

The probe data analytics (PDA) suite was used to gather the speed information for the NTE express lanes and general purpose lanes from the RITIS website (https://pda.ritis.org/suite/). The probe data analytics suite offers real-time and historical speed data for a variety of roadway networks. The projected harmonic mean speed for the road segments during a five-month period (February 2 to May 28, 2022) was used for analysis.

The NTE segments were split into segment 1, segment 2, and segment 3, which are depicted in Figure 12 and Figure 13. The I-820 loop and SH 183/SH 121 were divided into segment 1 and 2. Segment 1 starts at the western end of the I-820 express lanes and ends where the I-820 loop turns south. Segment 2 starts at the point where segment 1 ends and closes at the eastern terminus of the SH 183/SH 121 express lanes. The I-35 W highway, in both northbound and southbound directions, makes up segment 3.

Each roadway segment is made up of multiple smaller segments in RITIS that are each given a unique ID. There are two types of such segments: (i) XD (eXtreme Definition) and (ii) TMC (Traffic Message Channel).

In comparison to TMC segments, XD segments typically include more roadway links because they adjust to the changes in the road network more quickly. Therefore, XD segments were used for this analysis. For instance, XD IDs for segment 1 for the general-purpose lane are shown in Table 14.

Table 14: XD IDs for Segment 1 GPL

xd	road-name	road-num	bearing	miles	frc	county	state	zip	timezone_name	start_latitude	start_longitude	end_latitude	end_longitude
429368646	22B		E	0.044837	2	TARRANT	TX	76180	America/Chicago	32.83258	-97.21282	32.83253	-97.21205
1563118205	I-820 E	820	S	0.250225	2	TARRANT	TX	76180	America/Chicago	32.84007	-97.23845	32.83992	-97.23415
1563118876	I-820 E	820	S	0.516193	1	TARRANT	TX	76137	America/Chicago	32.8395	-97.31747	32.8389	-97.30875
1562875828	I-820 E	820	S	0.528454	2	TARRANT	TX	76148	America/Chicago	32.83928	-97.26626	32.83971	-97.25718
1562797602	I-820 E	820	S	0.454171	2	TARRANT	TX	76180	America/Chicago	32.83925	-97.2305	32.83609	-97.22368
1562923918			E	0.299098	2	TARRANT	TX	76180	America/Chicago	32.83208	-97.20944	32.83192	-97.2044
1563089531	I-820 E	820	S	0.688191	2	TARRANT	TX	76180	America/Chicago	32.83609	-97.22368	32.83258	-97.21282
429368481	I-820 E	820	S	0.217173	2	TARRANT	TX	76180	America/Chicago	32.83992	-97.23415	32.83925	-97.2305
464350866	I-820 E	820	S	0.282884	2	TARRANT	TX	76137	America/Chicago	32.8392	-97.29463	32.83929	-97.28976
1562968950	I-820 E	820	S	0.454842	2	TARRANT	TX	76117	America/Chicago	32.83929	-97.28976	32.83929203	-97.28192889
1563062681	I-820 E	820	S	0.840349	2	TARRANT	TX	76180	America/Chicago	32.83993	-97.25292	32.84007	-97.23845
1563111228	I-820 E	820	S	0.454845	2	TARRANT	TX	76117	America/Chicago	32.8393037	-97.27409471	32.83928	-97.26626
1562968934	I-820 E	820	S	0.454842	2	TARRANT	TX	76117	America/Chicago	32.839292	-97.28192889	32.83930369	-97.27409471
1562877197			E	0.33399	2	TARRANT	TX	76180	America/Chicago	32.83192	-97.2044	32.83405	-97.19924
464330260	I-820 E	820	S	0.364114	2	TARRANT	TX	76137	America/Chicago	32.83916	-97.3009	32.8392	-97.29463
429368806	I-820 E	820	S	0.457664	2	TARRANT	TX	76137	America/Chicago	32.8389	-97.30875	32.83916	-97.3009
1562837693	I-820 E	820	S	0.247936	2	TARRANT	TX	76180	America/Chicago	32.83971	-97.25718	32.83993	-97.25292
429368847	22B		E	0.154926	2	TARRANT	TX	76180	America/Chicago	32.83253	-97.21205	32.83208	-97.20944

For offline analysis, data can be downloaded from RITIS using either the “Massive data downloader” or the “Performance chart.” The PDA analytics screen is shown in Figure 35. “Massive data downloader” option shows the real-time harmonic mean of the speed for each smaller segment ID and can be downloaded for a long timeframe which is convenient for our analysis. The “Performance chart” creates a single time for each day for no more than seven days at a time and depicts aggregate conditions along the stretches of the roadway. For our analysis, the “Massive data downloader” was used.

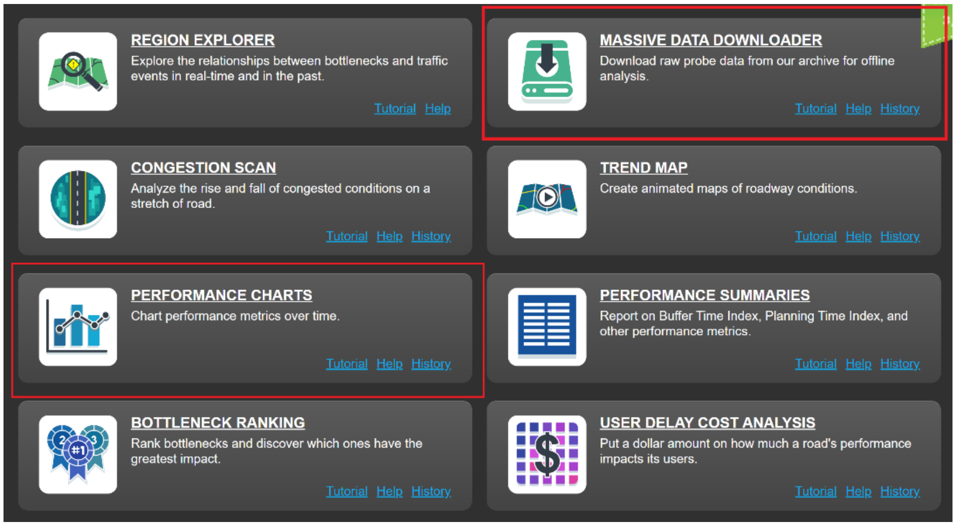


Figure 35: RITIS Probe data analytics screen

The steps involved in downloading the data are as follows:

Step-1: Selecting roadway segments

- "XD" was chosen as the segment type, while INRIX was chosen as the data source.
- The associated segments IDs for segments 1, 2, and 3 were entered and segments were added by clicking the "Add segments" option (see Figure 36).

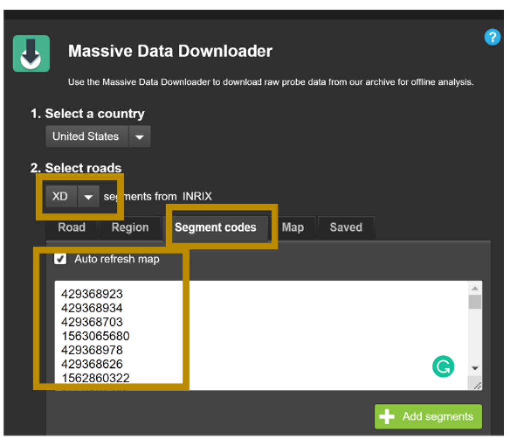


Figure 36: Selection of segments

Step 2: Adding time range and days of the week

The period, days of the week, granularity, and data source were selected. The granularity was set to 30 minutes. The process is shown in Figure 37 for the selection. After following the above steps, the data was downloaded.

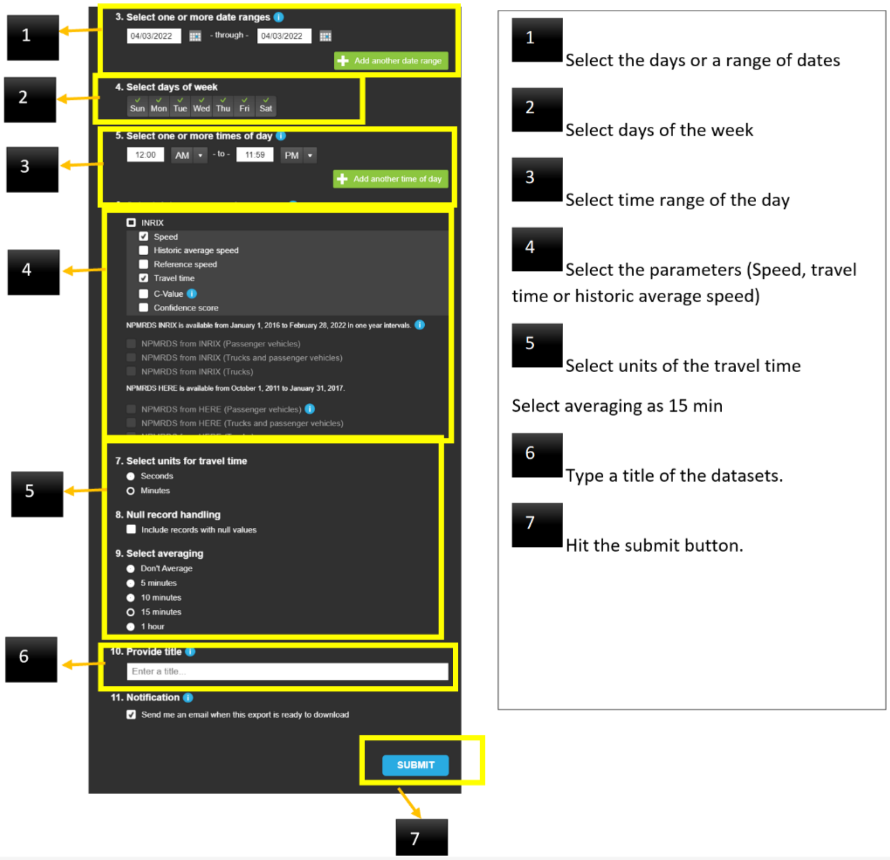


Figure 37: Adding time range, data source, and granularity in RITIS

Data Format

The data report is a compressed zip file containing three files:

- A CSV file with the data.
- Contents.txt that includes the title of the report.
- XD_Identification.csv: A list of all XDs segments associated with the dataset.

Data Analysis Procedure

The calculation procedure is as follows:

- The speed data were obtained for each XD segment that was part of NTE segments 1, 2, and 3. The speed data were averaged over the XD segments to get the mean speed of an entire segment (segments 1, 2, and 3) for a single day at any given 30-minute time of day (e.g., Monday 11:00 PM to 11:29:59 PM). All the speed measurements were with a granularity of 30 minutes.
- The mean speed for a segment on any given weekday (Monday, for example) at a specific time was obtained by averaging the speed data for the same weekdays (all Mondays) at the same time throughout the course of the previous five months. Table 15 exhibits a sample dataset for one of the freeways.

Table 15: Segment Eastbound GPL Speed Data for all Mondays

Day	Time	Speed	Date
Monday	0:00:00	65.46611111	2/7/2022
Monday	0:30:00	64.21777778	2/7/2022
Monday . .	1:00:00 . .	63.43722222 . .	2/7/2022 . .
Monday	23:00:00	65.74777778	2/7/2022
Monday	23:30:00	65.8	2/7/2022
Monday	0:00:00	65.99333333	2/14/2022
Monday	0:30:00	67.445	2/14/2022
Monday . .	1:00:00 . .	69.29166667 . .	2/14/2022 . .
Monday	23:00:00	64.46444444	2/14/2022
Monday	23:30:00	64.22555556	2/14/2022
Monday	0:00:00	65.21277778	2/21/2022
Monday	0:30:00	66.92333333	2/21/2022
Monday . .	1:00:00 . .	62.35444444 . .	2/21/2022 . .
Monday	23:00:00	64.33944444	2/21/2022
Monday	23:30:00	64.16388889	2/21/2022 . . . .
Monday	0:00:00	65.85777778	5/23/2022
Monday	0:30:00	66.85611111	5/23/2022
Monday . .	1:00:00 . .	64.03388889 . .	5/23/2022 . .
Monday	23:00:00	63.32277778	5/23/2022
Monday	23:30:00	63.47611111	5/23/2022

- As can be seen in Table 15, the mean speed for Monday at 23:00 (11:00 PM) was calculated by averaging the speeds recorded each Monday at 11:00 PM. From February 2 to May 28, there are approximately 21 segment points for each weekday (Monday to Friday). The number of sample points indicates the number of each weekday over the course of the 5-month period. So, we have an average of 21 sample points for Monday, Tuesday, Wednesday, Thursday, and Friday.
- The same procedure was followed for segments 1, 2, and 3 in both directions (EB-WB and NB-SB) both for general purpose lanes (GPLs) and the managed lanes (MLs).

A sample dataset for segment 1 Eastbound for GPL for Monday is shown in Table 16.

Table 16: Sample Dataset of Average Speed on GPL and ML

CONCESSION	WEEKDAY	TIMEWINDOW_30MIN	SEGMENT	DIRECTION	AVG_GP_SPEED	AVG_ML_SPEED	SAMPLE_POINTS
NTE	Monday	0:00	1	EB	65.604931	65.395000	21
NTE	Monday	0:30	1	EB	65.218264	66.011633	21
NTE	Monday	1:00	1	EB	64.915104	66.922041	21
. .	. .	. .	. .	. .	. .	. .	. .
NTE	Monday	22:30	1	EB	65.797083	67.308367	21
NTE	Monday	23:00	1	EB	64.628368	67.050612	21
NTE	Monday	23:30	1	EB	64.525833	68.677857	21
NTE	Tuesday	0:00	1	EB	65.192535	65.710408	21
NTE	Tuesday	0:30	1	EB	66.045069	65.466633	21
NTE	Tuesday	1:00	1	EB	64.724167	63.907245	21
NTE . .	Tuesday . .	1:30 . .	1 . .	EB . .	64.900104 . .	66.043776 . .	21 . .
NTE	Tuesday	22:30	1	EB	65.321736	68.581633	21
NTE	Tuesday	23:00	1	EB	65.444861	67.508265	21
NTE	Tuesday	23:30	1	EB	65.648611	67.267347	21 . . . .
NTE	Friday	0:00	1	EB	64.933987	65.645417	21
NTE . .	Friday . .	0:30 . .	1 . .	EB . .	64.403170 . .	65.215238 . .	21 . .
NTE	Friday	22:30	1	EB	63.968203	69.611411	21
NTE	Friday	23:00	1	EB	64.885784	68.799500	21

Displaying the Speed Data

To visualize and better understand the variation in travel speeds throughout the day, boxplots were developed based on the speed data. The boxplots were plotted for a full day of operation using the datasets generated using the above approach. The arithmetic mean speed data was determined for each workday in 30 minutes intervals. Therefore, for a single period, we have the 5-speed data for each of the five workdays. Each of these speed measurements was based on the mean speed of 21 sample points for each weekday. "TIMEWINDOW_30MIN" in Table 16 represents the time variable for a day after every 30 minutes for each weekday. For each timestamp, the time was treated as a variable and was plotted along the x-axis, while the matching speed data for each period were shown along the y-axis.

Boxplots divide the data into sections, each of which contains around 25% of the total data for a single time. It displays the speed distribution using a five-number summary (minimum, first quartile, median, third quartile, and maximum). It gives information about the range of speed values and how tightly the data is grouped. It also tells us about the distribution type of the data. If the median is in the middle of the boxplot, it means the data conform to the normal distribution. If not, the data follow a skewed distribution. The standard deviation for each timestamp can also be derived from the interquartile range (IQR). The higher the standard deviation, the higher the IQR, meaning the dataset is more evenly spread out. The data points outside the boxplots represents outliers. Figure 38 is an example of a boxplot:

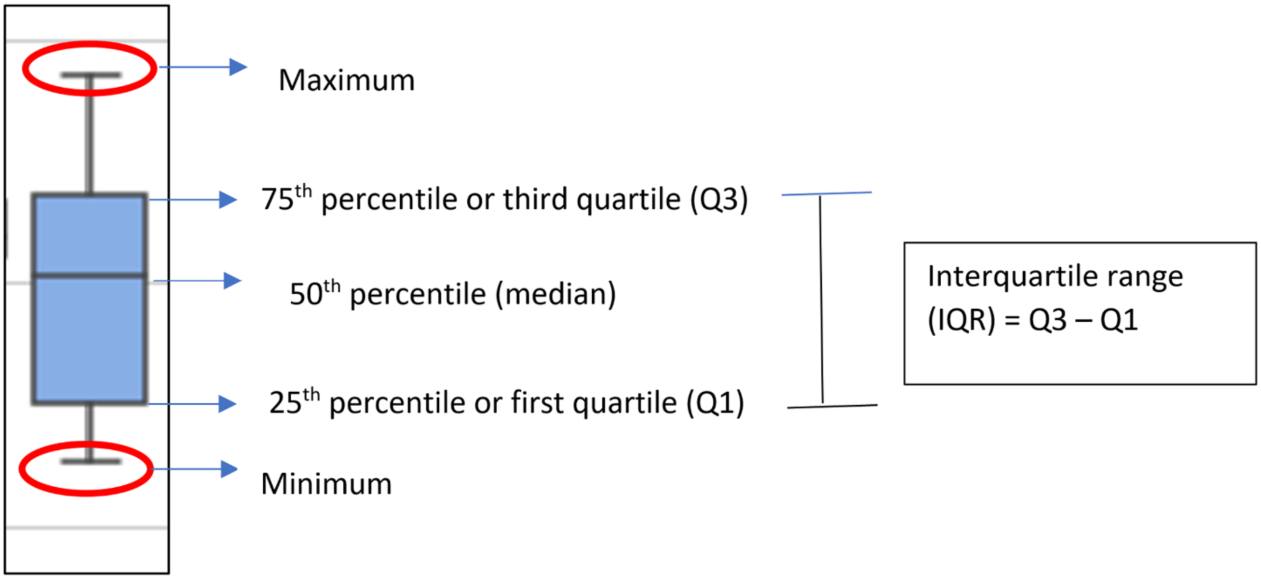
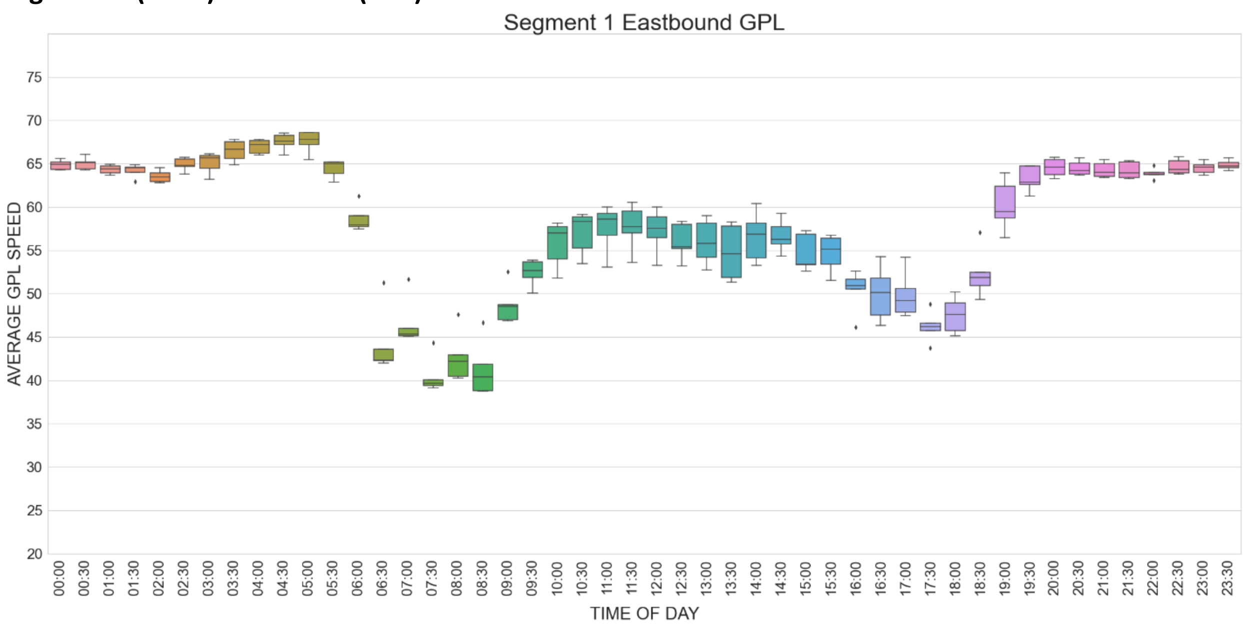


Figure 38: Interpretation of a boxplot

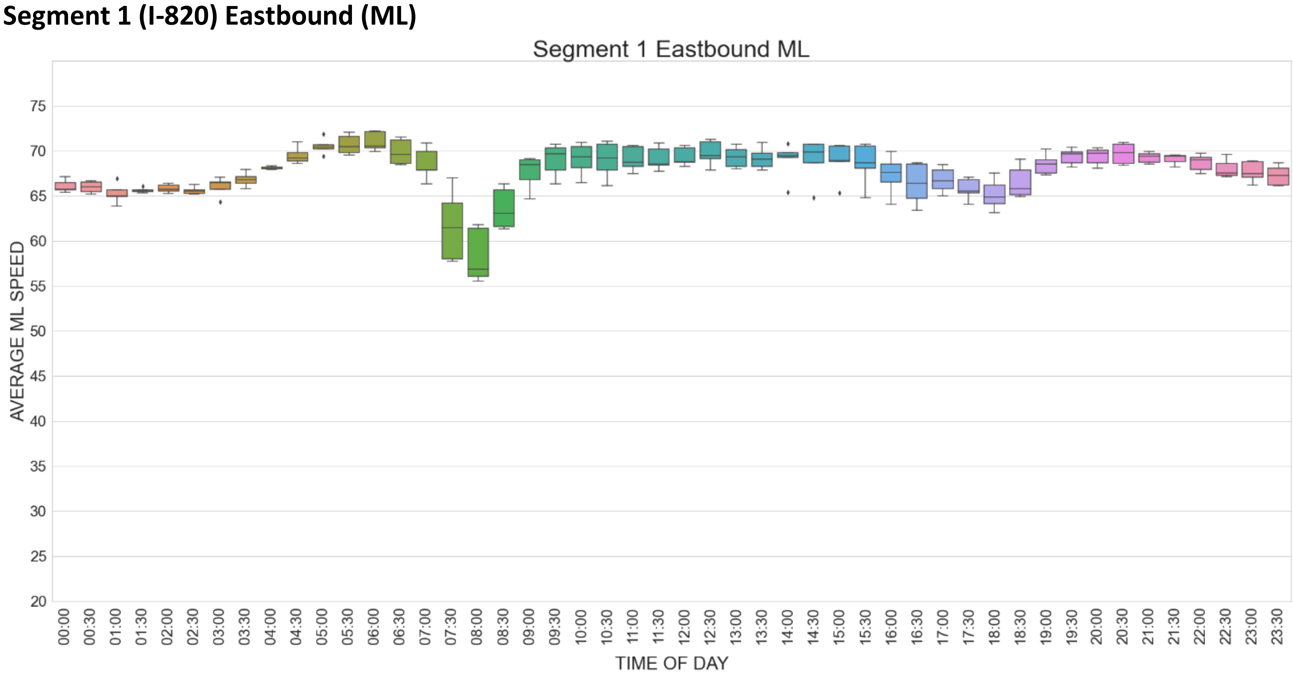
The boxplots provided a quick visual summary of speed for each 30-minute time window. The range, mean, and dispersion of the data at each timeframe were observed using the boxplots. It would also be possible to extract the values of the 25th, 50th, 75th, and 85th percentile speed values for each time window. The minimum indicates the lowest data points in the data set excluding outliers and the maximum indicates the highest point of the dataset excluding outliers. Those plots were helpful to identify the peak and off-peak periods for each roadway segment in each direction. As expected, the general-purpose lanes experienced a large reduction in speed during the morning and evening peak periods while the speed on the managed lane exhibited lower speed variability throughout the day.

Appendix C: Speed Profiles for Target Roadways by Time of Day

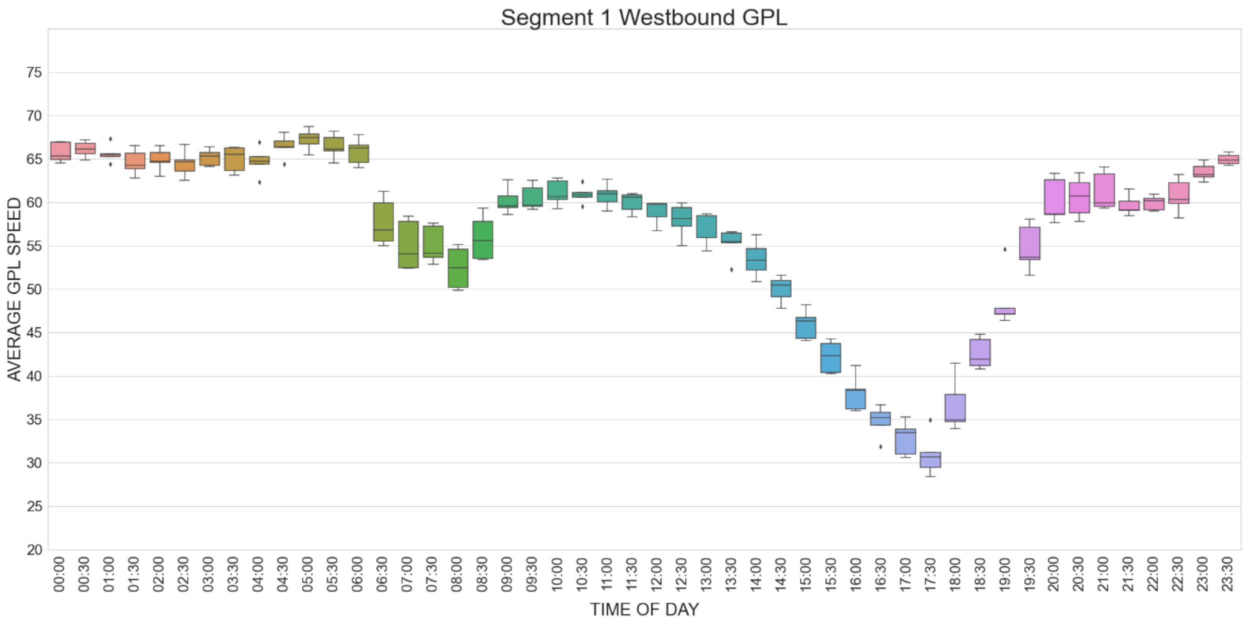
Segment 1 (I-820) Eastbound (GPL)



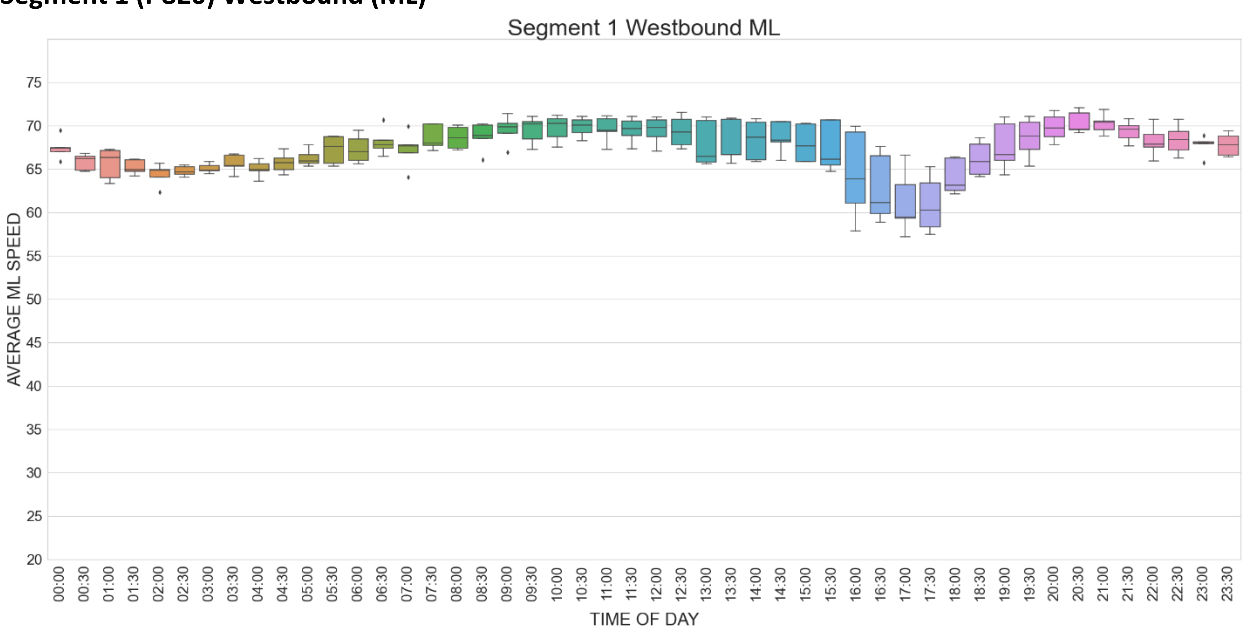
Segment 1 (I-820) Eastbound (ML)



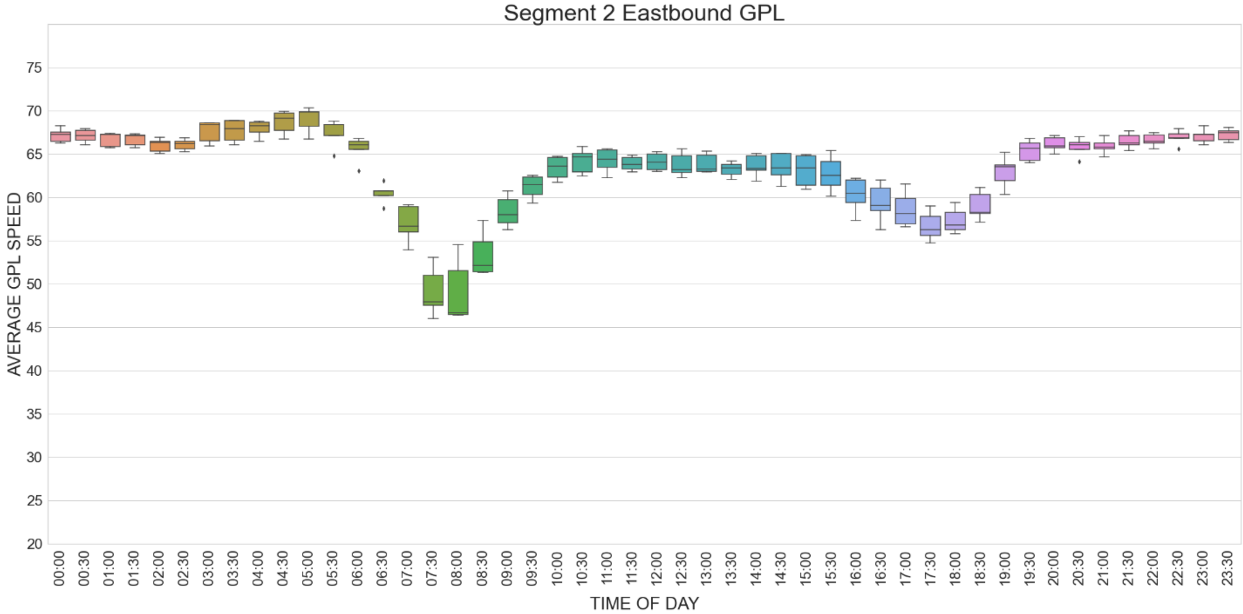
Segment 1 (I-820) Westbound (GPL)



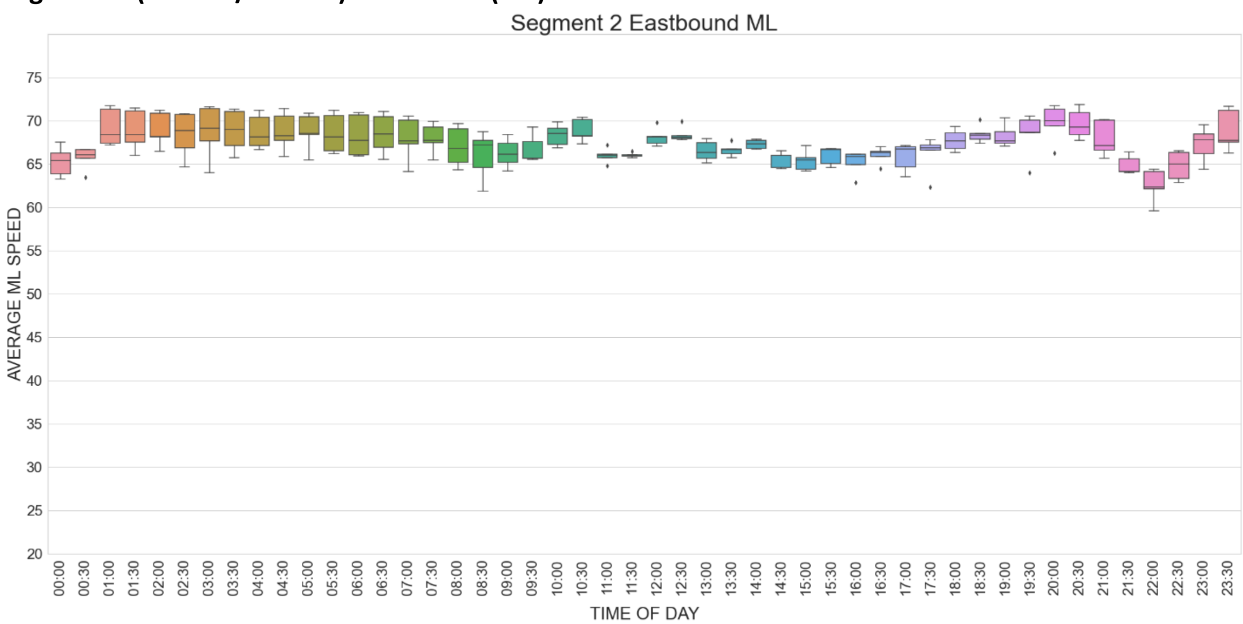
Segment 1 (I-820) Westbound (ML)



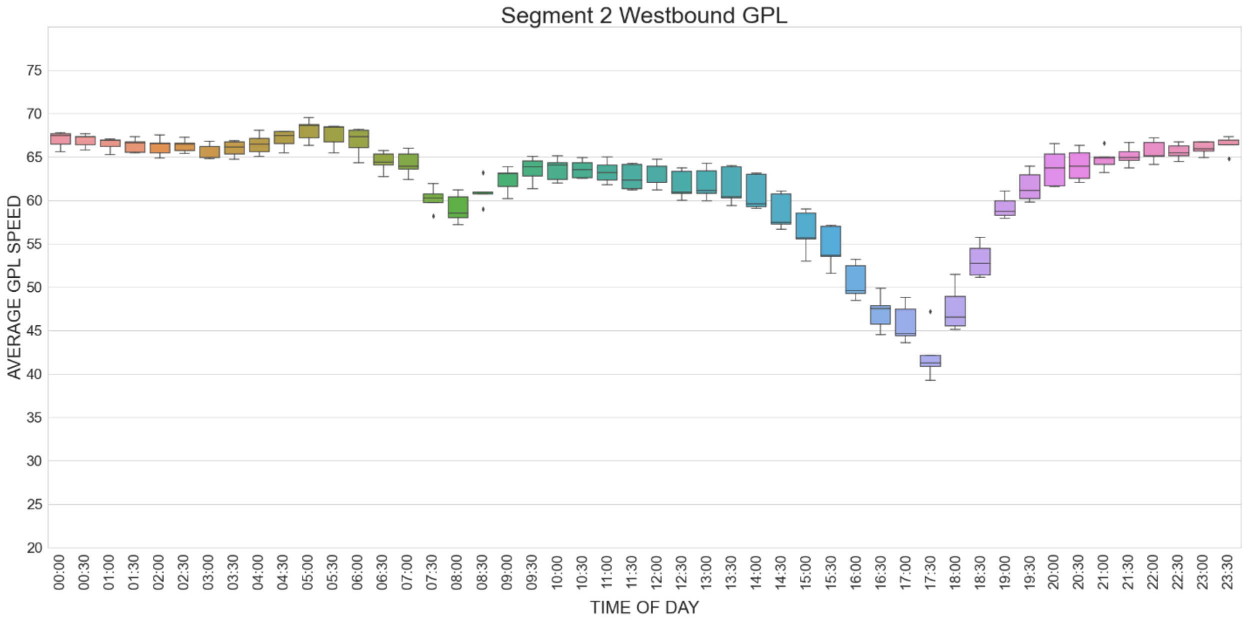
Segment 2 (SH 183 / SH 121) Eastbound (GPL)



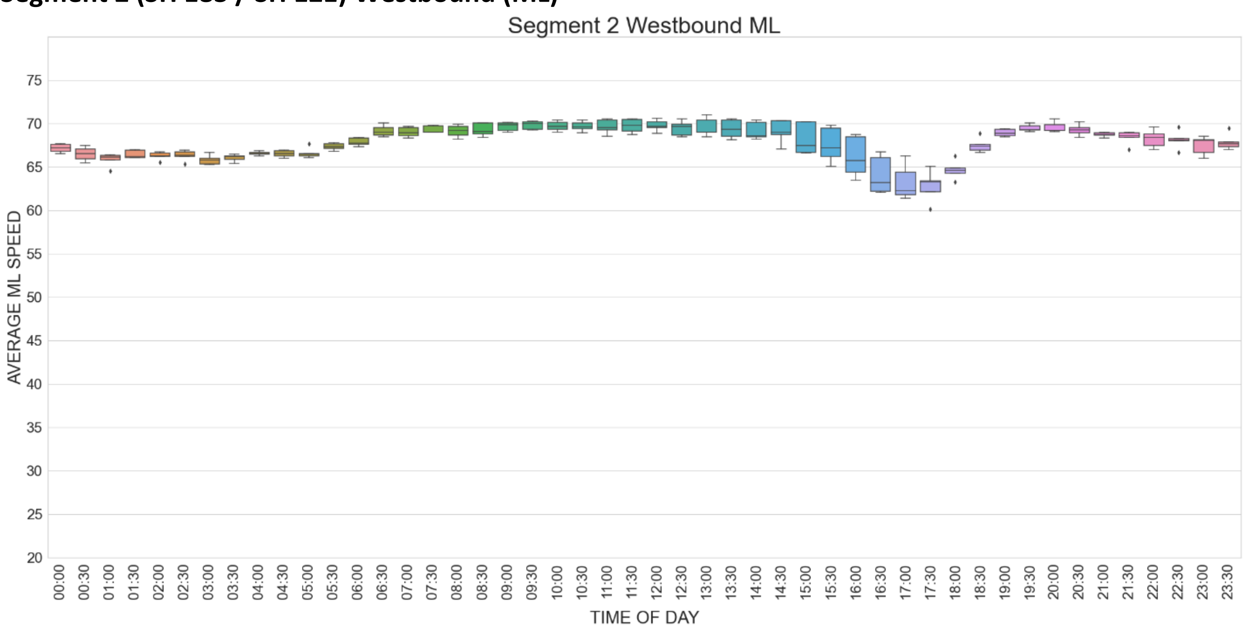
Segment 2 (SH 183 / SH 121) Eastbound (ML)



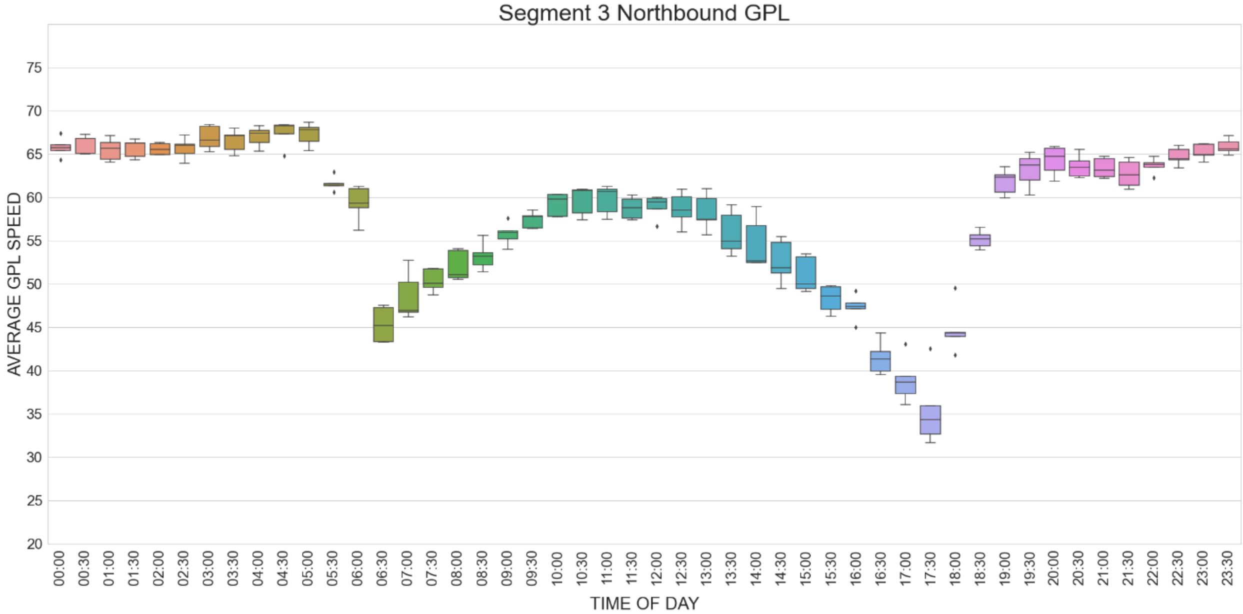
Segment 2 (SH 183 / SH 121) Westbound (GPL)



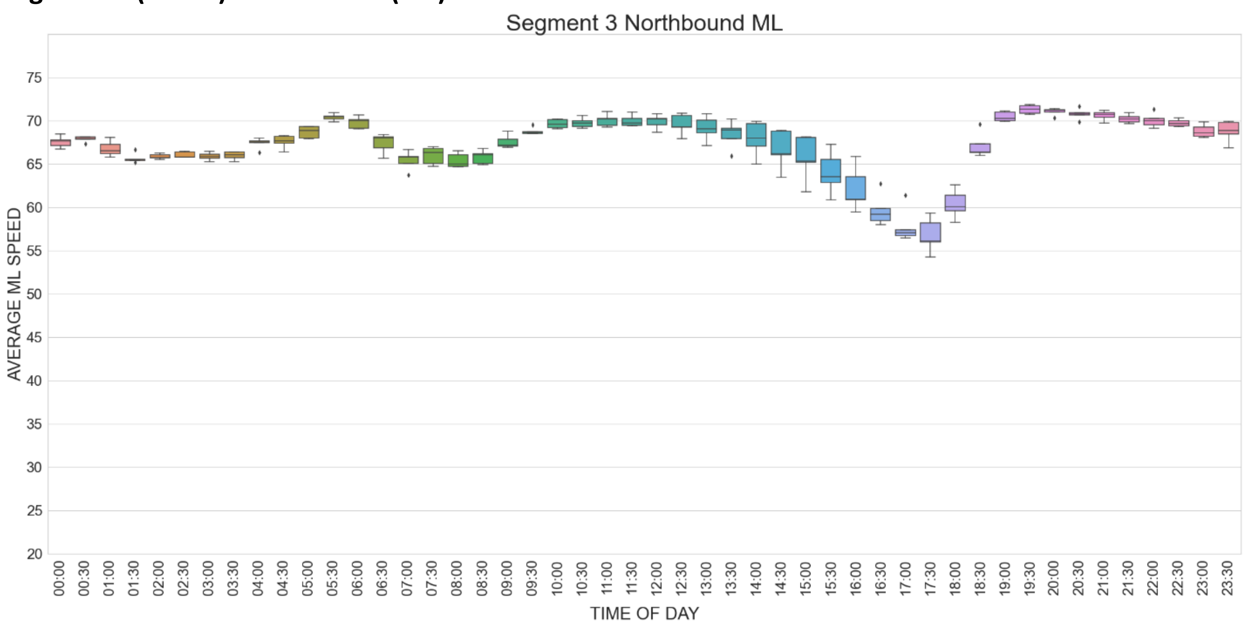
Segment 2 (SH 183 / SH 121) Westbound (ML)



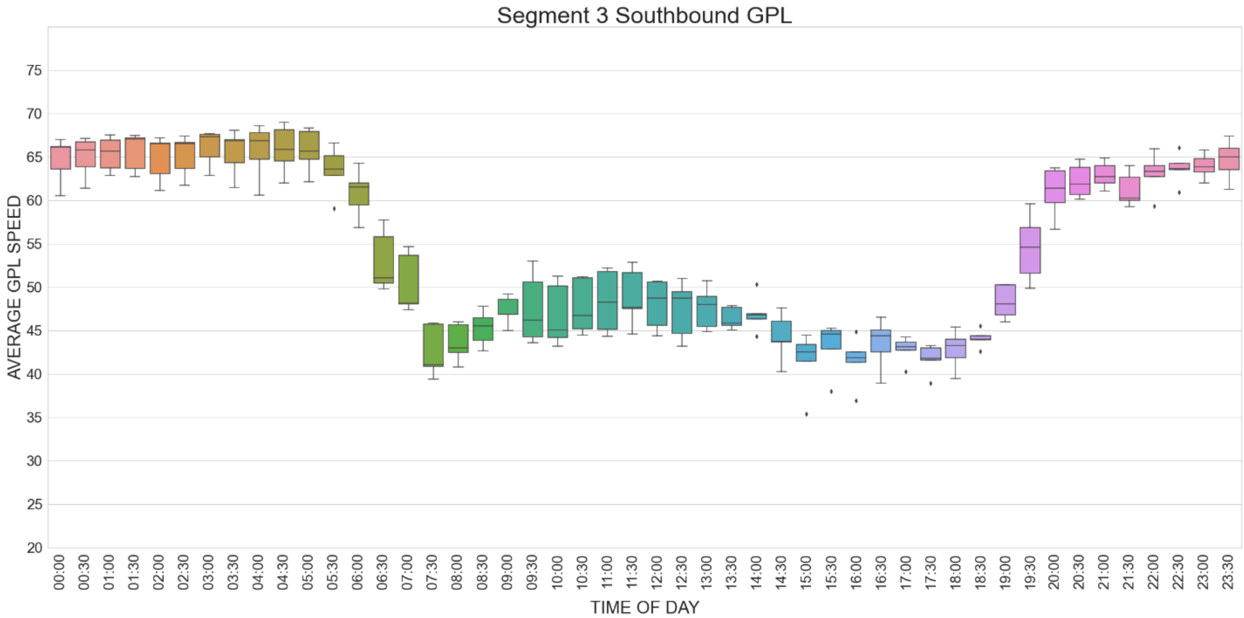
Segment 3 (I-35W) Northbound (GPL)



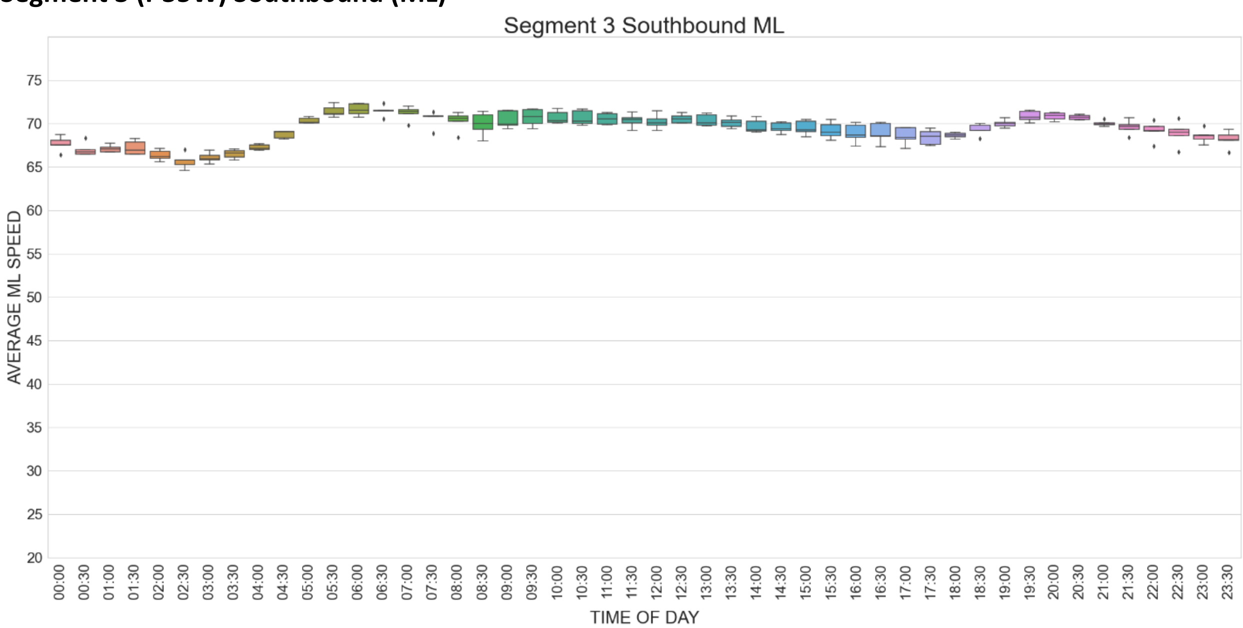
Segment 3 (I-35W) Northbound (ML)



Segment 3 (I-35W) Southbound (GPL)



Segment 3 (I-35W) Southbound (ML)



Appendix D: Vehicle Runs

Table 17: Appendix D Notations

Notations	Description
V1	2021 Chevy Equinox
V2	2018 Toyota Camry
V3	2019 Nissan Sentra
Seg 1 & 2	I-820/SH121/SH183
Seg 3	I-35W
Link length	0.2
Speed difference	Last 1/3 – First 1/3rd speed
X-axis	Speed difference
Y-axis	Speed brackets and fuel consumption

The following table gives information on the total number of trips made by each vehicle on different road segments and has been plotted graphically. Although vehicle 1 did one trip on I-35W on the GPL, a graph has not been plotted for that one trip as it's not enough data.

Table 18: Initial Vehicle Runs

	V1		V2		V3	
	Lane Type	No. of Trips	Lane Type	No. of Trips	Lane Type	No. of Trips
I-35W	ML	5	ML	2	GPL	7
			GPL	2		
I-820/ SH183/ SH121	ML	3	GPL	2	GPL	2

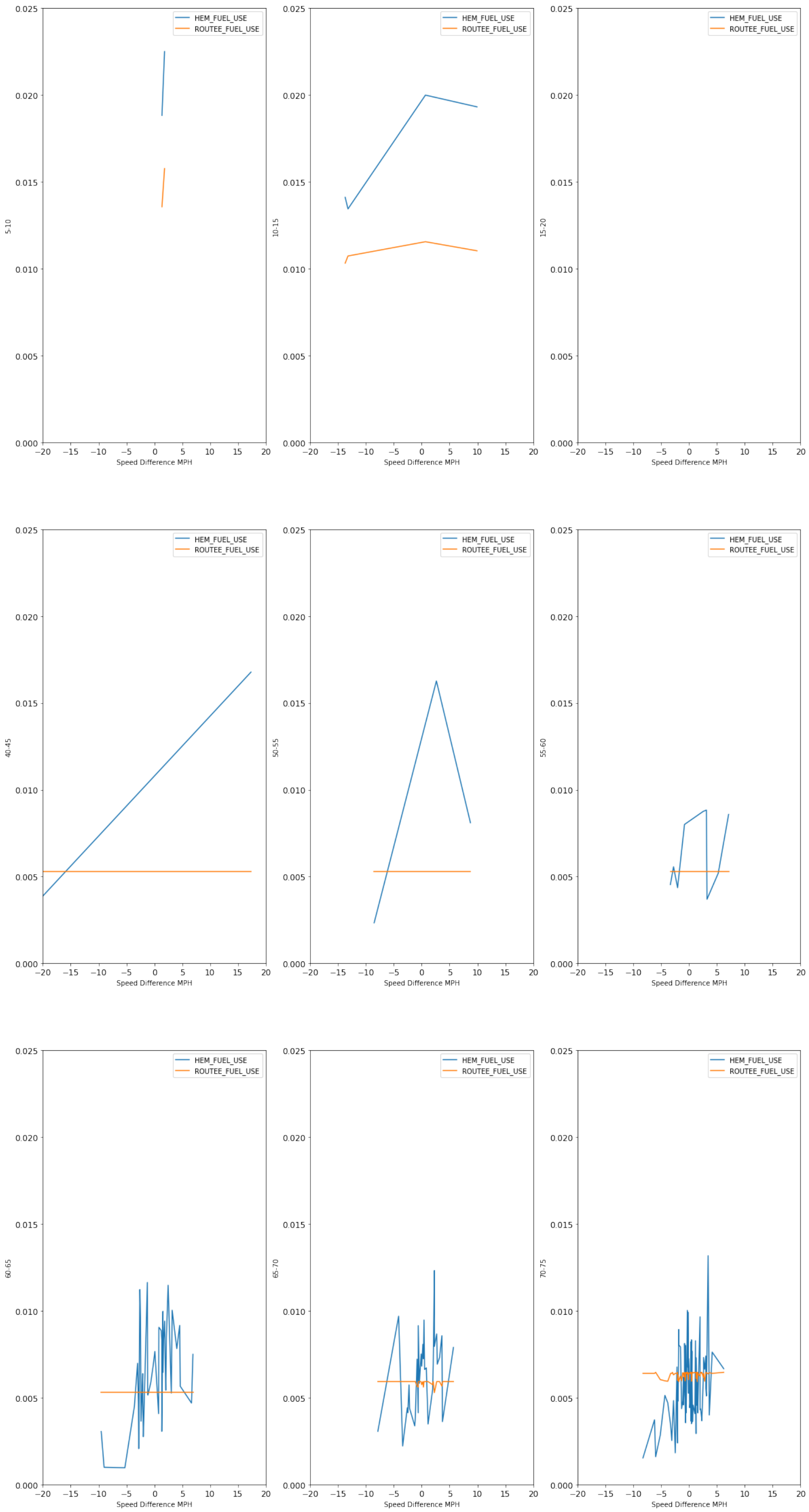


Figure 39: Fuel consumption from RouteE and HEM: SUV_ML

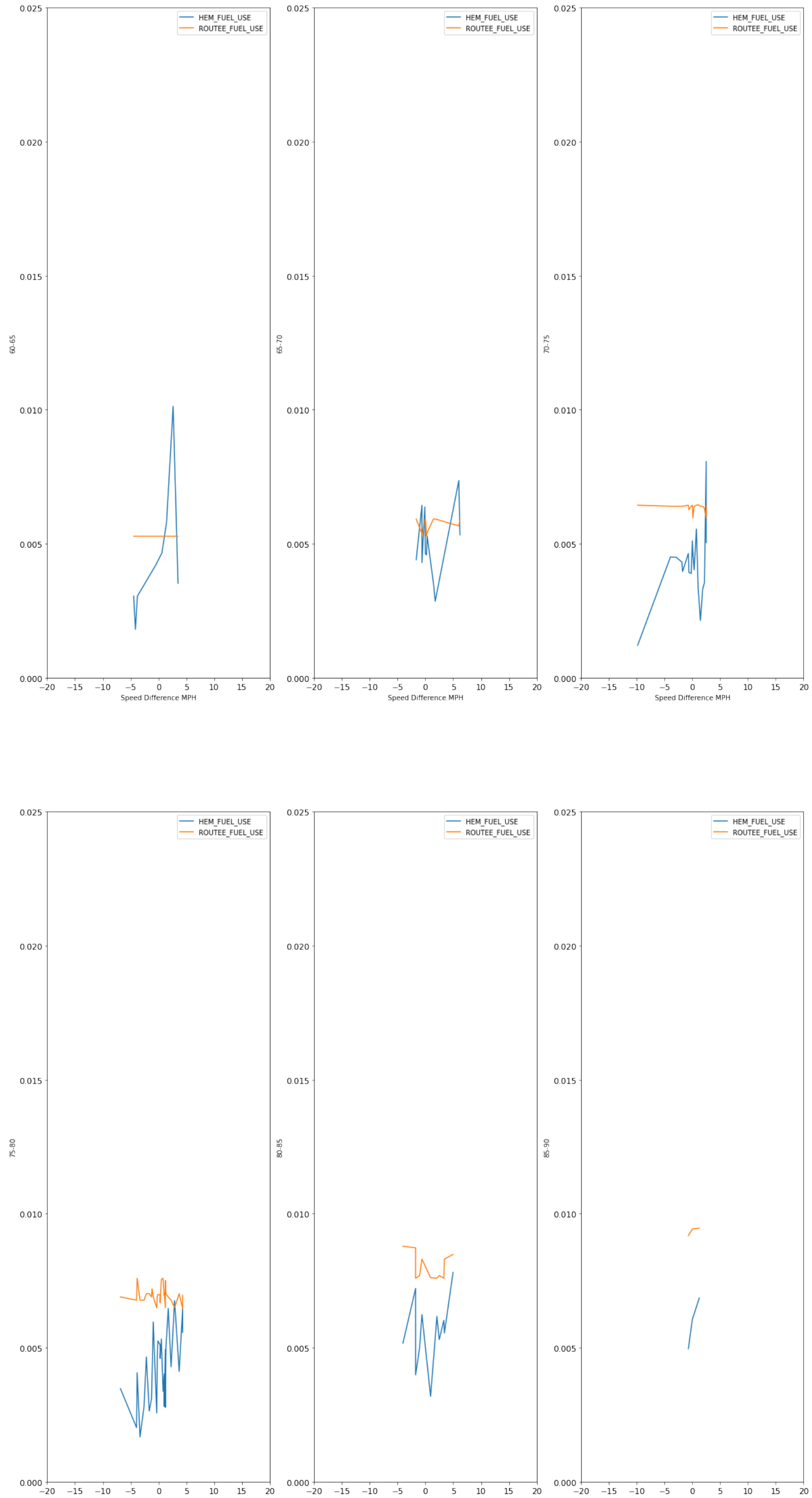


Figure 40: Fuel consumption from RouteE and HEM: Sedan_ML

Figure 41: Fuel consumption from RouteE and HEM: Sedan_GPL

Figure 42: Fuel consumption from RouteE and HEM: Hybrid_GPL

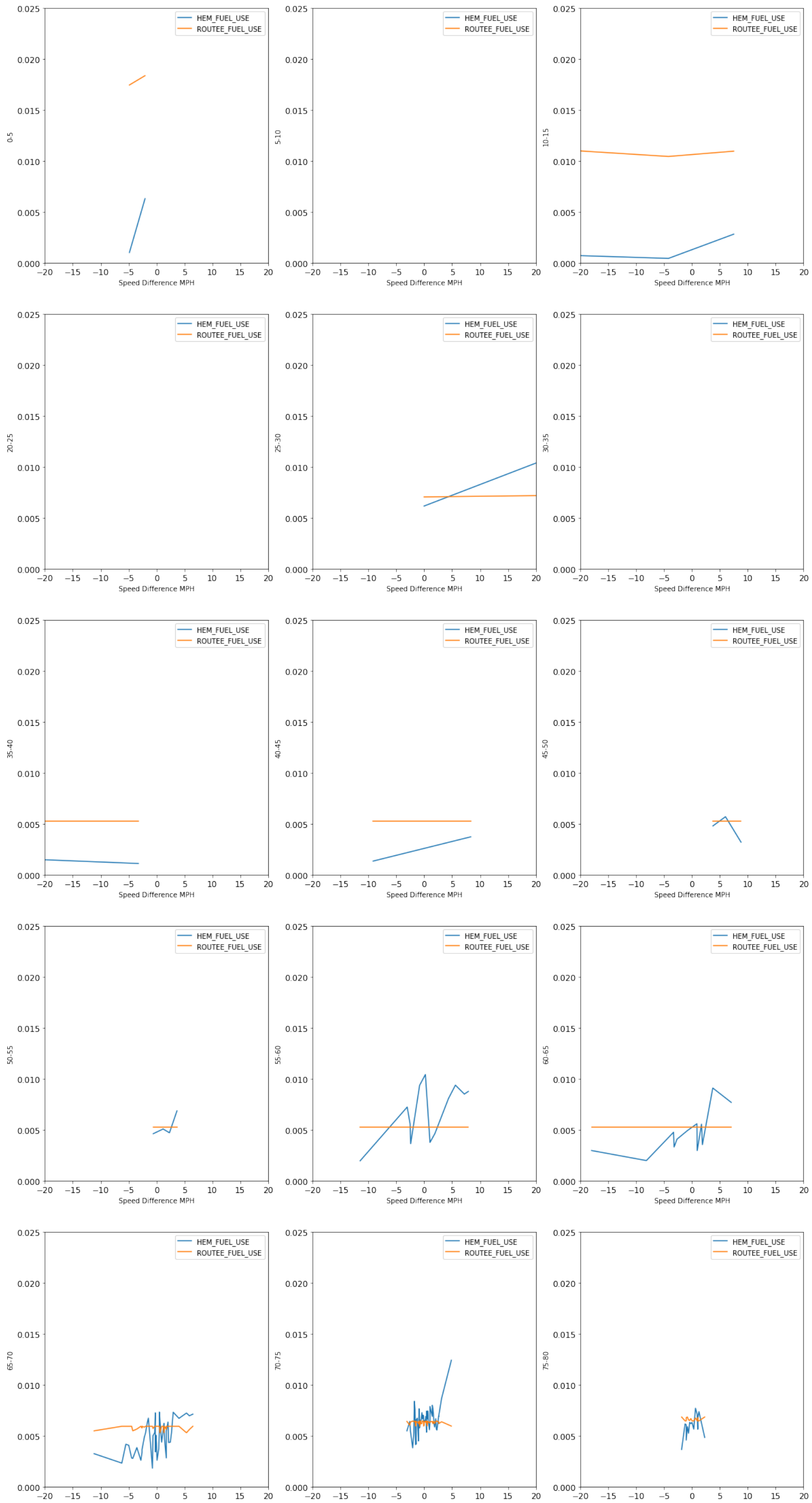


Figure 43: Fuel consumption from RouteE and HEM: Hybrid_ML

Table 19: All Vehicle Runs

VEHICLE	DATE	TRIP NUMBER	TRIP START	TRIP END	AVEL TIME (min:s	ROAD	DIRECTION	LANE TYPE	DISTANCE	AVG SPEED	HEM FUEL ESTIMATE	MOVES FUEL ESTIMATE
V1 - 2021 Chevy Equinox	7/21/2022	1	10:57:13	11:04:30	0:07:17	I35W	N	ML	8.91	73.40	0.2857	0.233
		2	12:40:40	12:48:24	0:07:44	I35W	S	ML	8.94	69.36	0.242	0.228
		3	13:09:51	13:17:01	0:07:10	I35W	N	ML	8.96	75.01	0.27	0.232
		4	13:51:28	14:10:26	0:18:58	RIVERSIDE	S	SS	9.89	31.29	0.268	0.267
		5	14:53:22	15:18:56	0:25:34	Pipeline Rd	E	SS	10.7	25.11	0.385	0.337
		6	16:54:37	17:08:10	0:13:33	820/183	W	ML	10.25	45.39	0.333	0.28
	7/22/2022	7	8:11:20	8:18:45	0:07:25	I35W	S	ML	8.94	72.32	0.258	0.227
		8	8:22:24	8:29:31	0:07:07	I35W	N	ML	8.95	75.46	0.254	0.241
		9	9:25:14	9:33:26	0:08:12	820/183	E	ML	10.2	74.63	0.275	0.269
		10	9:44:38	9:52:49	0:08:11	820/183	W	ML	10.2	74.79	0.346	0.264
		11	10:37:18	10:50:27	0:13:09	I35W	S	GPL	8.97	40.93	0.305	0.275
V2 - 2018 Toyota Camry	7/21/2022	12	11:30:26	11:34:31	0:04:05	I35W	N	ML	2.6	38.20	0.085	0.093
		13	11:34:55	11:39:30	0:04:35	I35W	N	GPL	6.15	80.51	0.145	0.159
		14	11:39:31	11:42:37	0:03:06	I35W	N	ML	2.86	55.35	0.05	0.076
		15	12:44:26	12:55:13	0:10:47	I35W	S	GPL	8.89	49.47	0.211	0.257
		16	13:05:41	13:18:20	0:12:39	I35W	N	GPL	8.9	42.21	0.236	0.262
		17	13:51:29	14:10:25	0:18:56	RIVERSIDE	S	SS	9.88	31.31	0.25	0.294
		18	14:53:22	15:18:55	0:25:33	Pipeline Rd	E	SS	10.7	25.13	0.3525	0.378
	7/22/2022	19	8:11:40	8:18:52	0:07:12	I35W	S	ML	8.87	73.92	0.235	0.253
		20	8:22:40	8:29:43	0:07:03	I35W	N	ML	8.9	75.74	0.218	0.263
		21	9:24:55	9:36:00	0:11:05	820/183 FWY	E	GPL	10.26	55.54	0.2376	0.294
		22	9:41:44	9:51:23	0:09:39	820/183 FWY	W	GPL	10.3	64.04	0.248	0.291
V3 - 2019 Nissan Sentra	7/21/2022	23	11:30:43	11:39:52	0:09:09	I35W	N	GPL	8.93	58.56	0.2216	0.244
		24	12:42:33	12:54:07	0:11:34	I35W	S	GPL	8.94	46.37	0.2219	0.249
		25	13:06:52	13:19:45	0:12:53	I35W	N	GPL	8.93	41.59	0.257	0.26
		26	13:49:00	14:09:21	0:20:21	RIVERSIDE	S	SS	9.87	29.10	0.315	0.305
		27	14:54:58	15:21:00	0:26:02	Pipeline Rd	E	SS	10.62	24.48	0.3603	0.378
		28	16:55:28	17:00:05	0:04:37	820/183	W	ML	2.34	30.41	0.079	
		29	17:00:06	17:25:16	0:25:10	820/183 FWY	W	GPL	8.6	20.50	0.347	0.347
		30	20:46:41	20:55:08	0:08:27	I35W	S	GPL	8.9	63.20	0.224	0.242
		31	21:05:18	21:13:51	0:08:33	I35W	N	GPL	8.95	62.81	0.234	0.252
	7/22/2022	32	8:10:59	8:20:10	0:09:11	I35W	S	GPL	8.92	58.28	0.215	0.246
		33	8:23:06	8:31:14	0:08:08	I35W	N	GPL	8.93	65.88	0.21	0.253
		34	9:28:31	9:40:31	0:12:00	820/183 FWY	E	GPL	10.3	51.50	0.262	0.332
		35	9:50:00	10:00:39	0:10:39	820/183 FWY	W	GPL	10.3	58.03	0.279	0.318
2021 - 2556 _Sedan_Hyundai_Elantra_KIA_Forte	9/13/2022	36	7:47:18	7:57:53	0:10:35	I35W	N	GPL	8.94	50.68	0.183	0.214
		37	8:30:42	8:45:07	0:14:25	I35W	S	GPL	8.96	37.29	0.204	0.343
		38	17:38:19	18:10:06	0:31:47	SEG1&2	W	GPL	10.41	19.65	0.29	0.156
	9/14/2022	39	17:35:58	17:53:49	0:17:51	I35W	N	GPL	8.97	30.15	0.224	0.088
		40	8:35:07	8:48:59	0:13:52	SEG1&2	W	GPL	10.28	44.48	0.218	0.068
	9/15/2022	41	7:34:29	7:48:54	0:14:25	SEG1&2	W	GPL	10.16	42.28	0.2122	0.071
		42	8:02:39	8:32:03	0:29:24	SEG1&2	E	GPL	10.3	21.02	0.287	0.145
	9/21/2022	43	17:44:51	18:00:28	0:15:37	I35W	S	GPL	8.91	34.23	0.191	0.077
	9/22/2022	44	17:32:48	17:51:49	0:19:01	SEG1&2	E	GPL	10.2	32.18	0.237	0.094
2007, - Ford Explorer	9/7/2022	45	7:34:53	7:43:05	0:08:12	I35W	N	ML	8.95	65.49	0.421	0.196
		46	7:49:29	8:12:38	0:23:09	I35W	S	GPL	8.97	23.25	0.465	0.25
		47	8:31:24	8:43:02	0:11:38	I35W	N	GPL	8.96	46.21	0.391	0.306
		48	8:58:35	9:06:28	0:07:53	I35W	S	ML	8.96	68.19	0.366	0.267
		49	17:11:29	17:25:29	0:14:00	I35W	N	ML	8.96	38.40	0.441	0.336
		50	17:35:47	17:51:20	0:15:33	I35W	S	GPL	8.96	34.57	0.39	0.352
	9/8/2022	51	7:32:56	7:56:44	0:23:48	SEG1&2	E	GPL	10.25	25.84	0.519	0.453
		52	8:34:53	8:49:53	0:15:00	SEG1&2	W	GPL	10.25	41.00	0.409	0.37
		53	17:34:31	17:54:04	0:19:33	I35W	N	GPL	8.96	27.50	0.496	0.382
		54	18:02:43	18:16:34	0:13:51	I35W	S	GPL	8.95	38.77	0.4369	0.335
	9/13/2022	55	17:39:40	18:11:19	0:31:39	SEG1&2	W	GPL	10.26	19.45	0.636	0.542
	9/21/2022	56	7:37:21	7:54:57	0:17:36	SEG1&2	W	GPL	10.26	34.98	0.504	0.407
		57	8:04:21	8:32:45	0:28:24	SEG1&2	E	GPL	10.26	21.68	0.57	0.503
2007 - 2855 - Ford F250	9/1/2022	80	7:32:18	7:56:22	0:24:04	SEG1&2	E	GPL	10.4	25.93		0.33
		81	14:37:04	14:45:27	0:08:23	I35W	N	ML	8.96	64.13		0.193
		82	14:59:04	15:08:35	0:09:31	I35W	S	ML	8.95	56.43		0.189
	9/7/2022	83	14:26:13	14:34:07	0:07:54	I35W	N	ML	8.96	68.05		0.196
		84	15:02:44	15:10:18	0:07:34	I35W	S	ML	8.95	70.97		0.187
		85	17:11:54	17:26:15	0:14:21	I35W	N	ML	8.96	37.46		0.242
		86	17:36:11	17:51:52	0:15:41	I35W	S	GPL	8.95	34.24		0.25
	9/8/2022	87	15:03:57	15:12:47	0:08:50	SEG1&2	w	ML	10.4	70.64		0.222
		88	15:24:32	15:33:14	0:08:42	SEG1&2	E	ML	10.4	71.72		0.222

2012 Ford Escape Hybrid	oct/12/2022	58	17:33:40	17:53:15	0:19:35	I35W	N	GPL	8.96	27.45	0.2249	0.217
		59	18:12:25	18:21:24	0:08:59	I35W	S	GPL/ML	8.94	59.71	0.25	0.266
	oct/13/2022	60	7:35:32	7:49:48	0:14:16	820/183 FWY	W	GPL	10.3	43.32	0.253	0.296
		61	8:02:50	8:29:03	0:26:13	820/183 FWY	E	GPL	10.4	23.80	0.215	0.254
		62	14:24:04	14:31:35	0:07:31	I35W	N	ML	8.95	71.44	0.319	0.274
		63	15:03:58	15:23:51	0:19:53	I35W	S	GPL	8.95	27.01	0.21	0.229
		64	16:58:28	17:08:22	0:09:54	I35W	N	ML	8.95	54.24	0.303	0.26
		65	17:32:24	17:53:12	0:20:48	I35W	S	GPL	8.95	25.82	0.196	0.225
	10/18/2022	66	7:01:46	7:17:09	0:15:23	I35W	N	ML	8.95	34.91	0.286	0.268
		67	7:34:22	7:53:29	0:19:07	I35W	S	GPL	8.95	28.09	0.224	0.243
		68	8:03:57	8:19:11	0:15:14	I35W	N	GPL	8.95	35.25	0.259	0.256
		69	9:04:18	9:12:03	0:07:45	I35W	S	GPL/ML	8.95	69.29	0.235	0.257
		70	14:20:42	14:28:37	0:07:55	I35W	N	ML	8.95	67.83	0.301	0.276
		71	15:03:22	15:11:17	0:07:55	I35W	S	ML	8.95	67.83	0.23	0.261
		72	17:31:04	17:50:51	0:19:47	820/183 FWY	E	GPL	10.4	31.54	0.22	0.242
	10/19/2022	73	7:31:55	7:54:52	0:22:57	820/183 FWY	E	GPL	10.4	27.19	0.223	0.23
		74	8:34:21	8:47:06	0:12:45	820/183 FWY	W	GPL	10.4	48.94	0.258	0.304
		75	15:06:16	15:28:11	0:21:55	820/183 FWY	W	GPL	10.4	28.47	0.225	0.262
		76	15:40:19	15:55:56	0:15:37	820/183 FWY	E	GPL	10.4	39.96	0.221	0.268
	10/25/2022	77	15:04:58	15:14:09	0:09:11	820/183	W	ML	10.4	67.95	0.319	0.295
		78	15:26:00	15:34:45	0:08:45	820/183	E	ML	10.4	71.31	0.344	0.31
		79	17:37:34	18:08:20	0:30:46	820/183 FWY	W	GPL	10.4	20.28	0.229	0.295
2017 FORD F-350	7-Nov-22	89	1:40:42	1:43:15 AM	0:02:33	on B Johnson Fre	E	GPL	2.57	60.47	0.425	0.181
		90	8:08:40	8:12:23	0:03:43	on B Johnson Fre	E	GPL	2.57	41.49	0.337	0.261
08_2017 FORD F-350	8-Nov-22	91	1:46:37 PM	1:49:02 PM	0:02:25	on B Johnson Fre	E	GPL	2.57	63.81	0.37	0.178
2015 FORD F-650		92	3:51:19	3:54:13	0:02:54	on B Johnson Fre	E	GPL	2.57	53.17	0.45	0.272
2015 FORD F-650		93	3:11:27	3:14:22	0:02:55	on B Johnson Fre	W	GPL	2.57	52.87	0.3	0.272
2011 FORD F-250	16_NOV_22	94	2:14:22 PM	2:17:07 PM	0:02:45	on B Johnson Fre	E	GPL	2.57	56.07	0.198	0.213
2017 FORD F-350	17_NOV_22	95	11:40:00 PM	11:42:05 PM	0:02:05	on B Johnson Fre	E	GPL	2.57	74.02	0.388	0.148
2017 FORD F-350		96	1:11:51 AM	1:14:41 AM	0:02:50	on B Johnson Fre	E	GPL	2.57	54.42	0.26	0.201
2011 FORD F-250	19_nov_22	97	10:57:55 PM	11:00:44 PM	0:02:49	on B Johnson Fre	E	GPL	2.57	54.75	0.2	0.219
2011 FORD F-250		98	2:04:35 AM	2:07:17 AM	0:02:42	on B Johnson Fre	E	GPL	2.57	57.11	0.187	0.209

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