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National Training Center (NTC) Fuel Consumption Analysis Overview

by Greg Dogum

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14. ABSTRACT
The study objective was to analyze U.S. Army ground vehicle usage data (e.g., engine operations, traveled distance, fuel consumption) from National Training Center rotations and to develop a methodology using these data to estimate fuel consumption for future exercises. By examining recorded vehicle platform usage (i.e., each vehicle serial number matched to specific miles driven and engine hours), assumptions can be applied relative to vehicle movement and idle times, as well as individual terrain splits to predict total training event fuel consumption quantities. With this methodology it is possible to generate estimates of ground vehicle fuel consumption for future training events as well as the associated magnitude of potential error. The basis for this study is the Fuel Consumption Prediction Model developed by the U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center, known as DAC, and field data collection through DAC's former Sample Data Collection program.

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fuel consumption prediction, predicting fuel requirements, Class IIIB estimation, ground wheeled vehicle, ground tracked vehicle, National Training Center

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Executive Summary

The study objective was to analyze U.S. Army ground vehicle usage data (e.g., engine operations, traveled distance, fuel consumption) from National Training Center, Ft. Irwin, CA, rotations and develop a methodology using these data to estimate fuel consumption for future exercises. This methodology is based on mileage recorded during low and high operating tempo (OPTEMPO) portions of the training exercises while utilizing traditional Operation Mode Summary/Mission Profile (OMS/MP) calculation techniques (e.g., percent distance on terrain, speed on terrain).

By examining recorded vehicle platform usage (i.e., each vehicle's serial number matched to specific miles driven and engine hours), assumptions can be applied relative to vehicle movement and idle times as well as individual terrain profiles to predict total training event fuel consumption quantities per platform category. Additionally, changes in seasonal idle fuel consumption can be discerned that likely reflect changing electrical demands for environmental control units. With this methodology it is possible to generate estimates of ground vehicle fuel consumption for future training events and the associated magnitude of potential error. The basis for this study was the Fuel Consumption Prediction Model used by U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center, known as DAC, and field data collection through DAC's former Sample Data Collection program.

The higher fidelity methodology uses collected training data from previous unit deployments. These data include metrics such as average daily mileage and engine hour values, to include idle and moving operations. Drawing additional insight from previously established OMS/MP speeds and terrain characteristics, DAC can reasonably estimate fuel consumption for most vehicles within 7%. The lower fidelity methodology, which only used the OMS/MP for model input, provides less accurate but more easily made estimations. However, with sufficient data, both methodologies are relatively fast and are not computationally intensive.

1. INTRODUCTION

This report describes a methodology development to predict fuel quantity requirements for wheeled and tracked ground vehicles during National Training Center (NTC) rotations. This methodology strives to establish a better estimator of expected fuel quantities in comparison to a traditional Operation Mode Summary/Mission Profile (OMS/MP)-based approach.

The goal of this study was to assess ground vehicle usage data sourced during NTC rotations and develop a method of estimating fuel consumption for future exercises. One method to plan for fuel requirements over a defined period is to identify an appropriate OMS/MP document. This document outlines expected vehicle operating tempo (OPTEMPO) over various mission phases. This OPTEMPO is then applied to estimate training fuel requirements. This document, however, is typically focused on generalized, large-scale operations. The goal is to determine if the OPTEMPO observed during the training exercises aligns with the OMS/MP's OPTEMPO.

The study's objective was to acquire operationally relevant training exercise usage data and create a methodology that could be used to predict fuel consumption for a specific platform. If successful, the training exercise's fuel quantity requirements could be more accurately scaled up or down. Ultimately, a training rotation will employ many different platforms. This technical report focuses on two platforms, one wheeled and the other tracked, to demonstrate a potential capability to increase the accuracy of expected fuel quantity requirements.

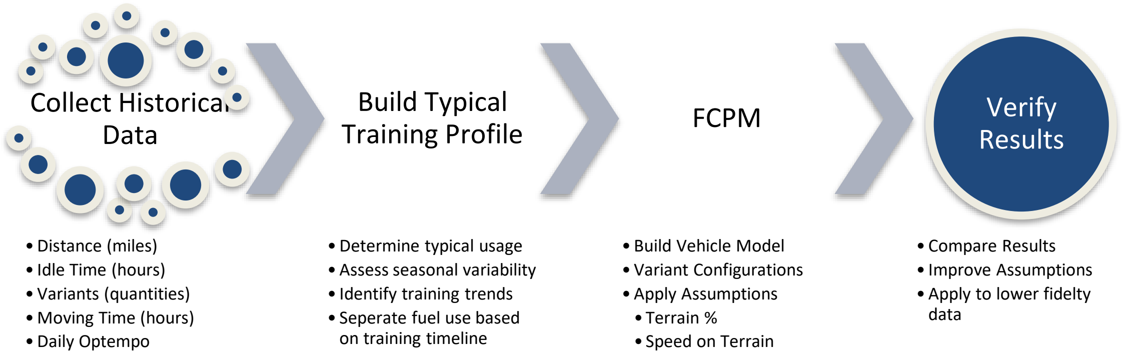
Two data sets, one for each vehicle type, are explored. The wheeled data set is of higher fidelity and was sourced from an onboard data collection system that captures several key metrics per vehicle serial number. Included in this data set are elements such as engine operating hours, idle and moving operations, distance traveled, and fuel consumed per day. The tracked vehicle data set is of a much lower fidelity and did not utilize the electronic data collection system that was installed on the wheeled platforms. The tracked vehicle data set relied on manually recorded vehicle odometer and engine-hour meter readings taken on a periodic basis through the training rotation.

This report is written in three sections. The first section includes a review of the Fuel Consumption Prediction Model (FCPM) and how it was employed in this study. The second section addresses the wheeled vehicle analysis, and the third section examines the tracked vehicle data set.

2. METHODS, ASSUMPTIONS, AND PROCEDURES

2.1 Methodology and Procedure Review

The general methodology used for both wheeled and tracked vehicles is described by four primary steps shown in Figure 1. Following Figure 1, additional details are provided regarding the steps taken to transform the larger wheeled vehicle data set into a tangible and cohesive representative usage profile. Data for the wheeled vehicle effort were obtained through the U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center, known as DAC, Sample Data Collection (SDC) team and were recorded over several years. The advantage of comparing usage data over time is evident through the identification of consistent item-level vehicle quantities and specific variant distributions, as well as differentiating usage by season.



- Distance (miles)
- Idle Time (hours)
- Variants (quantities)
- Moving Time (hours)
- Daily Optempo

- Determine typical usage
- Assess seasonal variability
- Identify training trends
- Seperate fuel use based on training timeline

- Build Vehicle Model
- Variant Configurations
- Apply Assumptions
  - Terrain %
  - Speed on Terrain

- Compare Results
- Improve Assumptions
- Apply to lower fidelty data

Figure 1. General methodology process flow

2.1.1 Step 1: Collect and Preprocess Data

The first step involved acquiring collected usage data that would be important to predicting future energy consumption. Those data elements include individual vehicle travel distances (miles), engine operation (hours), and idle and moving fuel consumed (gallons). Idle and moving fuel consumption are calculated based on an SDC algorithm for distinguishing between idle (or non-moving) and moving operations when the engine ignition is on. Data are prepared on a per-day basis for the duration of the training, which is useful in identifying how the vehicle activities increase prior to the event and then ramp down as the unit leaves for their next assignment. Additionally, non-numerical information (e.g., vehicle type binning) is used to determine appropriate model assumptions. The model assumptions, in turn, are used to supply FCPM vehicle characteristics and parameter inputs (e.g., vehicle weight in pounds). A quality check is performed to ensure the data is suitable for this specific analysis; for example, if the collected data had erroneous data or unrealistic values compared to the total data set.

2.1.2 Step 2: Analyze and Create Usage Profile

The second step in the process was to develop a representative usage profile for each vehicle variant. This step involved combining collected vehicle usage data, using some historical OMS/MP guidance as applicable, and calculating FCPM-derived fuel quantity estimates. As the collected data captures only a portion of what is typically provided in OMS/MP documents, multiple sources are used to provide vehicle input for FCPM. For example, OMS/MP documents include average speed and percent of distance on terrain, which are useful inputs for the analysis. This methodology combines information from multiple sources to generate a profile that will align with the training exercises observed.

Additionally, numerous usage profiles (i.e., data sets) were examined given the number of training rotations recorded overtime. This technique can be beneficial to identify usage trends since the number of vehicles from one rotation to the next can change. Additionally, this provides an opportunity to determine if there are any distinguishable rotational differences from one season to the next. This potential variability, due to seasonal operations, could provide an additional factor to support usage profile trends.

2.1.3 Step 3: Populate FCPM

The third step involves assumptions regarding individual vehicle configurations and how relevant OMS/MP terrain percentages and speed on terrain factors may be used. This serves as a demonstration of DAC's FCPM capabilities to estimate total fuel consumption as well as whether collected data and modeling and simulation can be used in concert to develop a representative profile that closely matches past training rotations.

2.1.4 Step 4: Compare FCPM Predictions to Measured Fuel Consumption

In the final step, FCPM is used to predict fuel consumed given observed NTC usage profiles and mobility demands. Comparisons to measured and predicted fuel consumption estimates are assessed to confirm steady-state rates and mission validity.

2.2 FCPM Review

FCPM is a steady-state ground vehicle fuel consumption model utilizing empirical data and physics-based equations. FCPM characterizes a vehicle's fuel usage over various operating environments, terrains, and speeds. The physics-based equations estimate the total mobility resistance based on those vehicle parameters and environmental considerations to determine the total force that would act on the vehicle at steady-state. These forces include air, rolling, and grade resistances. Based on the total resistance, an estimated combined mobility power requirement is calculated. Non-mobility electrical power demands and powertrain inefficiencies are incorporated as well. This total power demand estimation is then used to determine the percent of maximum power available for that specific vehicle. This determination provides a point along a 2-D Specific Fuel Consumption (SFC) curve, which provides an estimated steady-state fuel consumption rate (gallons/hour). The SFC is an empirically derived curve based on a set of standard Army fuel consumption tests. Figures 2 and 3 illustrate the inputs and workflow of the FCPM; for example, the Vehicle Cone Index, which is a measure of the ground pressure for soft soil mobility calculations. An example SFC is shown under "Vehicle Model" in Figure 3.

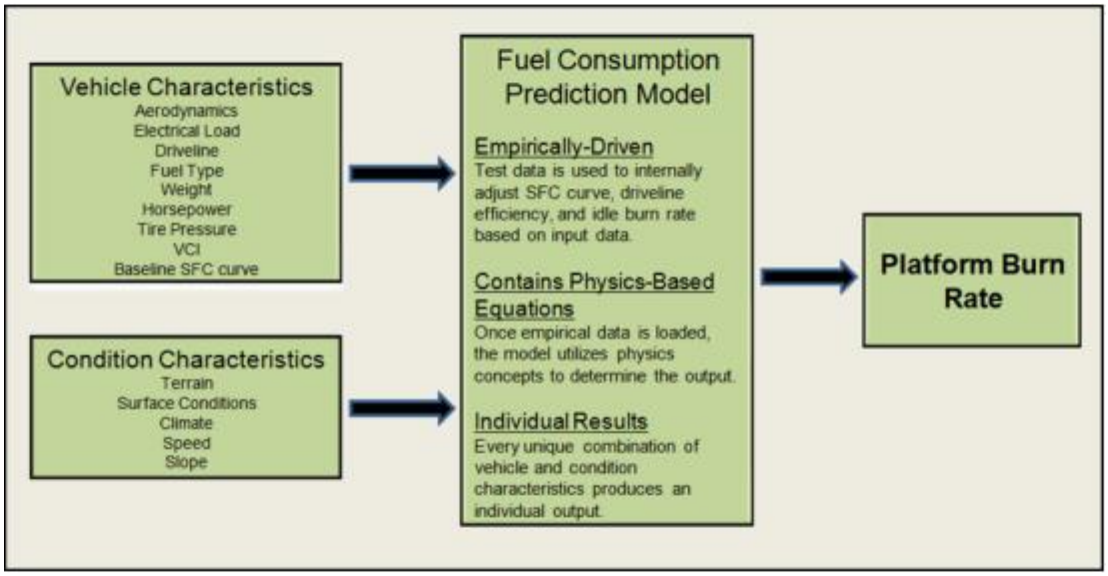


Figure 1. **FCPM data requirements**

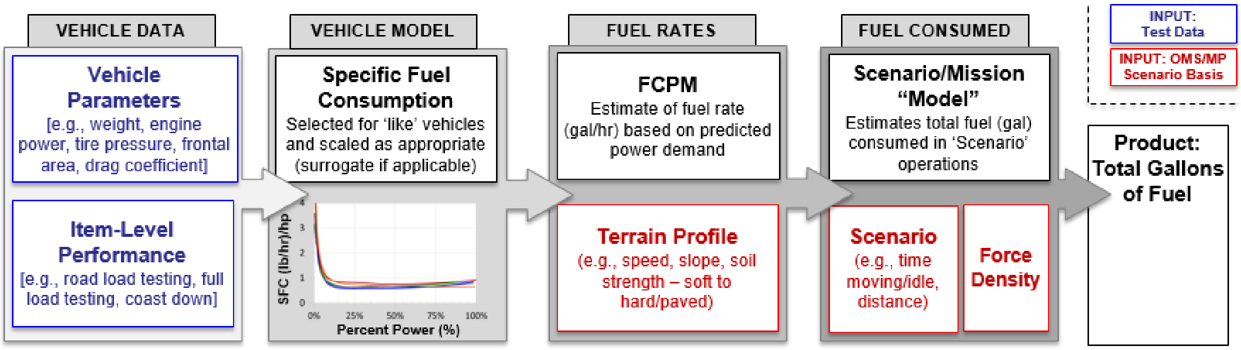


Figure 2. **FCPM flow chart for data requests**

3. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

3.1 Constraints

No restrictions were imposed.

3.2 Limitations

Limited data were available for consideration. One high-fidelity data set (wheeled vehicles; sourced from the vehicle's Controller Area Network [CAN] bus) and one low-fidelity data set (tracked vehicles; sourced from manual data collection) were available at the time of this study.

The results of this study must be verified with future training rotations to determine if this methodology is fully feasible to predict fuel consumption for other platforms. There are many variables not captured in this study that could be used to enhance the predictions, for example terrain usage data or individual vehicle weights. Some assumptions were made to model these vehicles due to those limitations in the data collection. The focus of this study, however, was to assess the feasibility of FCPM's steady-state modeling capability to utilize generalized, historical, high-level vehicle usage profiles to make reasonable fuel quantity requirements for future NTC training rotations.

3.3 Assumptions

To estimate fuel consumption using only the vehicle's CAN bus data, modeling assumptions were made with respect to the traversed terrain. While the wheeled vehicle speed was known through the CAN bus (the tracked vehicle had no CAN bus), the terrain being traversed at any point in time was unknown. In addition, assumptions were necessary to develop the vehicle's characteristic model and electrical load power profiles necessary to represent operations during the data collection period. The takeaway is that while an OMS/MP may be appropriate to describe a large-scale operation, using an OMS/MP to predict singular training events may not be the best fit. The OMS/MP typically breaks down usage into three phases for a 180-day mission, but for a training event the scale is much smaller at approximately 30 days. Given that was the case, OMS/MP phases were selected that best matched the training event's OPTEMPO to develop the initial predictions.

4. RESULTS AND DISCUSSION

4.1 Wheeled Data Set

The following subsections outline how a representative variant-level vehicle usage profile was generated for a wheeled platform with high-fidelity CAN bus data.

4.1.1 Measured Vehicle Usage and Fuel Data Analysis Summary

Daily wheeled vehicle item-level usage data sets were analyzed for six training rotations. These higher fidelity data allow for a better understanding of unit-level vehicle usage patterns, which can subsequently be applied to future data sets with less detail. Furthermore, additional charts and summaries can be found for all data discussed in this chart in Appendix A – Additional Data, Charts, and Visualizations.

Key usage metrics identified from the CAN bus data set include the following:

- Unit Statistics
  - Vehicle variant quantities
  - Total vehicles
  - Length of training rotation
- Mobility Metrics
  - Distance traveled per day
  - Moving operational engine hours per day
- Non-mobility Metrics
  - Idle operational engine hours per day
  - Time of year

4.1.1.1 Sample Data Collection Training Rotation General Patterns

A summary table of the data obtained from DAC's SDC is shown in Table 1. The rotations in bold font (TR1, TR3, TR4, TR5, TR8, and TR10) are the focus of this wheeled vehicle analysis. DAC's SDC field data collection equipment can monitor and record vehicle data. The SDC data collection system then processes daily usage across several metrics DAC used in this study to understand fuel requirements for training events.

Table 1. Training rotation usage summary

Vehicle data		Engine time (h)			Distance traveled (miles)	Fuel usage (gal)			Fuel consumption rates (gal/h)		
Rotation	Qty	On	Idle	Move		On	Idle	Move	Total	Idle	Move
TR1	284	41,677	32,058	9,619	107,829	100,662	55,649	45,013	2.4	1.7	4.7
TR2	12	167	137	29	314	291	189	102	1.7	1.4	3.5
TR3	278	40,965	33,032	7,934	91,494	89,079	51,853	37,227	2.2	1.6	4.7
TR4	286	42,821	34,469	8,351	92,161	74,280	38,548	35,731	1.7	1.1	4.3
TR5	285	38,200	29,279	8,921	103,872	72,245	32,488	39,757	1.9	1.1	4.5
TR6	19	1,263	970	293	4,946	3,023	1,492	1,531	2.4	1.5	5.2
TR7	3	565	478	88	981	850	506	344	1.5	1.1	3.9
TR8	278	34,380	27,053	7,327	76,837	75,891	42,584	33,308	2.2	1.6	4.5
TR9	18	2,758	2,263	496	4,750	4,748	2,577	2,171	1.7	1.1	4.4
TR10	228	26,665	21,293	5,372	55,366	46,926	23,216	23,710	1.8	1.1	4.4

In this section, several training rotations are summarized to reflect the overall and cumulative usage statistics. For this analysis, focus is placed on the large data sets as highlighted in Table 1. The statistics identified within these rotations will assist in making appropriate assumptions for future training rotations. This includes approximating the overall quantity of vehicles within a rotation as well as the range of operational fuel consumed.

Unfortunately, simplifying fuel consumption to a handful of metrics (e.g., vehicle item-level density, distance traveled, and engine operating hours) will not adequately predict total fuel usage. There are seasonal effects and variations between vehicle configurations that can impact the total fuel requirement that should be considered.

Referencing Table 1, while these highlighted data sets have a similar number of vehicles deployed, the total fuel consumption ranges from approximately 46,000 to approximately 100,000 gal. For planning purposes, this is a large discrepancy. Additionally, these data only capture a single platform type, so cumulatively predicting fuel quantities for other unit vehicle types, which may also exhibit a wide range in fuel requirements, could result in a large gap between actual fuel demands and the fuel resourced for a unit’s training rotation.

This can be seen in a side-by-side comparison of rotations TR1 and TR5. These rotations use a similar number of vehicles and accumulate a comparable number of miles. These rotations, however, have significantly different fuel quantities consumed, particularly with respect to idle fuel quantities. If the objective is to accurately predict fuel consumption for training rotations, then a simple set of input metrics will not be sufficient.

For the measured wheeled data, initial observations indicated that fuel consumption and distance traveled can vary across rotations as well as total engine operational time and the ratio of idle to movement. These variations can be seen in Figures 4–6.

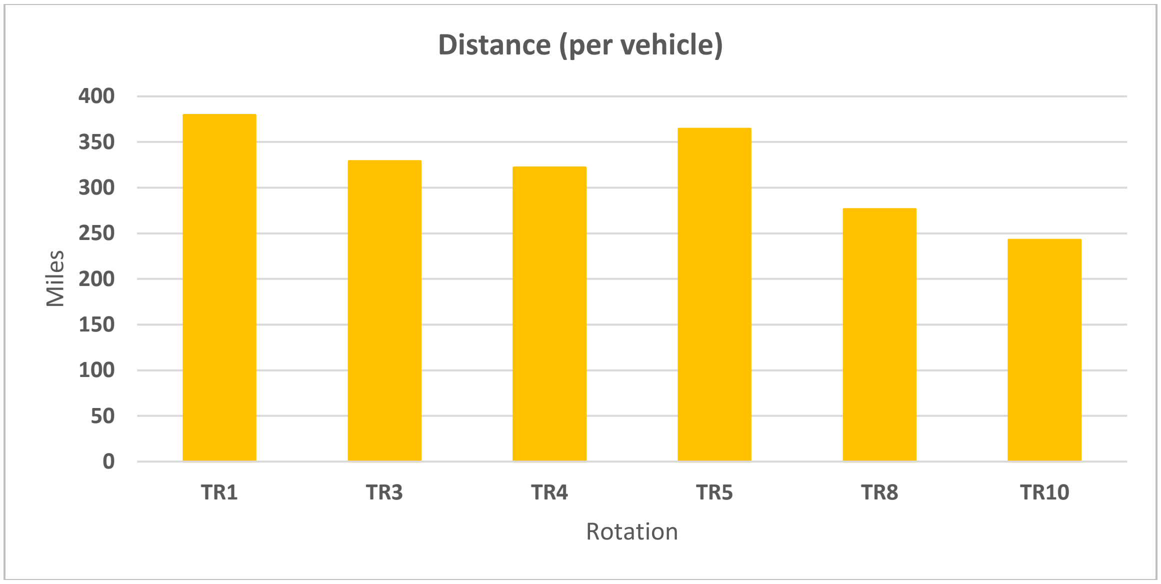


Figure 4. Average distance traveled per vehicle (miles)

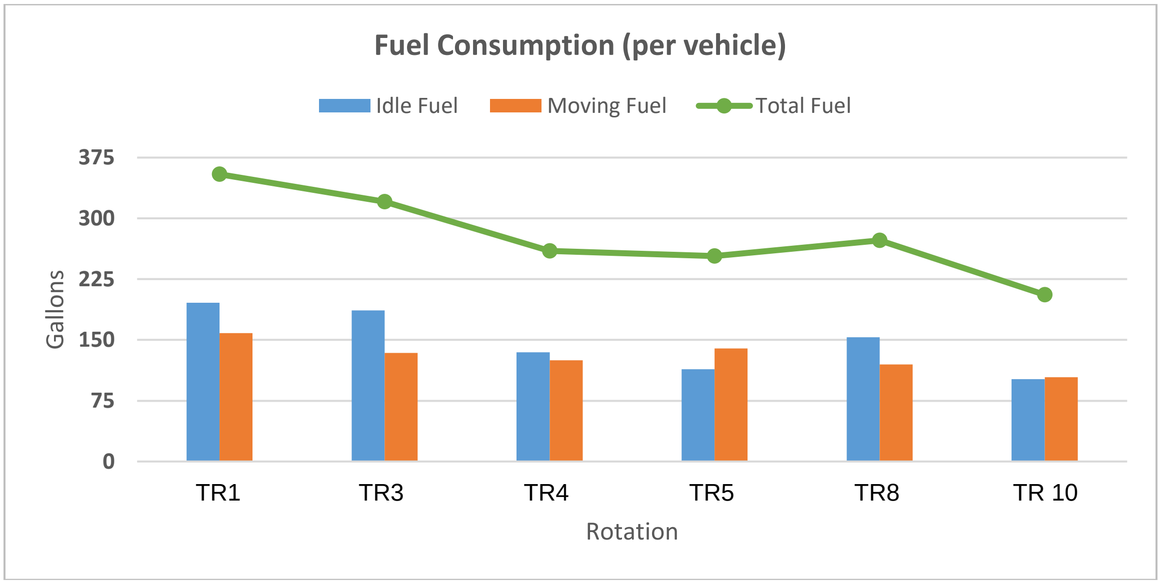


Figure 5. Idle and moving fuel consumption per vehicle (gallons)

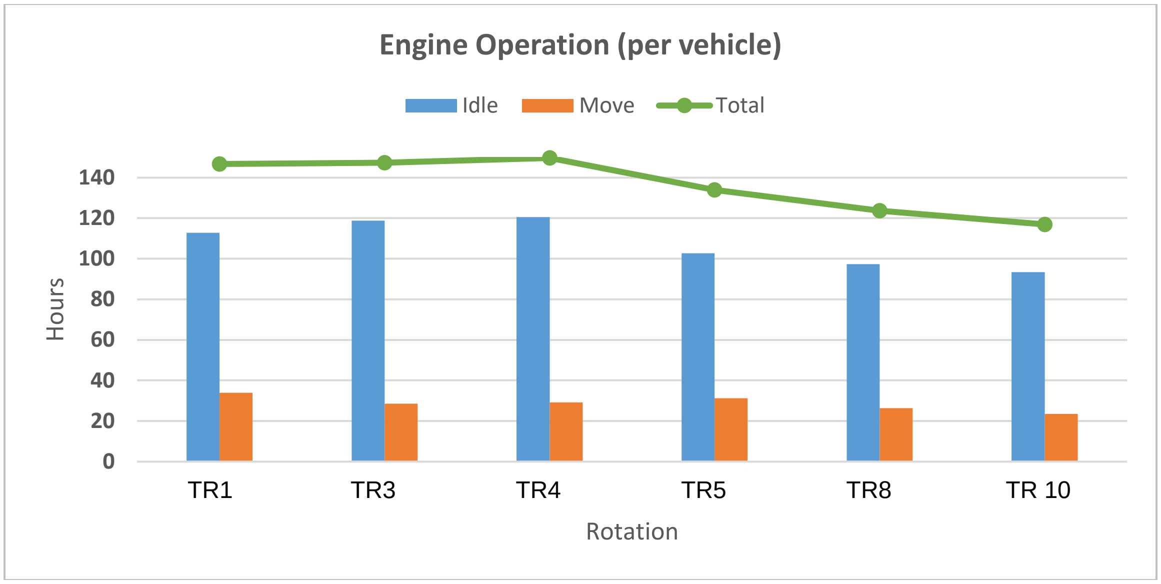


Figure 6. **Engine operational usage per vehicle (hours)**

4.1.1.2 Training Rotation OPTEMPO and Phases

In this section, measured data (sourced from the vehicle's CAN bus) were used to determine the cumulative daily OPTEMPO with respect to each of the key usage metrics. This will determine how to analyze fuel usage during a training rotation with a more representative operational usage profile—somewhat analogous to historical OMS/MP phases. In the measured data provided, one can determine how the fleet had operated within the training rotation and discern the vehicles' idle and movement hours and distances traveled. For example, the provided data included total distance and total movement time for each vehicle serial number for each day and each rotation. The total movement time was based on an onboard algorithm that was internal to the data collection system. The algorithm primarily looked at engine RPM and vehicle speed to determine if the vehicle was in a non-moving or moving condition. The data provided was a summary of those calculations. Thus, for movement speed, we used total distance and the total moving only time as our calculation method for average daily speed per day, per serial number, for each training rotation.

As expected, these data show that the bulk of operations occur during the training phase of the NTC rotation. Figures 7–9 align mostly with days 6–22 (i.e., training phase), which had a distinctly higher OPTEMPO. Additionally, these data are useful in determining the ratio of idle hours to movement hours daily as well as the cumulative percent of fuel spent while idling and moving. While these data show that idling cumulatively is approximately 80% of the engine operating time, the fuel consumption is still relatively even between idle and moving operations. These data suggest that understanding the operating environment during idle events (that is, time-of-year seasonal effects) as well as accounting for movement speeds and approximate terrains are important to accurately predicting total fuel consumption.

In Figures 7–9, there is a distinctly different OPTEMPO among days 1–5, 6–22, and 23–35. While not all rotations have the same length, they are generally 30–35 days. Each phase or period was analyzed separately to determine an average operational usage, allowing us to categorize high and low usage into historical OMS/MP categories.

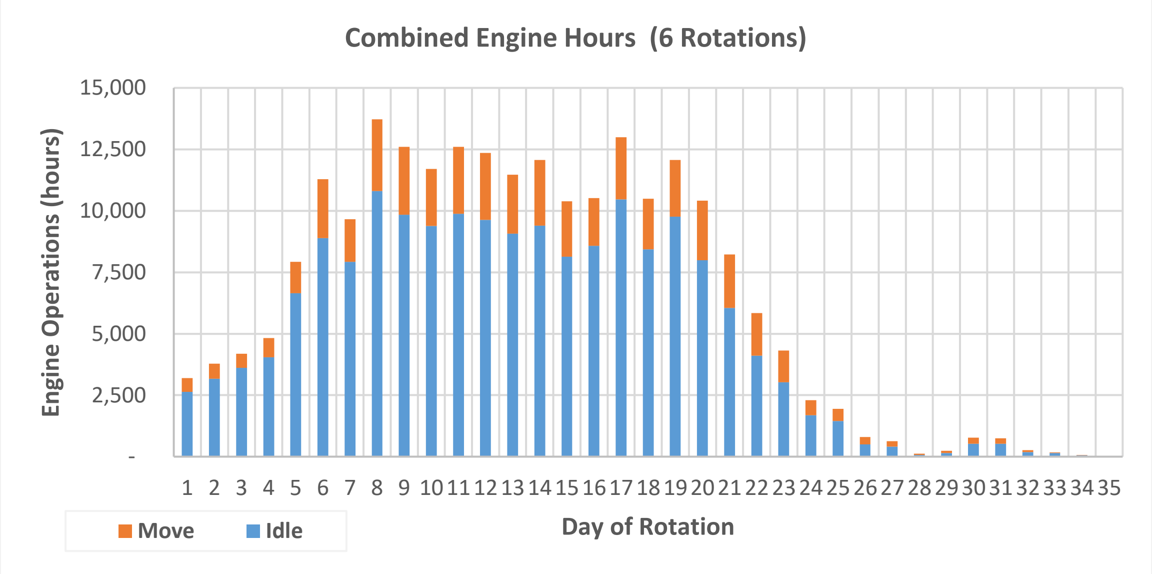


Figure 3. Moving and non-moving daily engine hour operational profile

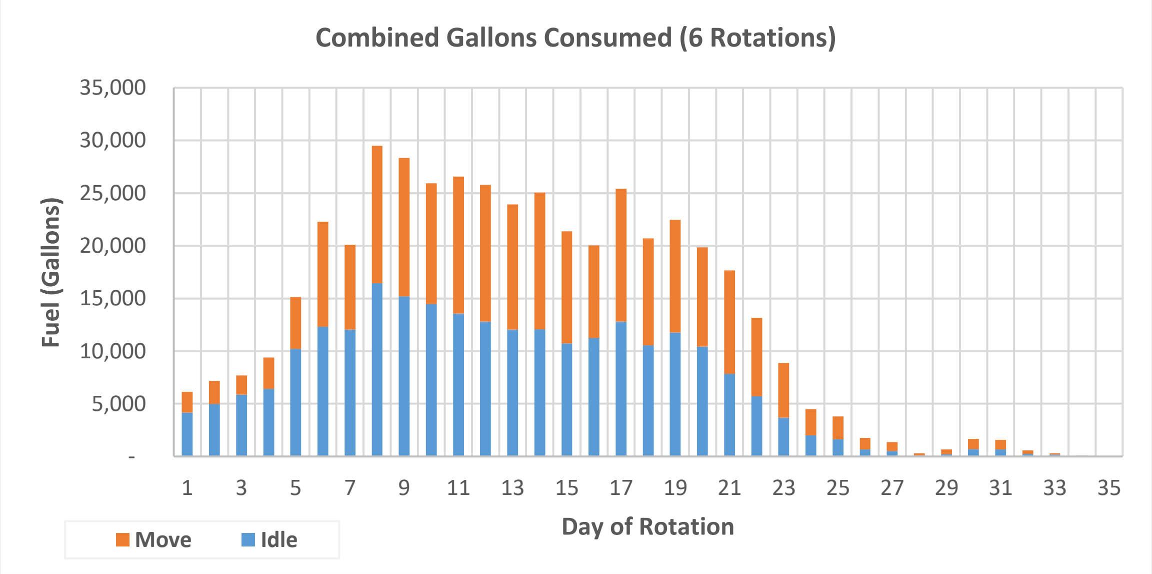


Figure 4. Moving and non-moving daily fuel consumed

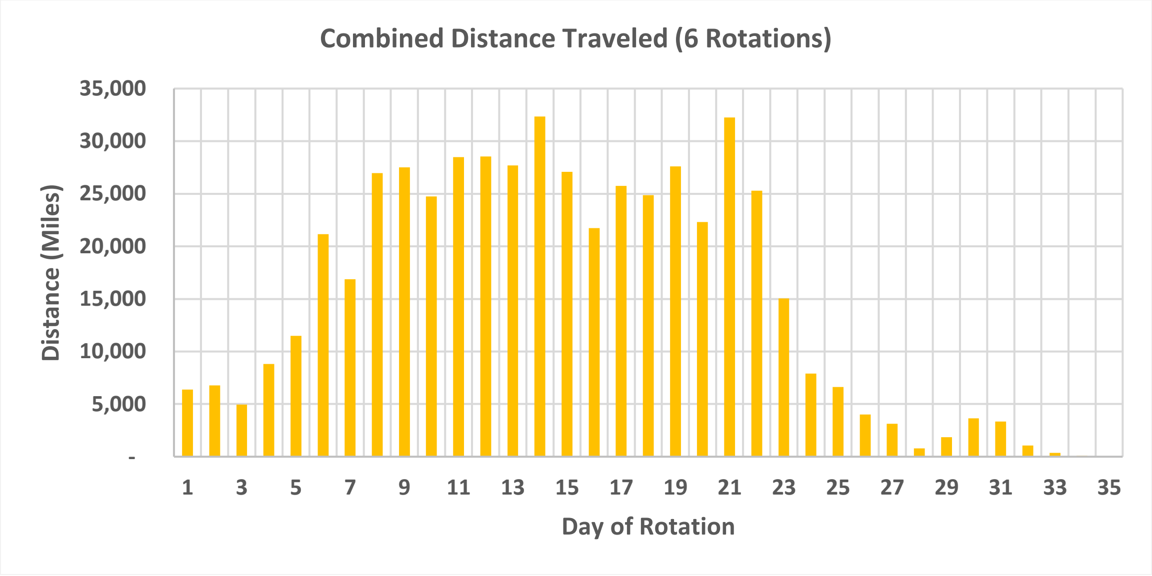


Figure 5. Daily movement distance

The takeaways from Figures 7–9 are the following:

- **Training Rotation Summary:** Data presented provides an overarching perspective of the selected rotations (e.g., distance, fuel usage, and engine operation).
- **Operational Engine Usage (time):** Total engine on time predominantly spent idling (~78.8%) during 84% of all engine operations during days 6–22.
- **Operational Fuel Consumption (gallons):** Fuel consumed, as a percent idle and moving operations, is somewhat evenly split (53% idle, 47% move). Most fuel is consumed during days 6–22 (reflects the 14-day training phase, though from unit to unit this may shift a day or two from the start of the training rotation).
- **Distance traveled (miles):** Highest daily movement operations occur during days 6–22 (83.6%).

4.1.1.3 Training Rotation Seasonality Effects

The next step was to determine if fuel usage requirements had any noticeable or distinguishable difference across various times of year from one training event to another, which could suggest possible seasonal changes that affect energy demands, particularly under idle conditions.

Typically, for idle fuel rate predictions, the general practice is to use a single auxiliary electrical load regardless of the time of year. However, during the analysis of this data set, a single electrical load approach did not prove to be a good method to determine idle fuel consumed. To refine our idle energy predictions, the data were divided into monthly bins to calculate the idle fuel rate. During the summer months there was an observed increase in usage compared to other months. This is potentially due to the

Environmental Control Unit (ECU) being used to cool the equipment and/or crew, but ultimately, regardless of the reason, there was increased fuel consumed during summer idle events. To reflect this observation, a seasonally adjusted electrical load was simulated for idle events. From the observed data points, DAC noticed an increase in gallons per hour from the collected data at idle. This increase in idle rate followed a seasonal trend and did not appear to be random from one month to another.

Normally for moving operations, vehicles are modeled with a constant auxiliary electrical load. A seasonally adjusted electrical load was considered for moving events, as was the case for idle events, but doing so was eventually considered inconsequential and was not implemented within the study. The predominant fuel demand during moving operations is due to vehicle propulsion; therefore, small variations in the auxiliary electrical load would have little impact on the overall moving fuel consumed (i.e., seasonal increases would be difficult to discern). Furthermore, vehicle weights were not recorded during these NTC rotations. DAC assumed a nominal platform weight based on similarly configured system. Weight is a key driver with respect to moving fuel consumption, while auxiliary power loads are considered to have minor influence. Thus, a single auxiliary electrical load was assumed for all variants during movement.

Figures 10 and 11 depict a seasonal difference in average idle fuel consumption rates that may be indicative of increased cooling during warmer periods (i.e., increased fuel consumption with the ECU operating). As can be inferred from Figures 12 and 13, this seasonal increase is not as apparent in the moving fuel rate since the quantities of fuel consumed are due primarily to propulsion requirements and not to electrical load requirements.

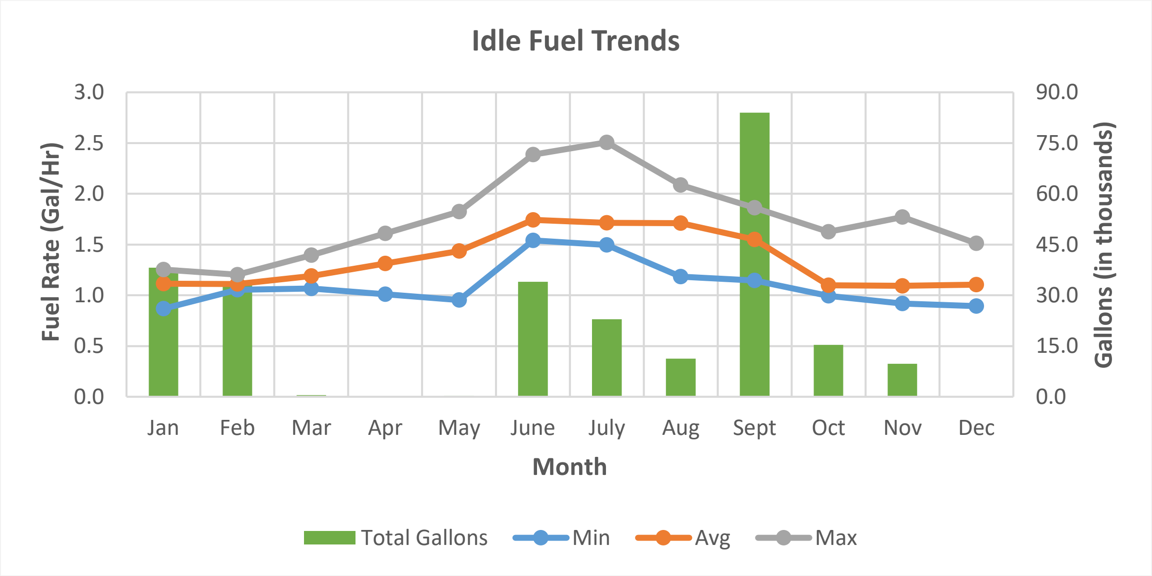


Figure 10. **Seasonal idle fuel consumption rate**

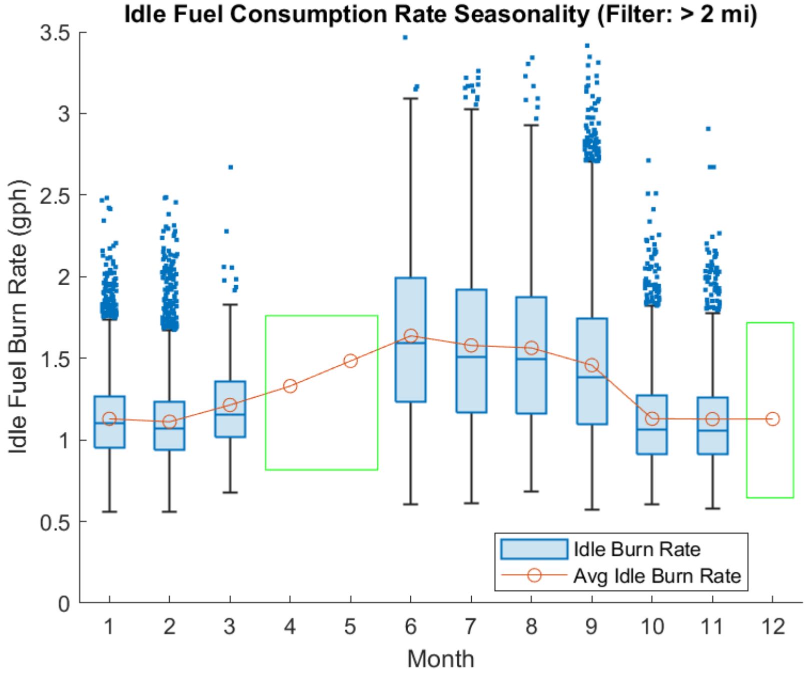


Figure 11. **Seasonal idle fuel consumption rate box chart**

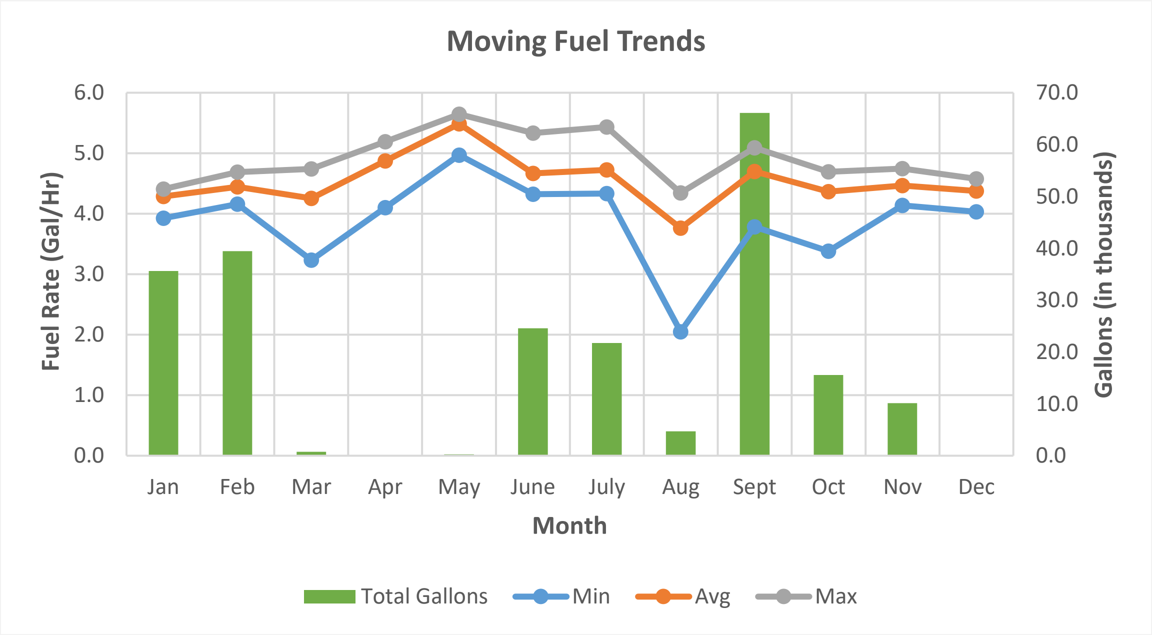


Figure 12. **Seasonal moving fuel consumption rate**

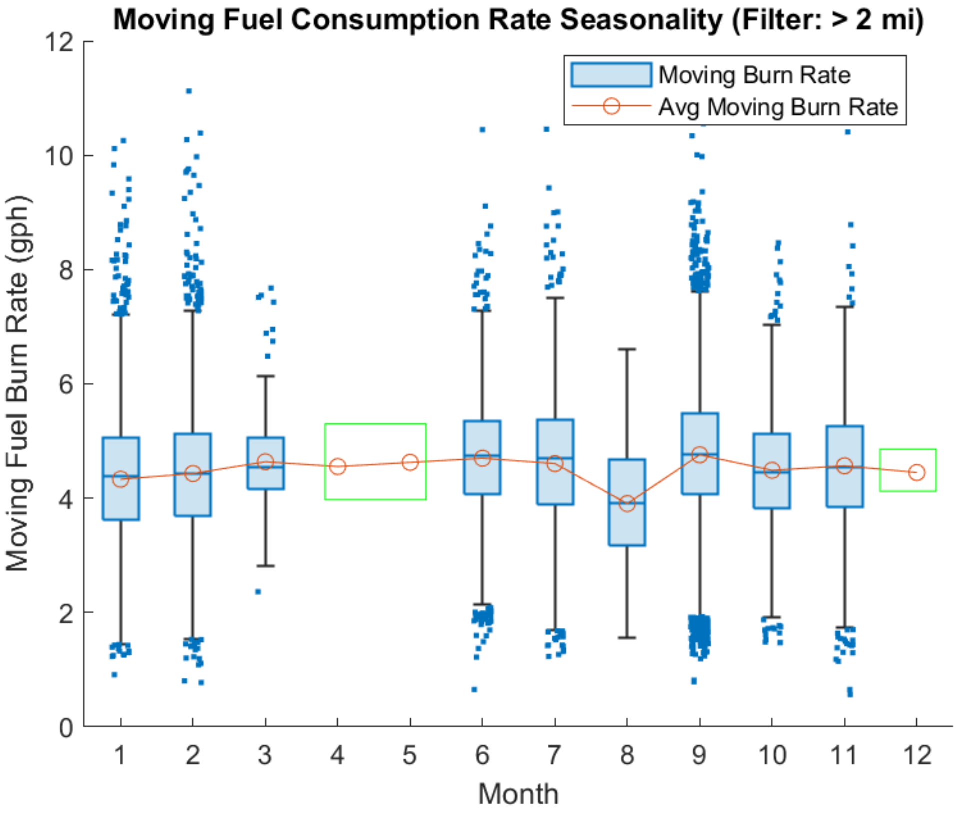


Figure 13. Seasonal moving fuel consumption rate box chart

The takeaways from Figures 10 and 12 are the following:

- **Variant Consumption Rates:** Variances likely attributed to potential equipment differences from variant to variant and seasonal changes in ECU requirements.
- **Seasonal Idle Fuel Trends:** Distinct increase in average idle fuel consumption rate in the summer (low sample sizes in March, April, May, and December; see Figure 12 for low idle gallons available to analyze).
- **Seasonal Moving Fuel Trends:** Relatively consistent moving fuel consumption rates across all time periods suggest that any potential increase in ECU usage during the warmer months had an insignificant impact on fuel consumed.

4.1.1.4 Variant-Level Usage Comparison

This section addresses the wheeled vehicle data set to investigate if modeling the entire set as a single representative variant type or as individual variant types had an impact on the outcome. As depicted in Table 2, the observed training rotations had a consistent quantity of each variant. While Var5 makes up approximately 60% of the vehicle miles traveled in the measured training data set, the other 40% of vehicles contribute a uniquely different configuration. This implies that modeling the variants individually could improve the overall fuel consumption predictions under moving operations.

Table 2 and Figure 14 provide summaries of the platforms broken down by variant type for each training rotation and the distribution of the accumulated miles.

Table 2. Variant and rotation distribution data

Rotation	Var1	Var2	Var3	Var4	Var5	Var6	Var7	Var8	Var9	Var0	Total
TR1	9	29	12	12	168	32	1	17	4	0	284
TR3	8	29	11	13	171	36	0	7	0	3	278
TR4	9	28	11	13	168	34	0	20	3	0	286
TR5	8	30	11	13	163	32	0	21	7	0	285
TR8	9	32	10	13	149	31	0	22	9	3	278
TR0	8	25	9	10	120	25	0	19	9	3	228
Total	**51**	**173**	**64**	**74**	**939**	**190**	**1**	**106**	**32**	**9**	**1639**
Avg.	**8.5**	**28.8**	**10.7**	**12.3**	**156.5**	**31.7**	**0.2**	**17.7**	**5.3**	**1.5**	**273.2**

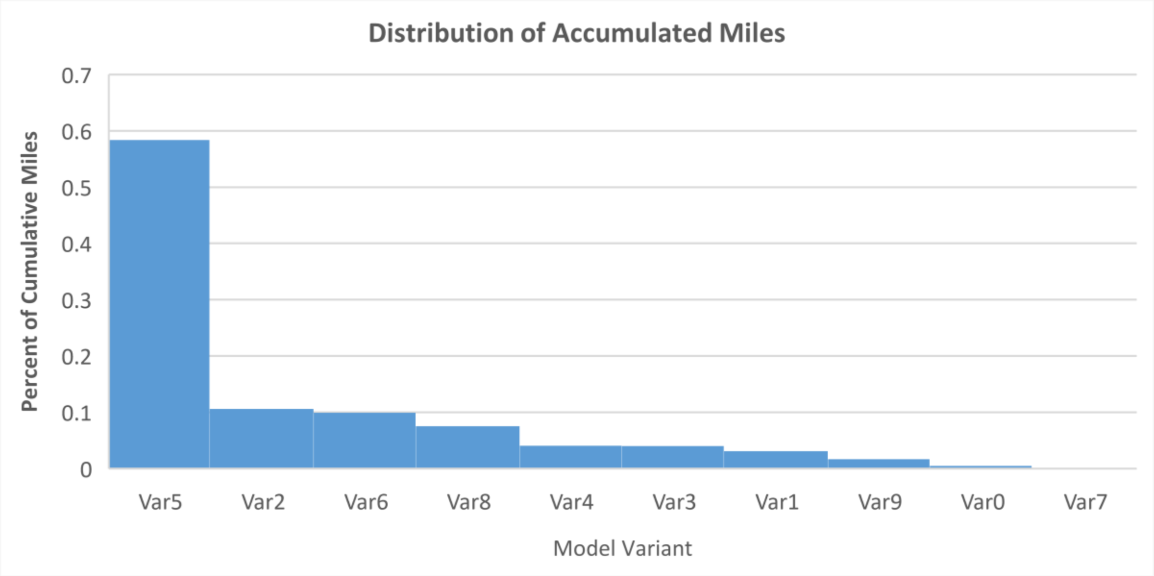


Figure 14. Distribution of accumulated miles

Figure 15 shows the difference in fuel economy between the variants. The differences shown were likely be caused by variations in variant weight and speeds traveled. Figure 16 verifies the breakdown between moving and non-moving operations for each variant is relatively consistent.

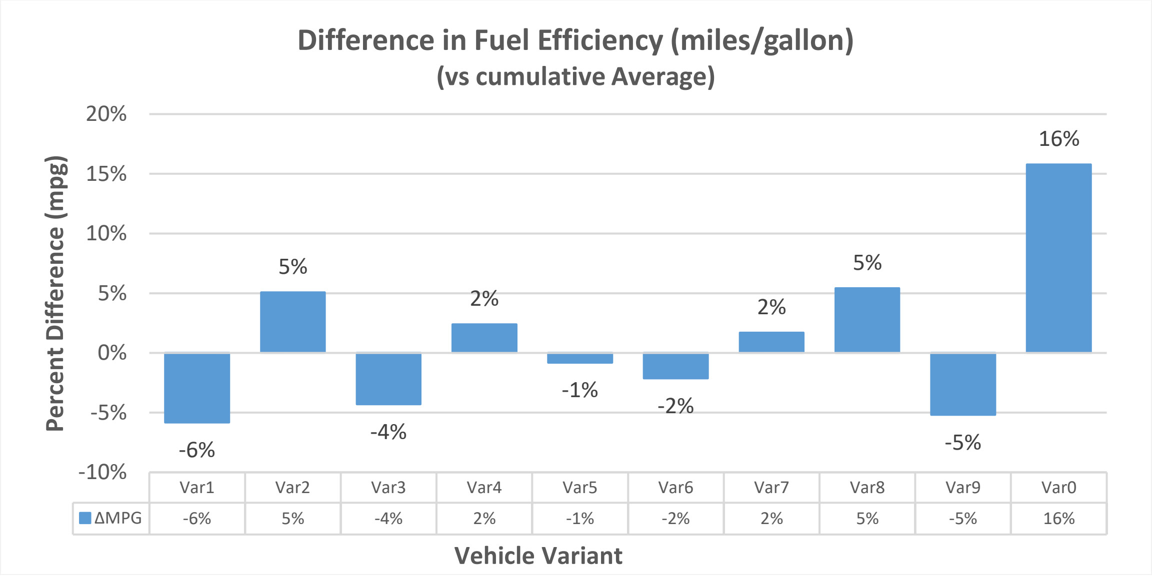


Figure 15. **Difference in fuel efficiency between variants vs. fleet average**

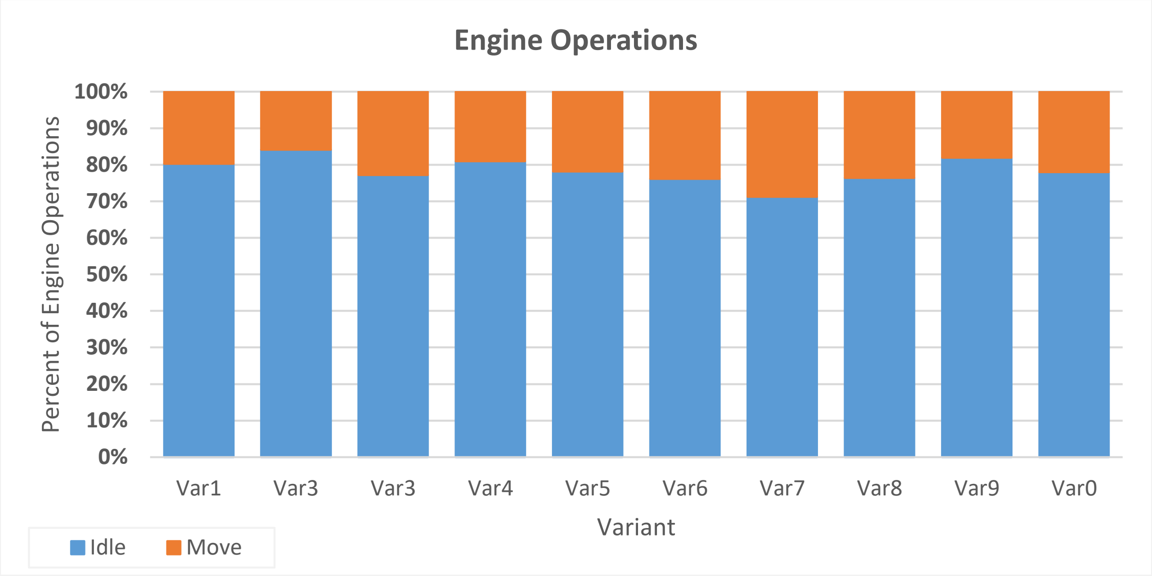


Figure 16. **Distribution of engine operations between variants**

The variant quantities show a degree of consistency from one training rotation to the next. It was shown that variant types are used differently during the training rotations (e.g., miles driven) and may consist of different weights that impact fuel consumed. Given this situation, individual model input assumptions would likely improve predictions.

4.1.2 Predicted Fuel Usage Analysis

4.1.2.1 Measured Fuel Consumption vs. Predicted Fuel Consumption

In this analysis segment, the measured wheeled vehicle consumption quantities and rates are compared to FCPM estimates utilizing predicted and calculated mission profile and vehicle characteristics. The primary focus in predicting the fuel consumption for each vehicle, using its unique serial number, is to verify if the mission profile modeling assumptions and the vehicle modeling characteristic inputs are sufficient for reasonable estimates. If the model can demonstrate that the steady-state approach for mission assumptions can accurately represent the vehicles in terms of moving or non-moving fuel consumption, then one can potentially use the OMS/MP approach of average speed on terrain, terrain type percentages, and estimated idle hours as our input for future training rotations.

In Figures 17–20, each data point represents a unique vehicle, by serial number, measured across multiple NTC training rotations. In other words, a particular vehicle may be used by different units across distinct training rotations. This method allows for a blended usage profile for each specific vehicle across multiple rotations but assumes a single configuration per platform variant based on its mission role designation (i.e., an infantry carrier platform is an infantry carrier in all training rotations).

Figures 17 and 19 indicate that FCPM results compare well to the measured quantities of fuel consumed during moving and idle operations. There is a strong relationship (i.e., data points are clustered around the trend line) between FCPM estimates and the measured results. With respect to fuel consumption rates, Figure 18 indicates that the moving consumption rates predicted by FCPM trend well with the measured values. Figure 20, however, identifies significant variability between the predicted and measured idle gallons per hour. This variability could be a result of, for example, different equipment electrical load profiles or other operational requirements. The two trend groupings represent the general high- and low-idle electrical usage requirements DAC modeled depending on time of year.

Error in the moving operation fuel quantity predictions could be due to 1) the need to refine the average specific vehicle variant weight assumptions, 2) the weights of specific vehicle variants cover a wide weight range, and/or 3) the vehicles experience some statistical difference from the assumed OMS/MP profile. Thus, this technique may be a poor estimator for any single vehicle but potentially can provide a reasonable and useful fuel consumption quantity estimate to characterize an entire training rotation fleet. Given that this technique is based on the OMS/MP profile, which by its nature is a generalized view of how a unit operates in the field, it is expected that this technique would be more appropriate for larger training formations as opposed to individual vehicles.

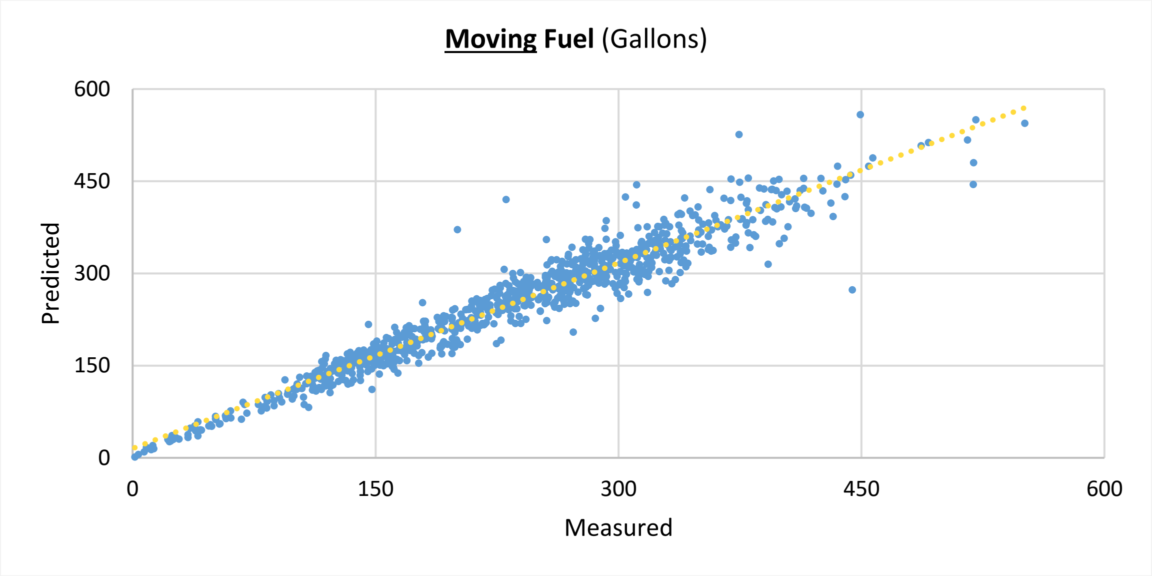


Figure 17. Moving predictions vs. measured gallons consumed

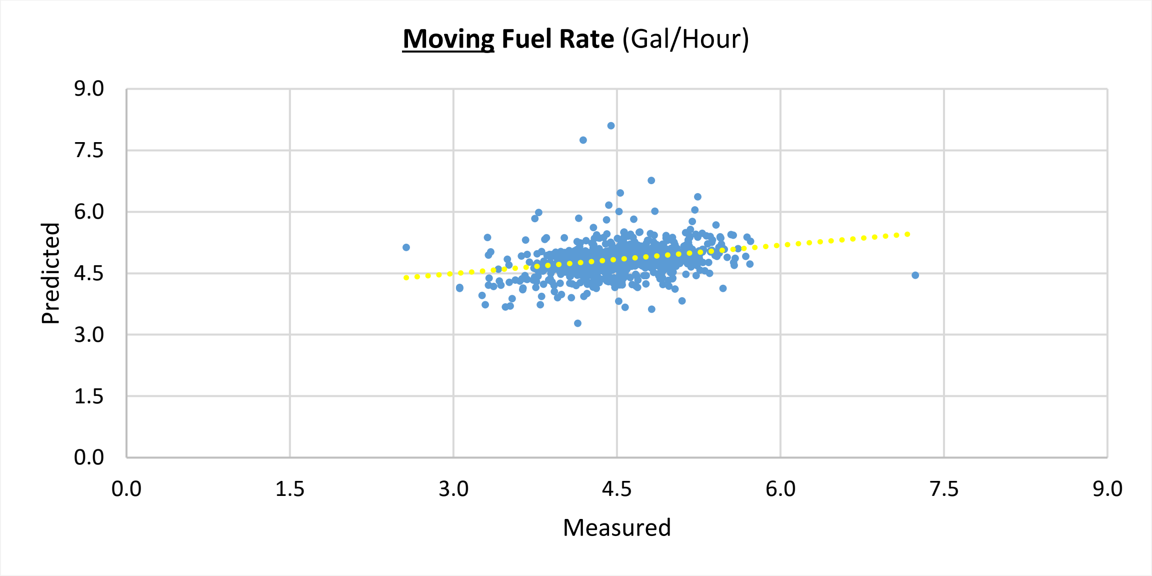


Figure 18. Moving predictions vs. measured consumption rate

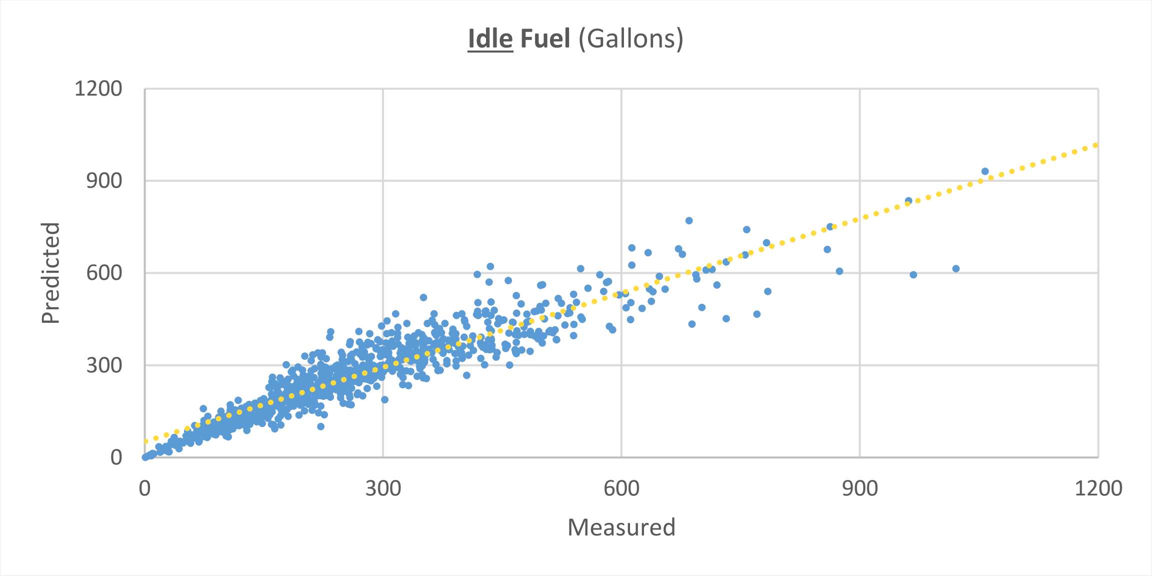


Figure 19. Idle predictions vs. measured gallons consumed

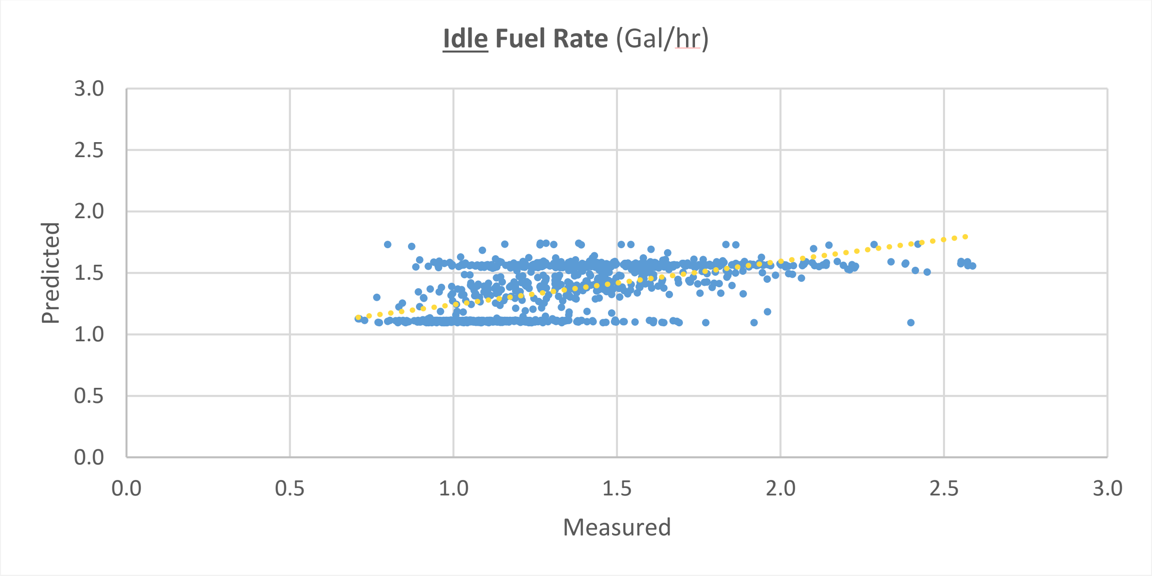


Figure 20. Idle predictions vs. measured consumption rate

4.1.2.2 Comparing Variant Results with OMS/MP Only

In this section the predictions are assessed without the benefit of historical data (i.e., CAN bus usage data recorded during previous training rotations). In these cases only the OMS/MP is used to represent the platform's OPTEMPO within FCPM. The predicted values in Figures 21–24 are fuel consumption results for the 14-day training event.

The OMS/MP profiles were modified to reflect the training events, as follows:

- **Training Rotation Summary:** Data presented provides an overarching perspective of the selected rotations (e.g., distance, fuel usage, and engine operation).
- **Operational Engine Usage (time):** Total engine on time predominantly spent idling (~78.8%), with 84% of all engine operations during days 6–22.
- **Operational Fuel Consumption (gallons):** Fuel consumed, as a percent of idle and moving operations, is somewhat evenly split (53% idle, 47% moving). Most fuel is consumed during days 6–22 (reflects the 14-day training phase, though from unit to unit this may shift a day or two from the start of the training rotation).
- **Distance traveled (miles):** Highest daily movement operations occur during days 6–22 (83.6%).

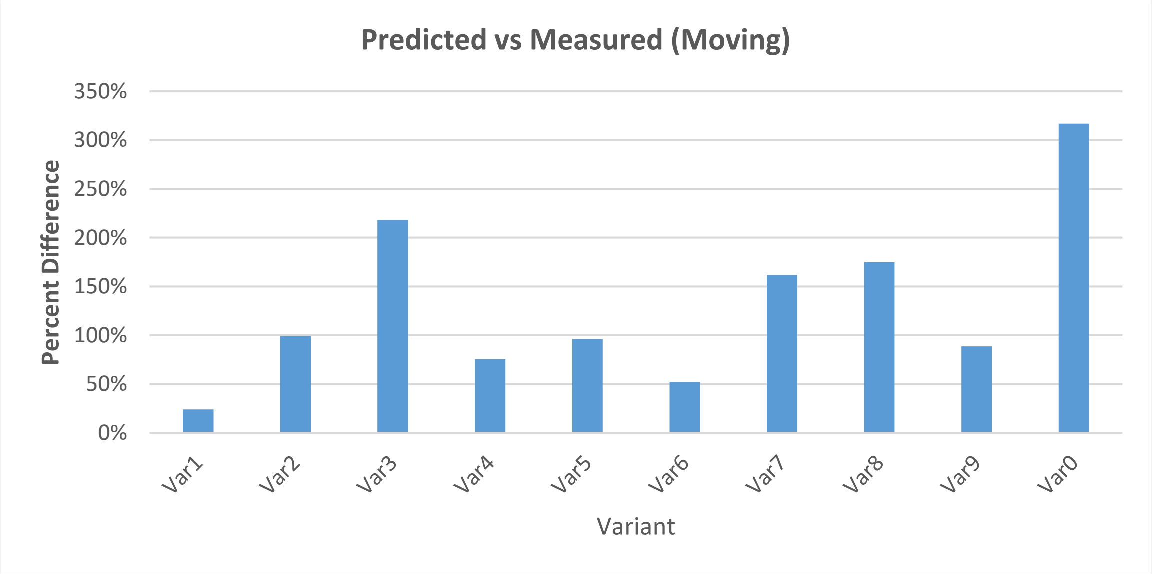


Figure 21. Variant fuel prediction difference (moving operations)

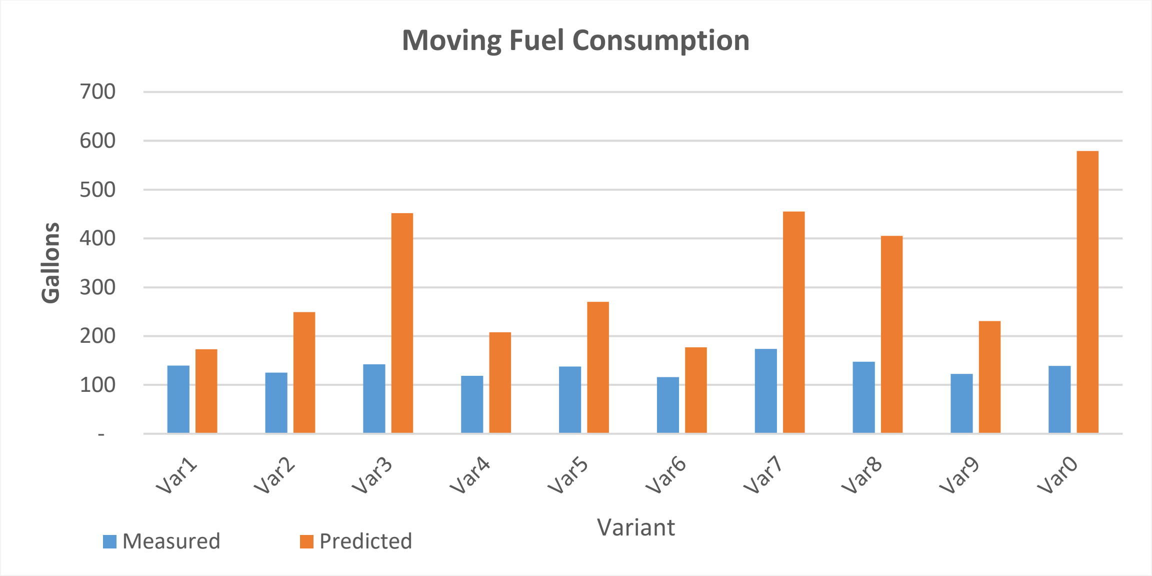


Figure 22. **Measured vs. predicted fuel consumption (moving)**

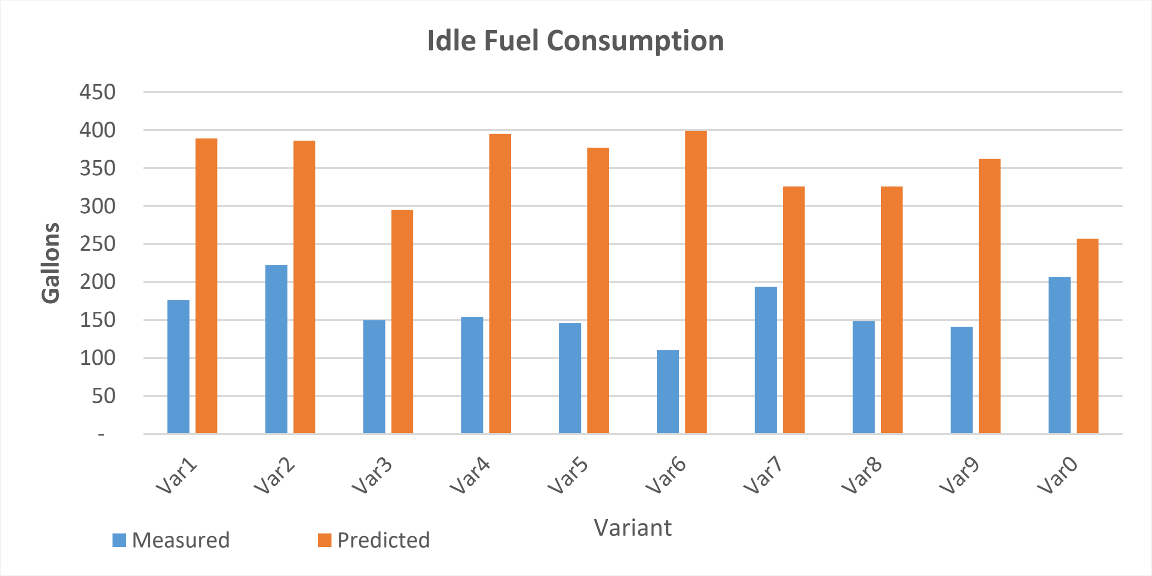


Figure 23. **Measured vs. predicted fuel consumption (non-moving)**

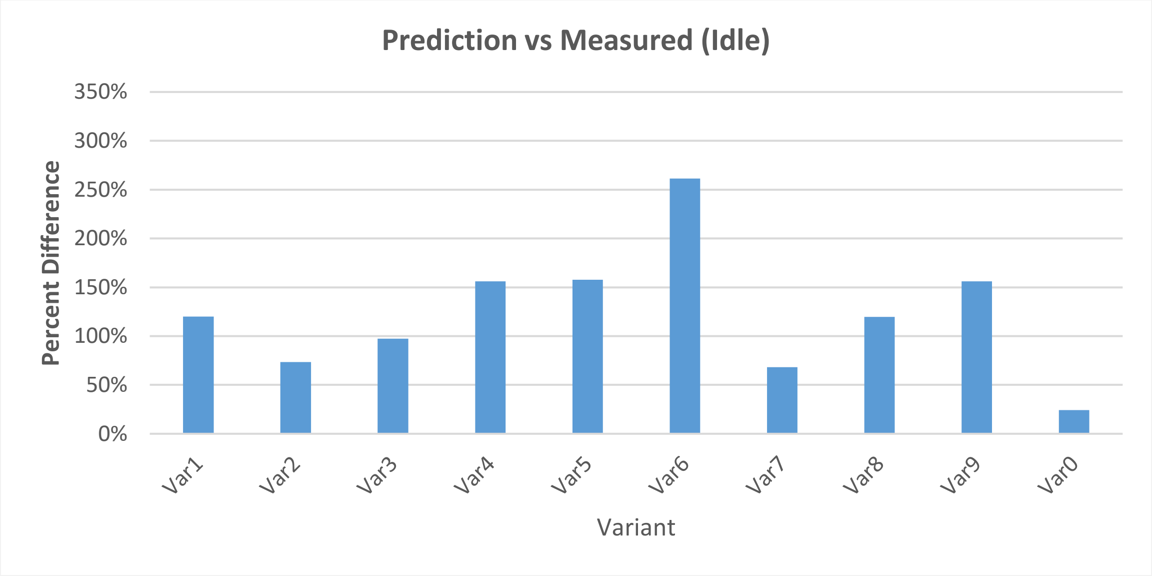


Figure 24. **Variant fuel prediction percent difference vs. measured (non-moving)**

4.1.2.3 Comparing Variant Results with Usage Profile

In this section, combining historical measured training rotation data with assumptions from the OMS/MP can provide more accurate fuel consumption predictions for training rotations. The outcomes are shown in Figures 25–28.

Our findings, as follows, indicate that FCPM closely predicts fuel consumption with the benefit of usage data.

- Average wheeled mission profile developed using measured data from selected rotations, to include
  - mission distance
  - movement hours
  - idle hours
  - seasonal variances in idle burn rates
- Terrain profile extracted from wheeled OMS/MP since specific terrain used at any point in time is unknown. As noted previously, the terrain profile is not data captured by the CAN bus; therefore, the OMS/MP is used to define the terrain profile.
- Results compare measured fuel consumption moving and idle compared to FCPM predictions using the developed wheeled mission profile (i.e., combination of measured [CAN bus] and OMS/MP terrain input).
- Idle and Total Consumption Results were developed *with* Seasonal Idle Adjustments. Seasonal Adjustments for Moving were not considered and are expected to have a minimal impact.

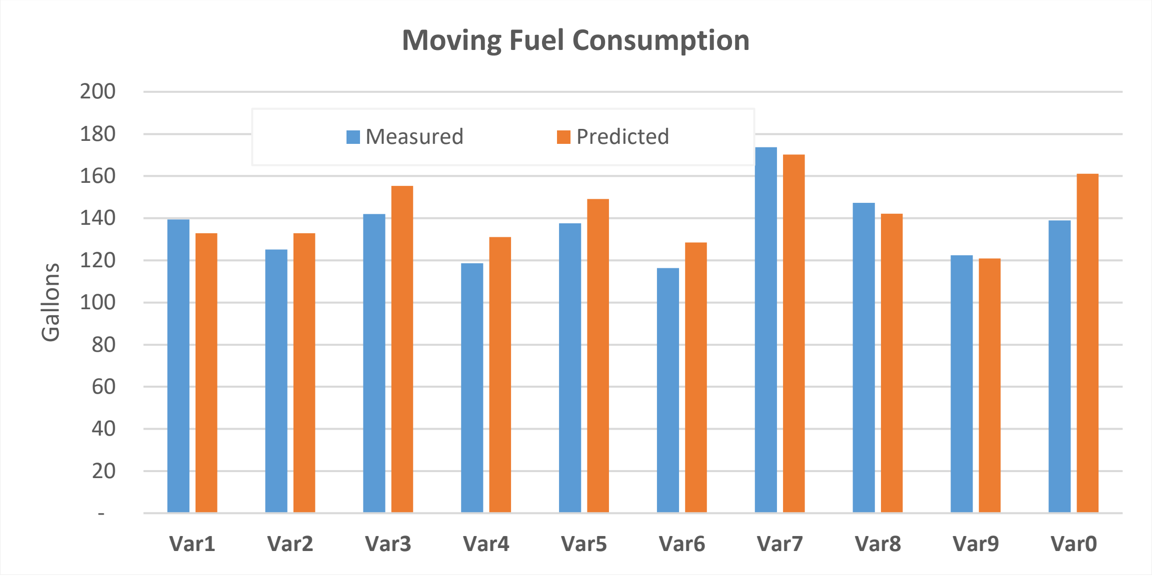


Figure 25. Moving fuel prediction vs. measured

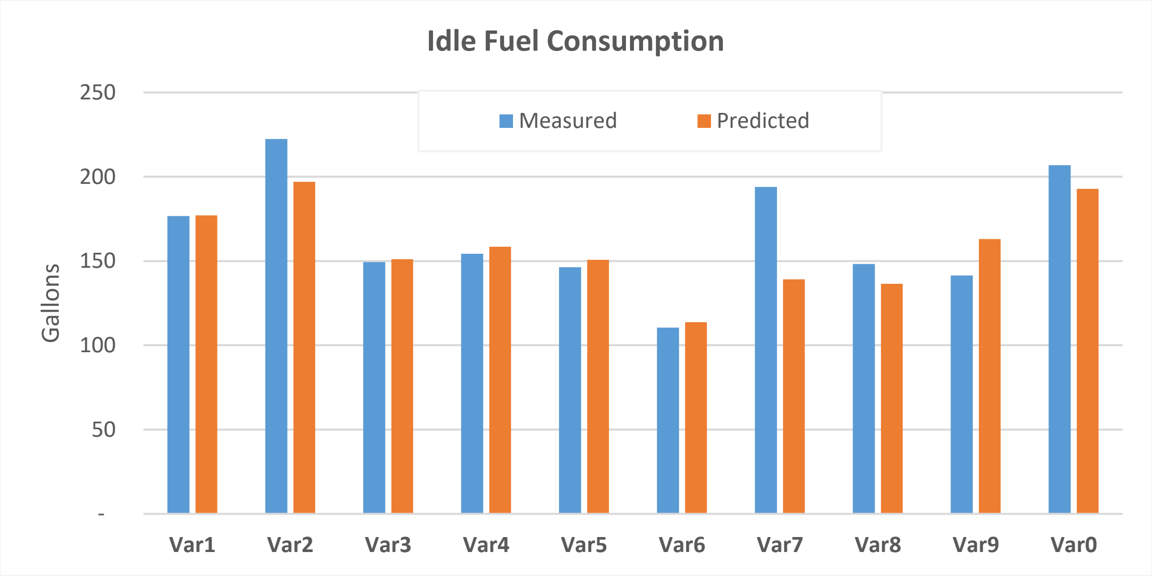


Figure 26. Non-moving fuel measured vs. predicted

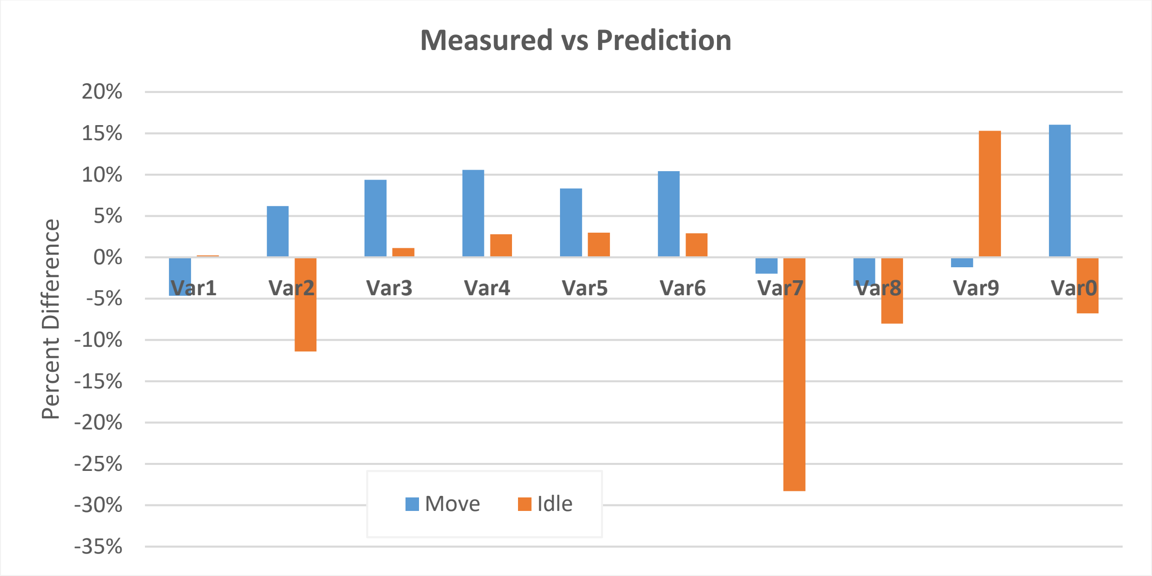


Figure 27. Moving and idle comparison of measured vs. predicted fuel consumption by variant

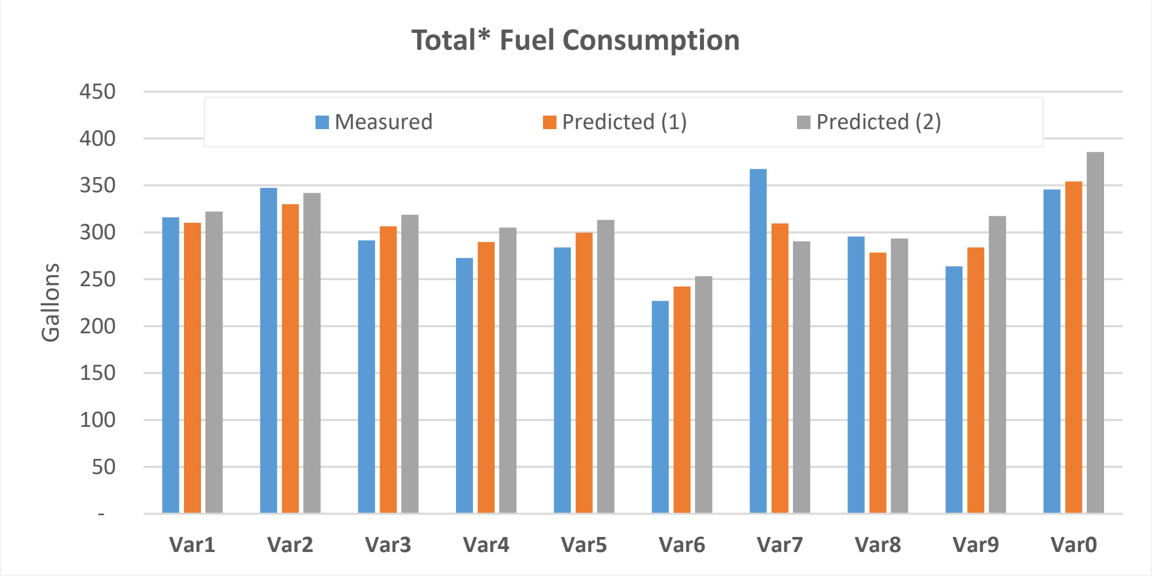


Figure 28. Measured vs. predicted notional example scenarios (1 and 2)

4.1.3 Wheeled Data Set Summary

This analysis provides confidence that usage data from historical training rotations (obtained from the CAN bus) coupled with OMS/MP-based terrain and speed profiles can produce accurate fuel quantity estimates for training rotations.

- Using historical data improves fuel-consumption predictions significantly relative to a solely OMS/MP-based estimation

  - Establishing fuel consumption with historical usage trends addressing average miles, total engine hours, idle-to-move ratio, and length of mission while modeling terrain profiles and terrain speeds based on the platform's OMS/MP improves estimations
  - OMS/MP mission phase lengths and mileage values were not indicative of training OPTEMPO

4.2 Tracked Data Set Review

The following example applies the methodology just described, where the platform's OMS/MP and limited usage data are combined, to develop a refined fuel quantity prediction for the training rotation. In this tracked vehicle case, measured fuel quantity data was *not* available, but by using those previously discussed techniques a refined estimate for three training rotations was developed.

4.2.1 Data Limitations

For this data set there were several limitations associated with the collected training rotation data:

- Only odometer (i.e., miles driven) and engine hour meter (i.e., engine on time) data were available (i.e., no CAN bus data were available).
- Generally, data were only collected at four points per vehicle serial number (i.e., start of rotation, before and after training event, and end of rotation).
- Not all vehicle odometer and hour meter data collected on same day.
  - Some variations for data collection between individual units or individual vehicles within a rotation were observed.
  - For example, some vehicles had data collected on day 6 while others were few days before or after.
- Not all vehicles have recorded hour meter usage data (see Table 3).

Additionally, data set Rotation B had a significant number of vehicles flagged for missing data or other issues.

4.2.2 Cleaning Data Set

Prior to developing a typical usage profile, the limited collected data set was scrubbed to filter out vehicles with either insufficient data or potentially erroneously reported values. For example, vehicles were flagged based on very low average usage per day (in terms of miles and hours) or extreme usage (e.g., more hours reported than length of entire rotation). For this data set, low usage thresholds of under 2 miles per day and/or under 1 h of engine operation per day were used as filters. The purpose of doing this is to identify vehicles that can potentially assist in categorizing candidate vehicles as non-mission-capable, undergoing service, or used as floats for each training rotation. These vehicles would not have the same impact on fuel consumption as fully operational vehicles performing the complete training rotation OPTEMPO.

Of the three rotations examined, 176 of the 250 tracked platforms were identified as having sufficient usage to be used to create the initial usage profile. Table 3 illustrates the summary of this process. Figure 29 is an overall combined usage comparision of distance traveled, and Figure 30 is an overall combined usage comparison of engine hours.

Table 3. Rotation data set summary

A Rotation % and Type		**Qty**	**Miles**	**Hours**
. . .	All Vehicles	78	11,246	6,101
23%	Flagged	18	1,711	1,647
77%	Cleaned	60	9,535	4,454
B Rotation % and Type		**Qty**	**Miles**	**Hours**
. . .	All Vehicles	85	14,739	7,193
46%	Flagged	39	4,176	2,945
54%	Cleaned	46	10,563	4,248
C Rotation % and Type		**Qty**	**Miles**	**Hours**
. . .	All Vehicles	87	19,267	10,921
20%	Flagged	17	1,680	2,667
80%	Cleaned	70	17,587	8,254

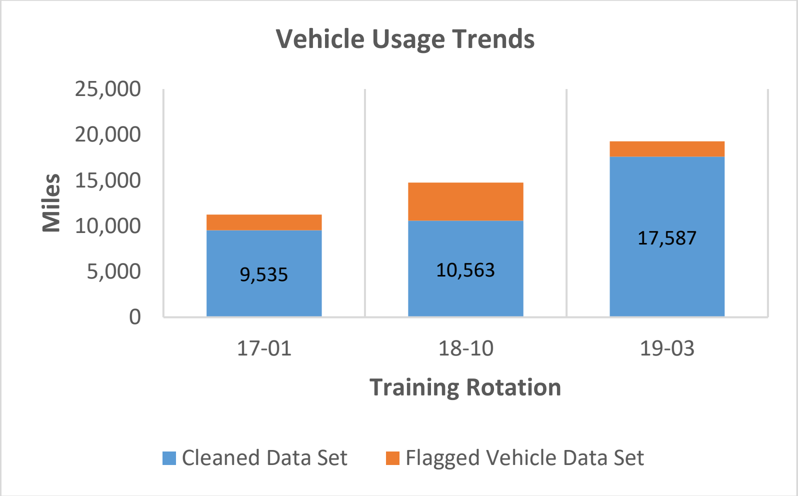


Figure 29. Overall combined usage comparison (distance traveled)

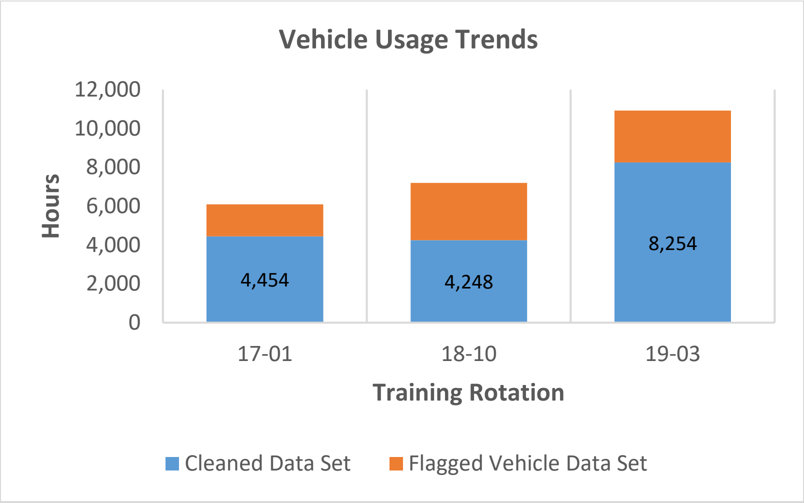


Figure 30. **Overall combined usage comparison (engine hours)**

4.2.3 Comparison of Rotations

Figures 31–35 provide tracked vehicle usage trends for three NTC training rotations. Additionally, comparison of vehicle usage within rotation event indicates mileage occurs primarily during the middle portion of each rotation (as was the case with the wheeled data set—indicative of the primary training phase). The wheeled data set had clear high and low OPTEMPO and usage profiles, and the tracked data set displays similar varying usage at the start, middle and end of the rotation which mirrors the low and high OPTEMPO of vehicles from before. That is, the rotation fuel requirements are unique to setting up for the middle portion (the actual training event) and additional fuel used after the training event is complete. We have taken similar assumptions that the OPTEMPO, speeds, and idle requirements vary based on the different portions of the rotation.

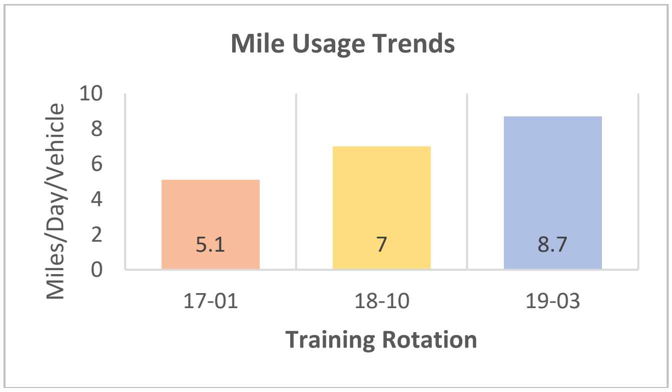


Figure 31. **Usage data normalized for vehicle density (miles per day per vehicle)**

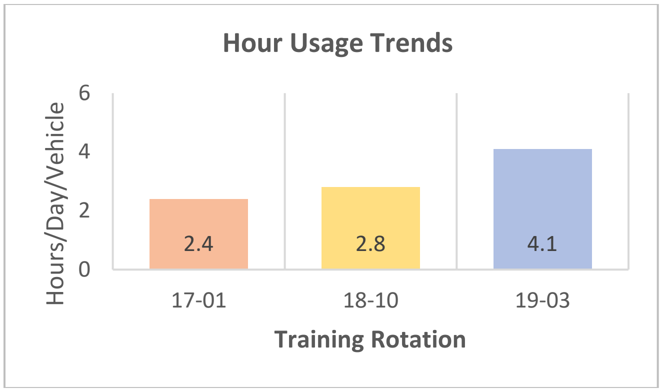


Figure 32. Usage data normalized for vehicle density (hours per day per vehicle)

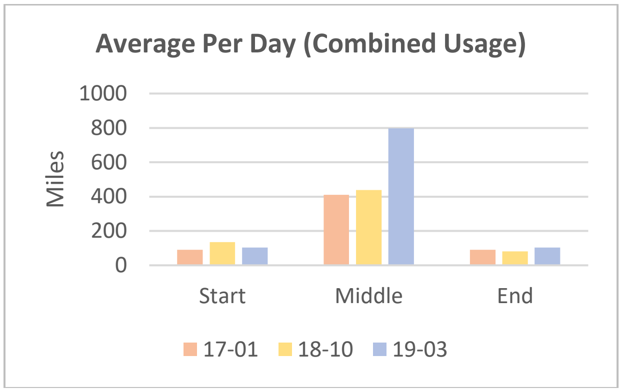


Figure 33. Average miles combined per phase (all vehicles)

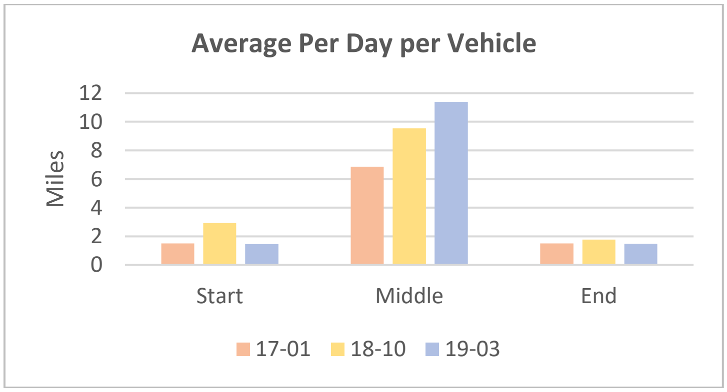


Figure 34. Average miles per day per vehicle for each phase

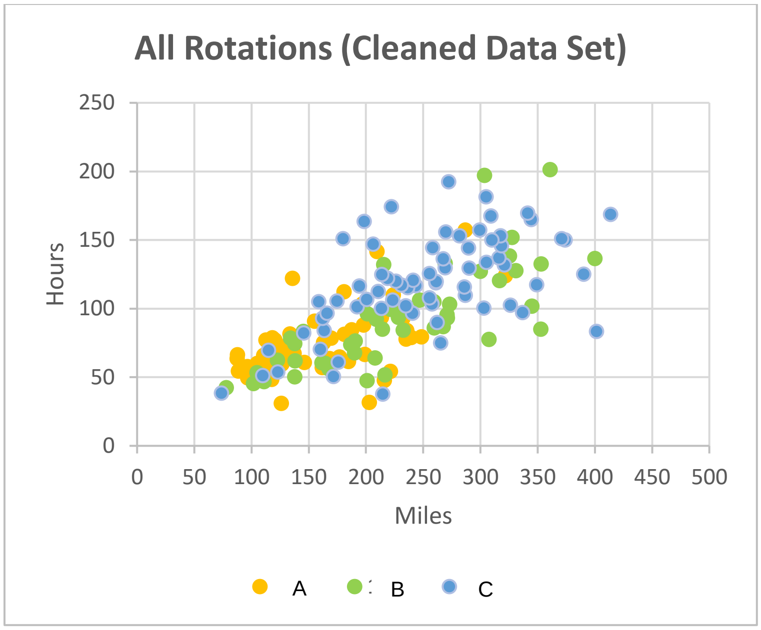


Figure 35. **Comparison of each training event**

Figure 35 is a side-by-side comparison of each of the three training events highlighting usable cleaned data. The objective is to determine if the cleaned data set can be used to infer a single tracked platform usage profile to address fuel consumption predications.

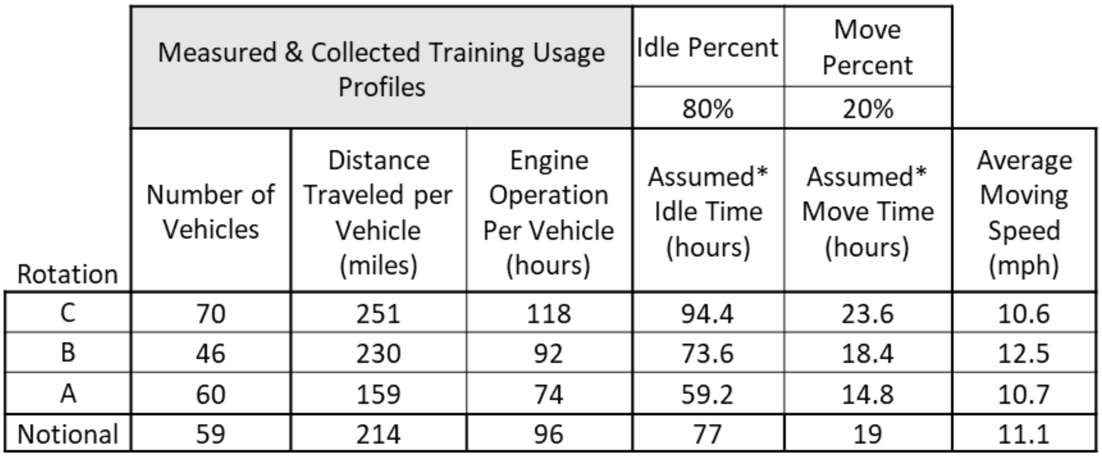
4.2.4 Fuel Consumption Model Inputs

The following list, to include Tables 4 and 5, provides a summary of modeling considerations:

- The "MCO" phase from the tracked vehicle's OMS/MP provided the terrain percentages and speed parameters used to develop the fuel estimate for the NTC rotation's "Middle" phase.
- Operational breakdown in terms of percent distribution of traveled distances, idle event times, and engine operations were assumed to be consistent with the Wheeled data set.
- Used a simplified speed and terrain percentage distribution for the "Start" and "End" phases, instead of a day-by-day prediction. Speed configurations and terrain percentages based on OMS/MP values:
  - Middle Phase (MCO): Primary – 30 mph; Secondary – 20 mph; X-Country – 4 mph.
  - Start/End Phase (PO): Primary – 30 mph (100%).
  - The middle phase is typically 14–16 days, while the start and end phase are 5–7 days. In total, the rotations span approximately 1 month.
  - Idle Fuel Consumption Loads for Rotations C, B, and A modeled with baseline 5-kW electrical loads.

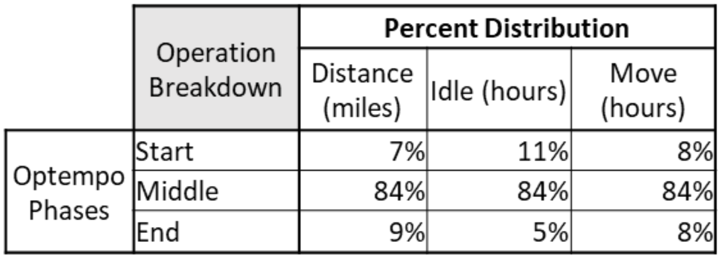
- Notional example modeled with baseline 5-kW electrical loads and 33% idle fuel rate increase to account for potential seasonal increase as identified in wheeled case. The notional example here is an average of previous rotations to illustrate an estimation based on different inputs into the methodology.

Table 4. Individual measured training usage profiles



	Measured & Collected Training Usage Profiles			Idle Percent	Move Percent	
				80%	20%	
Rotation	Number of Vehicles	Distance Traveled per Vehicle (miles)	Engine Operation Per Vehicle (hours)	Assumed* Idle Time (hours)	Assumed* Move Time (hours)	Average Moving Speed (mph)
C	70	251	118	94.4	23.6	10.6
B	46	230	92	73.6	18.4	12.5
A	60	159	74	59.2	14.8	10.7
Notional	59	214	96	77	19	11.1

Table 5. OPTEMPO usage profile breakdown



	Operation Breakdown	Percent Distribution		
		Distance (miles)	Idle (hours)	Move (hours)
Optempo Phases	Start	7%	11%	8%
	Middle	84%	84%	84%
	End	9%	5%	8%

- Assumptions for distribution of engine operation hours and distance traveled derived from wheeled lessons learned (time idling and moving of wheeled platform assumed for this data set).
- Terrain breakdown for middle phase derived from tracked OMS/MP document.
- Primary terrain (i.e., primary road) only assumed for start and end phases.

4.2.5 Fuel Consumption Model Results

The “Notional (1)” example is derived from an average vehicle density from previous training rotations and a combined average usage profile (Table 6). The “Notional (2)” example adds a seasonal increase factor to the idle fuel consumption estimate (Figures 36–38).

- Number of vehicles deployed for rotation (density factor)

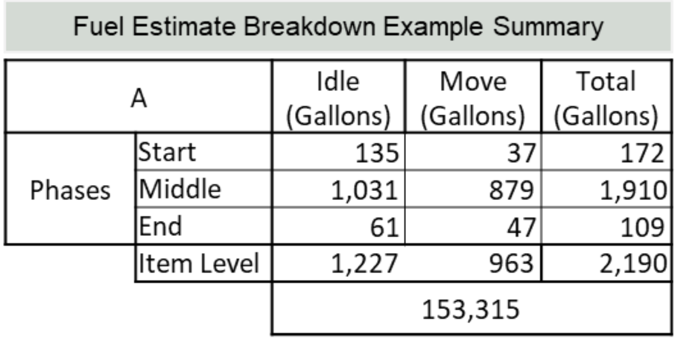
- Length of training mission (days)

Potential input parameters:

- Level of training “intensity” (intensity factor), show in Figure 38

Fuel estimates can be made through a process of historical knowledge of major trends (e.g., idle-to-move ratio, average distance traveled) and using document-based terrain assumptions to derive fuel estimates. Figure 36 is an estimate of each vehicle’s fuel consumption requirements based on idle or moving, and for each phase. The final total, 153,315 includes the total for this vehicle and not the fuel requirement for the entire training rotation which includes other vehicles. This example fuel analysis is for the previously described notional rotation.

Table 6. Example fuel analysis



Fuel Estimate Breakdown Example Summary

A		Idle (Gallons)	Move (Gallons)	Total (Gallons)
Phases	Start	135	37	172
	Middle	1,031	879	1,910
	End	61	47	109
	Item Level	1,227	963	2,190
		153,315		

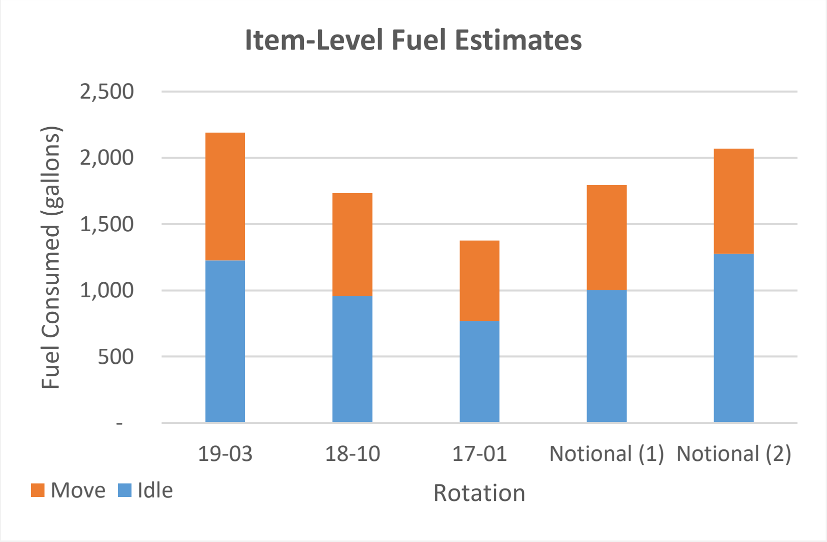


Figure 36. Item-level fuel estimates

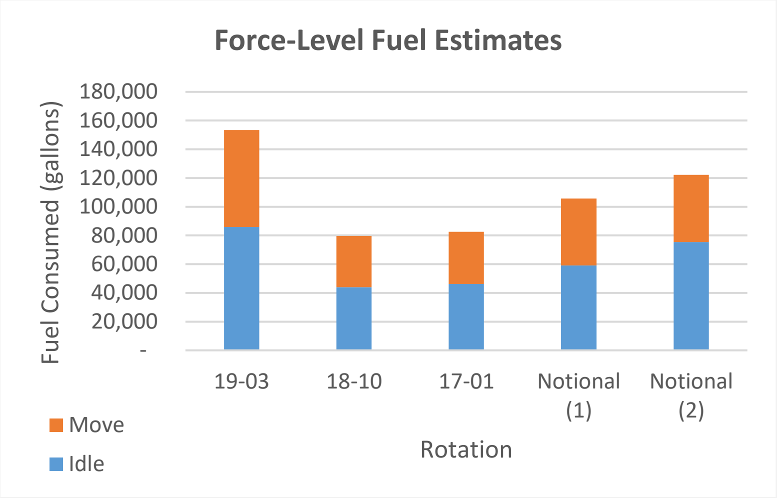


Figure 37. Force-level fuel estimates

Figure 38. Training intensity factor

5. CONCLUSION AND RECOMMENDATIONS

This report compares two fuel-quantity prediction methodologies. These methodologies each address a specific vehicle type operating within a training rotation. The primary difference between the two are the input parameters considered, as follows:

- OMS/MP parameters only (specific to the platform in question), or
- OMS/MP parameters combined with historical usage statistics

The methodology where a combination of historically collected training data and its OMS/MP were used as model inputs (i.e., wheeled platform case described in the report) provided a higher fidelity fuel quantity estimate compared to solely using the platform's OMS/MP. This is intuitive in that the additional input data available should indeed provide an overall better result. This report helps to quantify that approach to better understand the accuracy of those predictions given that measured fuel quantity data was available for the comparison. Insights from the analysis are as follows:

- Using a family of vehicles usage data (e.g., engine on/off statistics) in combination with its OMS/MP parameters (e.g., terrain parameters) predicted the family's fuel consumption quantities near measured quantities.
- Using collected training average mileage and engine hour values, which include idle and moving operations, in combination with the vehicle's OMS/MP speeds and terrain attributes can produce reasonable fuel consumption estimates—most vehicles within 7%.
- The lower fidelity methodology, which only used the OMS/MP for model input, provides easily made but limited accuracy estimations. Filtering of collected data will likely be necessary to remove unrealistic outliers.
- Given no historical rotation data and only using OMS/MP usage attributes, resulting fuel quantity estimate was of *low confidence* (e.g., results overpredicted fuel consumption by as much as 78% to 238%).

As a possible future use case, estimating the fuel required for a single system based on the expected item level density for an upcoming planned rotation can be predicted taking into consideration the factors discussed in this report, and can be augmented with any additional data if available. That is, applying historical average mileage per vehicle and total engine hours, the time of year seasonality on idle consumption rates, reasonable estimate of fuel consumption for rotation may be provided using FCPM.

Path Forward

- The methodology of combining limited usage data and OMS/MP parameters has promise in refining future training rotation fuel quantity estimates; however, this work was only the first step to developing a full methodology.
- Verify/validate methodology on other classes of high quantity/usage systems.
- Obtain higher fidelity data on platforms that do not have CAN bus data (i.e., better daily odometer mileage and hour meter engine data, as well as daily fuel refill for model validation).
- Continue to develop individual vehicle platform training exercise usage profiles.
- Apply methodology to estimate fuel consumption for all vehicles participating in training rotations.

For future analyses, we believe taking a data-informed approach on individual-item-level vehicle usage can better inform fuel planning for training events. Additional data on other platforms, generators, and other power and energy requirements would be required to create a baseline for all the equipment a unit may bring or require, but the same methodology can be used to create usage profiles. These next steps would be required to understand fuel requirements for a unit across all the relevant equipment that may be employed.

Appendix A – Additional Data, Charts, and Visualizations

Data Set Deep Dive and Individual Daily Profiles

Tables A-1 through A-4 and Figures A-1 through A-10 summarize the individual daily usage for each vehicle serial by day for six training rotations for the wheeled data set.

Table A-1. Statistics of measure data, daily observations

Statistic	Distance (miles)	Total consumed (gal)	Idle consumed (gal)	Move consumed (gal)	Total engine ops (h)	Idle engine ops (h)	Move engine ops (h)
Min	0.00	0.16	0.02	0.00	0.15	0.02	0.00
Max	196.20	85.57	74.86	51.38	24.00	23.98	9.45
Median	9.85	11.00	4.87	4.37	5.29	3.92	1.04
Mode	0.00	13.72	1.33	0.00	24.00	0.34	0.01
Mean	14.84	12.89	6.86	6.03	6.31	4.97	1.34
Std	16.24	10.75	7.06	6.07	4.88	4.24	1.23
Var	263.58	115.51	49.80	36.88	23.82	17.95	1.52

Table A-2. Average usage by variant (wheeled data)

Variant	Count	Distance (miles)	Total consumption (gal)	Idle consumption (gal)	Moving consumption (gal)	Total engine operation (h)	Idle engine operation (h)	Moving engine operation (h)
Var1	1162	14.2	13.9	7.8	6.1	6.9	5.5	1.4
Var2	3842	14.8	15.7	10.0	5.7	7.5	6.3	1.2
Var3	1371	15.5	13.5	6.9	6.6	6.5	5.1	1.5
Var4	1661	13.0	12.0	6.8	5.2	6.3	5.1	1.2
Var5	20,226	15.3	12.9	6.6	6.3	6.3	5.0	1.4
Var6	4124	12.7	10.3	5.0	5.3	4.9	3.8	1.2
Var7	2363	16.8	13.1	6.6	6.5	5.8	4.5	1.4
Var8	686	13.0	11.9	6.3	5.6	7.2	5.9	1.3
Var9	172	15.4	13.2	7.9	5.3	6.5	5.1	1.4

Table A-3. Average values per rotation per observation

Rotation	Count	Distance (miles)	Total consumption (gal)	Idle consumption (gal)	Moving consumption (gal)	Total engine operation (h)	Idle engine operation (h)	Moving engine operation (h)
TR1	6562	16.5	15.3	8.5	6.9	6.4	4.9	1.5
TR3	5897	15.6	15.1	8.8	6.3	6.9	5.6	1.3
TR4	6329	14.6	11.7	6.1	5.6	6.8	5.4	1.3
TR5	6731	15.4	10.7	4.8	5.9	5.7	4.3	1.3
TR8	5709	13.5	13.3	7.5	5.8	6.0	4.7	1.3
TR10	4379	12.6	10.7	5.3	5.4	6.1	4.9	1.2

Table A-4. Variant average use per observation

Variant	Distance (miles)	Total consumed (gal)	Idle consumed (gal)	Move consumed (gal)	Total engine ops (h)	Idle engine ops (h)	Move engine ops (h)	Count
Var1	14.20	13.87	7.76	6.12	6.90	5.54	1.36	1162
Var2	14.78	15.68	10.01	5.67	7.47	6.28	1.20	3842
Var3	15.49	13.52	6.94	6.58	6.55	5.05	1.50	1371
Var4	13.03	11.96	6.78	5.18	6.27	5.07	1.19	1661
Var5	15.25	12.88	6.62	6.25	6.34	4.96	1.39	20,226
Var6	12.72	10.30	5.01	5.29	4.95	3.77	1.18	4124
Var7	16.83	13.06	6.58	6.48	5.84	4.46	1.38	2363
Var8	12.99	11.88	6.32	5.56	7.21	5.90	1.30	686
Var9	15.37	13.15	7.88	5.27	6.49	5.05	1.43	172

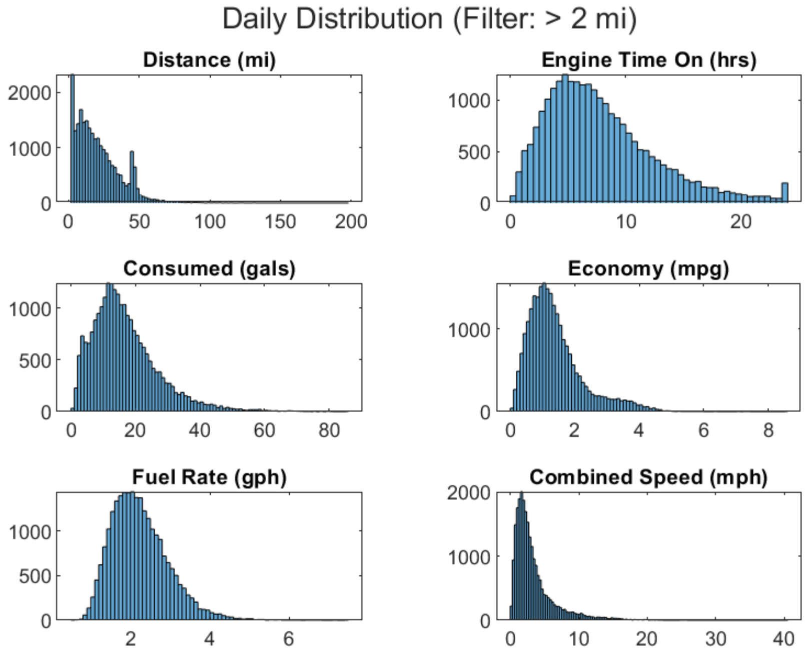


Figure A-1. Daily usage metric histograms (filtered out low movement)

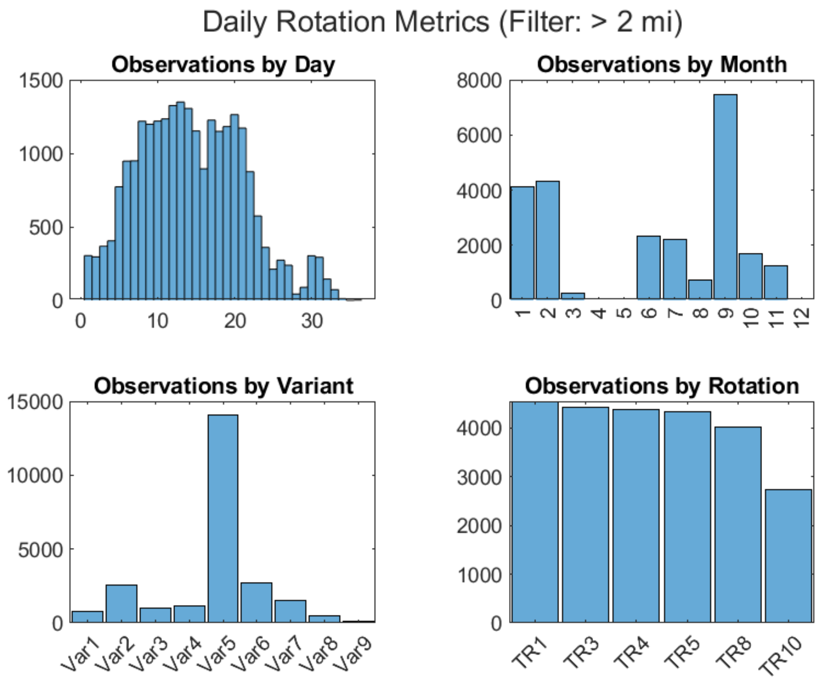


Figure A-2. Observations of day, month, variant, and rotation (wheeled data)

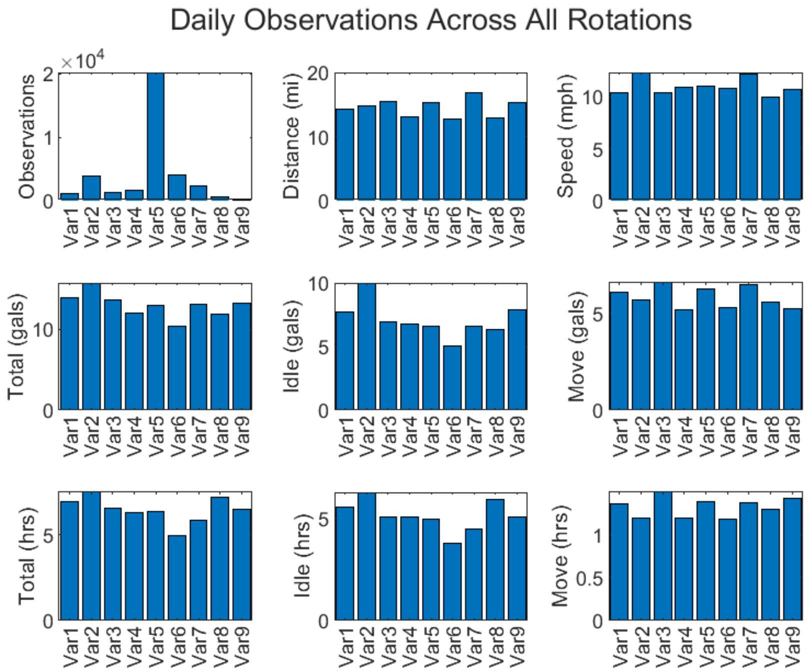


Figure A-3. Average usage per day by variant

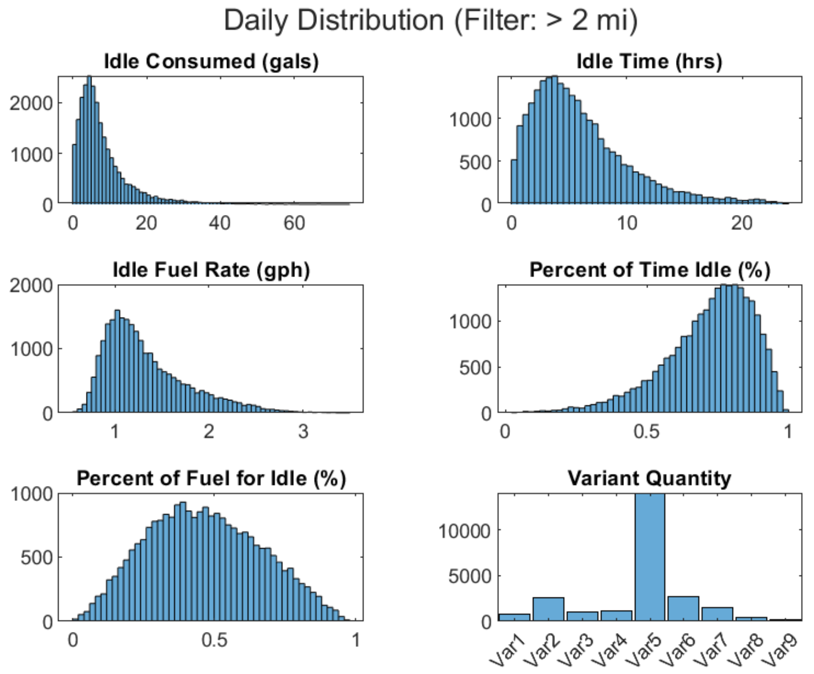


Figure A-4. **Idle-only usage metric distribution**

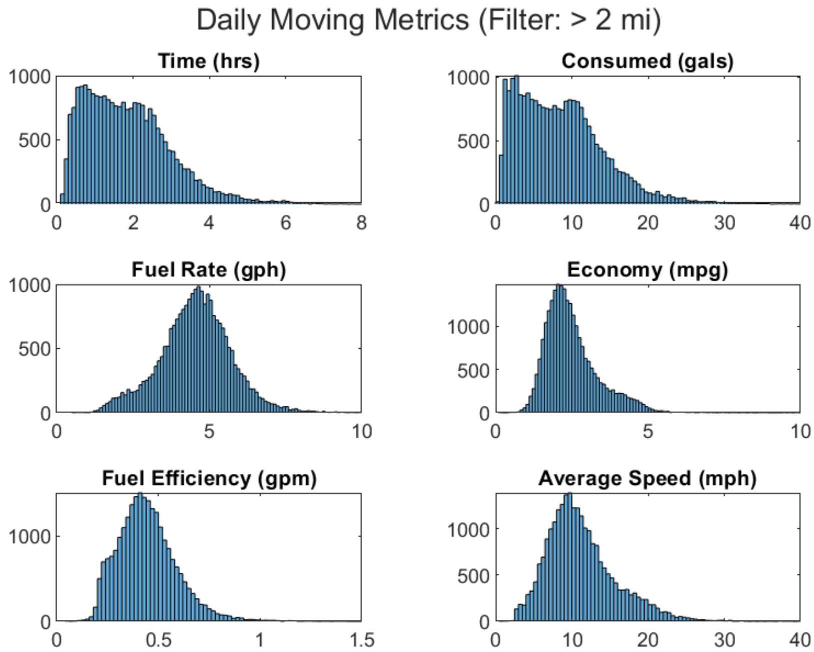


Figure A-5. **Moving-only usage metric distribution**

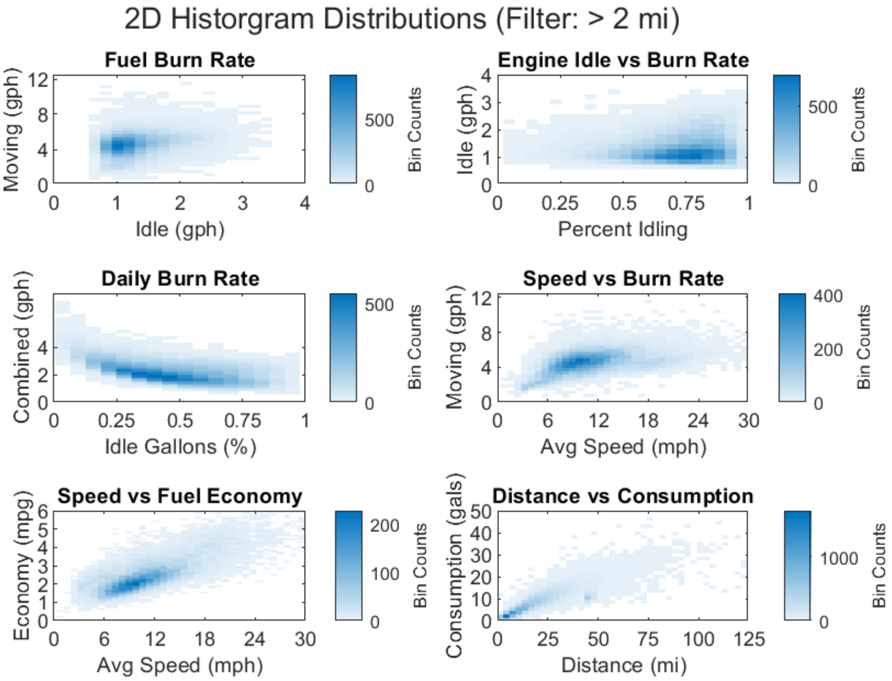


Figure A-6. Scatter histograms of measured metrics

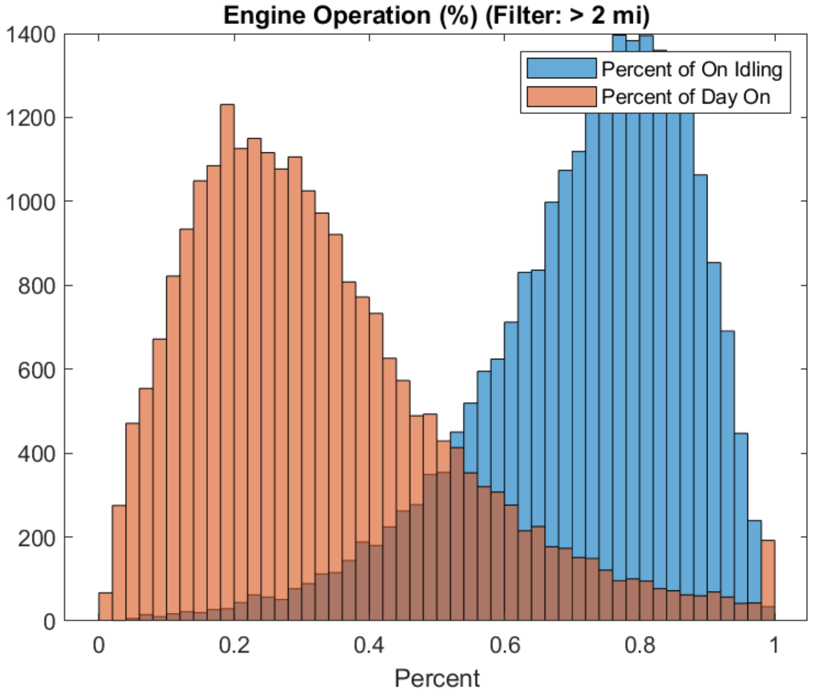


Figure A-7. Histogram of idle time and engine on operation

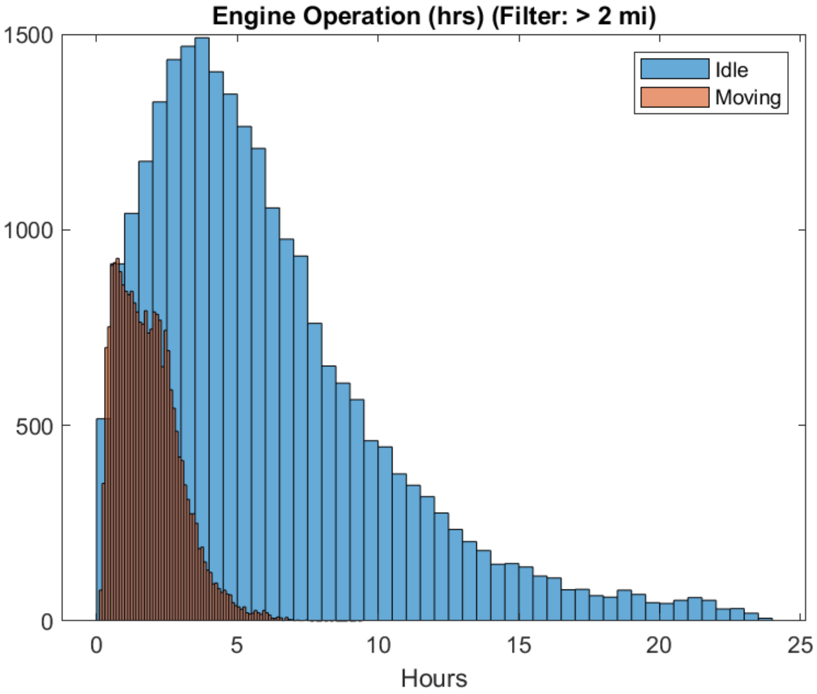


Figure A-8. Histogram of idle and moving time per day

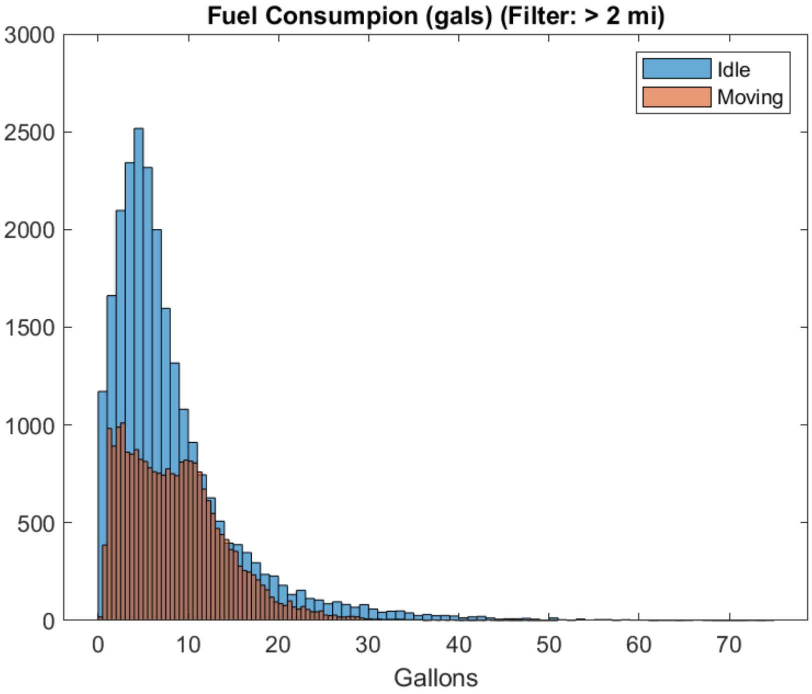


Figure A-9. Histogram of idle gallons and moving gallons consumed

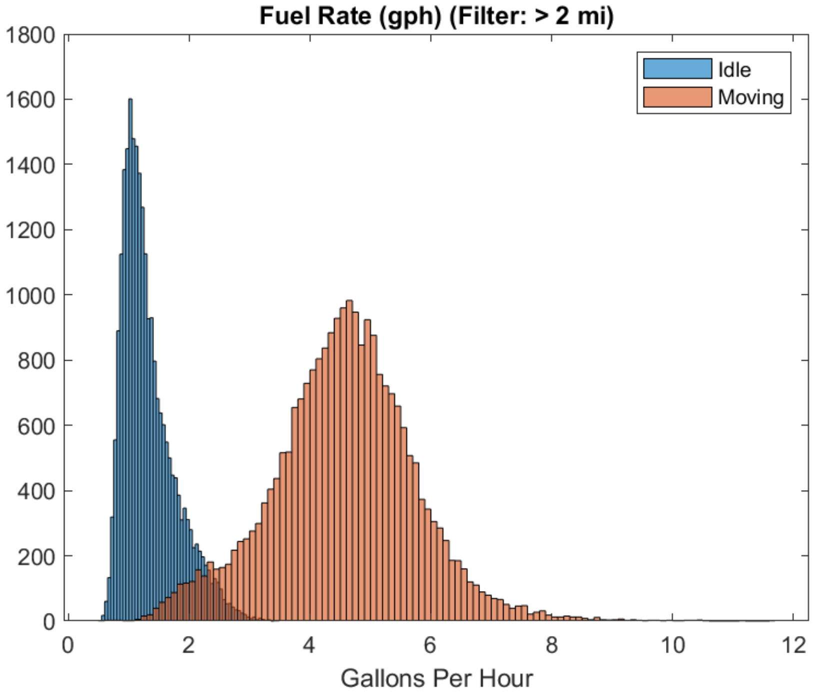


Figure A-10. Histogram of idle and moving fuel rates

LIST OF ACRONYMS

CAN	Controller Area Network
DAC	DEVCOM Analysis Center
DEVCOM	U.S. Army Combat Capabilities Development Command
ECU	Environmental Control Unit
FCPM	Fuel Consumption Prediction Model
OMS/MP	Operation Mode Summary/Mission Profile
OPTEMPO	operating tempo
NTC	National Training Center
RPM	revolutions per minute
SDC	Sample Data Collection
SFC	Specific Fuel Consumption

ORGANIZATION

DEVCOM Analysis Center
FCDD-DAS-O/G. Dogum
6896 Mauchly St.
Aberdeen Proving Ground, MD 21005-5071

DEVCOM Army Research Laboratory
FCDD-RLB-CI/Tech Library
2800 Powder Mill Rd.
Adelphi, MD 20783

Defense Technical Information Center
ATTN: DTIC-O
8725 John J. Kingman Rd.
Fort Belvoir, VA 22060-6218