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ABSTRACT

Accurate measurement of fuel consumption is required to quantify the efficiency of an engine or predict emissions. As part of a larger project, accurate instantaneous fuel consumption data was required for a John Deere 4045T diesel engine. While establishing test criteria, it became evident that literature did not provide clear recommendations on the number of data points or time duration for data collection, for a diesel engine. Fuel consumption tests were conducted using up to 15 data points of percent fuel rate and up to 15 min of data collection. Based on statistical analysis of test results, at least 2 data points (0% and 100% of fuel rate) and 2 min of data collection are recommended for similar fuel-injected, diesel engine fuel rate tests. When a non-fuel injected engine is used, the Hogan et al. (2007) recommendation of at least 3 data points and 3.5 min of data collection should be followed.

Keywords: Fuel consumption, diesel, USA

1. INTRODUCTION

Fuel consumption is commonly used to quantify the efficiency and performance of a diesel engine. Hansson and others (1999) determined fuel consumption to be critical in predicting emissions of a diesel engine. A John Deere 4045T diesel engine was selected for an emissions monitoring project. The engine was equipped with a controller area network (CAN) that included fuel rate data, but preliminary fuel consumption tests indicated the CAN fuel rate averaged 10% less than the measured fuel rate. This discrepancy led to a series of randomized, replicated fuel consumption tests to relate the CAN fuel rate data to measured fuel rate. Standards and literature were reviewed for recommendations on the number of data points to collect and the duration of each fuel consumption test.

As part of the engine power test code standard, SAE J1995 (SAE, 1995) specified a minimum of 5 approximately evenly spaced operating points at full throttle to define the power curve. SAE J1312 (SAE, 1995) detailed a procedure for mapping engine performance that recommended collecting data at 10% increments (11 points) of rated speed and 25% increments (5 points) of load. The ISO 8178-4 (ISO, 1996) standard for engine emissions measurement includes a compression ignition (CI) test cycle which requires testing at 0%, 10%, 50%, 75%, and 100% loads, and a B test cycle which adds 25% load to the CI test engine loads, resulting in 5 or 6 data points.

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.

SAE J1995 (SAE, 1995) did not specify a time for data collection, but did specify that engine torque, speed, and temperature must be maintained within a specified range for at least 1 min before data collection. ISO 8178-4 (ISO, 1996) required a 7 min period for engine adjustment and stabilization, followed by a 3 min data collection duration. Generally, researchers did not report data collection duration, other than referencing a standard. Athanassiadis (2000), Birch and Kubesh (2003), Hansson *et al*. (2001, 2003), and Lindgren and Hansson (2004) referenced ISO 8178-4 (ISO, 1996).

With one exception, neither the standards nor available literature provided 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. The lone exception is a study by Hogan *et al.* (2007) using a LPG engine to determine the number of data points and duration of data collection. The resulting recommendation was 3.5 min of data collection and at least 3 evenly spaced data points. A diesel fuel injection system may not require the same number of data points and duration of data collection. A 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 Deere 4045T diesel engine.

2. EQUIPMENT AND PROCEDURES

A 2003 John Deere 4045T, 4.5L, I-4, turbocharged diesel engine was used for this study. The engine was rated for continuous operation at 394 Nm of torque at 1,400 rpm and 77 kW at 2,500 rpm. This engine was equipped with a SAE J1939 (SAE, 2000) CAN. The data collection and analysis procedure of Hogan *et al*. (2007) was adapted for this study. 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 500 ms intervals.

Ambient conditions were measured with a Honeywell HIH3610 humidity sensor, an Opto 22 ICTD temperature sensor, and a Novalynx WS16BP barometric pressure sensor. All sensors were placed within 4 m of the engine and were connected to the PAC for data acquisition. Fuel storage consisted of a 55 gal polyethylene drum for supply fuel and two 30 gal polyethylene drums for return fuel. The 3 drums were placed on a pallet which was rigged with a frame for lifting from a single attachment point. The fuel storage was suspended from an Omega LC101 strain gage. An Omega DP41-S strain gage meter processed the strain gage signal to provide a 0-10 VDC output 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. During operation, the load on the strain gage would fluctuate due, in part, to return fuel flow. Strain gage readings were smoothed by averaging the most recent 15 data points (at 200 ms intervals) of data.

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 200 ms.

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 5 equally spaced load intervals and 11 equally spaced engine speeds 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 idle fuel rate of 1 L/h was used as 0% fuel rate. The rated power fuel rate of 26 L/h was used as 100% 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 15 min in 30 s intervals were selected for comparison in this study. The 15 min duration data was considered accurate for the purpose of this study.

Data collection for the number of data points and duration was accomplished by collecting data for 15 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 diesel 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. A hydraulic dynamometer was used to apply a load to the engine to attain higher fuel rates. 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, 7 min 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 15 min period. At each 30 s interval, the fuel weight was subtracted from the fuel weight at the beginning of the 15 min test and the rest of the data were averaged. The difference in fuel weight was used to calculate fuel consumption in L/h.

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)	1.00	X	X	X	X	X	X	X
10	3.50						X	X
20	6.00					X	X	X
25	7.25				X			X
30	8.50						X	X
33	9.35			X				X
40	11.00					X	X	X
50	13.50		X		X		X	X
60	16.00					X	X	X
67	17.65			X				X
70	18.50						X	X
75	19.75				X			X
80	21.00					X	X	X
90	23.50						X	X
100	26.00	X	X	X	X	X	X	X

All 4 replications of CAN fuel rate and measured fuel rate (for 15 min) 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, 8 observations were used to generate a linear equation for the 2 data points of 0% and 100% fuel rate. 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. The minimum number of data points to use in collecting fuel consumption data was determined by the least number of data points with an absolute error that was not significantly different from the 15 data points.

Data for 30 different time durations (30 s to 15 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 15 min of data. The assumed accurate measurement of fuel rate was the 15 min data. The absolute error of the 15 min data and the measured data was calculated for each of the 1,800 observations (30 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 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 among all tests as Tukey's HSD (Navidi, 2008). The minimum duration to use in collecting fuel consumption data was determined by the shortest duration with an absolute error that was not significantly different from the 15 min duration.

3. RESULTS

A comparison of the CAN and measured fuel rates based on 15 data points and 15 min of data resulted in a 0.999 correlation coefficient. The measured fuel rate was higher than CAN fuel rate at each of the 15 data points (see Figure 1).

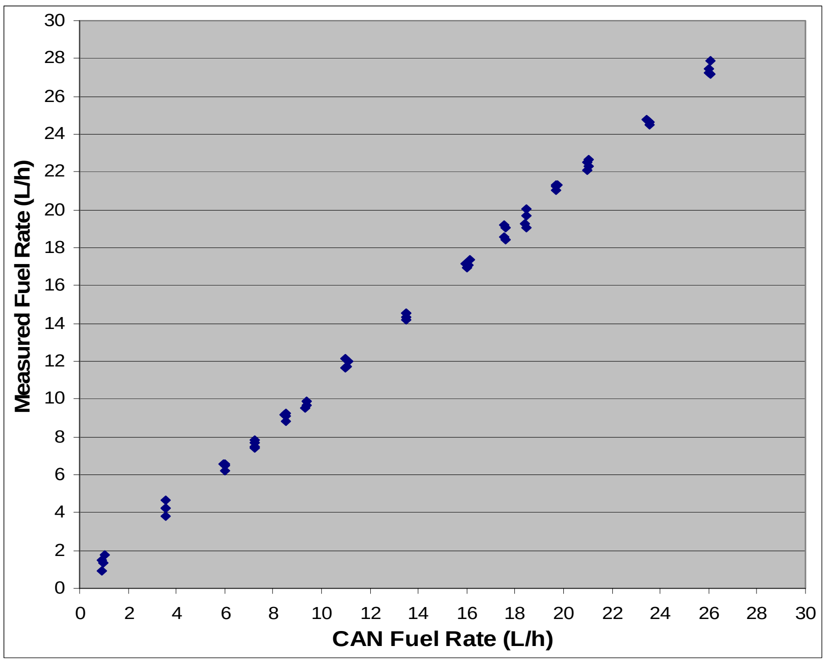

Figure 1. Measured fuel rate at each CAN fuel rate, indicating higher CAN fuel rates than measured values.

There was no difference in the absolute error among the number of data points ($F_{6, 413} = 0.02$, $P = 1.0$) with 15 min of data collection. Thus, 2 data points was the least number of data points that was not significantly different from 15 data points. Table 2 summarizes the absolute error for the different numbers of data points.

There was a significant difference in the absolute error among the different time intervals for fuel rate data collection ($F_{29, 1770} = 106.21$, $P < 0.0001$) with 15 data points. Table 3 summarizes the differences among the time intervals. The 0.5 min time duration had a significantly higher absolute error than the other time durations. The 1 min and 1.5 min time durations had a significantly lower absolute error than the 0.5 min duration, but a significantly higher absolute error than the 2 min to 15 min durations. Both Tukey's HSD and Fisher's LSD resulted in the 2 min duration as the shortest duration with an absolute error that was not significantly different from the 15 min duration.

Table 2. Comparison of number of data points (with 15 min of data collection) to collect CAN fuel rate data to predict actual fuel rate for 15 data points.

Number of points	Mean Absolute Error (N = 60)*	Intercept		Slope	
		Coefficient	P-value	Coefficient	P-value
2	0.2403	0.367	0.0636	1.039	< 0.0001
3	0.2414	0.378	0.0129	1.039	< 0.0001
4	0.2343	0.238	0.1368	1.046	< 0.0001
5	0.2368	0.246	0.0489	1.050	< 0.0001
6	0.2391	0.320	0.0018	1.045	< 0.0001
11	0.2411	0.375	< 0.0001	1.039	< 0.0001
15	0.2344	0.261	0.0015	1.047	< 0.0001

* The means were not significantly different ($\alpha = 0.05$).

4. DISCUSSION

The first objective of this study was to determine the minimum number of data point combinations required to accurately estimate instantaneous fuel consumption for the Deere 4045T diesel engine. Comparing absolute error, there was not a significant difference among the number of data points. Based on this result, future fuel consumption tests on this engine need use only 2 data points (0% and 100% fuel rate). Hogan *et al*. (2007) when conducting a similar test using a LPG engine found 3 data points as the least number of data points that was not significantly different from 15 data points. The diesel engine used in this test had 2 potential advantages over Hogan's LPG engine. The Deere 4045T diesel engine had fuel injection and the CAN fuel rate was calibrated for the fuel used. The CAN fuel rate for Hogan's LPG engine had been factory calibrated for gasoline. For a similar diesel engine, 2 data points are sufficient. When fuel injection is not used or CAN fuel rate is not calibrated for the fuel used, the Hogan *et al*. (2007) recommendation of using at least 3 data points (0%, 50%, and 100% fuel rate) should be followed.

The second objective of this study was to determine the minimum time duration to collect data for accurately estimating fuel consumption for the Deere 4045T diesel engine. Durations of less than 2 min resulted in significantly higher absolute errors and should be avoided. Based on Tukey's HSD and Fisher's LSD, there were no significant differences among time durations ranging from 2 min to 15 min. At least 2 min of data collection should be used for tests on a similar diesel engine. Hogan *et al*. (2007), when conducting a similar test using a LPG engine, found a minimum duration of 2 min using Tukey's HSD and a minimum duration of 3.5 min using Fisher's LSD. Hogan recommended the more conservative 3.5 min duration. The results of this test, with a diesel engine, support the 2 min duration. As a result, a minimum time duration of 2 min is recommended for future fuel consumption studies.

Table 3. Comparison of time durations to collect CAN fuel rate data to predict actual fuel rate for 15 min.

Time Duration (min)	Mean Absolute Error (N = 60)	Tukey's HSD*	Fisher's LSD*
0.5	3.0270	a	a
1.5	1.0126	b	b
1.0	0.8520	b	c
2.0	0.3493	c	d
2.5	0.3342	c	d
3.0	0.2841	c	d
6.0	0.2729	c	d
6.5	0.2635	c	d
3.5	0.2631	c	d
4.0	0.2559	c	d
4.5	0.2520	c	d
5.0	0.2515	c	d
9.0	0.2440	c	d
5.5	0.2432	c	d
7.0	0.2426	c	d
9.5	0.2412	c	d
8.5	0.2399	c	d
8.0	0.2397	c	d
10.0	0.2391	c	d
7.5	0.2387	c	d
12.5	0.2371	c	d
11.5	0.2361	c	d
13.5	0.2356	c	d
12.0	0.2355	c	d
11.0	0.2353	c	d
13.0	0.2350	c	d
15.0	0.2344	c	d
10.5	0.2343	c	d
14.5	0.2343	c	d
14.0	0.2338	c	d

* Means with the same letter are not significantly different ($\alpha = 0.05$).

5. CONCLUSIONS

This study was conducted to determine the minimum number of data points and minimum duration of data collection required to accurately estimate fuel consumption for a John Deere 4045T diesel engine. Two data points was the fewest number of points that resulted in an absolute error that was not significantly different from 15 data points. Based on these results, at least 2 data points (0% and 100% of fuel rate) should be used for fuel rate tests for a similar diesel engine. For a non-fuel injected engine, the Hogan et al. (2007) recommendation of at least 3 data points (0%, 50%, and 100%) should be followed.

Thirty time intervals (30 s to 15 min in 30 s intervals) were tested for data collection duration for a Deere 4045T diesel engine. Two min was the minimum time duration with an absolute error that was not significantly different from 15 min. Based on this result, a data collection duration of at least 2 min is recommended for fuel rate tests.

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