Data Points and Duration for Estimating Fuel Consumption of a LPG Engine

John A. Hogan[1], Dennis G. Watson[2], and Tony V. Harrison[3]

[1,2]Dept of Plant, Soil and Agricultural Systems, Southern Illinois University, MC 4415,

Carbondale, IL 62901 USA

[3]JPT Integrated Solutions, Inc, Gainesville, FL 32609

[2]E-mail: dwatson@siu.edu

ABSTRACT

Accurate measurement of fuel consumption is critical in quantifying the efficiency of an engine or predicting emissions. As part of a larger project, accurate instantaneous fuel consumption data was needed for a Ford LPG engine. A detailed review of literature did not provide clear recommendations on the number of data points or time duration for data collection. To provide a research basis for the number of data points and the duration of data collection, fuel consumption tests were conducted using up to 15 data points of percent fuel rate and up to 12 minutes of data collection. Based on analysis of these detailed test results, at least 3 data points (0%, 50%, and 100% of fuel rate) and 3.5 min of data collection are recommended for similar fuel rate tests for a LPG engine.

Keywords: Fuel consumption, LPG

1. INTRODUCTION

Accurate measurement of fuel consumption is critical in quantifying the efficiency of an engine or predicting emissions (Hansson *et al*., 1999). As part of an emissions monitoring project, instantaneous fuel consumption data was needed for a Ford ESG-642 LPG (liquefied petroleum gas) engine. The engine was equipped with a controller area network (CAN) that included fuel rate data, but the fuel rate was factory calibrated for gasoline rather than LPG (Pennala, 2003).

Planning was initiated for a series of fuel consumption tests to relate the CAN fuel rate data to actual LPG fuel rate. Literature was reviewed for recommendations on the number of data points to collect and the duration of each fuel consumption test. Researchers using throttle position at various engine speeds included, Al-Hasan (2003) using only 75% throttle and Arcaklioglu and Celikten (2005) using 50%, 75%, and 100% throttle. Several researchers used percent load instead of percent throttle. Canakci and Van Gerpen (2003) used 100% load. Singh *et al*. (2007) used 63%, 84%, and 98% loads. Bhattacharya *et al*. (2006) used 25%, 50%, 75%, 100%, and 110% loads. Athanassiadis (2000) and Birch and Kubesh (2003) used 0%, 10%, 50%, 75%, and 100% loads. Hansson *et al*. (2001, 2003) and Lindgren and Hansson (2004) used 0%, 10%, 25%, 50%, 75%, and 100% loads.

The ISO 8178-4 (ISO, 1996) standard for engine emissions measurement includes a C1 test cycle which requires testing at 0%, 10%, 50%, 75%, and 100% loads, and a B test cycle which adds 25% load to the C1 test engine loads. The SAE J1312 (SAE, 1995) procedure for mapping engine performance, requires testing an engine at no less than five loads. Unless specific operating characteristics of the engine are known, the J1312 procedure requires the load intervals to be equally spaced (i.e. 0%, 25%, 50%, 75%, and 100%).

In general, researchers did not report data collection duration other than to reference a standard. SAE J1312 (SAE, 1995) does not specify a duration. ISO 8178-4 (ISO, 1996) used by Athanassiadis (2000), Birch and Kubesh (2003), Hansson *et al*. (2001, 2003), and Lindgren and Hansson (2004), requires a seven minute period for engine adjustment and stabilization and then a three minute data collection duration. Since ISO 8178-4 (ISO, 1996) is an emissions measurement standard, the three minute duration could be a requirement for emissions measurement rather than fuel consumption measurement.

Neither the standards nor available literature provided clear recommendations on data points and duration for fuel consumption tests. This may be due to the wide variety of testing equipment and configurations available for fuel consumption tests, yet a description of a specific study would provide a reference point for researchers. This study was conducted to determine the minimum number of data points and minimum duration of data collection needed to accurately estimate fuel consumption for the Ford ESG-642 LPG engine.

2. EQUIPMENT AND PROCEDURES

The engine used for this study was a 2003 Ford model ESG-642, 4.2L, V-6 LPG engine rated for continuous operation at 325 Nm of torque at 2,200 rpm and 78 kW at 3,000 rpm. This engine was equipped with a SAE J1939 (SAE, 2000) CAN. An Opto 22 SNAP Ultimate I/O programmable automation controller (PAC) was selected for data acquisition. Dearborn Group Technology's Dearborn Protocol Adapter (DPA) model DPA III/i was used to interface between the CAN and the PAC. The DPA was connected to a diagnostic port on the engine wiring harness and to a serial module controlled by the PAC. SAE J1939-71 (SAE, 2002) was referenced to interpret CAN signals and program the PAC to extract engine speed, throttle position, and fuel rate data. The PAC monitored CAN data at 250 ms intervals.

A Honeywell HIH3610 humidity sensor, an Opto 22 ICTD temperature sensor, and a Novalynx WS16BP barometric pressure sensor were placed within 4 m of the engine to measure ambient conditions. These sensors were connected to the PAC for data acquisition. The actual fuel rate was measured by suspending the fuel tank and attaching it to an Omega LC101 strain gage. An Omega DP41-S strain gage meter provided an analog output signal which was connected to an analog input module on the PAC. The strain gage was calibrated and was accurate to 0.0023 kg (0.005 lb), based on testing by the Illinois Department of Agriculture's Bureau of Weights and Measures.

A Lebow TMS 9000 torque measurement system was used to measure torque. This device was interfaced to the PAC. The system included a rotating torque sensor mounted between the dynamometer driveshaft and the engine flywheel and a signal processing module. The rotating torque sensor had an accuracy of 0.50% and the signal processing module had an accuracy of 0.002%. An M&W P-400B hydraulic dynamometer was used to apply a load to the engine to attain higher fuel rates.

LabVIEW (National Instruments, 2003) was programmed to provide a user interface to the data monitored by the PAC, to collect the data at the specified time intervals, and store the data from each fuel rate in a comma-separated values (CSV) file. The LabVIEW program was installed on a computer and used by the operator to control data collection. OPC (object linking and embedding for process control) server software was used to transfer data between the PAC and OPC client of LabVIEW. This system provided real-time data access with updates as frequent as 250 MHz.

Standards were used as a reference in selecting the number of data points and time durations for the study. The SAE J1312 (SAE, 1995) specification of five equally spaced load intervals was applied to fuel rate. Equally spaced fuel rate intervals of 2, 3, 4, 5, 6, and 11 points were selected. The combined 15 points of the data point combinations was considered the accurate fuel rate measurement, for this study. The range of CAN fuel rates for testing was determined by operating the engine at idle without a load and at rated power. For testing purposes, the 30.50 L/h fuel rate at the engine's rated power was used as 100% fuel rate. The idle fuel rate of 2.15 L/h was used as 0% fuel rate. Table 1 lists the percent fuel rate, CAN fuel rate and the percent fuel rates used for each number of data points. ISO 8178-4 (ISO, 1996) required 3 min of data collection. Data collection durations from 30 s to 12 min in 30 s intervals were selected for comparison in this study. The average of the 12 min duration data was considered accurate for the purpose of this study.

Table 1. Percent fuel rate, corresponding L/h fuel rate, and grouping of fuel rates for analysis.

Percent fuel rate	CAN fuel rate (L/h)	2 points	3 points	4 points	5 points	6 points	11 points	15 points
0 (idle)	2.15	X	X	X	X	X	X	X
10	5.00						X	X
20	7.80					X	X	X
25	9.25				X			X
30	10.65						X	X
33	11.60			X				X
40	13.50					X	X	X
50	16.35		X		X		X	X
60	19.15					X	X	X
67	21.05			X				X
70	22.00						X	X
75	23.40				X			X
80	24.85					X	X	X
90	27.65						X	X
100	30.50	X	X	X	X	X	X	X

Data collection for the number of data points and duration was accomplished by collecting data for 12 min for each of the 15 percent fuel rates. CAN fuel rate, CAN engine speed, CAN throttle position, torque, fuel tank weight, and ambient condition data were collected while the LPG engine was operated at 0%, 10%, 20%, 25%, 30%, 33%, 40%, 50%, 60%, 67%, 70%, 75%, 80%, 90%, and 100% of fuel rate (see Table 1 for the CAN fuel rate for each percent fuel rate). The fuel rate tests were conducted in a randomized order within each of four replications.

Each fuel rate was achieved by adjusting the throttle and engine load. During the first replication, the throttle position and engine torque settings were recorded and used to attain the same fuel rate for the other replications. Each time the fuel rate setting was changed, seven minutes were allowed for fuel rate adjustment and stabilization before data collection started, per ISO 8178-4 (ISO, 1996). Data was recorded at 30 s intervals over a 12 min period. At each 30 s interval, the fuel weight was subtracted from the fuel weight at the beginning of the 12 min test and the rest of the data were averaged. The difference in fuel weight was used to calculate fuel consumption in L/h.

All four replications of CAN fuel rate and measured fuel rate at the 15 fuel rate levels were separated into 7 groups of data points (see Table 1). For each group of data points, linear regression analysis was used to determine slope and intercept. The resulting coefficients were used with CAN fuel rate to predict measured fuel rate for all 15 fuel rate levels. For example, for the 2 data points of 0% and 100% fuel rate, the 8 observations were used to generate a linear equation. From the linear equation, the CAN fuel rate from all 60 observations was used to predict measured fuel rate. The absolute error between the predicted value and the measured fuel rate was determined for each of the 60 tests for each group. A one-way ANOVA was used to determine any differences ($\alpha = 0.05$) among absolute error for the 7 groups of data points. Tukey's honestly significant difference (HSD) and Fisher's least significant difference (LSD) tests were used to separate means among the number of data points. Tukey's HSD method is based on the q-statistic while Fisher's LSD is based on the t-statistic. While Fisher's LSD is commonly used in agricultural research, it does not maintain the same alpha level (α) among all tests as Tukey's HSD (Navidi, 2008). Fisher's LSD only controls the α for each individual pairwise comparison, but not the experimentwise α; whereas Tukey's HSD controls the experimentwise error rate at the selected α (Montgomery, 2005). With Fisher's LSD, as the number of independent mean comparisons increases, the probability of significance increases (0.23 for 5 tests, 0.40 for 10 tests, and 0.64 for 20 tests) (Hoshmand, 2006). The minimum number of data points to use in collecting fuel consumption data was determined by the least number of data points with a mean absolute error that was not different from the 15 data points.

Data for twenty four different time durations (30 s to 12 min in 30 s intervals) were extracted from each percent fuel rate data set, by taking the first occurrence of the time duration from the 12 min of data. The assumed accurate measurement of fuel rate was the mean of the 4 replications of 12 min data. The absolute error of the mean and the measured data was calculated for each of the 1,440 observations (24 time durations, 15 fuel rates, and 4 replications). A one-way ANOVA was used to determine any differences ($\alpha = 0.05$) among data collection durations. Tukey's HSD and Fisher's LSD tests were used to separate means among the durations. The minimum duration to use in collecting fuel consumption data was determined by the shortest duration with a mean absolute error that was not different from the mean 12 min duration.

3. RESULTS

The correlation coefficient of the CAN and measured fuel rates based on 15 data points and 12 min of data was 0.992, indicating a strong linear relationship. The comparison of measured fuel rate and CAN fuel rate is illustrated in Figure 1.

There was a significant difference in the absolute error among the number of data points ($F_{6,\,52} = 2.14$, $P = 0.0484$). Table 2 summarizes the differences among the number of data points. Based on Tukey's HSD, the absolute error of 15 data points is significantly better than 2 data points. There were no other differences with Tukey's HSD. Fisher's LSD indicates that while there is no difference among 4, 5, 6, 11, or 15 data points, while each of these is significantly better than 2 data points. For both Tukey's HSD and Fisher's LSD, 3 data points was the least number of data points that was not different from 15 data points.

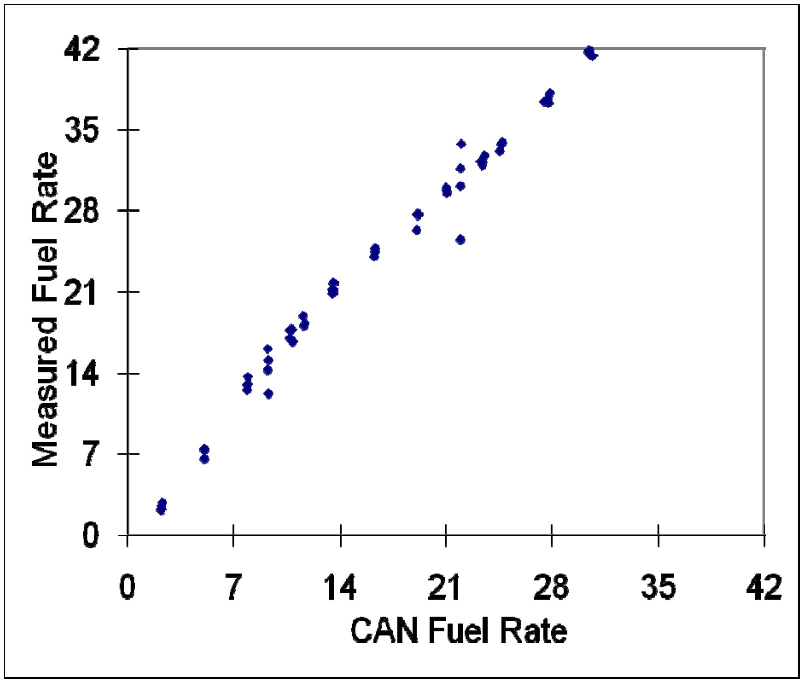

Figure 1. Measured fuel rate at each CAN fuel rate.

Table 2. Comparison of number of data points to collect CAN fuel rate data to predict actual fuel rate for fifteen data points.

Number of points	Mean Absolute Error (N = 60)	Tukey's HSD *		Fisher's LSD*		Intercept		Slope	
						Coefficient	P-value	Coefficient	P-value
2	1.6190	a		a		-0.605	0.0116	1.384	< 0.0001
3	1.2978	a	b	a	b	0.245	0.7227	1.384	< 0.0001
4	1.2284	a	b		b	0.722	0.2459	1.367	< 0.0001
5	1.2133	a	b		b	0.843	0.1591	1.361	< 0.0001
6	1.1437	a	b		b	1.442	0.0130	1.336	< 0.0001
11	1.1168	a	b		b	1.652	0.0015	1.326	< 0.0001
15	1.0867		b		b	1.943	< 0.0001	1.315	< 0.0001

* Means with the same letter are not significantly different.

There was a significant difference in the absolute error among the different time intervals for fuel rate data collection ($F_{23, 1415} = 13.89$, $P < 0.0001$). Table 3 summarizes the differences among the time intervals. Both Tukey's HSD and Fisher's LSD separate the 0.5 minute time duration as having a significantly higher absolute error than the other time durations. Based on Tukey's HSD, the absolute error of any time duration of at least 6.0 minutes is significantly better than durations of 1.5 minutes or less, yet there is no difference in durations of 2.0 minutes or more.

Based on Fisher's LSD there is no difference among time durations of 3.5 minutes through 12.0 minutes. The minimum time duration with a mean absolute error that was not different from 12.0 min, was 2.0 min or 3.5 min for Tukey's HSD and Fisher's LSD, respectively.

Table 3. Comparison of time durations to collect CAN fuel rate data to predict actual fuel rate for twelve minutes.

Time Duration (min)	Mean Absolute Error (N = 1440)	Tukey's HSD*	Fisher's LSD*
0.5	7.8018	a	a
1.0	3.2328	b	b
1.5	3.2101	b	b
2.0	2.0862	b c	b c
3.0	1.8548	b c	c d
2.5	1.7039	b c	c d e
3.5	1.4435	b c	c d e f
4.0	1.4008	b c	c d e f
4.5	1.3241	b c	c d e f
5.5	1.1726	b c	c d e f
5.0	1.1554	b c	c d e f
6.0	0.8495	c	d e f
6.5	0.7786	c	d e f
9.5	0.6695	c	e f
8.0	0.6516	c	e f
7.0	0.6316	c	e f
7.5	0.6112	c	e f
8.5	0.6081	c	e f
11.5	0.5296	c	f
9.0	0.5273	c	f
10.0	0.5250	c	f
11.0	0.4993	c	f
10.5	0.4816	c	f
12.0	0.4771	c	f

* Means with the same letter are not significantly different.

4. DISCUSSION

The first objective was to determine the minimum number of data point combinations needed for accurately estimating instantaneous fuel consumption for the LPG engine. Comparing only the mean absolute error, as the number of data points increased the mean absolute error decreased, with the lowest mean absolute error resulting from 15 data points. Using either Tukey's HSD or Fisher's LSD, three data points was the fewest number of data points that results in an mean absolute error that was not significantly higher than 15 data points. Based on these results, future fuel consumption tests should use at least 3 data points (0%, 50%, and 100% of fuel rate).

The second objective was to determine the minimum time duration to collect data for accurately estimating fuel consumption for the LPG engine. A duration of 0.5 minute resulted in a significantly higher mean absolute error and should be avoided. Using Tukey's HSD method the minimum time duration for accurate testing would be 2.0 minutes, but using Fisher's LSD the minimum number of minutes would be 3.5 minutes. The ISO standard 8178-4 (ISO, 1996) requires no less than 3 minutes of data collection for emission measurement. Fisher's LSD result of 3.5 minutes is closer to the ISO 8178-4 requirement. Based on the results of this study, a minimum time duration of 3.5 minutes is recommended for future fuel consumption studies.

Researchers may apply these results differently depending on their test objectives and preferred tests for means separation. The two mean separation methods of Fisher's LSD and Tukey's HSD result in different mean groupings. When several means are compared, Tukey's HSD is less likely to reject a true null hypothesis compared to Fisher's LSD (Navidi, 2008).

The results are specific to the engine and fuel measurement apparatus used for this study, but provide some guidance for similar testing. Watson and Gowdie (2000) found a significant difference in fuel consumption based on LPG composition, so fuel rate must be calibrated for the proper LPG grade.

5. CONCLUSIONS

This study was conducted to determine the minimum number of data points and minimum duration of data collection needed to accurately estimate fuel consumption for a LPG engine. Three data points was the fewest number of points that resulted in a mean absolute error that was not significantly different from 15 data points. Based on these results, at least 3 data points (0%, 50%, and 100% of fuel rate) should be used for fuel rate tests.

Twenty four time intervals (30 s to 12 min in 30 s intervals) were tested for data collection. The 0.5 min time duration resulted in a significantly higher mean absolute error than longer durations. The minimum time duration with a mean absolute error that was not different from 12.0 min, was 2.0 min or 3.5 min for Tukey's HSD and Fisher's LSD, respectively. The 3.5 min duration is recommended for fuel rate tests.

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