

Comparison of Vehicle-Broadcasted Fuel Consumption Rates against Precise Fuel Measurements for Medium- and Heavy-Duty Vehicles and Engines

Alex Pink, Adam Ragatz, Lijuan Wang, Eric Wood, and Jeffrey Gonder
National Renewable Energy Laboratory

ABSTRACT

Vehicles continuously report real-time fuel consumption estimates over their data bus, known as the controller area network (CAN). However, the accuracy of these fueling estimates is uncertain to researchers who collect these data from any given vehicle. To assess the accuracy of these estimates, CAN-reported fuel consumption data are compared against fuel measurements from precise instrumentation. The data analyzed consisted of eight medium/heavy-duty vehicles and two medium-duty engines. Varying discrepancies between CAN fueling rates and the more accurate measurements emerged but without a vehicular trend—for some vehicles the CAN under-reported fuel consumption and for others the CAN over-reported fuel consumption. Furthermore, a qualitative real-time analysis revealed that the operating conditions under which these fueling discrepancies arose varied among vehicles. A drive cycle analysis revealed that while CAN fueling estimate accuracy differs for individual vehicles, that CAN estimates capture the relative fuel consumption differences between drive cycles within 4% for all vehicles and even more accurately for some vehicles. Thus, in situations where only CAN-reported data are available, CAN fueling estimates can provide relative fuel consumption trends but not accurate or precise fuel consumption rates.

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INTRODUCTION

During operation, vehicles broadcast real-time estimates of all pertinent operating conditions, including fuel consumption estimates, over a vehicle data bus called the controller area network (CAN). Recording these broadcast estimates over time involves connecting a CAN data logger to the vehicle of interest and storing the CAN signals of interest. This process is fairly inexpensive, relatively unobtrusive, and easily implemented. As such, CAN data logging is a popular way of gathering vehicle fuel consumption data. Unfortunately, these vehicle-reported estimates are not direct measures of fuel usage, and errors may arise based on assumptions implemented in the vehicle's electronic control module [1]. These assumptions vary among vehicle manufacturers and even among different powertrains produced by the same manufacturer [2]. Thus, the trustworthiness of these estimates is uncertain.

However, several methods exist for obtaining precise fuel consumption measurements. Dynamometer test facilities, which measure several different vehicle performance metrics, contain instrumentation that precisely measures fuel consumption rates. This instrumentation includes gravimetric fuel scales, fuel flow meters, and carbon balance emission collections systems [3]. If a vehicle cannot undergo testing in a laboratory setting, various forms of on-road instrumentation exist. Devices such as in-line fuel flow meters and fuel scales installed onto a vehicle's existing fuel system allow for on-road collection of precise fuel consumption data [4].

In this paper, precise fuel measurements are compared against CAN-broadcasted engine fueling rates. Fueling data on eight heavy-duty vehicles and two heavy-duty engines are provided by the National Renewable Energy Laboratory's Renewable Fuels and Lubricants (ReFUEL) laboratory. These data sets include accurate fuel consumption measurements from gravimetric fuel scales and CAN fuel rate estimates, both recorded simultaneously.

Data comparisons performed include:

- Quantitative total fuel consumption analysis
- Qualitative real-time (second-by-second) fuel analysis
- Relative fuel consumption analysis over different drive cycles.

The quantitative total fuel consumption analysis compares the percent differences between the CAN and more accurate fuel measurements for all vehicles and drive cycles. The real-time qualitative analysis illuminates vehicle operating conditions under which fuel consumption discrepancies do or do not arise. Furthermore, it seeks to identify any trends between different vehicles and engines to explore if a broadly-applicable, operating-condition-based fuel estimation compensation algorithm is possible. The drive cycle analysis examines the trends between vehicle-reported fueling estimates and precise laboratory measurements on a drive-cycle basis within each data set.

DATA DESCRIPTION

The fuel comparison analysis contains ten separate data sets, eight from medium/heavy-duty vehicle testing and two from medium-duty engine testing. Six of the eight vehicles were tested on the ReFUEL laboratory's heavy-duty chassis dynamometer, each over multiple drive cycle tests. Each of these different drive cycles contains several repetitions of the same test. The other two vehicles were tested on-road to compare different aerodynamic features and their effect on fuel efficiency [5]. The two medium-duty engines analyzed in this report underwent dynamometer testing in the ReFUEL laboratory's engine test cell. Table 1 contains further information on each individual data set. Vehicle and engine names are anonymized to protect manufacturer identity.

Table 1. Details on vehicle and engine data sets

Name	Displacement (L)	Horsepower	Test Type
2015 Day Cab Tractor –Renewable Diesel	12.9	455	Chassis dynamometer
2015 Day Cab Tractor – Ultra Low Sulfur Diesel (ULSD)	12.9	455	Chassis dynamometer
2015 Heavy-Duty Refuse Truck	11.9	350	Chassis dynamometer
2012 Light Heavy-Duty Utility Vehicle	6.7	300	Chassis dynamometer
2011 Medium-Duty Walk-In Van	6.7	200	Chassis dynamometer
2010 Medium-Duty Walk-In Van	6.7	280	Chassis dynamometer
2012 Medium-Duty Box Truck	6.7	240	On-road
2011 Medium-Duty Box Truck	6.7	240	On-road
2012 Medium-Duty Diesel Engine	8.9	345	Engine dynamometer
2008 Medium-Duty Diesel Engine	9.3	330	Engine dynamometer

All of the vehicles and engines conformed to the SAE J1939 CAN standard [6]. Accordingly, the data logger recorded estimated fuel use from the standard CAN signals. Relevant measurements were also recorded from ReFUEL-provided instrumentation and, for the on-road tests, from an inline fuel scale installed on the vehicles. The signals of interest and their corresponding units in this paper include:

- EngFuelRate (J1939) - liters per hour (L/hr)
- Gravimetric fuel scale reading (ReFUEL) - kilograms (kg)
- Distance (ReFUEL) - miles (mi)

Every data set contains total fuel directly reported by the precise measurements and as an integration of the fuel estimates. However, the two on-road vehicles do not have second-by-second precise fuel

measurements. Thus, a real-time analysis is not possible for these data sets. Furthermore, the engine dynamometer cells do not measure driving distance, and thus fuel efficiency and fuel consumption metrics per distance are unavailable for these tests.

METHODOLOGY

Each vehicle or engine was analyzed with separate scripts (programmed in Python), which adjusted for differences in fuel densities, number of test cycles, and moving-average window data filtering requirements for the qualitative real-time analyses. The Python scripts used the scientific computing libraries NumPy, SciPy, and Matplotlib.

Quantitative Total Fuel Analysis

Integrating the CAN fueling rate signal over a test cycle's duration yields the total estimated fuel use by volume (L). Subtracting a gravimetric fuel scale's final mass from its beginning mass gives the total fuel used by mass (kg). The data set's fuel density converts this mass into a volumetric value. For each vehicle data set, the National Renewable Energy Laboratory performed a fuel analysis on the particular fuel used during the tests to obtain that data set's fuel density.

For the chassis dynamometer data sets, the ReFUEL dynamometer instrumentation records the vehicle's distance travelled during the test cycle. For the two on-road data sets, integrating the vehicle's speed over the duration of the test results in the total distance travelled.

Dividing the fuel use in gallons by the total distance travelled in miles results in gallons per mile, a metric of fuel consumption. Multiplying this value by 100 results in the more relatable unit of gallons per 100 miles.

After calculating the fuel use and consumption rate from both fueling sources for a particular drive cycle, the percent difference (PD) between these two numbers was calculated (Equation 1).

$$PD = \frac{F_{grav} - F_{CAN}}{F_{CAN}} \times 100 \quad (1)$$

F_{grav} refers to the total fuel (use or consumption rate) measurement as reported by the gravimetric fuel scale, while F_{CAN} refers to the corresponding fuel estimate obtained by integrating the CAN-reported fueling rate. For every drive cycle in a vehicle data set, this computation was carried out. Next, calculation of the statistical mean, median, and standard deviation across all drive cycle percent differences reveals the general CAN fueling rate characteristics of an individual data set. Appendix A contains an example table listing the fueling consumption totals, percent difference, and statistical measures for one of the data sets.

Qualitative Real Time Fuel Analysis

The six chassis dynamometer data sets and the two engine data sets contain second-by-second fueling data. Comparing the two different fueling sources in real time reveals under which vehicle operating conditions CAN fueling estimates are accurate and inaccurate.

Differentiating the gravimetric fuel scale's reading results in a real-time fueling rate, allowing for comparison to the fuel estimation signal. However, the low real-time precision of the ReFUEL laboratory's fuel scale (5 grams) results in a quantized real-time fuel signal containing large amounts of high-frequency noise. This high-frequency content ends up in the differentiated signal and makes a second-by-second comparison of the two fuel signals difficult to perform. To alleviate this noise problem, the raw signals (both the differentiated gravimetric fuel scale and the CAN-reporting fueling rates) first pass through a moving-average window that filters out the undesired high frequency content.

The moving average window size changed between data sets (Table 2). The optimal window size for each data set was found empirically by observing the smoothness of the differentiated fuel scale signal and judging whether or not it would suffice for a second-by-second comparison.

Table 2. Moving average window size used for the qualitative real-time analysis

Name	Moving-Average Window Size (s)
2012 Medium-Duty Diesel Engine	120
2015 Day Cab Tractor – Renewable Diesel	40
2010 Medium-Duty Walk-In Van	180
2008 Medium-Duty Diesel Engine	120
2015 Day Cab Tractor - ULSD	60
2015 Heavy-Duty Refuse Truck	90
2012 Light Heavy-Duty Utility Vehicle	35
2011 Medium-Duty Walk-In Van	30

After filtering the fueling signals with a moving average, five real-time plot types per drive cycle were generated:

1. Overall fueling scatter plots, colored by percent difference
2. Acceleration/speed category fueling scatter plots
3. Vehicle and engine condition maps
4. Percent difference overlay on speed trace
5. Cumulative fuel difference over time.

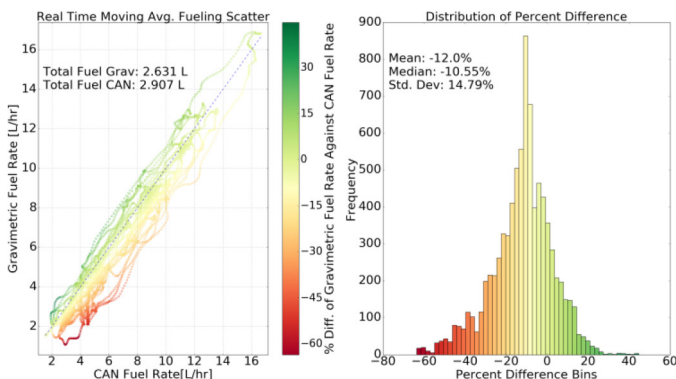


Figure 1. Qualitative real-time analysis: illustrative example of fueling scatter plot, colored by percent difference, for one vehicle test.

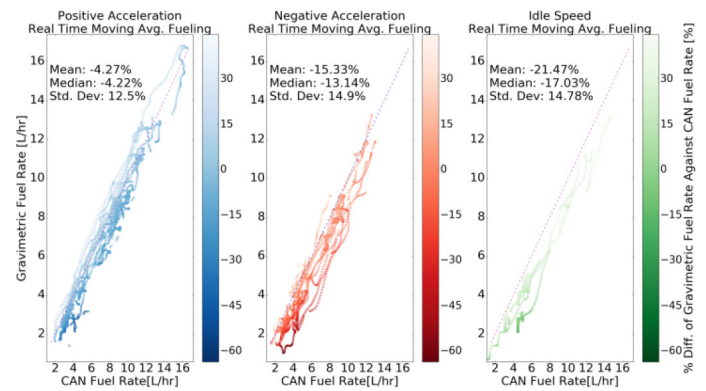


Figure 2. Qualitative real time analysis: illustrative example of acceleration/speed category fueling scatter plot for one vehicle test. Blue: positive acceleration operating points. Red: negative acceleration operating points. Green: idle speed operating points.

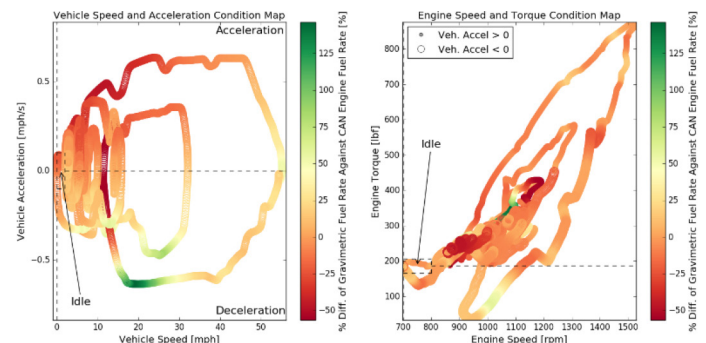


Figure 3. Qualitative real-time analysis - illustrative example of vehicle condition map (left) and engine condition map (right) for one vehicle test.

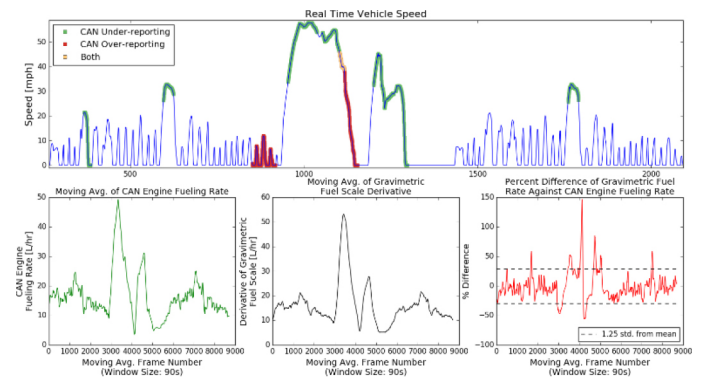


Figure 4. Qualitative real-time analysis: illustrative example of percent difference overlay on speed trace for one vehicle test.

Figures 1, 2, 3, 4, 5 show an example of each of the plots listed above. Note the plots shown in Figure 1, 2, 3, 4 use the moving-average filtered fueling signals while the cumulative fuel difference plot in Figure 5 uses the original, unfiltered signals. For the plots with a red/green color map, the red side represents where the CAN fueling rate estimates over-report compared to the gravimetric fuel scale, while the green side represents where the CAN fueling rate estimates under-report compared to the gravimetric fuel scale.

Each type of plot in Figures 1, 2, 3, 4, 5 reveals different information about the recorded fuel consumption of each vehicle over the tested drive cycles. Qualitative analysis of each of these plots reveals where