The Society for engineering in agricultural, food, and biological systems

Paper Number: 01-6173
An ASAE Meeting Presentation
UILU 2001-7007

ON-FARM EVALUATION OF DIESEL FUEL OXYGENATED WITH ETHANOL

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Written for presentation at the
2001 ASAE Annual International Meeting
Sponsored by ASAE
Sacramento Convention Center
Sacramento, California, USA
July 30-August 1, 2001

Abstract. *The benefits of burning an ethanol-diesel blend in a diesel engine primarily include lower emissions and the use of a renewable bio-based product. Specially formulated additives can effectively overcome problems of fuel separation, reduced cetane number and reduced fuel lubricity. Laboratory-based tests have shown that these blends can fuel diesel engines without damaging the engine. The objective of this work is to evaluate the effects of E diesel (a blend containing 10% ethanol, an additive and diesel) on selected tractors and combines working under normal field conditions. Two tractors and two combines were instrumented with data loggers that collected data through the CAN bus. One of each vehicle type was fueled with E diesel and the other with no.2 diesel. Comparisons showed that increases in fuel consumption of approximately 4 to 5% occurred on average with both the tractor and the combine, which was equivalent to the reduced energy content of the blend. Timeliness penalties increased as the engine loading increased, but were mostly negligible. The operators reported no differences between the vehicles running on the respective fuels while performing the daily tasks.*

Keywords. Ethanol, diesel, blends, biomass, farm, energy resource, performance, durability

Introduction

Concern over harmful emissions from diesel fuels, as well as foreseeable future depletion of worldwide petroleum reserves, has prompted research on alternative fuel sources. Ethanol-diesel blends have been the subject of research for at least two decades. Ethanol is a renewable fuel, produced from biomass such as corn. Carbon dioxide from the combustion of ethanol does not build up in the atmosphere because it is used to grow more plants, which produce more fuel (Goering *et al*., 1992). However, ethanol and diesel fuel do not blend easily. Wrage and Goering (1980) found that the presence of water, or extreme cold temperatures, cause the mixture to separate. High engine temperatures cause vaporization of the ethanol, leading to vapor lock, and storage is difficult due to ethanol evaporation. Other problems with alternative fuels have included reduction in engine power and engine life, high fuel cost, and requirements for custom designed engines to handle the nonstandard fuel.

Recent advances have produced a "flash-mixing" blending agent that enhances the mixing of diesel fuel with ethanol, resulting in a fuel called "E diesel". This fuel has the potential to be used interchangeably with diesel fuel in standard engines, and reduce polluting emissions from machinery, in the effort to meet future environmental regulations. Its expected ability to be used in existing, unmodified equipment would keep associated costs low. Early tests have indicated compatibility with existing engines, good cold weather performance, and reasonable cost. Furthermore, since ethanol is derived from corn, the use of E diesel may have important implications for the short and long-term profitability of corn production.

For an alternative fuel to be adopted, it is necessary to prove its performance, durability and compatibility in all working environments, including on the farm. Successful on-farm evaluation can lead to stronger leverage in the use of E diesel because of the vested interest in promoting the use of the fuel and hence expanding the market for corn.

Objectives

The objectives of this research were the following:

- Demonstrate E diesel as an alternative fuel for use in tractors and combines.
- Compare machine performance and durability with E diesel to that with standard diesel fuel.
- Determine if E diesel is suitable for on-farm use without engine modification.
- Develop a meaningful and practical way to evaluate on-farm machine durability.
- Determine the economic impact of E diesel to the profitability of the individual farmer, in particular, and to the broader agricultural sector, in general.

Review of Literature

Evaluations of ethanol-diesel blends on farms in South Africa were reported by Meiring *et al*. (1981), Hansen *et al*. (1982) and Meiring *et al*. (1983). Meiring *et al*. (1981) achieved satisfactory results from a 2000-hour test on a single tractor running for alternate 100-hour periods on a 15%ethanol-diesel blend containing no other additives, and on diesel. Their investigation was extended to include four tractors, three of which ran on a 2.9% ethyl acetate, 14.6% dry ethanol and 82.5% diesel, while the fourth, operating on diesel, was employed as a reference (Hansen *et al*., 1982). After 1000 hours of in-field operation, no abnormal deterioration in engine performance and condition resulting from the blend could be detected. Meiring *et al*. (1983) studied the performance and durability of a tractor running on a 30% dry ethanol, 4.5% octyl nitrate, 4% ethyl acetate, and 61.5% diesel blend. The delivery of the fuel pump was uprated to compensate for the reduction in energy content of the fuel. After 1000 hours on the blend, Meiring et al. (1983) concluded that there was no noticeable deterioration in the condition of the engine or fuel injection system.

Evaluations of ethanol-diesel blends have also being carried out in other countries, notably Brazil where the emphasis shifted to the development of vehicles that could run on 100% ethanol. More recently in the mid 1990's, Sweden tested a blend of 15% hydrous ethanol and diesel with an emulsifying agent in a small fleet of logging trucks. No significant losses in performance or fuel economy were reported and no fuel-related problems were encountered. In the USA, the Illinois Department of Commerce and Community Affairs took the initiative in 1997 to develop a program to test 10%, 15% and 20% blends of ethanol with diesel in trucks and urban transit buses with the fuel being referred to as "E diesel"(Marek and Evanoff, 2001). They specified four requirements for the blended fuels. The first was that the additive should be "splash-blendable" thus requiring no extensive heating or blending steps. The second requirement was that the blend should be reasonably priced with the goal being to keep it within $0.05 per gallon of No. 2 diesel. Thirdly, diesel engines would not require any modification when run on E diesel. Finally, engine/vehicle performance and fuel economy should be as close to conventional No. 2 diesel as possible.

Engine tests to determine the benefits of E diesel in reducing emissions have yielded results in which reductions in emissions of particulate matter (PM) have ranged from 30-40% with 15% ethanol blends and 20-27% with 10% ethanol blends. Reductions in NO_x emissions have ranged from 0-5% and 0-4% for 15% and 10% ethanol blends respectively. However, another engine test showed considerable variations in both PM and NO_x over the load-speed range of the engine with reductions varying 22-75% and 60-84% respectively (Marek and Evanoff, 2001)

Over-the-road tests by Archer Daniels Midland (ADM) in Decatur, Illinois on two trucks operating on 15% ethanol blend of E diesel have resulted in an accumulation of approximately 270,000 miles (434,511 km) on each vehicle with no abnormal deterioration in condition (Marek and Evanoff, 2001). The Chicago Transit Authority (CTA) monitored the condition and overall performance of a fleet of 30 buses, of which 15 operated on the 15% ethanol blend and 15 were the control and ran on No. 1 diesel. After 270,000 miles (434,511 km) accumulated by the 15 buses running on the blend, no abnormal maintenance or fuel-related problems were encountered (Marek and Evanoff, 2001).

The success of these latter tests provided the impetus to expand the evaluation of E diesel to the agricultural sector where farmers would have the incentive of testing a product that had potentially would have a direct impact on the marketing of their corn production.

Materials and Methods

Fuel

The E diesel blend consisted of 10% dry ethanol, 1.3% additive from BetzDearborn and the remainder no. 2 low sulfur diesel. This fuel was 'splash-blended" by Growmark, Inc. and then shipped to each farm as required. A 3,800 liter (1000 gal) tank was temporarily installed on each farm to accommodate the fuel separately from existing fuel storage. In addition, because E diesel is classified as a Class I liquid, appropriate storage and handling measures were put into place.

Test vehicles

Tractors: Two John Deere 9400 4WD tractors situated on a farm near Wyoming, Illinois were the first agricultural vehicles to participate in this project. One tractor was operated on standard

No. 2 diesel as a control and the other on E diesel. Specifications for the two 9400 tractors are summarized in Table 1. In-field performance data for both tractors pulling implements of the same size were collected in addition to a daily log of overall fuel usage, types of operation and operator observations. The data logging was performed with the aid of a custom interface box supplied by Deere & Company that enabled a laptop computer to communicate with the electronic tractor bus and to monitor and record the relevant variables. Oil samples were taken at 100-hour intervals from both tractors as an assessment of engine condition. The tractors were monitored during Spring cultivation and during chisel plowing operations in the Fall.

Table 1. Summary of specifications for John Deere 9400 4WD tractor

Rated power (gross engine power)	316 kW (425 hp)
Rated speed	2100 rev/min
Type of engine	In-line, 6-cylinder
Aspiration	Turbocharged and air-to-air aftercooled
Displacement	12.5 L (765 cu. In)
Bore and stroke	127 x 165 mm (5 x 6.5 in.)
Fuel system	Unit-injection with electronic governor
Compression ratio	16 to 1
Transmission	12-speed Powershift
Fuel tank capacity (maximum usable)	973 L (256 U.S. gal.)

The data captured while the tractors were working in the field included fuel flow, engine speed, wheel speed and true vehicle speed. The sampling rate was fixed at 0.25 s and could not be modified thus generating very large data files. Each data sample included a time stamp, relative to the start of the sampling period and the actual time and date were included at the start of each data file.

Combines: Two new John Deere 9650 combines (see Table 2 for engine specifications) were identified for evaluation of E diesel on a farm near Bloomington, Illinois using a similar approach as adopted for the two John Deere 9400 4WD tractors. The specific maximum power output for the engines fitted to each combine was obtained from Deere & Company and the engine developing 2% more power was selected to run on E diesel in order to minimize the fuel energy content differential, with the other combine engine running on standard no. 2 diesel. Both combines were fitted with GreenStar® yield mapping systems and custom data logging systems from Deere & Company for recording torque, engine speed, fuel consumption rate, ground speed, grain unloading status, coolant, fuel and manifold air temperatures. The GreenStar® yield mapping system includes a GPS antenna, so engine performance data could be mapped in a GIS, along with the yield. A one-second sampling rate was selected. A daily log of overall fuel usage was also kept. Oil samples were collected at the beginning and at 100-hour intervals from both combines as an assessment of engine condition.

Table 2. Summary of specifications for John Deere 9650 combines

Specification	**Diesel Combine**	**E Diesel Combine**
Rated horsepower (Factory)	204 kW (274 hp)	208 kW (279 hp)
Horsepower with power boost	223 kW (308 hp)	
Rated speed	2200 rev/min	
Type of engine	In-line, 6-cylinder	
Aspiration	Turbocharged and aftercooled	
Displacement	496 cu. in (8.1 L)	
Fuel tank capacity (maximum usable)	150 U.S. gal. (565 L.)	

Results and discussion

Results are presented from data collected from the two tractors operating in both Spring and Fall 2000 and from the combines harvesting in the Fall 2000.

Tractor Performance

A daily log of fuel consumption and engine hours was recorded for each tractor and a summary is presented in Table 3. The overall results showed a 4.5% increase in consumption by volume for the tractor operating on E diesel. This percentage was close to the estimated decrease in heating value of E diesel of 3.9% by volume. The fact that it was higher than the decrease in heating value was attributed to a higher work rate, especially on the last day of monitoring as reflected in the logged performance data.

Table 3. Summary of fuel usage for tractors and combines

Vehicle	Fuel Type	Total Fuel Used (L)	Total Hours	Ave. Fuel Consumption (L/h)	Percent Increase
Tractor	Diesel	4,537	85	53.4	4.5
	E diesel	5,186	93	55.8	
Combine	Diesel	6,775	194	34.9	5.4
	E diesel	6,986	190	36.8	

In analyzing the data collected while the tractors were working in the field, it was possible to distinguish between the times that the tractor was traveling to or between fields, and when it is working within the field, according to observations of tractor speed and stoppages as illustrated in Figure 1. In order to make useful comparisons between the two tractors it was necessary to focus on the operation of the tractors within the field. Therefore only the in-field work segments such as those shown in Figure 1 were selected for further analysis. The mean, minimum and maximum values for fuel flow, engine speed and true ground speed for these segments are shown in Figures 2 to 4 for four days of operation. As can be seen, there is considerable variability between fields for each tractor and it was difficult to make a reliable comparison between the tractors based on these values alone.

By plotting a graph of fuel flow versus engine speed, it was possible to obtain some measure of the level of power at which the tractor operated. Figures 5 and 6 are scatter diagrams of the fuel flow and corresponding engine speed recorded for a full day and therefore include stoppages and movement between fields. Of particular significance is the number of points situated along the margin of the governed range and the maximum fuelling curve. These points largely represent the operation of the tractor in the field. Hence these points were examined further.

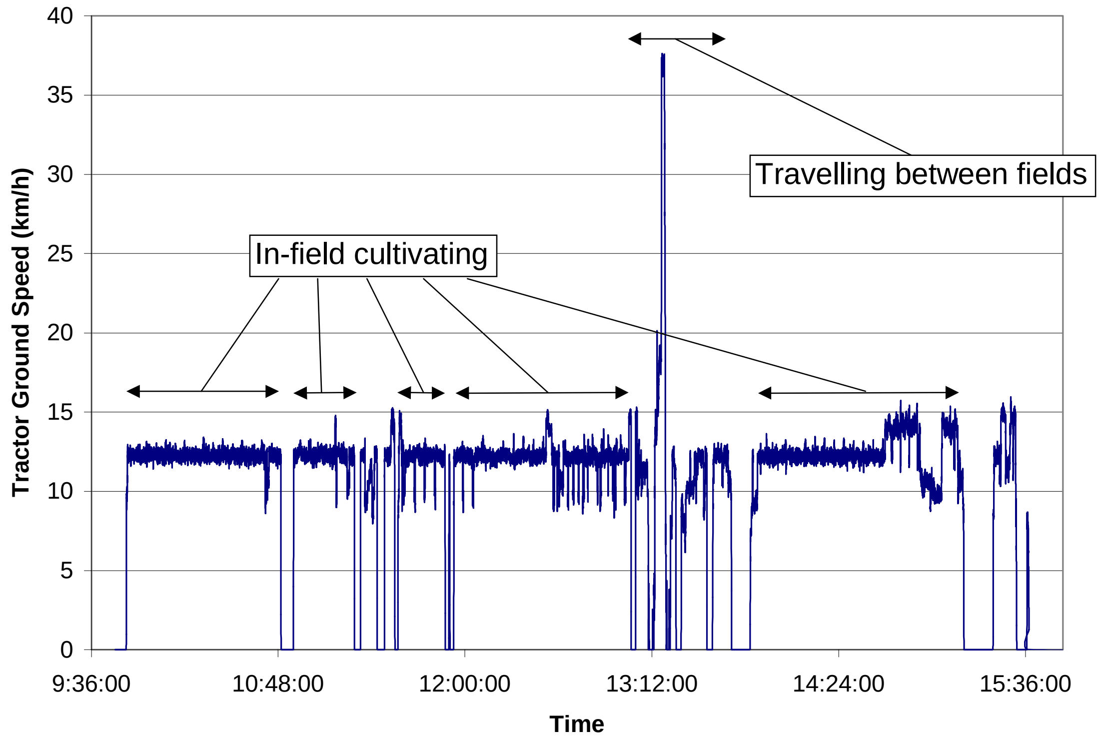

Figure 1. Variation of tractor ground speed during one day of cultivation using diesel fuel

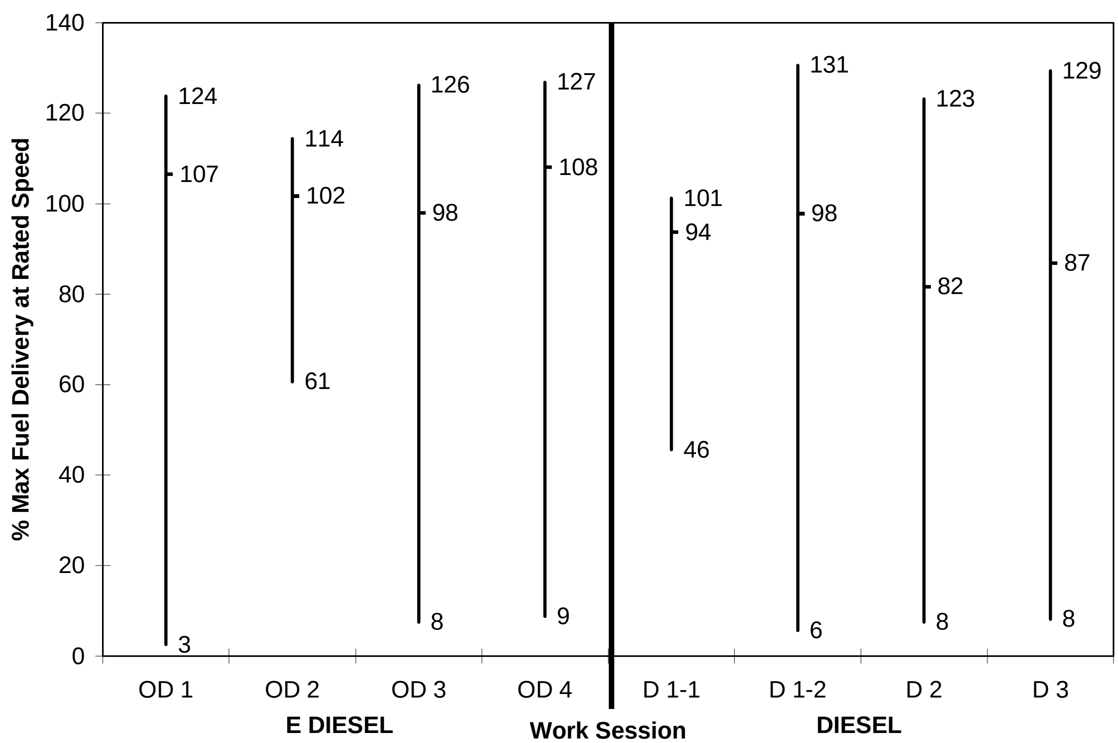

Figure 2. Maximum, mean and minimum values of % maximum fuel delivery at rated speed recorded for the two tractors during four work sessions

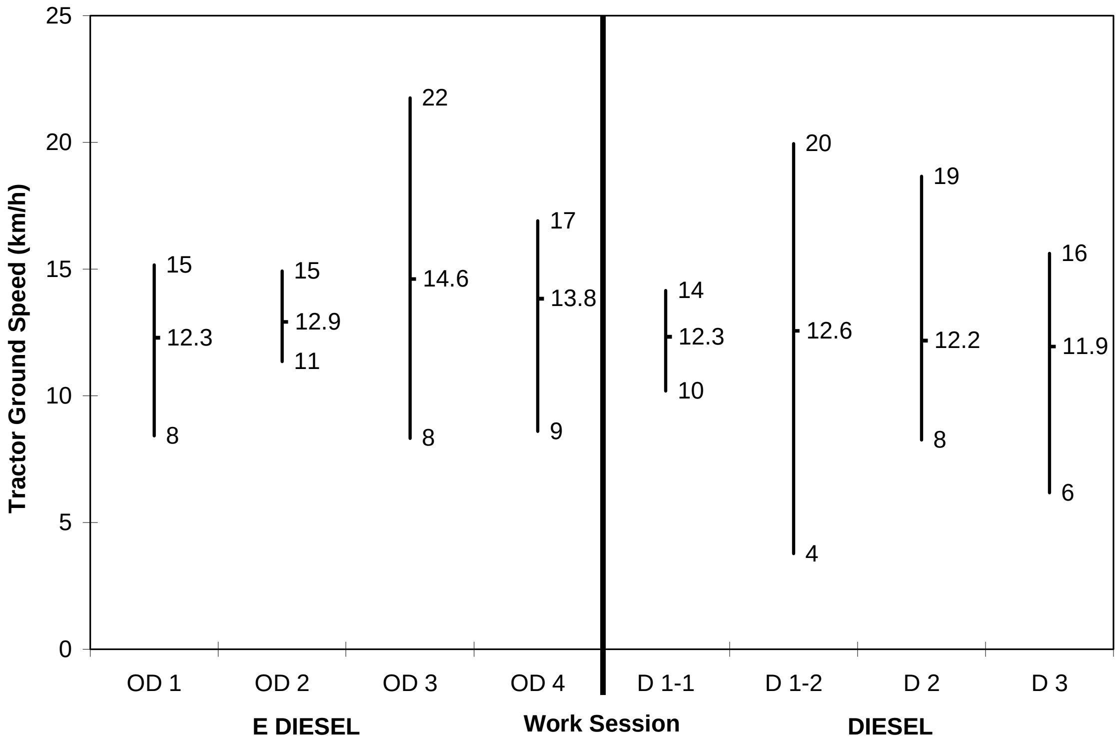

Figure 3. Maximum, mean and minimum values of tractor ground speed recorded for the two tractors during four work sessions

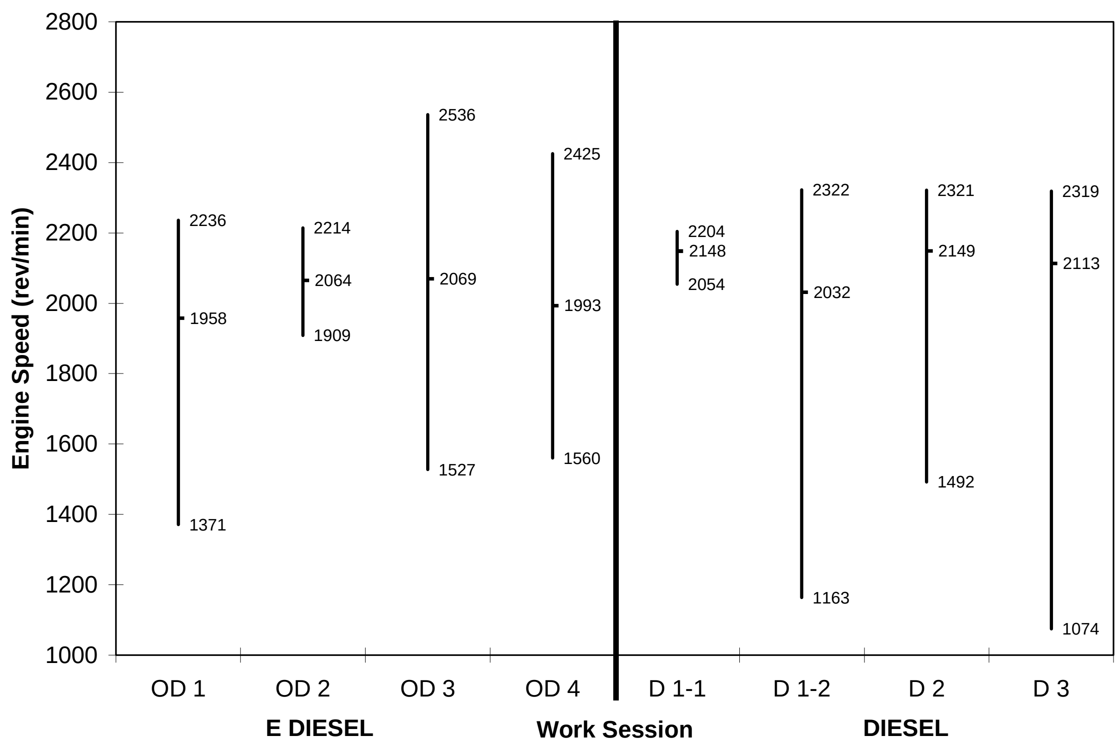

Figure 4. Maximum, mean and minimum values of engine speed recorded for the two tractors during four work sessions

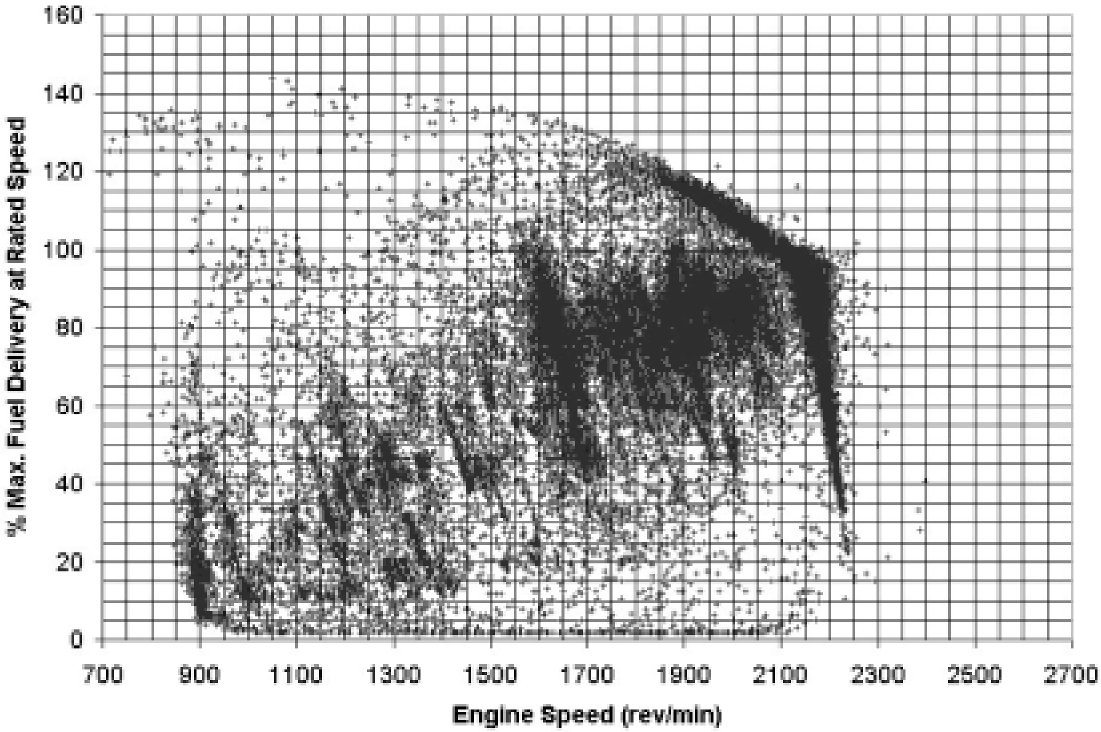

Figure 5. Variation of diesel fuel delivery with engine speed during one day of cultivation.

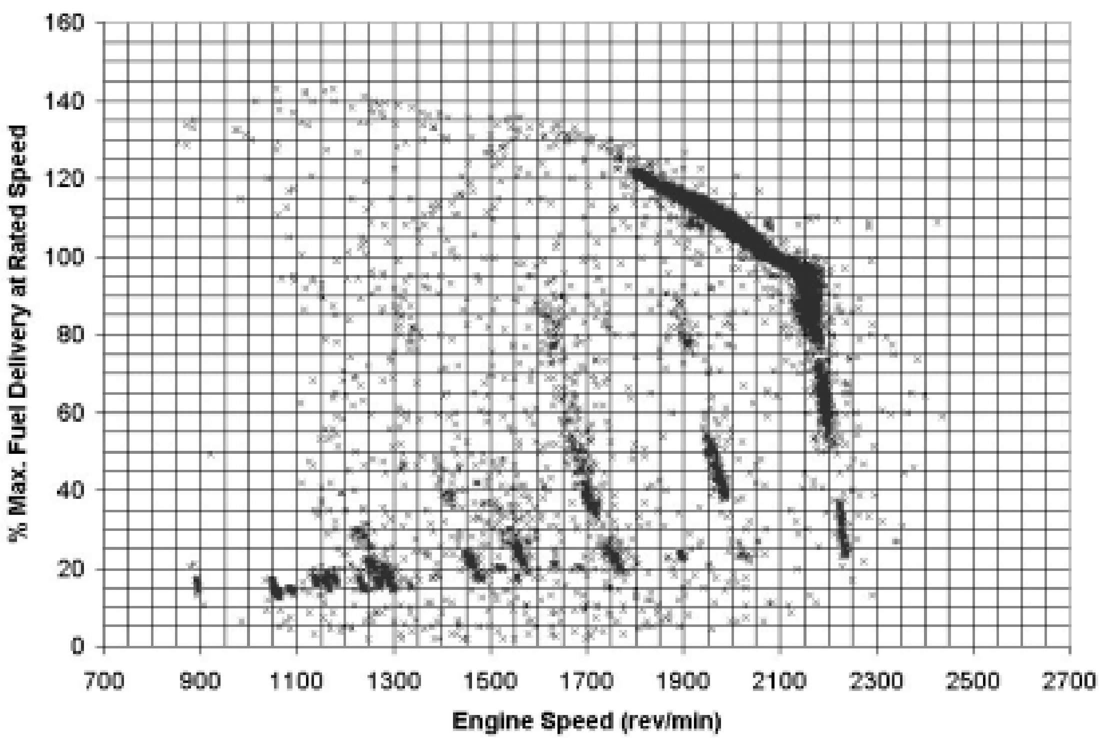

Figure 6. Variation of E diesel fuel delivery with engine speed during one day of cultivation.

The analysis of engine operation just within the operating envelope was carried out by first of all limiting the range of interest to above 50% fuel flow and above 1850 rev/min. This eliminated data at low speed and low torque where fueling rate was not limiting. Next, the engine speed and fuel flow axes were divided into 50 rev/min and 5% intervals and the time spent in each 50 rev/min by 5% fuel flow block was determined by summing the number of data points lying within the block. Ricketts and Weber (1961) and Hansen *et al*. (1986) used a similar approach. Data from all the field operations were accumulated for each tractor in this way. The results of this process are shown in Figures 7 and 8. The time given in each block is a percentage based on the total time accumulated for the blocks shown and therefore does not include time spent elsewhere within the operating range of the engine. The figures show that both tractors tended to operate for a large portion of time at a maximum fueling level close to rated speed, which would be regarded as optimum for minimizing fuel consumption and maximizing work rate. Figure 9 illustrates the differences between the two tractors. It is evident that the tractor running on E diesel tended to work more in the maximum fuelling range at a lower speed. And hence would be expected to consume more fuel. This would be partly expected because of the approximately 4% lower calorific value of the E diesel causing the engine to have to operate at a higher fuelling level and lower speed in order to deliver the same power as with standard diesel fuel.

Other factors also affected the loading on the engine, such as work rate and implement settings. With regard to implement settings, the tractor driver had had considerable experience in driving tractors and setting up implements and he made a special effort to ensure that the implements on both tractors were adjusted so that they had the same settings with particular reference to shank depth in the soil. The implements on the two tractors were almost identical, being DMI TigerMate II cultivators with 100 shanks giving a total width of 48.5 ft (14.8 m). A McFarlane spike tooth harrow was pulled behind the cultivator.

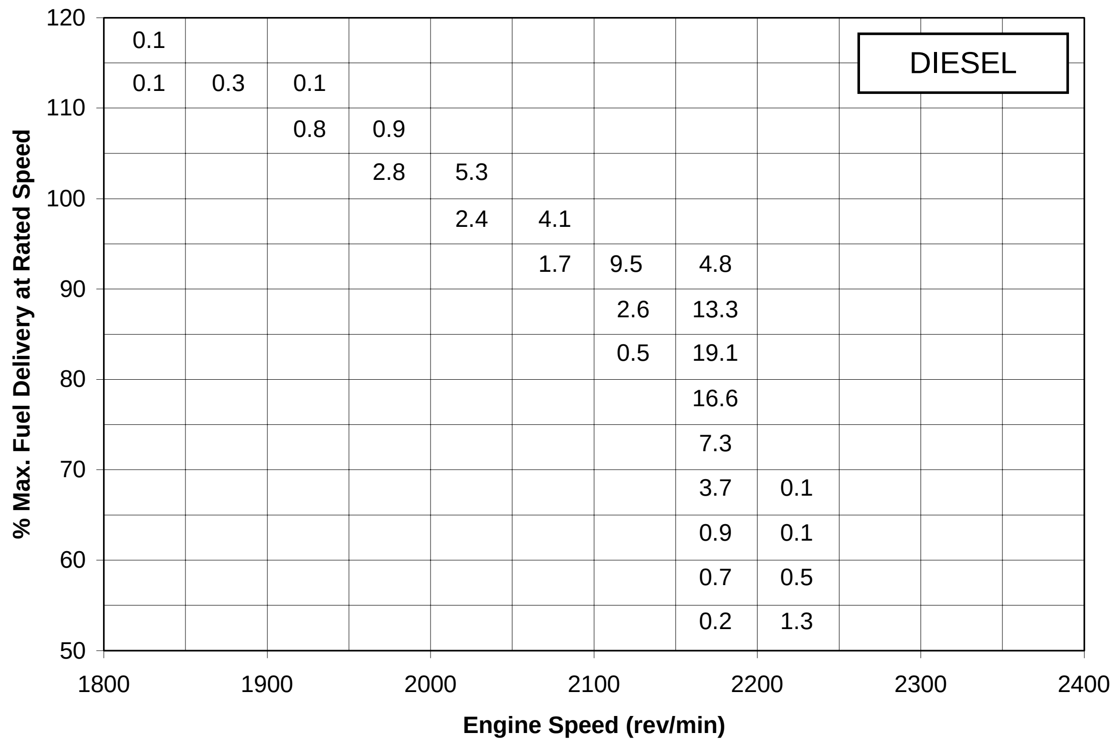

Figure 7. Percentage of time spent within speed-fuel delivery intervals on or near the maximum fueling limits of the engine run on no. 2 diesel fuel

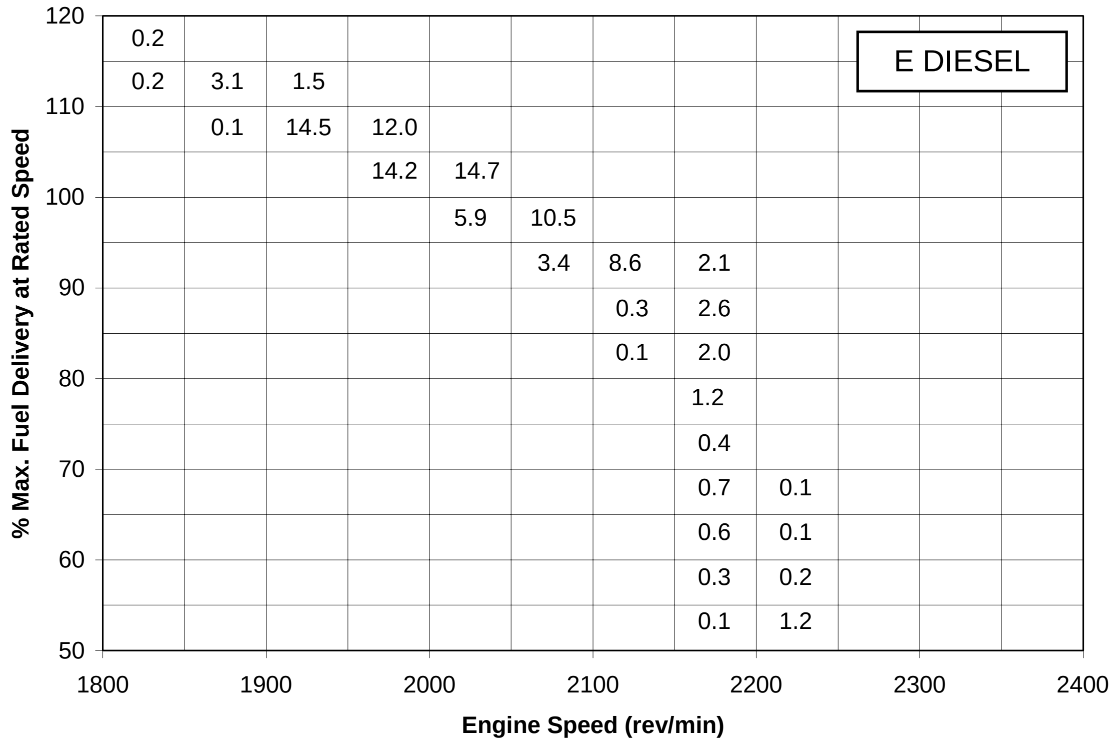

Figure 8. Percentage of time spent within speed-fuel delivery intervals on or near the maximum fueling limits of the engine run on E diesel

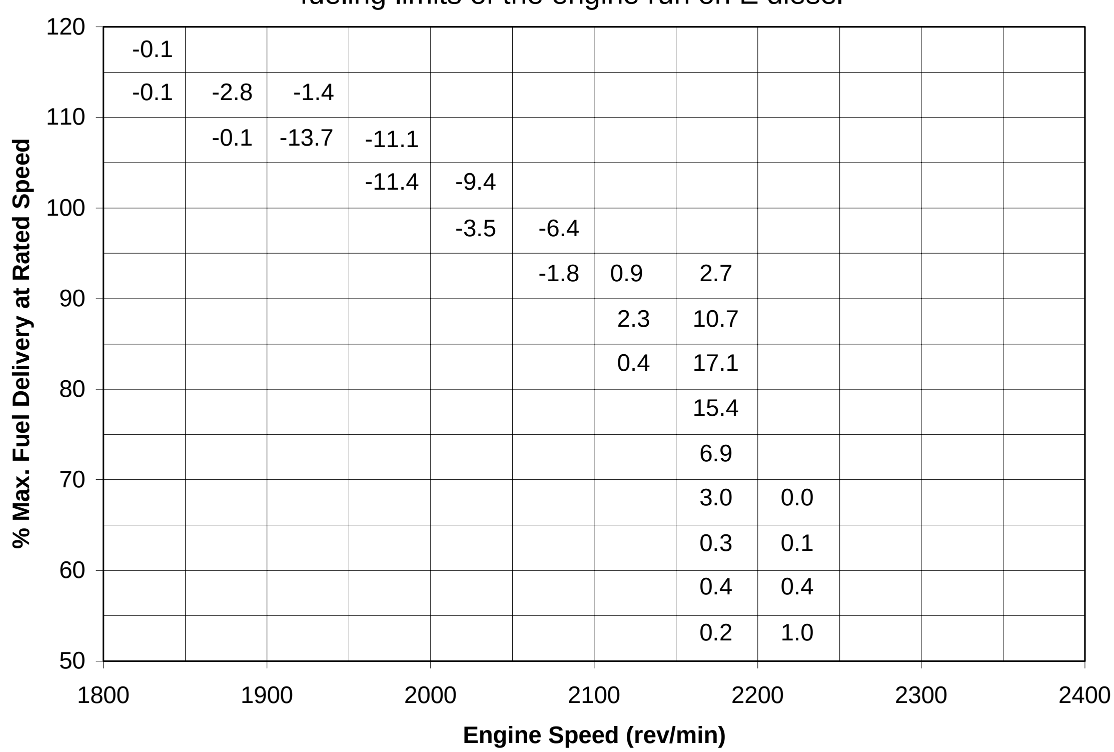

Figure 9. Differences in times shown in Figures 7 and 8 for corresponding intervals relative to diesel consumption

The true ground speed and hence the work rate of each tractor corresponding to the data in Figures 7 and 8 were also analyzed to establish any differences between the tractors. Figures 10 and 11 show histograms of ground speed for the two tractors. It is evident that the E diesel tractor was working at a higher torque level than the diesel tractor. This would account for the higher % maximum fuel delivery per engine revolution at rated speed seen in Figure 9.

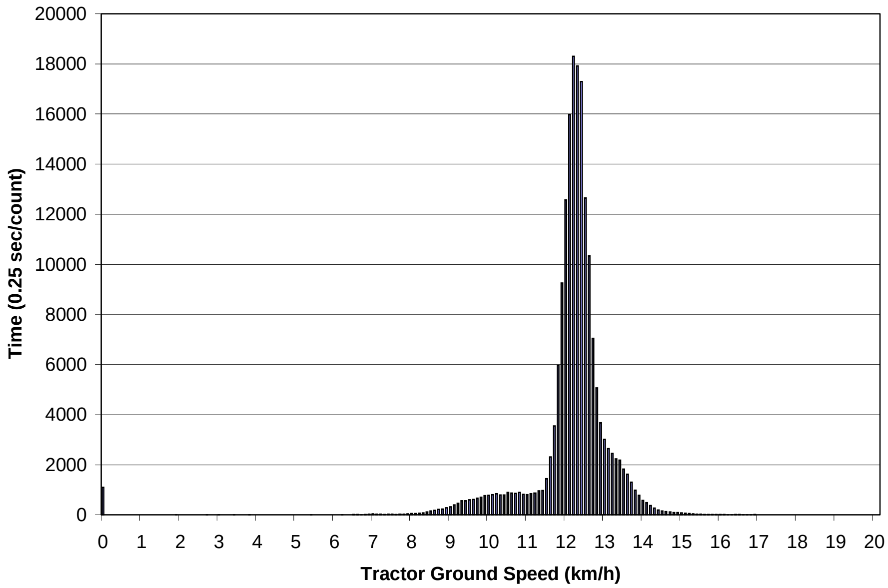

Figure 10. Histogram of diesel tractor ground speed while cultivating

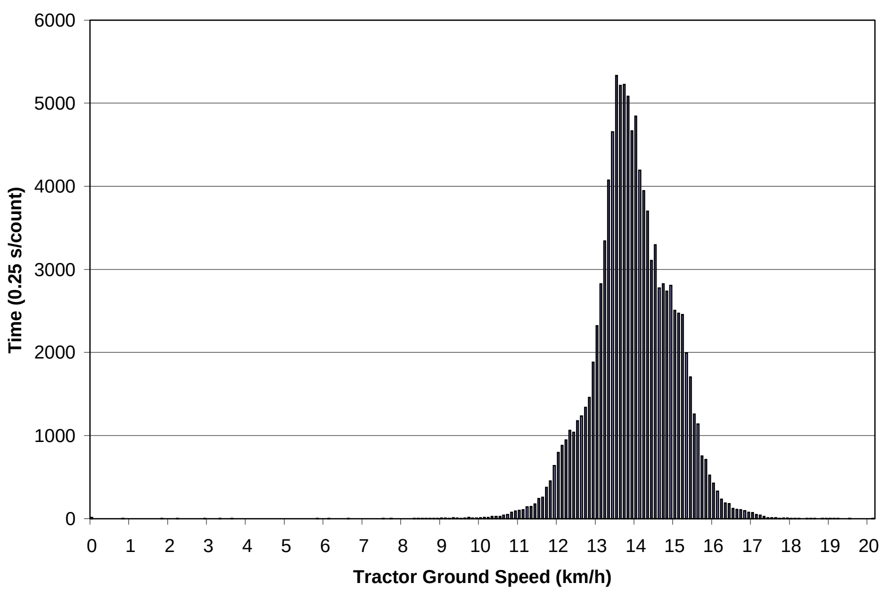

Figure 11. Histogram of E diesel tractor ground speed while cultivating

The results obtained from the in-field analysis did not provide a conclusive indication of the effect of E diesel on tractor performance and the overall fuel consumption figures showed that differences corresponded closely to the difference in calorific value of the two fuels. In order to obtain the same axle torque as for the tractor running on diesel, the fuel flow into the engine has to increase by an amount equivalent to the decrease in heating value of the E diesel fuel, assuming that the combustion efficiency is the same. This requirement applies at all operating points within the torque-speed envelope of the engine. In addition, for the energy input per unit area of the field cultivated to remain the same, the amount of E diesel fuel consumed per unit area will have to increase by the same amount as the decrease in heating value.

Within the torque-speed envelope of the engine operating range, it is possible to adjust the engine governor control so that the engine continues to work at the same speed and therefore at the same work rate but at a higher fuel flow (Figure 12, point A). Hence the only consequence of using E diesel in this case is the increase in fuel consumption.

When the engine operates on the edge of the envelope, there is a work rate reduction associated with the required increase in fuel flow, as it is no longer possible to adjust the governor control to maintain the original speed (Figure 12, points B and C). The increase in % fuel consumed per unit time equivalent to the % increase in fuel flow per engine revolution because of the loss of heating value becomes less as the speed decreases. Thus, when looking at fuel consumption alone, it appears that the increase in fuel consumption may be less than is reflected in the loss of heating value for E diesel. However, the work rate is reduced by an amount that is the same as the difference between the % fuel consumed and the % loss of heating value. This result is expected, as the energy input per unit area should remain the same. Hence, when the tractor is idling or operating in the speed control range, the extra E diesel fuel consumed per unit time will be close to the difference in heating value.

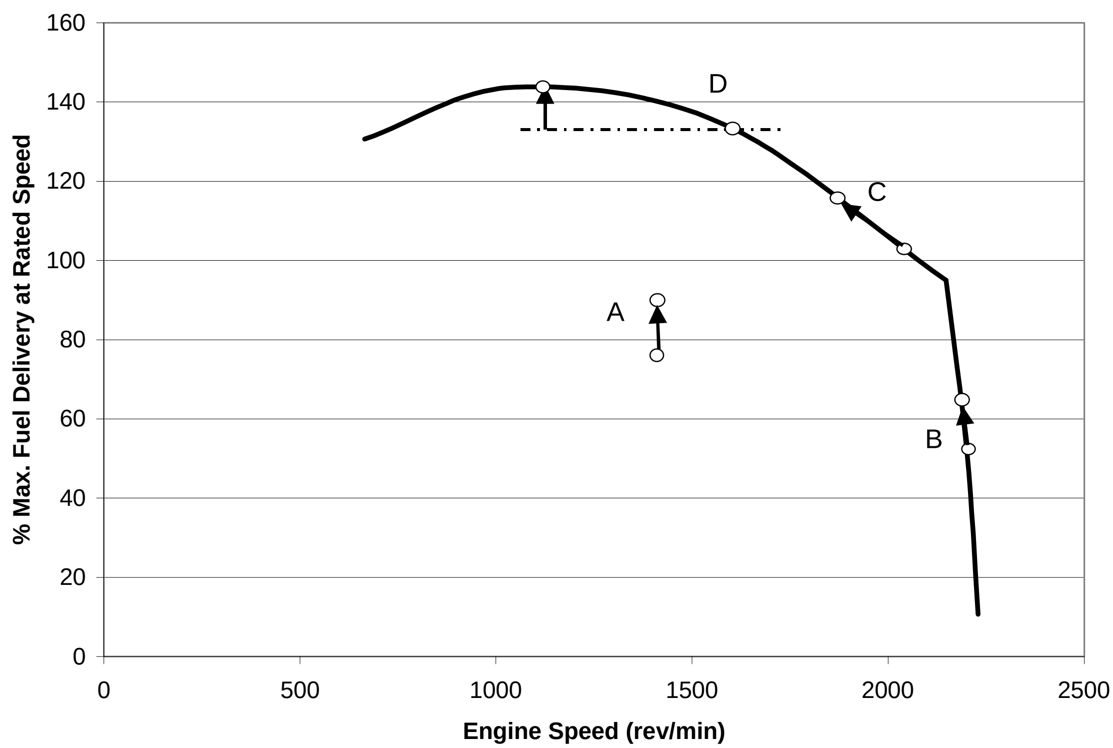

Figure 12. Schematic illustrating the shift in fuel delivery at different points in operating range of the engine when fueled with E diesel as compared to diesel

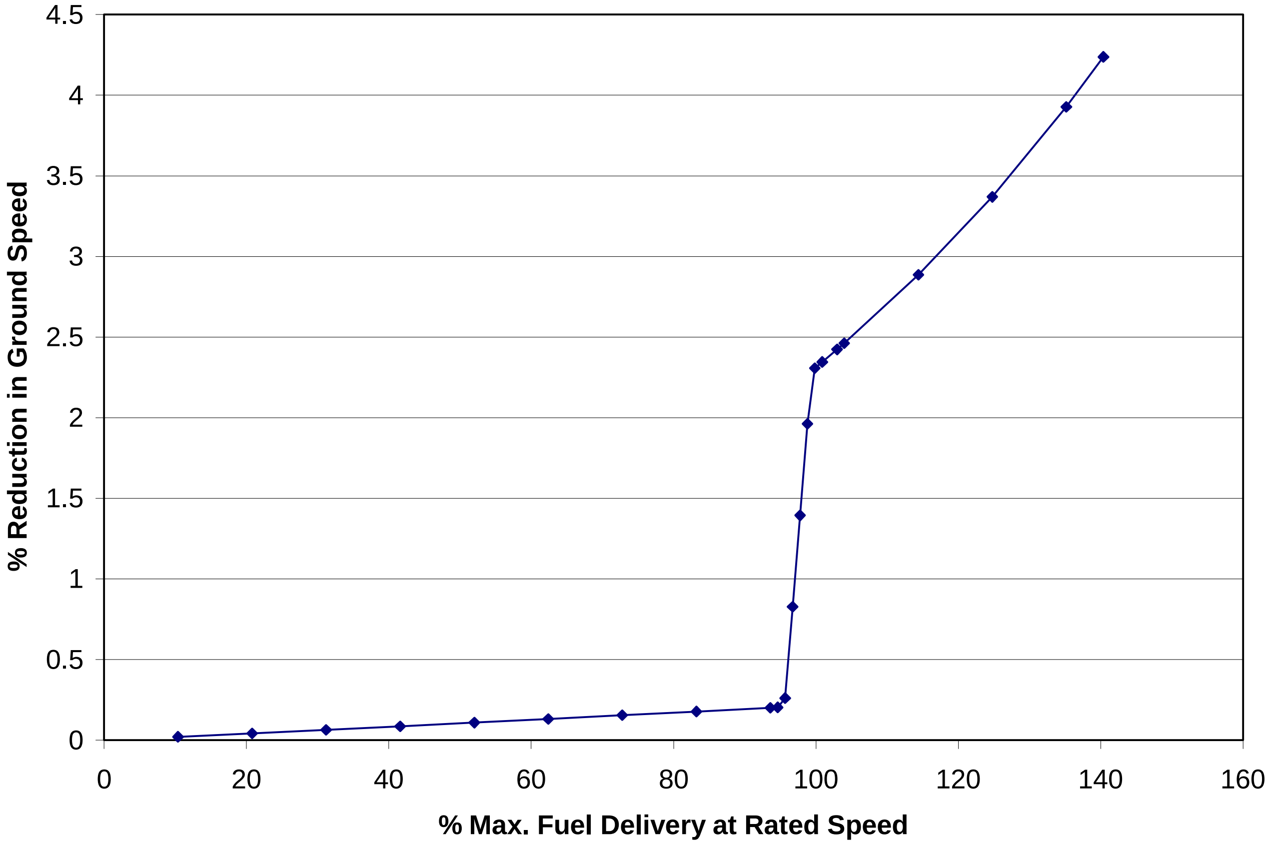

Figure 13. Percentage reduction in ground speed relative to the fueling level of the engine

In evaluating the effect on work rate of using E diesel, in the governed range, the drop in engine speed, especially at the low fueling levels is very small (Figure 12, point B). However, in the operating range where fuel delivery is at a maximum the drop in speed is greater (Figure 12, point C). Engine friction decreases with decreasing speed and this means that the increase in fueling required to achieve the same axle torque will be slightly less in practice. The percentage reduction in speed is shown in Figure 13. In the speed control range, the reduction in ground speed is relatively small. As the tractor starts to move into the load control range, the magnitude of the reduction in speed increases significantly with a steep rise initially of almost 2% followed by a more gradual increase but still at a much steeper rate than in the speed control range.

When the engine operates close to the point of overall maximum fuel flow in mg/rev (Figure 12, point D), maintaining axle torque may require a gear change as the fuel flow increment needed to compensate for the heating value decrease with E diesel cannot be met.

Combine Performance

The results from the daily log of fuel consumption and engine hours shown in Table 3 showed a 5.4% increase in consumption by volume for the combine operating on E diesel. This percentage was close to the estimated decrease in heating value of E diesel of 3.9% by volume. The fact that it was higher than the decrease in heating value can be attributed to different operating conditions rather than different combustion efficiencies as discussed later.

The data collected in the field were averaged for each combine. Table 4 shows a summary of results from five different fields (F1-F5) comprising three corn and two soybean fields for both the diesel (D) and the E diesel (E) combines. The ratios of E diesel to diesel (ED/D) are included. For the first field (F1) both combines operated on no. 2 diesel to establish a baseline from which to compare the two combines.

The power values shown in Table 4 were computed from torque and speed using the rated torque calculated from the respective power values supplied by Deere & Company for each combine engine.   A comparison of combine performance in field F2 indicated that the E diesel combine operating in corn required 19% more power than the diesel combine. The work rate of the E diesel combine was also 9% higher, which would account for a higher power requirement. Higher ground speeds result in higher frictional losses in the overall combine system in addition to the higher work rate achieved. A small increase in power was evident in soybeans for the E diesel combine in fields F4 and F5, however, the work rates were approximately the same.

In line with the increased power demand for the E diesel combine in corn in field F2, the fuel consumption increased by 8%. Much smaller increases occurred with E diesel in soybeans.

Both specific fuel consumption (SFC) and brake thermal efficiency were calculated as measures of engine efficiency. SFC is the ratio of fuel consumption to power and does not take into account differences in energy content of the fuel. Brake thermal efficiency is the ratio of power output to power input with the latter being determined from the energy content of the fuel and the fuel consumption rate. The energy content of no. 2 diesel was assumed to be 45,500 kJ/kg and the energy content of E diesel was computed by assuming that the petroleum-based additive had the same energy content as no. 2 diesel.

Table 4 shows that in field F1 the engine of the E diesel combine started out with 3.3% higher efficiency than the engine of the diesel combine, with both engines running on no. 2 diesel. In fields F2-F5 the E diesel combine ran at a higher efficiency ranging from 4.6 to 6% or a net efficiency gain of 1.3 to 2.7%. This efficiency gain can be attributed primarily to slightly improved combustion efficiency. Extra oxygen is made available for combustion via the ethanol present, thus helping to minimize any incomplete combustion in the combustion chamber. If the cetane rating of E diesel is lower than that of diesel, this would cause a longer ignition delay, more premixed combustion and greater efficiency. The cetane rating would be heavily dependent on the amount of cetane improver present in the additive.

Operator Feedback

The tractor and combine operators provided regular feedback on their experience regarding the difference in vehicle operation with the two fuels.   When interviewed, the farmers operating the combines stated that they had not noticed any less power with the vehicle running on E diesel under approximately the same conditions as for the combine operating on No. 2 diesel. They had also expected an increase in fuel consumption, however, they had found that on some days the consumption was higher and on others it was lower with E diesel and hence the consumption rates for the two machines were very close.

The farmers operating the tractors commented on the fact that the E diesel fuel was very effective in cleaning the sight glass for displaying the level of fuel in the fuel tank. It was necessary to replace the fuel filters at the beginning, however, thereafter filter changes were performed according to the schedule recommended by the manufacturer.

Table 4. Summary of combine field data

Field & Size (ha)	Crop	Combine	Fuel	Engine Speed (rev/min)	Work Rate (ha/h)	Fuel Cons. (L/ha)	Power (kW)	SFC (kg/kWh)	Brake Thermal Efficiency
F1 (22.7)	Corn	D	diesel	2315	3.47	10.0	140	0.208	0.38
		ED	diesel	2314	3.09	10.7	138	0.201	0.39
			ED/D (%)	100	91	107	103	103.3	103.3
F2 (16.2)	Corn	D	diesel	2324	2.72	11.9	132	0.205	0.39
		ED	Ediesel	2294	2.97	12.9	156	0.203	0.40
			ED/D (%)	99	109	108	119	101	104.6
F3 (16.2)	Corn	D	diesel	2296	4.25	9.1	155	0.207	0.38
		ED	Ediesel	2278	4.12	10.3	173	0.204	0.40
			ED/D (%)	99	97	114	111	101	104.8
F4 (32.4)	Soybeans	D	diesel	2263	4.70	9.3	177	0.207	0.38
		ED	Ediesel	2263	4.65	9.4	180	0.203	0.40
			ED/D (%)	100	99	101	102	102	106.0
F5 (80.9)	Soybeans	D	diesel	2253	5.81	7.9	184	0.209	0.38
		ED	Ediesel	2244	5.79	8.2	193	0.205	0.40
			ED/D (%)	100	100	104	105	102	105.6

Conclusions

1. The fuel usage recorded for the tractors and combines showed an approximate 5% increase in consumption for the vehicles fueled with E diesel, which was slightly above the estimated 4% increase based on the difference in heating value.
2. Large differences in in-field performance were observed from the data collected from the tractors and combines operating on the two fuels. Analysis showed that these differences were largely due to how the machines were operated rather than the fuel used.
3. An analysis of the consequences on tractor performance of using E diesel indicated that the fuel energy consumed per unit area of the field should remain the same for both fuels and therefore an extra 4% of E diesel by volume would be needed. When operating the engine at maximum speed and load, there was a small reduction in travel speed that increased as the load is increased. When the tractor was operated ideally in the speed control range close to rated speed at maximum power, as was the case for the diesel tractor, the reduction in travel speed was less than 1%.
4. Analysis of the in-field data from the combines showed a 1.3 to 2.7% increase in brake thermal efficiency with the use of E diesel.
5. Operator feedback confirmed that the effect on engine performance of running on E diesel could not be detected during the normal daily operations.
6. The overall conclusion is that the use of E diesel in these machines yielded largely positive results and provided justification for further on-farm evaluation and expansion of use to other machines.
7. Further in-field evaluation should be carried out as further verification of the effects of E diesel on agricultural machinery operation and should include machinery from different manufacturers.

Acknowledgements

This project was funded by the Illinois Council for Food and Agricultural Research and the Great Lakes Regional Biomass Energy Program, Council of Great Lakes Governors. The following have also provided substantial assistance and support:

Illinois Corn Marketing Board

Illinois Department of Commerce and Community Affairs

Growmark, Inc.

Bloomingdale Farms and Shafer Farms

Deere and Company

Cross Implements

BetzDearBorn

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