

Investigation of alternate fuel control parameters for a diesel engine

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Stumborg, M. A. 1989. **Investigation of alternate fuel control parameters for a diesel engine.** *Can. Agric. Eng.* **31**: 25-33. An Allis Chalmers 649T engine was equipped to operate as a dual-fueled CI engine on fumigated 190 proof ethanol and diesel fuel. Maximum, 75% of maximum, and 50% of maximum ethanol substitution levels were evaluated to determine parameters of a direct injection turbocharged diesel engine which reflect engine load (torque) and allowable alternate fuel substitution, and to evaluate the use of spark ignition (SI) knock sensing technology as a measure of combustion knock. Equations using engine speed, normalized fuel consumption, intake mass airflow, intake boost pressure, and rate of exhaust energy rejection were developed to predict engine torque and allowable secondary fueling level. The normalized fuel consumption equation was the best predictor of engine torque, but air consumption best reflected the maximum ethanol substitution limits. Two commercial combustion knock sensors were evaluated, and of these the Carter transducer showed the most promise. The use of normalized fuel flow or exhaust energy loss equations as measures of engine load combined with the use of combustion knock as determined by the Carter transducer showed promise as control and feedback parameters for a dual-fuel control system. Further research in the dual-fuel area should employ combustion pressure sensing to detect the onset of combustion knock and misfire and, therefore, determine the maximum allowable substitution levels of secondary fuels in a reliable manner.

INTRODUCTION

The substitution for, or supplementation of, diesel fuel with a reliable fuel that is reasonably priced, renewable, or more plentiful has been of interest since the oil crisis of the early 1970s. Since that time, agricultural producers have been concerned about security of supply and escalating energy costs associated with their farming operations. Consequently, the development of economic fuel alternatives that do not adversely affect engine performance and reliability is in the interest of all Canadians.

Past fuels research focused on identifying allowable substitution limits of alternatives to diesel fuel. Fuels examined included methanol, ethanol, compressed natural gas (CNG), and liquefied petroleum gas (LPG or propane). Ethanol was used as the alternate fuel for the research project at the Swift Current Research Station as a result of recommendations made by personnel from Agriculture Canada and the Department of Energy, Mines, and Resources.

Various methods of utilizing ethanol were considered to determine the most appropriate technology for retrofitting dual-fuel systems to turbocharged direct injection compression ignition (CI) engines. Tank mixing was examined by Wrage and Goering (1979), Meiring et al. (1983), and Smith and Jordan (1983). Addition of surfactants and phase separation inhibitors allowed increased quantities (greater than 15%) of pure ethanol to be mixed with the diesel fuel, but increased cost, injector fouling, uncertain mixture stability, and lower cetane levels made the mixture approach unacceptable as a long term solution for

ethanol substitution. Boruff et al. (1982) investigated the use of microemulsions of ethanol and diesel fuel but encountered severe problems with emulsion stability, alcohol control, and equipment cost. A novel approach to these problems was developed by Fujisawa and Yokota (1981). Alcohol was introduced into the diesel injection line during low pressure intervals. Control was provided by varying the alcohol supply pressure, and a check valve between the diesel injection line and the alcohol supply ensured proper operation of the injection system. Further developments beyond initial engine testing were not reported.

Fumigation of alcohol into a diesel engine had been studied from two approaches: the use of carburetion technology and the use of pressurized injection systems. Goering and Wood (1982) and Cruz et al. (1982) discovered that loss of volumetric efficiency, poor ethanol control, and unstable engine operation were serious problems with carburetion. Bro and Pederson (1977), Chen et al. (1981), Shropshire and Goering (1982), Shropshire and Bashford (1983), and Saito et al. (1984) investigated the use of pressured injection systems and found that ethanol control was acceptable provided the distribution system was properly designed. Intercooling of the charge air was a significant benefit of ethanol fumigation as it increased engine volumetric and operating efficiency.

Based on the literature reviewed, introduction of ethanol by pressurized fumigation was determined to be the most appropriate substitution technology because of the potential for a low-cost, universally adaptable fuel delivery system.

Various engine parameters have been investigated for controlling fumigated ethanol. Engine speed, torque (load), and ethanol concentration were the factors that determined the limits of secondary fuel substitution in a study conducted by Walter (1981) (Fig. 1). Engine load was determined by throttle position measurement (Walker 1982, 1984), engine exhaust gas temperature (Davies 1985), and intake boost pressure (Bassett 1981). Problems or shortfalls with the different control strategies included overfueling at high engine load and speed, over-powering, and eventual engine failure. Based upon previous studies in the dual-fueling area, work was needed to identify practical methods of determining engine output torque (load) experienced by a turbocharged, direct injection diesel engine fumigated with an alternative fuel. It should be noted that the economics of ethanol substitution were not studied as the experiment was designed to determine measurable engine parameters for dual-fuel control.

OBJECTIVES

The objectives of this research were:

(1) To determine the parameters of a direct injection turbocharged diesel engine which reflect engine torque and

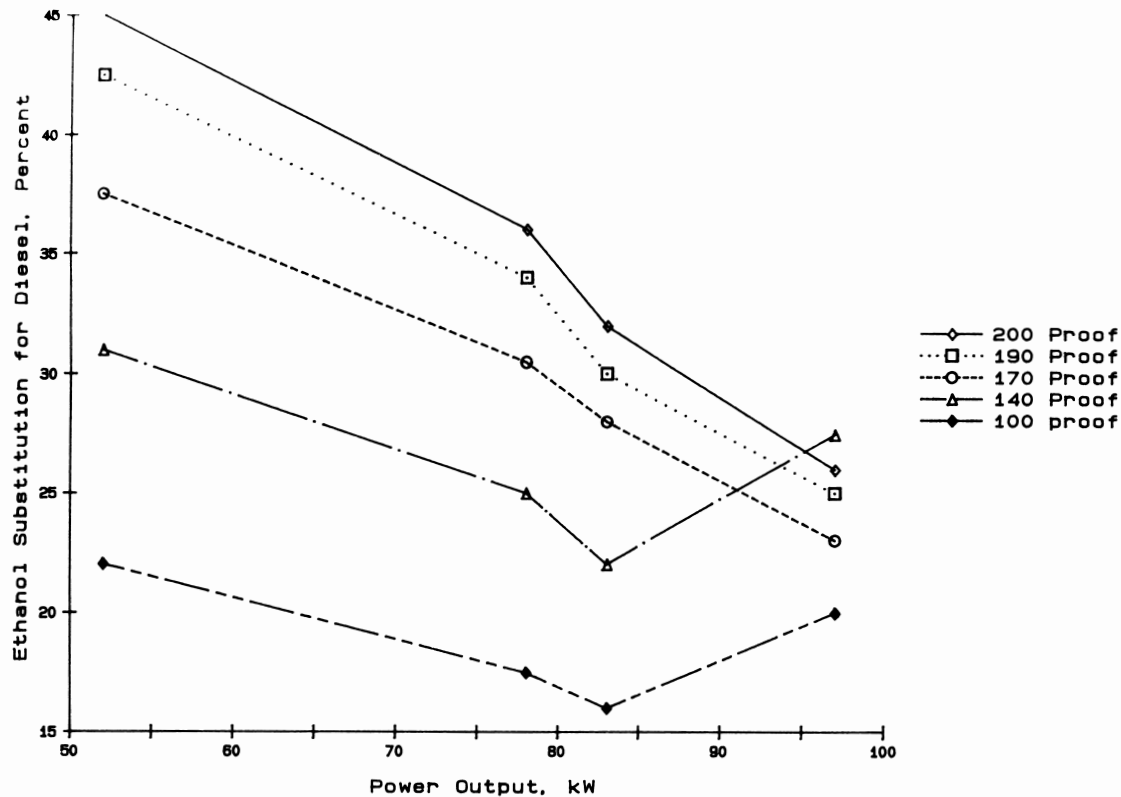


Figure 1. Maximum allowable substitution of various proofs of ethanol versus power output of a Ford 9000 tractor (Walter 1981).

allowable substitution limits of 190 proof ethanol for diesel fuel. Rate of energy consumed, rate of exhaust energy lost, exhaust temperature, and injection pump lever position were evaluated in diesel fuel only and dual-fuel modes.

(2) To determine the viability of using spark ignition knock sensing technology to determine the onset of damaging knock in a diesel engine. The outputs of two commercially available transducers were evaluated using a digitizing oscilloscope and an electronic integrating system devised for the project.

MATERIALS AND METHODS

The engine used for this study was an Allis Chalmers 649T direct injection, turbocharged, six cylinder diesel engine having a bore of 98 mm, a stroke of 108 mm, compression ratio of 15.1:1, and a maximum rated output of 82.5 kW at 2100 rev/min. Injection timing was set at 18° BTDC and was not altered during the experiment. The engine was coupled by a flexible coupling to a Taylor DX-32 waterbrake dynamometer. Water flow and, hence, engine load, was controlled by a Mason-Eilen current-to-pressure (I/P) valve remotely controlled by a current level set by an Acurex datalogger. Engine speed was controlled by an electronic control device and a linear actuator attached to the throttle lever.

Copper-constantan (type T) thermocouples were used to measure all temperatures other than exhaust temperatures. Exhaust temperatures were measured by chromel-alumel (type K) thermocouples. The coolant flow orifice plate pressure differential was determined by a Druck differential pressure sensor. A calibrated orifice plate and water-filled manometer were used to monitor engine airflow. Intake boost and alcohol nozzle pressures were determined by silicon semiconductor strain gage transducers.

Dynamometer torque was measured by a Transducers Inc. load cell on a 120-mm (effective length) lever arm. Excitation, filtering (10 Hz lowpass) and amplification were provided by a Vishay Model 2310 Signal Conditioning amplifier. The voltage representing the torque was then connected to a voltage to frequency (V/F) converter having a sensitivity of 10 Hz/Nm and a 2 kHz offset. Since the sampling frequency of the datalogger was much less than the 10 Hz filtered signal, the V/F technique ensured that neither peaks nor valleys would be sampled. The V/F converter pulse train was connected to the datalogger for digitizing and linear scaling. A magnetic inductance sensor and a 60-tooth gear were used to measure engine speed.

The alcohol nozzle pressure sensor was placed inline between the micrometer valve and alcohol nozzle. Alcohol flowrate was determined by a Bearingless Flowmeter Co. Model E15 turbine flowmeter. The pulse train from the Bearingless flowmeter was connected directly to an Acurex datalogger with flowrate determined by applying a regression equation in the datalogger software. See Fig. 2 for the alcohol delivery system schematic.

The primary fuel (diesel) flowrate was measured by a Fluidyne Model 284-285-210 positive displacement radial piston flowmeter. Return fuel was cooled, deaerated by a Halda fuel return reservoir and allowed to return to the fuel system downstream of the flowmeter to avoid double counting (Fig. 3).

Two knock detection sensors (Carter and American Motors) were evaluated. The low-level voltage signals from the knock detectors were displayed on a Tektronics 5223 digital storage oscilloscope and the scaled values were then sent to a Hewlett-Packard (HP) computer for analysis and storage. The output of the knock sensors was also converted to a pulse train by a voltage to frequency (V/F) circuit with a sensitivity of 10 kHz/V. This frequency was displayed on a 4-digit LED readout

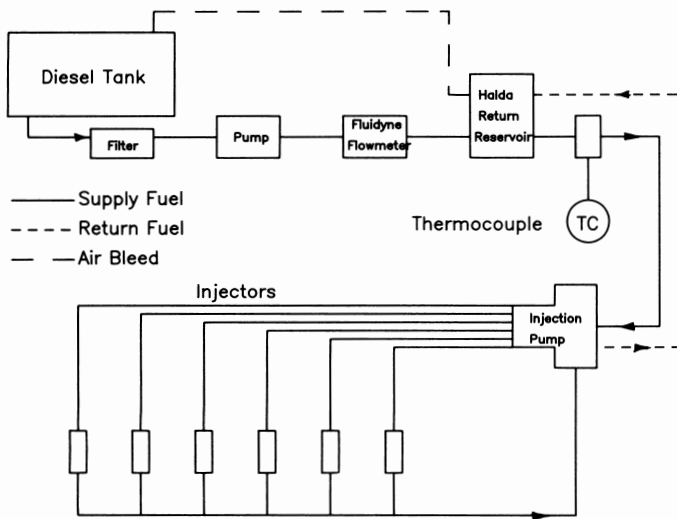


Figure 2. Alcohol delivery and measurement system schematic.

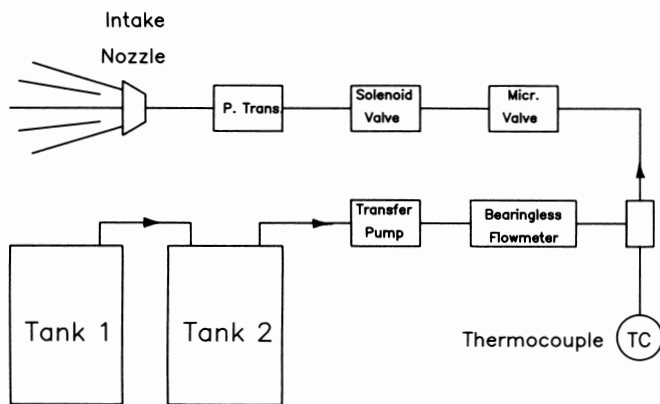


Figure 3. Diesel fuel measurement and delivery system.

using a 1-s integration time and recorded on an Acurex datalogger.

Information derived from the thermocouples and other transducers or signal conditioning devices was digitized by an Acurex Autodata Ten-10 datalogger and transferred to a Hewlett Packard Model 200-9816 personal computer for further analysis and storage.

TEST METHOD

Engine speed and torque ranges were observed during the engine break-in period, and maximum power levels were noted for the range of speeds intended for this series of tests. The following operating points were used to characterize the engine on diesel and alcohol:

- Loads —five loads. 100–300 Nm in 50-Nm increments.
- Speeds —four speeds. 1500–2100 rev/min in 200 rev/min increments.
- Fuel rates —three alcohol flowrates for dual-fuel: Maximum allowable, 75% of maximum allowable, and 50% of maximum allowable. Maximum substitution was determined by the onset of audible knock or engine misfire.

Choosing output torques that were reasonable for the engine, even at lower engine speeds, facilitated both constant speed/variable load and constant load/variable speed analyses of the data.

Stable engine and dynamometer operation were not reliable above the 300-Nm torque due to dynamometer water supply instability, engine overheating, and injection pump delivery limits.

The test regime was begun by starting the engine and allowing the engine coolant to reach 60°C at high idle. Engine speed was increased to the desired test speed and a torque of 100 Nm was then used to warm the engine up to operating temperature (95°C). Once the engine was fully warmed, full torque (300 Nm) was placed on the engine and diesel fuel only testing begun when exhaust temperature had stabilized. The full range of engine loads for a given speed were examined in decreasing order. The maximum alcohol substitution was determined for a given engine speed at all loads. The 75% level of substitution was determined from the diesel fuel only and maximum substitution tests. Experimentation was begun at the highest engine load and proceeded in decreasing load increments. This was repeated for the 50% level of substitution.

RESULTS

Observations of engine performance during ethanol fumigation of the Allis Chalmers engine were similar to those reported by other researchers. Smoke levels were reduced from a normal gray plume to a faint gray plume, indicating lower particulate emissions. Combustion knock at higher levels of ethanol substitution became audible and limited maximum substitution. The engine operated more smoothly at lower substitution levels where engine misfire was the limiting factor. It should be noted that audible knock did not occur at a definite substitution level, rather, combustion noise increased gradually, making it difficult to consistently determine the threshold of knock limited substitution over the operating range of the engine. Engine thermal efficiency was not significantly affected by the introduction of alcohol.

The inverse relationship between maximum allowable alcohol substitution and engine power output portrayed in Fig. 4 was apparent though not as clearly defined as in the study by Walter (1981) (Fig. 1). The differences between this and the study by Walter may have been caused by the lack of a definite knock threshold in the Allis Chalmers engine. Maximum substitution was limited by audible knock when engine power exceeded approximately 30 kW and by audible engine misfire below 30 kW.

The aftercooling effect of the alcohol on the intake air lowered the exhaust temperature, significantly affecting the relationship of power to temperature at all engine speeds. The aftercooling influence on torque prediction was decreased when the temperature difference between the intake and exhaust manifold temperature downstream of the fumigation nozzle and comparing it to the thermocouple placed immediately upstream of the turbocharger turbine. The slope or rate of temperature rise increased inversely with engine speed, a problem corrected by determination of the rate of energy lost through the exhaust (P_{exh}) as measured by the mass flow of air at the intake multiplied by the temperature difference between the intake and exhaust. Figure 5 shows the relationship between P_{exh} and engine power output.

Air consumption of the turbocharged engine varied with engine speed, load, and turbocharger boost pressure characteristics. The relationships of air consumption and boost pressure with power output are shown in Figs. 6 and 7, respectively. The goodness of fit of intake boost pressure to engine power

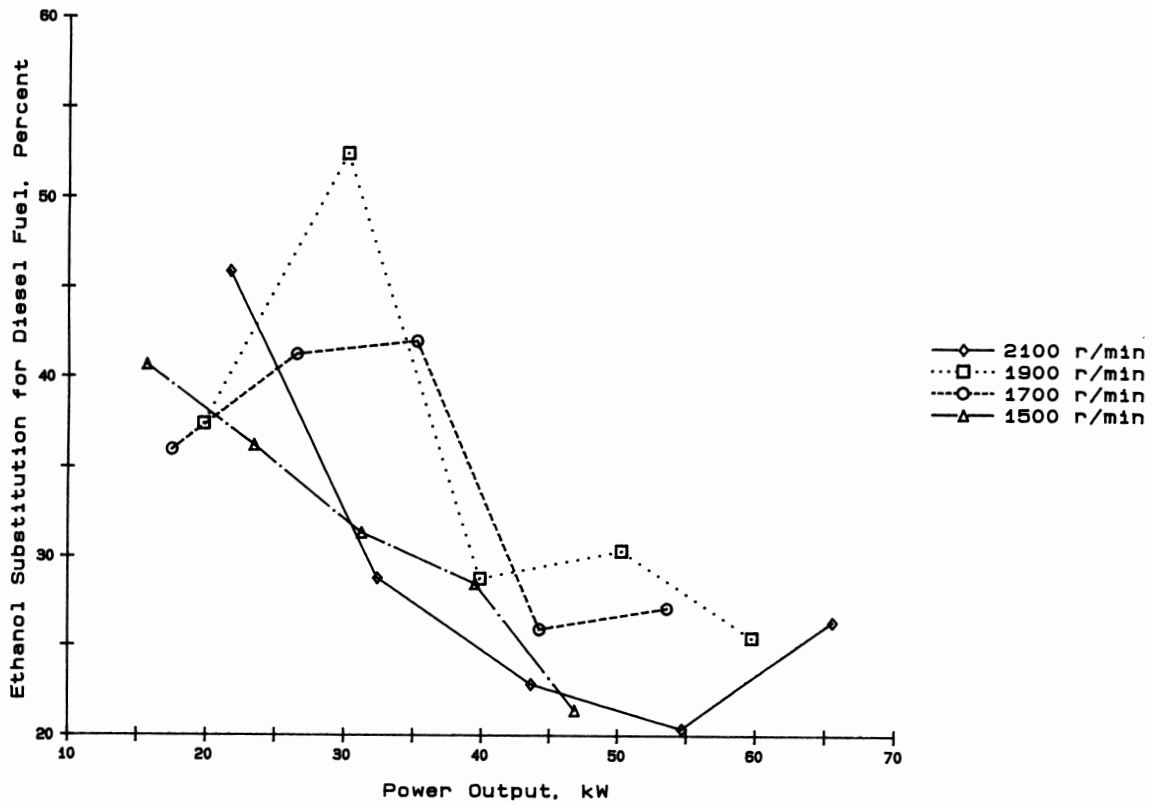


Figure 4. Maximum allowable substitution of 190 proof ethanol for diesel fuel versus power for the Allis Chalmers 649T engine.

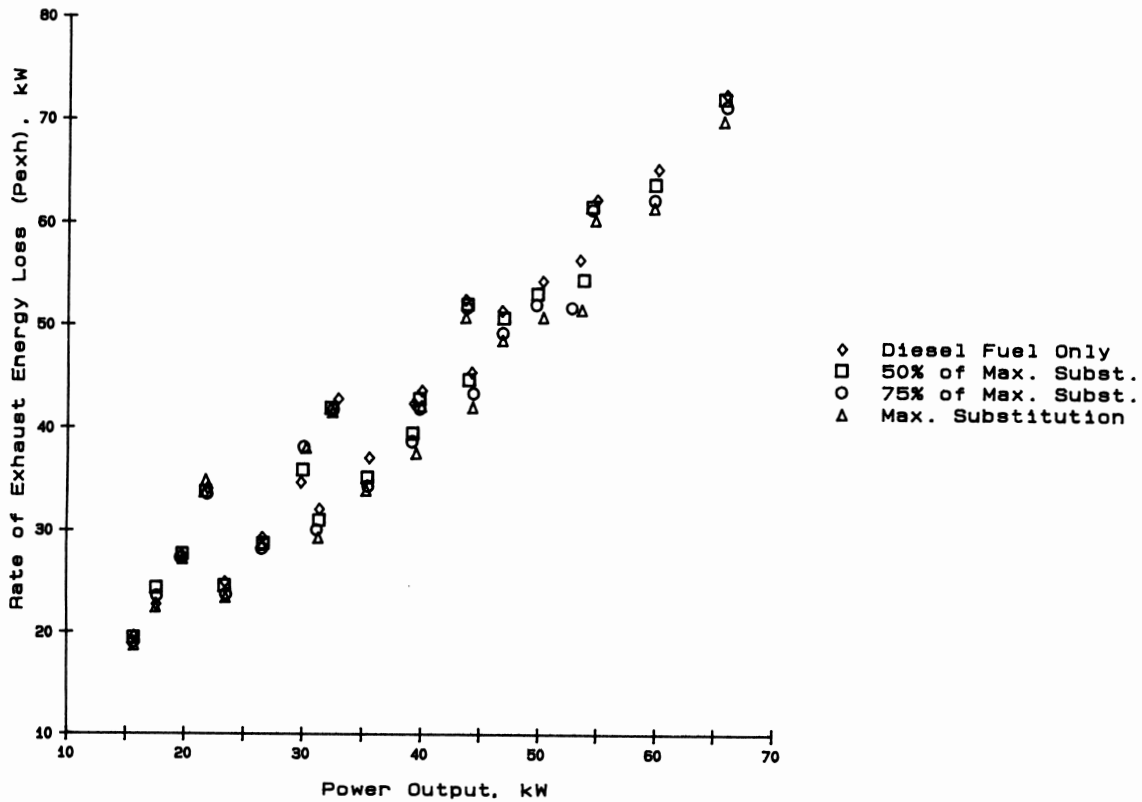


Figure 5. Rate of exhaust energy lost (P_{exh}) versus engine power output for the Allis Chalmers 649T engine.

was better than air consumption but both are acceptable indicators of engine power.

Normalized fuel consumption was defined as the sum of the rates of energy input in the form of diesel and 190 proof ethanol expressed as a diesel equivalent volume. The relationship

between normalized diesel and power output is shown in Fig. 8. The simple linear regression line and excellent correlation indicate that a good and predictable relationship existed.

Two methods of fuel consumption measurement were examined, the first being the use of an accurate flowmeter. The

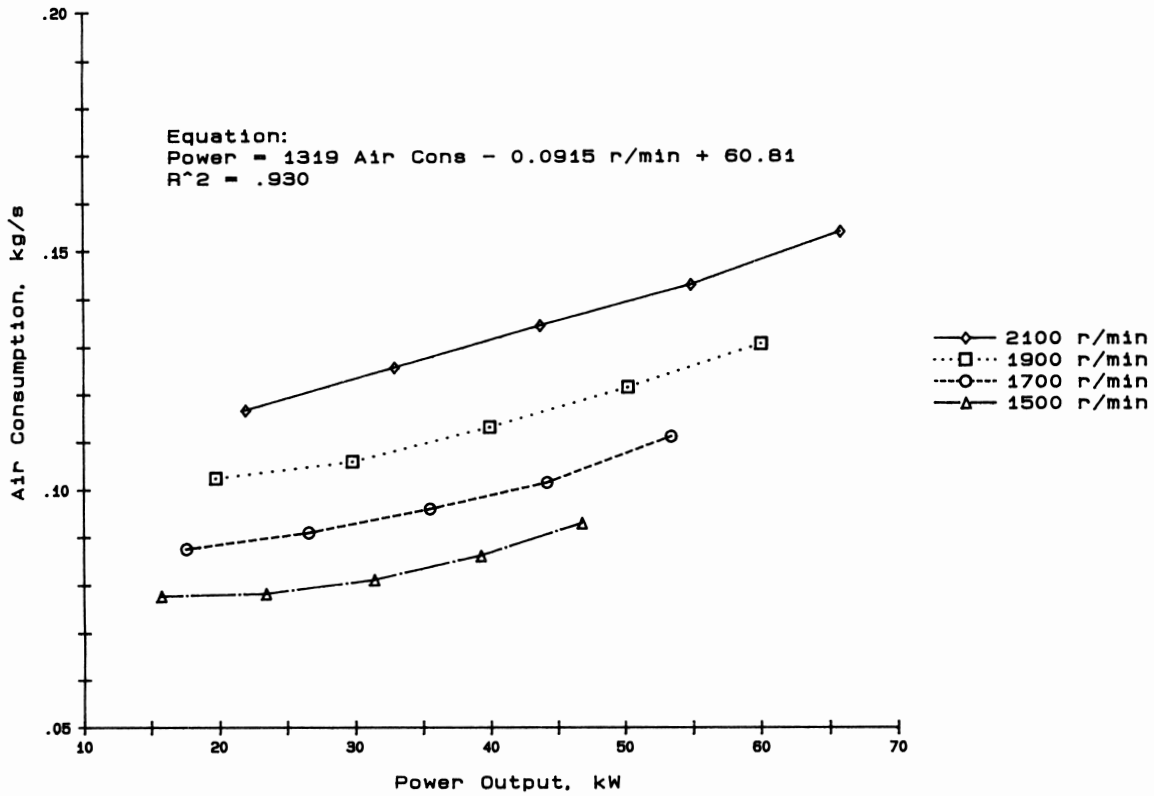


Figure 6. Mass airflow versus engine power output for the Allis Chalmers 649T engine for diesel fuel only.

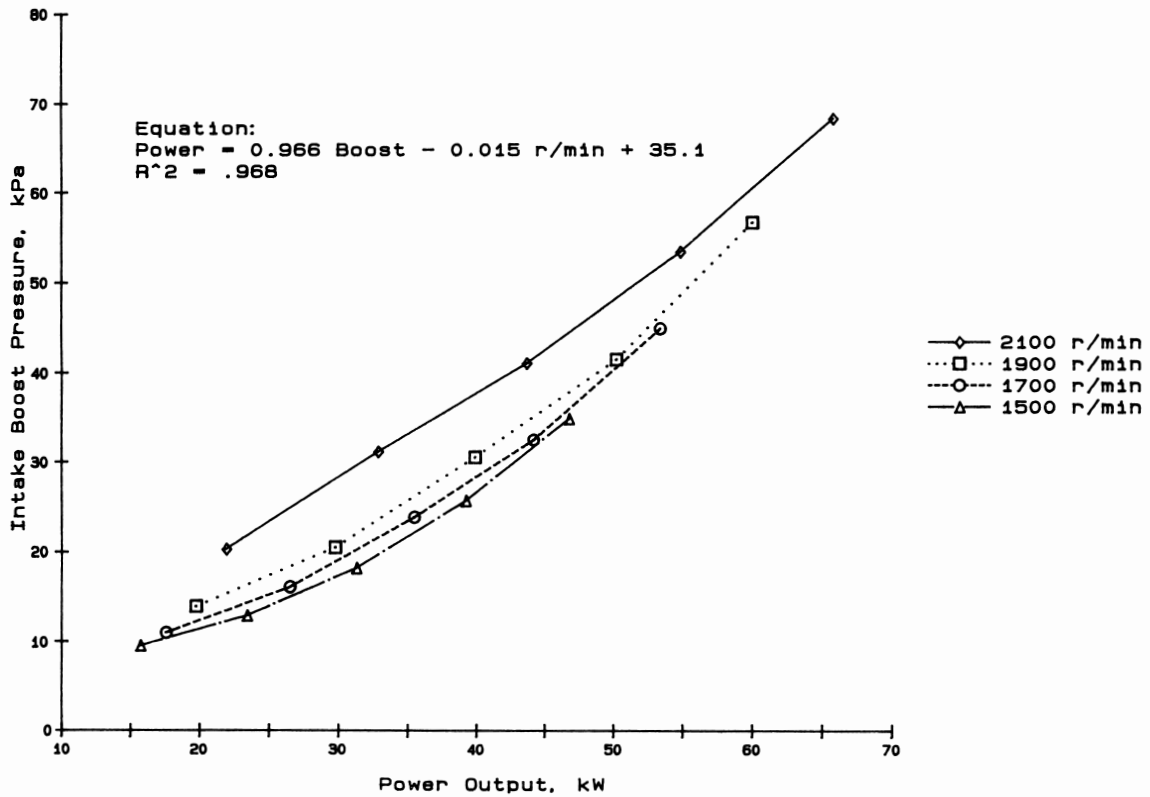


Figure 7. Intake boost pressure versus power output for the Allis Chalmers 649T engine for diesel fuel only.

normalized fuel flowrate/power output relationship shown in Fig. 8 was based upon data obtained in this manner. The second measure of diesel fuel consumption considered was the relationship between engine speed, throttle position, and fuel consumption as used by Walker (1982), Davies (1984), and Walker

(1984). Figure 9 displays the data observed for the Allis Chalmers engine. It should be noted that the upper two flowrates of the 1700 rev/min curve are in error due to the difficulties experienced with the fuel measurement system. A good fit existed when consistent operation of the fuel pump and

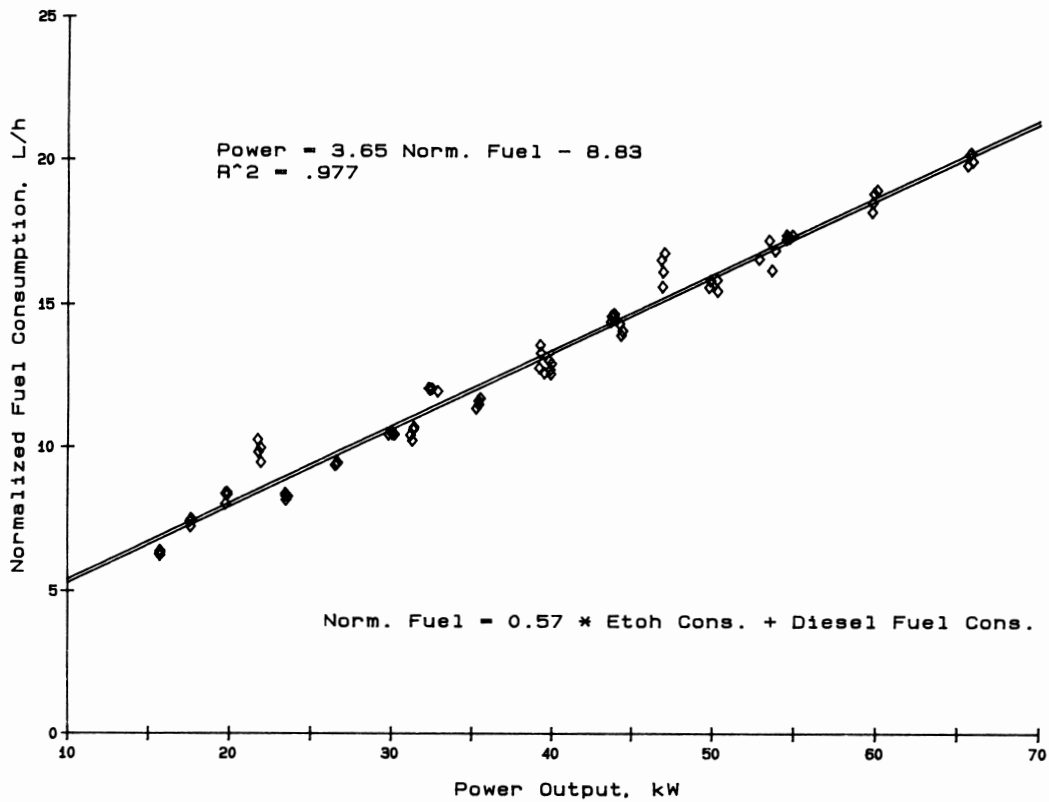


Figure 8. Normalized diesel fuel flowrate versus power output for Allis Chalmers 649T engine.

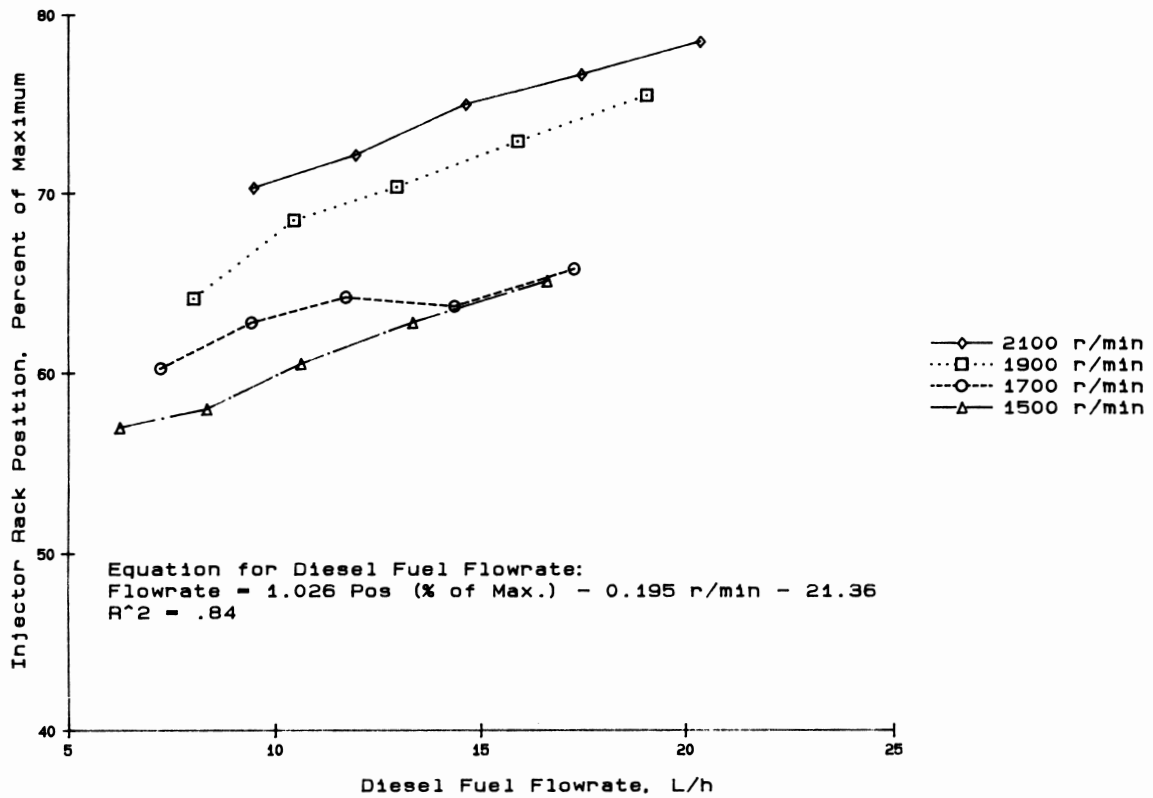


Figure 9. Injector rack (throttle) position and engine speed versus fuel consumption for the Allis Chalmers 649T engine using diesel fuel only.

throttle position sensor was achieved. Consistent operation was somewhat difficult to attain in the previously mentioned studies.

Figure 10 is a graphical comparison of the four linear engine torque prediction equations developed during the test. The

statistical highlights of each equation are also given. Normalized fuel flow, intake air consumption, intake boost pressure, and exhaust energy loss are good predictors of net engine power output.

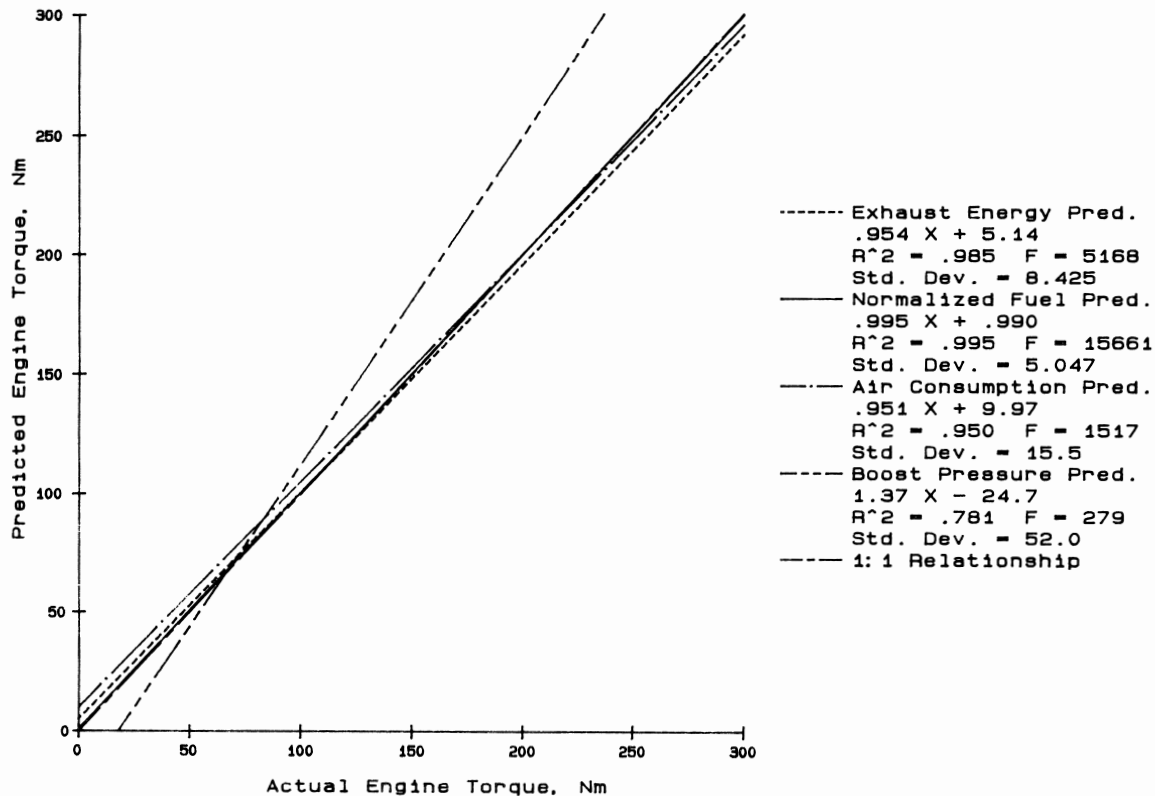


Figure 10. Linear regressions of engine torque predictions versus measured torque for the Allis Chalmers 649T engine. F values are significant to the 1% level.

The following regression equations were developed to predict engine torque:

$$\text{Torque (Nm)} = 0.248 (\text{rev/min}) + 7.70 (P_{\text{exh}}) - 1.26 \times 10^{-4} (\text{rev/min})^2 - 0.039 (P_{\text{exh}})^2 + 7.57 \times 10^{-4} (\text{rev/min} \times P_{\text{exh}}) - 138.8 \quad (1)$$

$$\text{where } P_{\text{exh}} (\text{kW}) = M_{\text{air}} \times (T_{\text{exh}} - T_{\text{int}})$$

$$\text{Torque (Nm)} = 0.0943 (\text{rev/min}) + 7.629 (\text{norm. fuel}) - 8.40 \times 10^{-5} (\text{rev/min})^2 - 0.0395 (\text{norm. fuel})^2 + 7.92 \times 10^{-4} (\text{rev/min}) \times (\text{norm fuel}) - 0.439 \quad (2)$$

where normalized total fuel flowrate (L/h) = diesel fuel flowrate (L/h)

$$+ 0.57 (\text{ethanol flowrate (L/h)}) \quad (3)$$

$$\text{Torque (Nm)} = 0.921 (\text{rev/min}) + 19908 (\text{air cons.}) + 2.187 (\text{rev/min} \times \text{air cons.}) - 70607 (\text{air cons.})^2 + 167$$

where air consumption is measured in kg/s.

$$\text{Torque (Nm)} = 0.966 (\text{boost}) - 0.015 (\text{rev/min}) + 35.1 \quad (4)$$

where Boost pressure is measured in kPa. The linear equation for boost pressure reflected the actual measured power as well as the polynomial equation so it was used instead.

Torque estimated by Eqs. 1 through 4 can be converted to power output by:

$$\text{Power} = k \times \text{Torque} \times \text{rev/min.}$$

The air consumption prediction equation of the engine power correlated best to the maximum allowable substitution of alcohol. Refer to Table I for the statistical results. Poor

determination of ethanol substitution limits may have had an influence on this result.

The American Motors knock transducer proved to have an unacceptably low output. Therefore, the Carter knock sensor was the sole knock transducer studied. The conversion of the transducer voltage to a scaled frequency was used as a method of integrating the area under the oscilloscope trace, representing the severity of knock.

The comparison between measured knock and engine torque (Fig. 11) indicated that increased knock severity was discernible as the level of alcohol substitution increased. The slopes of the curves increased with the greatest increase occurring between the 75% and maximum substitution levels. It should be noted that there was no attempt made to determine the optimum natural frequency of a knock sensor for this application. The results indicated there was merit in further investigating the application of knock transducers to dual-fueled diesel engines.

A linear regression analysis of engine parameters indicated that engine torque and alcohol substitution level were the two predominant factors affecting measured knock (see Table II). Intake air temperature measured after the fumigation nozzle also had an effect on measured knock but it was not sufficiently significant to warrant further investigations within this experiment.

CONCLUSIONS

Several conclusions regarding the use of engine parameters for measurement of engine torque can be made.

(1) Diesel fuel or normalized diesel fuel consumption related well to engine load. The advantages of a flowmeter (accuracy, adaptability, repeatability) may outweigh the simplicity of throttle position sensing.

Table I. Statistical highlights of the torque prediction regression equations versus maximum allowable substitution of alcohol for diesel

Variable name	Correlation	Standard deviation	F-value	Significance level
Intake airflow	-0.534	6.09	20.66	0.001
Exhaust energy	-0.515	6.22	19.08	0.001
Normalized fuel	-0.492	6.36	17.45	0.001
Boost pressure	-0.430	6.74	13.57	0.002

(2) Air consumption and intake boost pressure may serve as reasonable indicators of engine torque. The effects of intake air restriction, sensor life expectancy, response, and cost must be assessed.

(3) Exhaust temperature is not an acceptable measure of engine torque. Fumigated alcohol has an aftercooling effect on intake and exhaust temperatures and the degree of aftercooling changes with engine speed.

(4) The use of the rate of exhaust energy loss (P_{exh}) as measured by the mass flowrate of air and the temperature difference between the intake and exhaust manifold gases is an acceptable method of estimating engine output.

(5) The best predictor of maximum allowable substitution of ethanol for diesel, based on the four engine torque prediction equations, was the air consumption equation (Eq. 3).

(6) The output of the Carter knock sensor varied in a predictable manner with the amount of ethanol used. The use of a knock sensor to optimize ethanol substitution as predicted by engine torque (Eqs. 1-4) would provide a feedback signal to optimize ethanol usage in a prototype control and delivery system.

The results of this study indicated that a successful control strategy based upon normalized total fuel flowrate, exhaust power loss, or intake air consumption optimized by combustion knock sensing could be devised to safely retrofit an existing CI engine with a fumigation control system. This would allow the operator to supplement a portion of diesel fuel with an

Table II. Results of linear regressions on measured combustion knock

Variable name	Fitted value	Standard deviation	T-value	Significance level
Engine torque	51.63	8.72	5.92	0.001
% subst.	-82.42	73.57	-1.12	0.279
Engine speed	1.67	1.94	0.86	0.401

alternate fuel such as 190 proof ethanol fumigated into the intake of the engine. The use of alternate fuels would extend conventional diesel supplies, provide an opportunity for additional markets for agricultural commodities, and provide protection from rising fuel prices.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further fumigation research is required in four general areas. The maximum substitution level of alcohol was determined by two limits: (1) audible knock at higher engine loads, and (2) audible engine misfire at lower engine loads. The human ear is subjective, requiring the use of combustion pressure measurements for further dual-fueling research. The substitution levels reported in this study should be verified and any deviations corrected.

Transducers which are reliable, responsive, and reasonably priced are necessary for future prototype control system development. Parameters requiring measurement are fuel consumption, intake and exhaust temperature, engine speed, and mass airflow, depending on the engine torque prediction method used. The laboratory class transducers used in this study are too expensive to be considered for a prototype.

Further work to identify optimum sensing frequencies for knock transducers is justified. The change in knock sensor output with alcohol substitution level indicated that this may provide a method of optimizing secondary fuel use in a future dual-fuel control system.

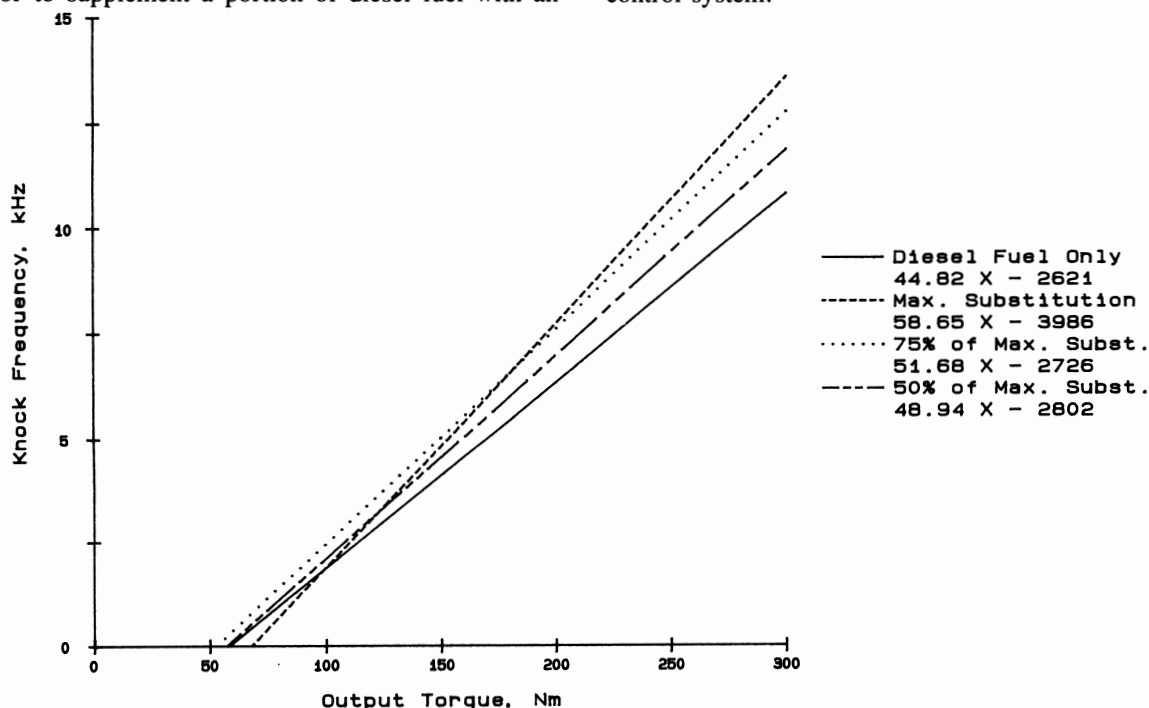


Figure 11. Amount of knock (measured as a frequency) versus engine torque for the Allis Chalmers 649T engine and Carter knock sensor.

The effect of intake temperature on the damaging knock threshold was not assessed. Although intake temperature was closely controlled during the experiment, temperature variations would have a significant effect on the knock threshold.

Additional research based on long-term engine evaluations with fumigated ethanol is necessary. Manufacturers' engine design specifications must be followed so that response, long-term engine efficiency, and reliability can be maintained. These are basic factors necessary for the acceptance of dual-fueled diesel engines by the farming public.

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