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Project Title: Evaluation of E diesel as an alternative fuel in agricultural machinery

After negotiations and planning with farmers and industry representatives in the middle of February, 2000, evaluation of E Diesel commenced at the beginning of April, 2000 on Shafer Farms near Wyoming, IL, comprising approximately 7000 acres. The objectives of this research are the following:

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

Two John Deere 9400 4WD tractors are participating in the first part of the evaluation with the one tractor operating on standard diesel fuel and the other on E Diesel (Figure 1). Specifications for this tractor are summarized in Table 1. In-field performance data for both tractors pulling implements of the same size are being collected in addition to a daily log of overall fuel usage, types of operation and operator observations. The data logging is performed with the aid of an interface box supplied by John Deere that enables a laptop computer to communicate with the electronic tractor bus and to monitor and record the relevant variables. Oil samples are being taken at 100-hour intervals from both tractors as an assessment of engine condition. The tractors have been monitored during cultivation this Spring 2000 and will also be monitored during chisel plowing operations in the Fall.

This report presents the results obtained from the two tractors during the Spring cultivation operations.

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

Rated power (gross engine power)	316 kW (425 hp)
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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.)

1. Monitoring of Daily Fuel Usage

A daily log of fuel consumption and engine hours was recorded for each tractor and is presented in Table 2. The overall results showed a 4.8% 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 can be attributed to a higher work rate, especially on the last day of monitoring as is shown later in this report.

2. In-Field Tractor Performance

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. Hence the data files were large in size and required a considerable amount of time for processing. Each data sample included a time stamp, relative to the start of the sampling period and the actual time and date was included at the start of each data file.

As a result of computer and data logging malfunctions, recording of data was somewhat irregular. Nevertheless it was possible to accumulate sufficient information to be able to make comparisons between the two tractors. Figures 2, 3 and 4 show typical corresponding recordings of fuel flow, engine speed and true tractor speed for the E Diesel tractor during one day of operation. Fuel flow was recorded as a percentage of the maximum fuel delivery at rated speed. It is possible to distinguish between the times that the tractor is 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 4. 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 4 were selected for further analysis. Figure 5 shows the accumulated time on specific days that the two tractors worked for which in-field data were analyzed. The mean, minimum and maximum values for fuel flow, engine speed and true tractor speed for these segments are shown in Figures 6 to 8. 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.

Table 2 Summary of fuel usage on Shafer Farms during field cultivation, Spring 2000

John Deere 9400 tractor operated on diesel

Date	Fuel Used (gal)	Tractor Hours	Consumption gal/h	L/h	kg/h
4/5/00	Full	389			
4/14/00	168	401.2	13.8	52.1	43.5
4/18/00	182.5	413	15.5	58.5	48.8
4/26/00	186	428	12.4	46.9	39.1
4/27/00	64	432	16.0	60.6	50.5
4/28/00	157	443.7	13.4	50.8	42.4
4/28/00	119	451.4	15.5	58.5	48.8
5/1/00	96	457	17.1	64.9	54.1
5/13/00	226	474.1	13.2	50.0	41.7
Total	1198.5	85.1	14.1	53.3	44.5

John Deere 9400 tractor operated on E Diesel

Date	Fuel Used (gal)	Tractor Hours	Consumption gal/h	L/h	kg/h
4/14/00	full	1318.8			
4/14/00	86	1324.6	14.8	56.1	46.5
4/26/00	179.8	1340	11.7	44.2	36.6
4/28/00	193	1352	16.1	60.9	50.5
4/29/00	210	1366.1	14.9	56.4	46.7
5/2/00	218.1	1379.6	16.2	61.2	50.7
5/6/00	254.6	1396.9	14.7	55.7	46.2
5/13/00	228.6	1411.6	15.6	58.9	48.8
Total	1370.1	92.8	14.8	55.9	46.3

% increase in fuel consumption with E Diesel (volume)= **4.8**
 Estimated vol% decrease in heating value of E Diesel fuel= **3.9**

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. Figure 9 and 10 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.

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. Data from all the field operations was accumulated for each tractor in this way. The results of this process are shown in Figures 11 and 12. 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 13 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 affect 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.

The true ground speed and hence the work rate of each tractor corresponding to the data in Figures 11 and 12 were also analyzed to establish any differences between the tractors. Figures 14 and 15 show histograms of ground speed for the two tractors. It is evident that the E Diesel tractor was working at a torque level than the diesel tractor. This would account for the higher % maximum fuel delivery per engine revolution at rated speed seen in Figure 13.

3. Effect of E Diesel on Tractor Performance

We would like to be able to answer the following question:

In what way is the use of E Diesel going to affect the performance of an existing tractor that normally runs on #2 diesel?

3.1 Fuel Consumption

In order to provide 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 16, 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 16, 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 as shown in Figure 17. 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 (Figure 18). 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.

3.2 Work Rate

In the governed range, the drop in rev/min, especially at the low fueling levels is very small (Figure 16, B). However, in the operating range where fuel delivery is at a maximum the drop in speed is greater (Figure 16, 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 18. 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 16, 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.

In summary, when the tractor is operating within its torque-speed range and there is a large enough buffer relative to the outer envelope of the engine working range, it is possible for the operator to adjust the engine speed control to maintain speed but at a higher fueling level, raised by an amount equivalent to the decrease in heating value of the E Diesel. When the engine is operating close to or on the maximum speed control limit, an additional work rate penalty comes into effect as the engine slows down a small amount in achieving the desired increase in fuel flow with E Diesel (Figure 18). The magnitude of this reduction increases as the load is increased. The overall fuel consumed per unit area of the field is not affected by the slowing down of the engine as the reduction in the extra fuel consumed per unit time at a given load level is offset by the extra time and fuel required to make up for the loss in area coverage.

Applying the calculated decreases in travel speed to the data obtained for the tractor working on diesel shown in Figure 11, an average overall decrease in travel speed of 0.63% was obtained. This decrease is regarded as negligible relative to the variation in field conditions.

4. Conclusions

a) The fuel usage recorded for both tractors showed that the tractor operating on E Diesel for 92.8 hours consumed an average of 14.8 gal/h (14.8 L/h) as compared to 14.1 Gal/h for the tractor on diesel, representing a 4.8% increase. This is a little more than the estimated 3.9% decrease in heating value by volume of E Diesel.

b) Performance data collected from both tractors operating on their respective fuels showed considerable variation from day to day and from field to field. By focusing on the time spent by both tractors on the edge of the working range of the engine under speed and load control, it was possible to obtain a measure of how the two tractors performed overall while cultivating. The diesel tractor had been loaded to very close to the optimum close to rated speed and maximum power while the E Diesel tractor had operated at a higher torque level, requiring a greater fuel energy input. The latter result was attributed to a higher average ground speed.

c) An analysis of the consequences on tractor performance of using E Diesel revealed that the fuel energy consumed per unit area of the field should remain the same for both fuels and therefore an extra 3.9% of E Diesel by volume would be needed. When operating the engine at maximum speed and loads, there is a small reduction in travel speed that increases 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%.

d) Apart from the approximate 4% increase in volumetric fuel consumption, a negligible difference in the performance of the tractor operating on E Diesel can be expected relative to running on diesel.

5. Future Work

a) The tractor evaluation will be extended to the chisel plowing operations in the Fall, which requires the tractor to operate at higher torque levels. These data will be used to verify the earlier observations from the Spring data.

b) Combine harvesting operations will be monitored in the same way as for the tractor operations, using two combines fitted with data loggers. In addition, GPS and yield mapping data will be recorded allowing some spatial analysis.

6. Acknowledgements

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Shafer Farms

Deere and Company

Cross Implements



Figure 1. John Deere 9400 4WD tractor running on E Diesel during cultivation.

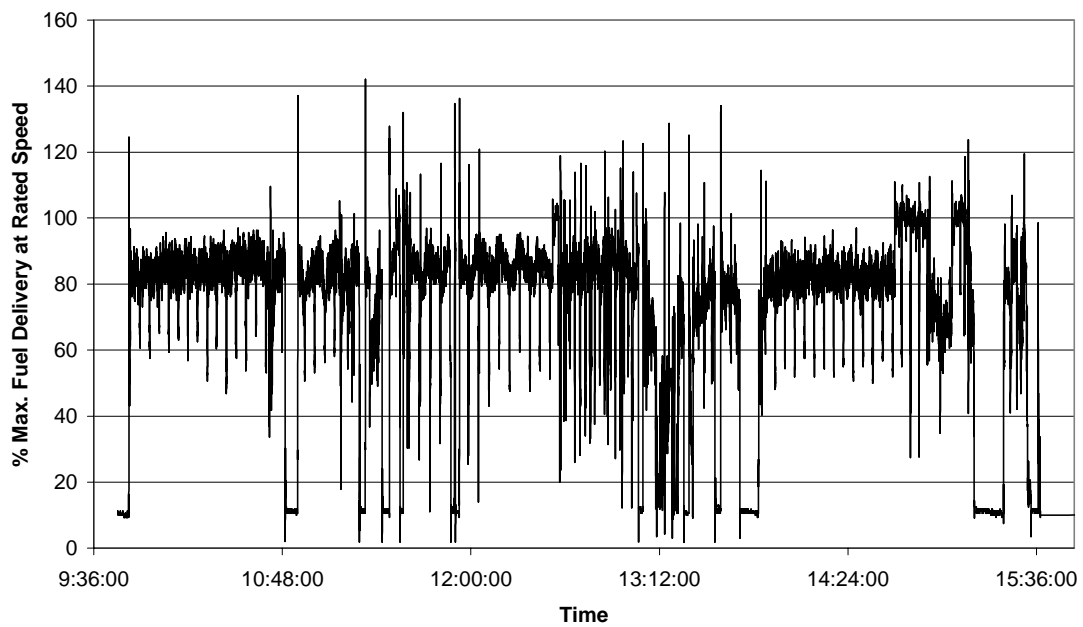


Figure 2. Variation of % maximum fuel delivery at rated speed during one day (4/26/00) of cultivation with diesel fuel.

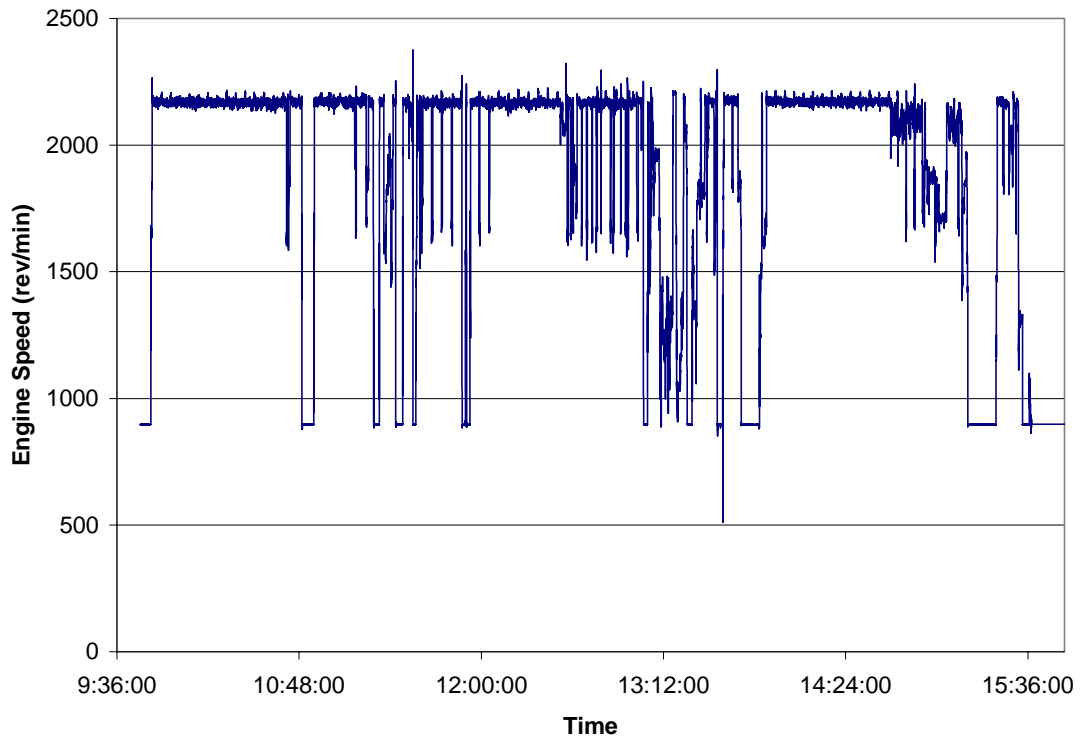


Figure 3. Variation of engine speed during one day (4/26/00) of cultivation with diesel fuel.

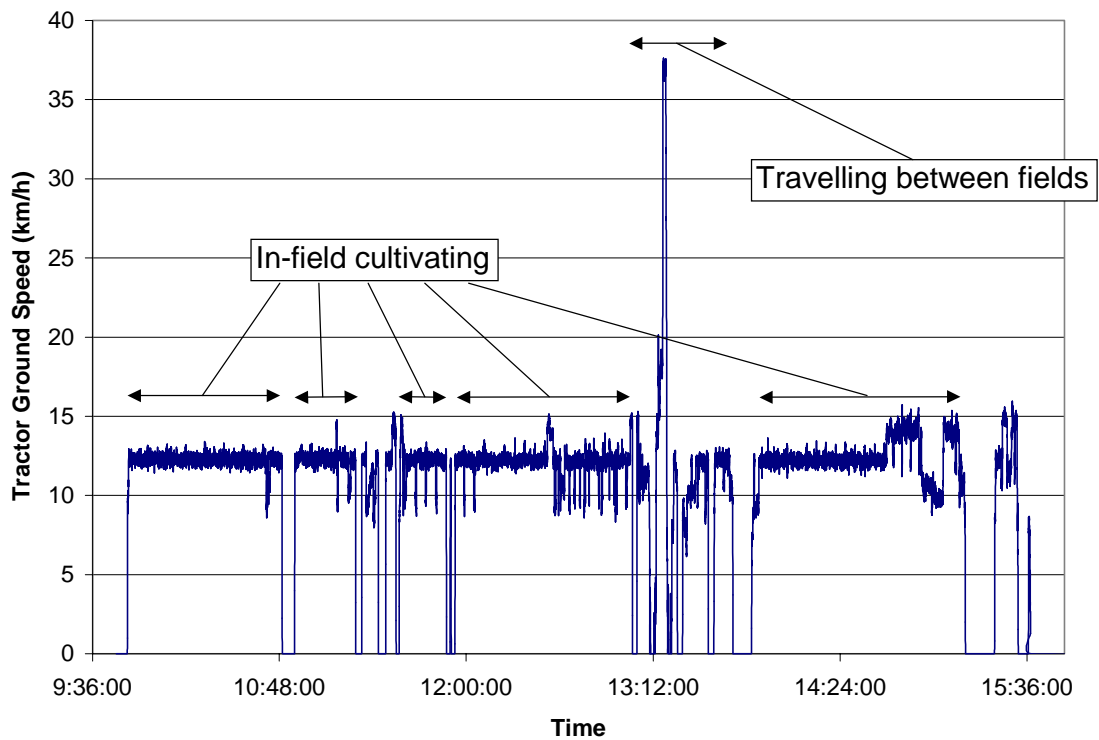


Figure 4. Variation of tractor ground speed during one day (4/26/00) of cultivation on diesel fuel.

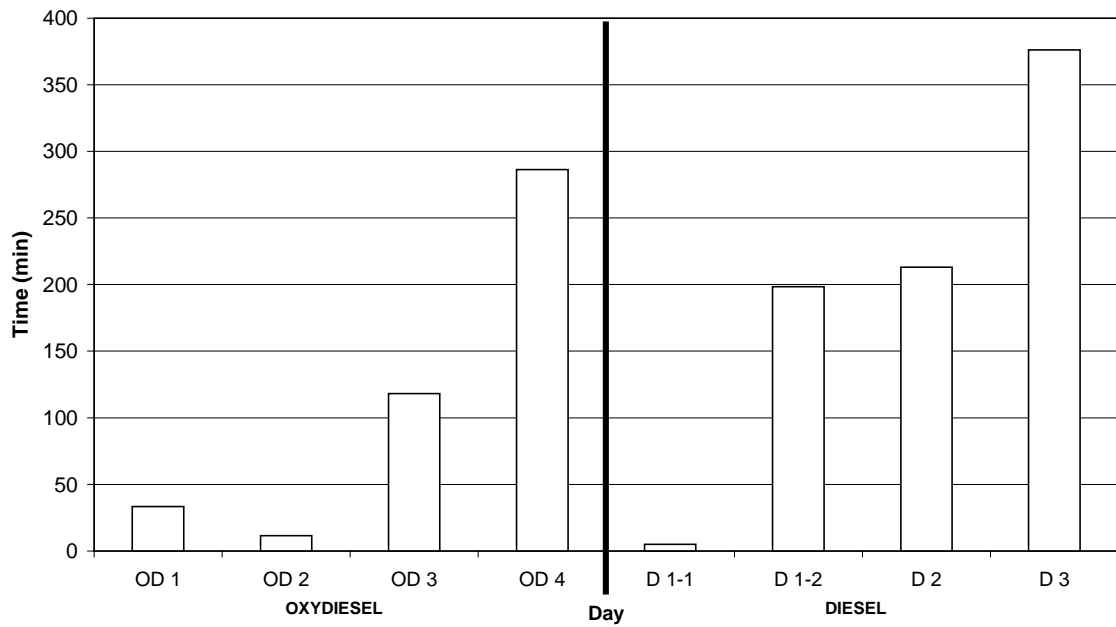


Figure 5. Time on specific days, for which data were collected and analyzed.

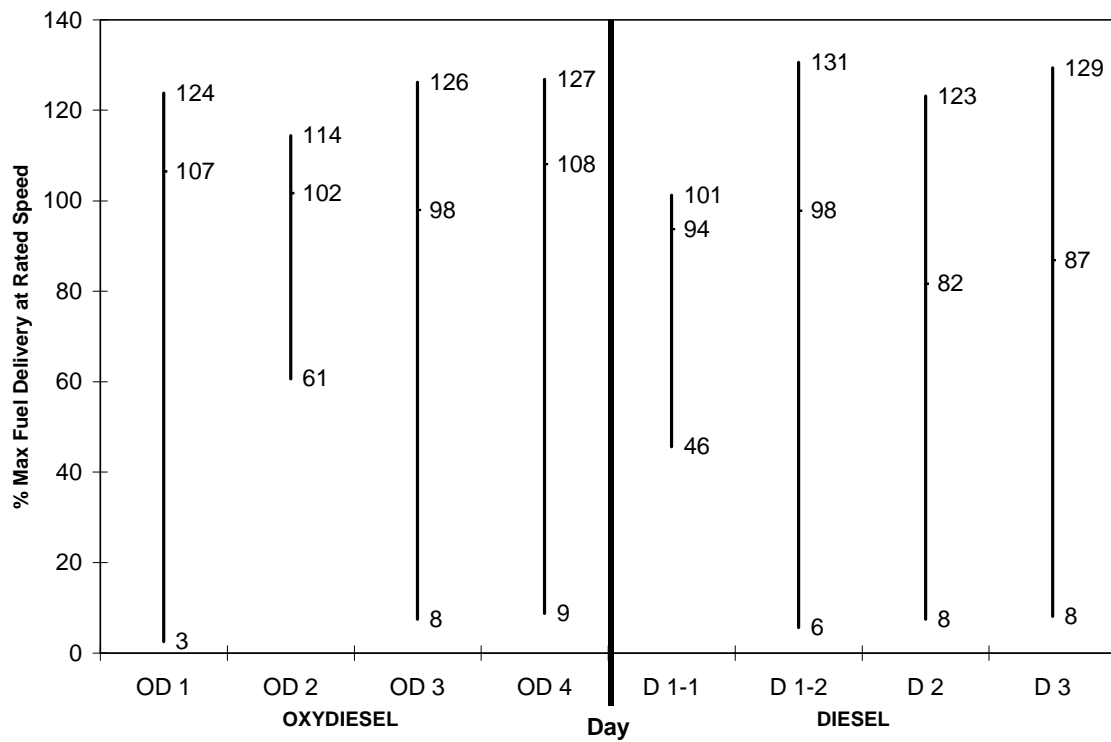


Figure 6. Maximum, mean and minimum values of % maximum fuel delivery at rated speed recorded for the two tractors on specific days.

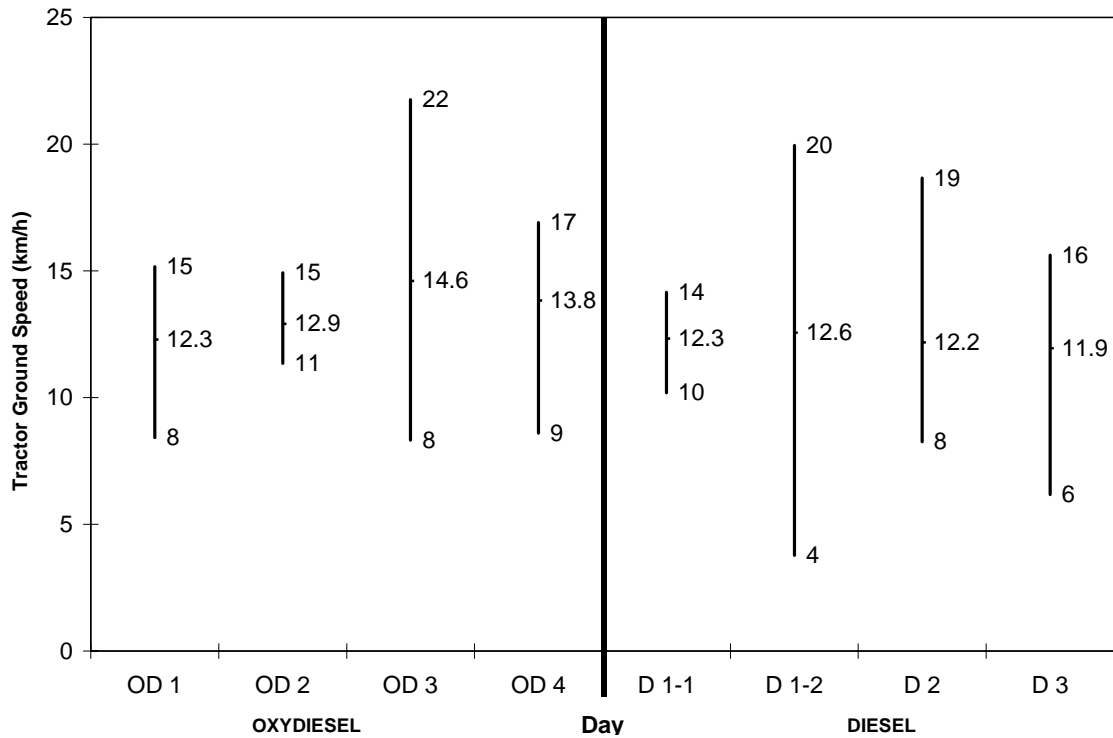


Figure 7. Maximum, mean and minimum values of tractor ground speed recorded for the two tractors on specific days.

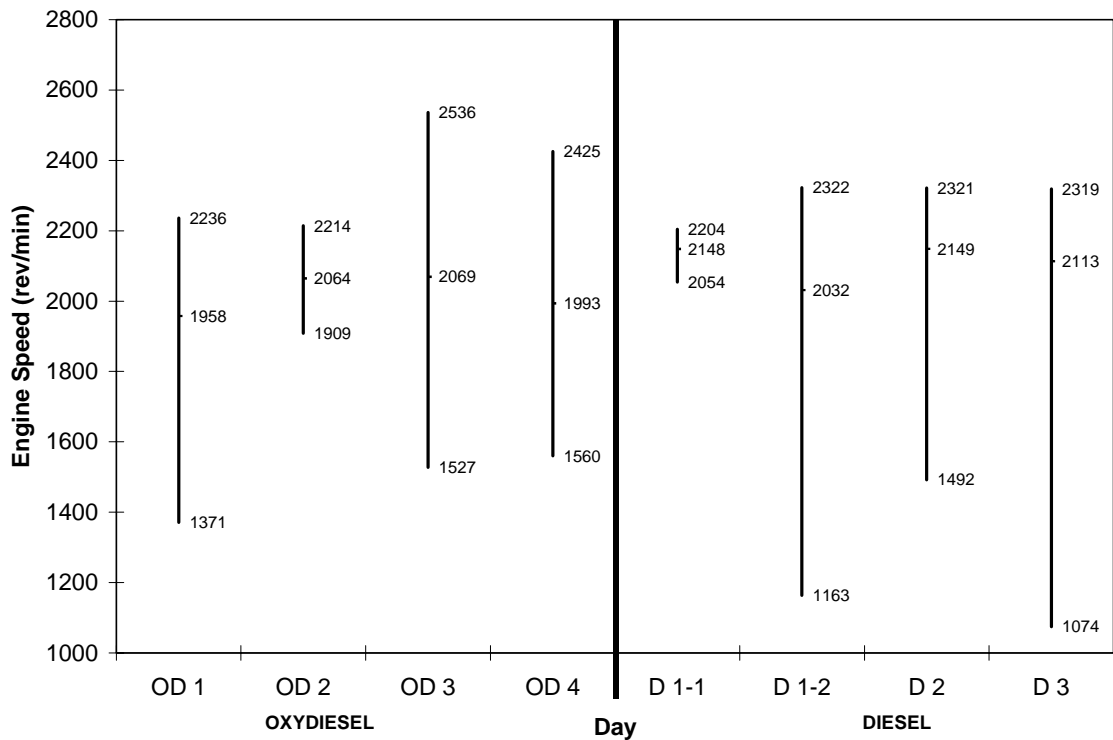


Figure 8. Maximum, mean and minimum values of engine speed recorded for the two tractors on specific days.

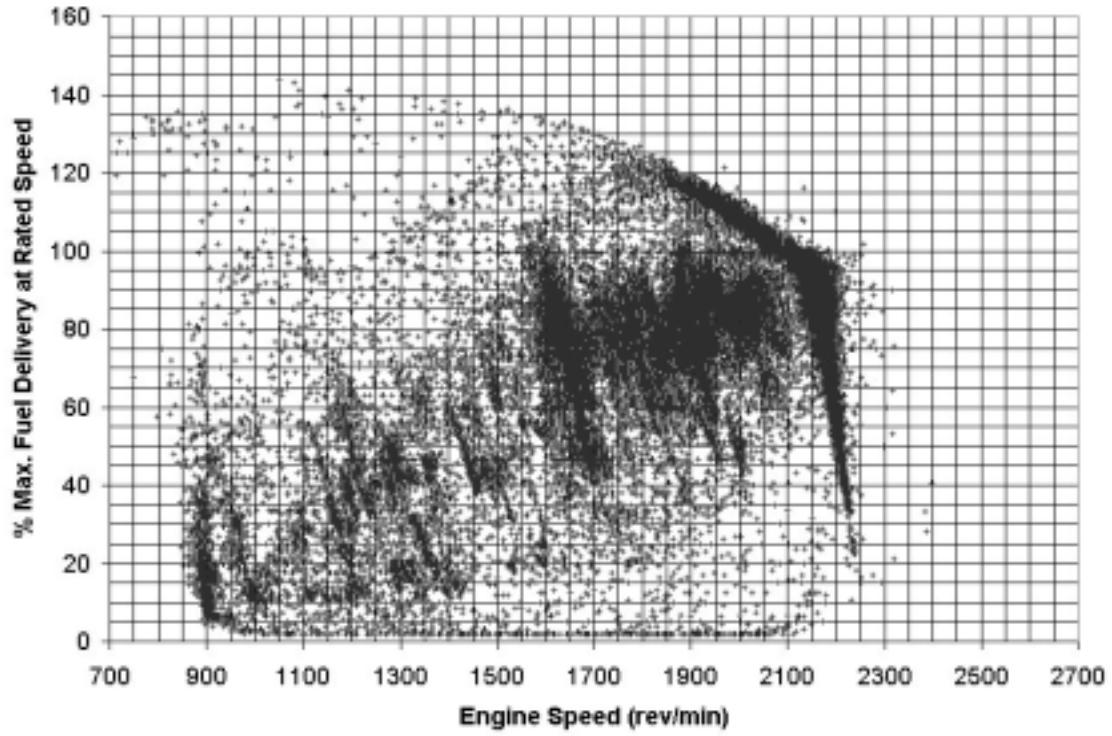


Figure 9. Variation of diesel fuel delivery with engine speed during a day of cultivation.

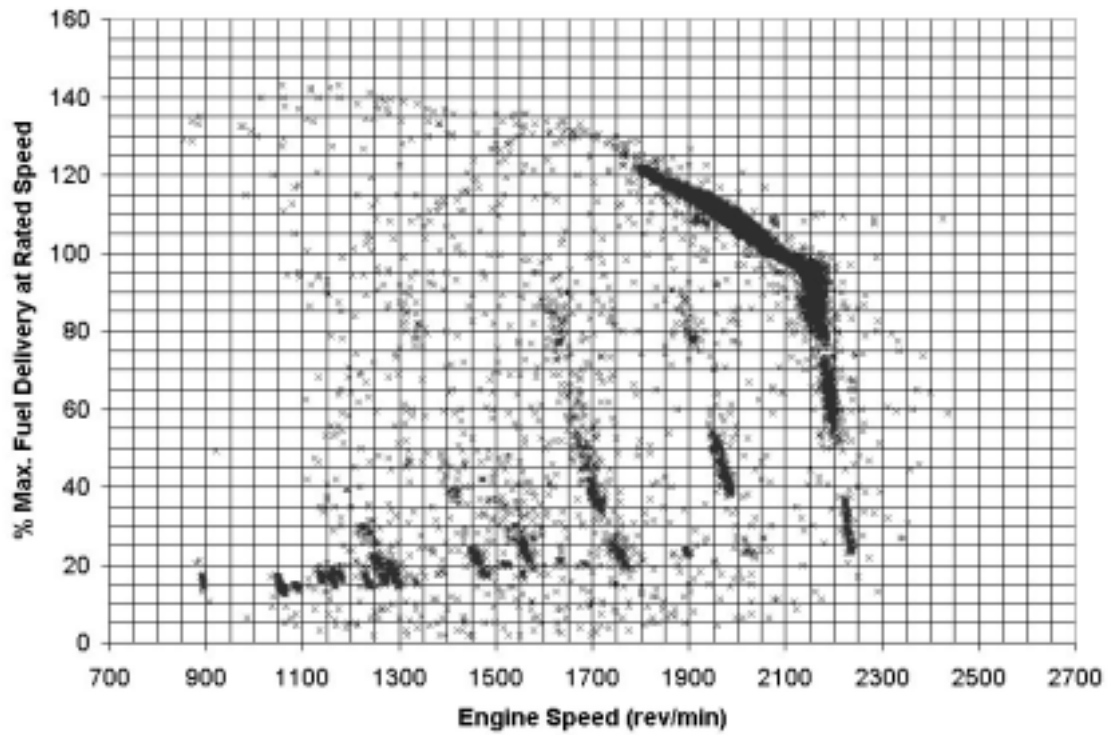


Figure 10. Variation of E Diesel fuel delivery with engine speed during a day of cultivation.

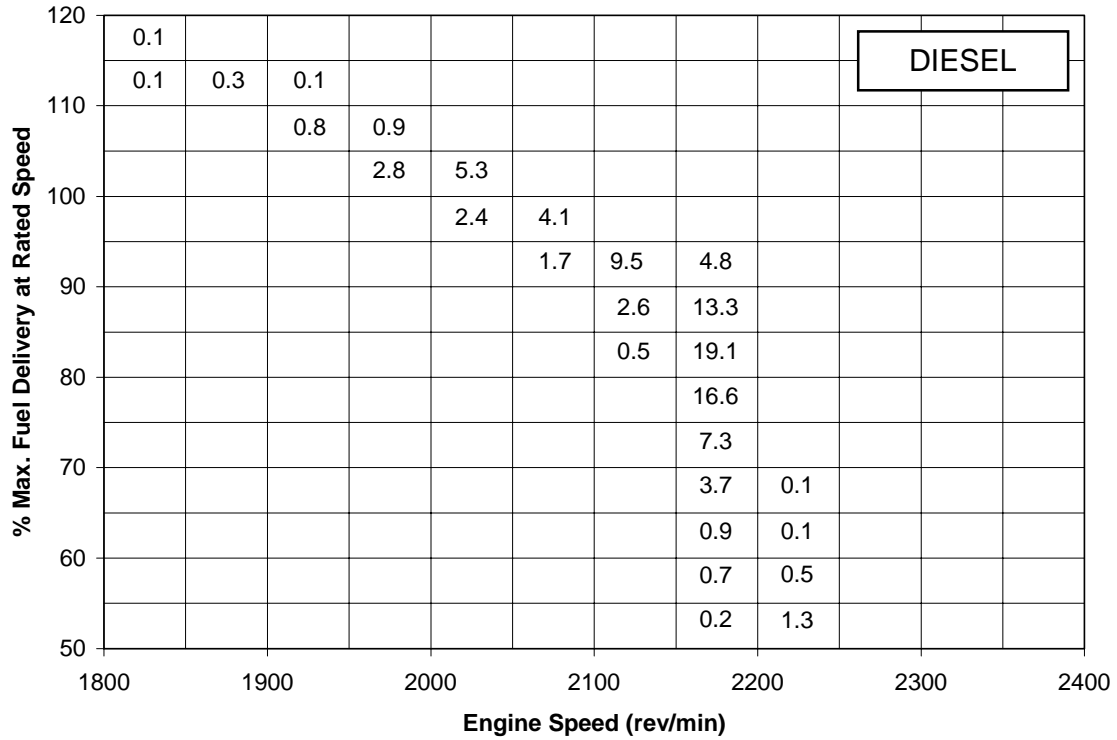


Figure 11. Percentage of time spent within speed-fuel delivery intervals on or near the maximum fueling limits of the engine run on no. 2 diesel fuel.

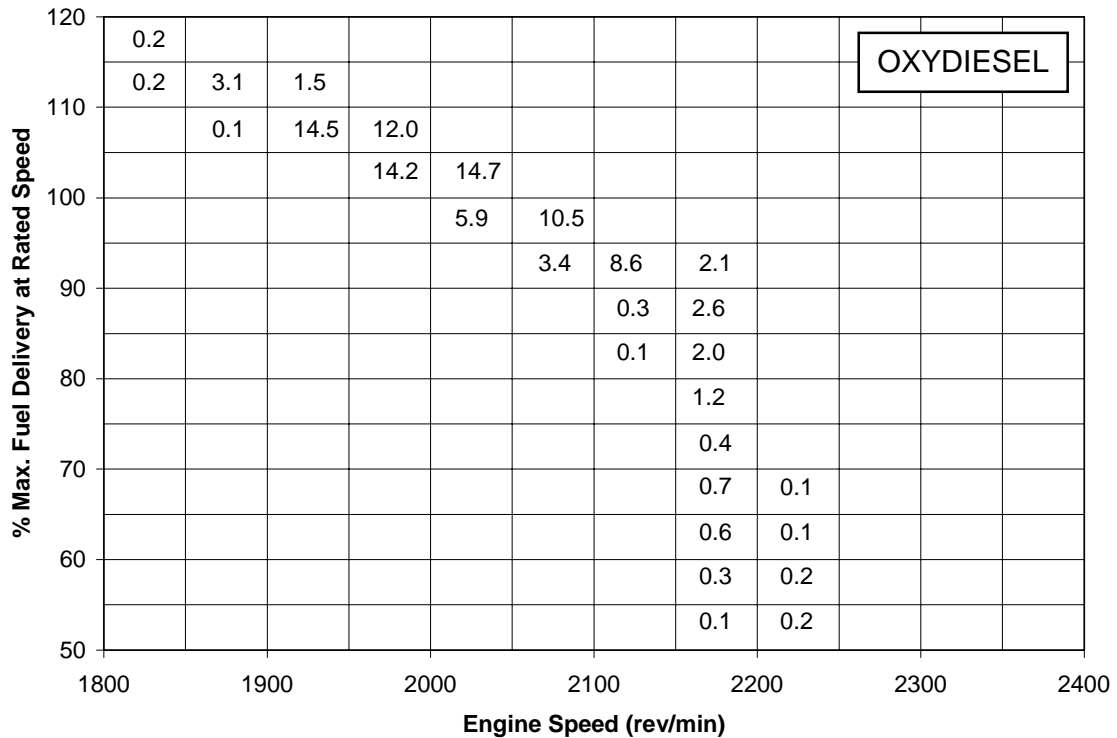


Figure 12. Percentage of time spent within speed-fuel delivery intervals on or near the maximum fueling limits of the engine run on E Diesel.

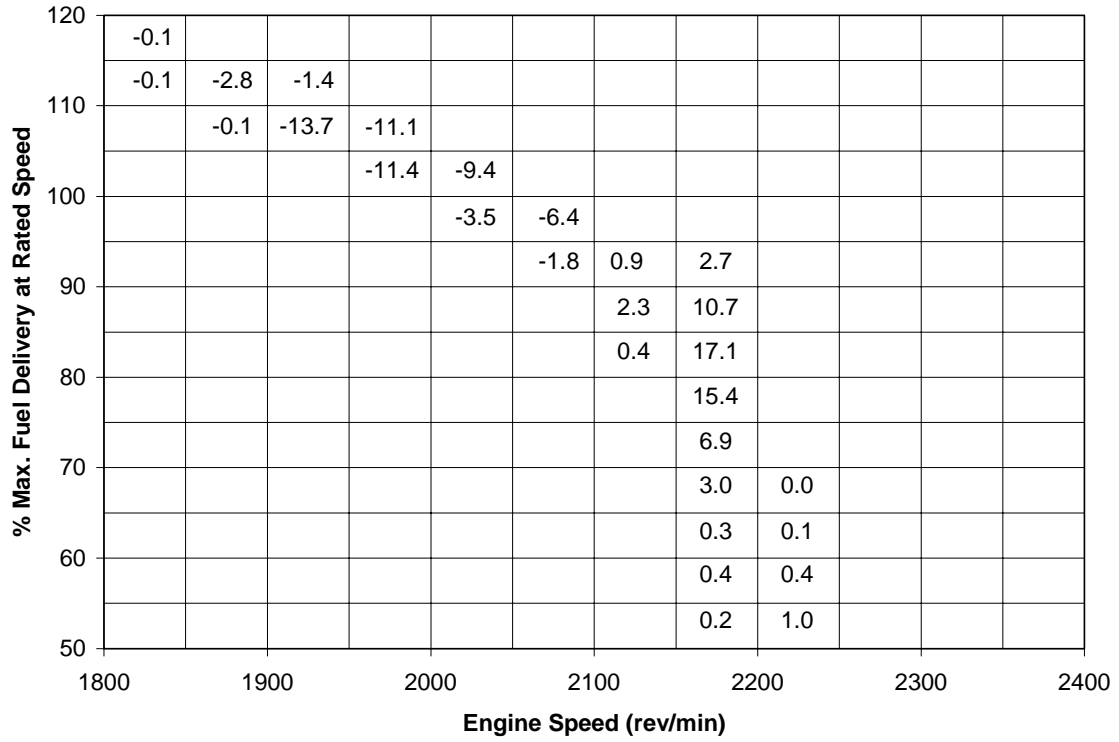


Figure 13. Differences in times shown in Figures 11 and 12 for corresponding intervals relative to diesel consumption.

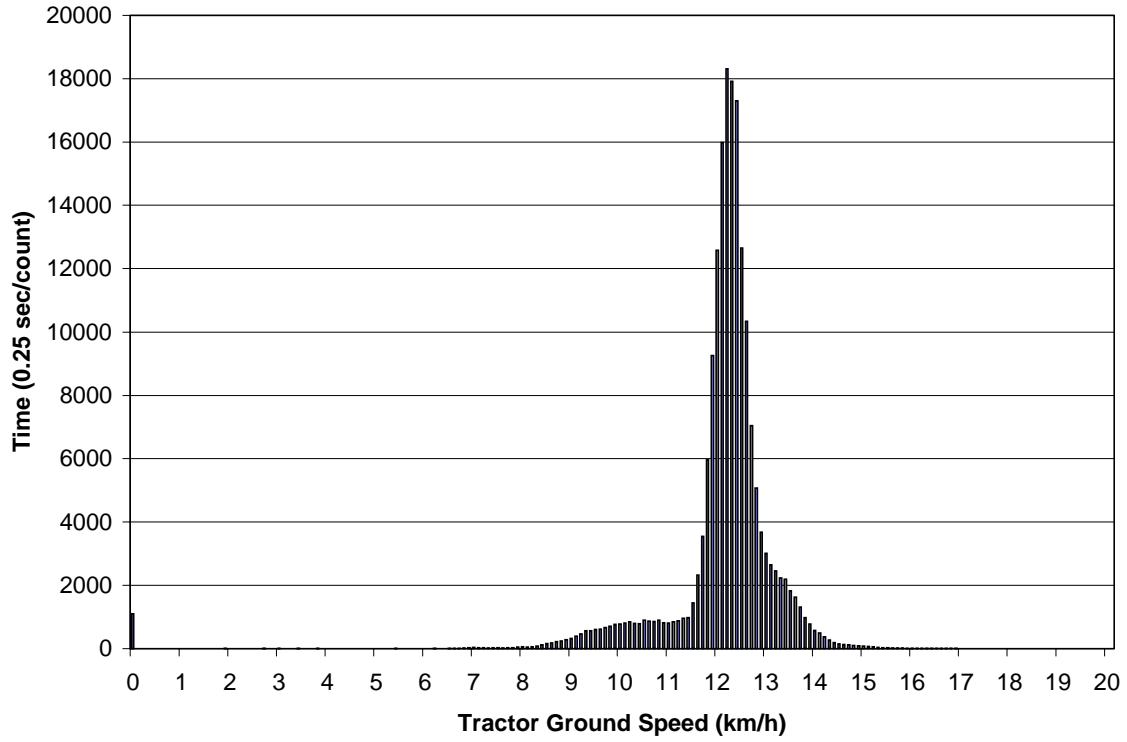


Figure 14. Histogram of diesel tractor ground speed while cultivating.

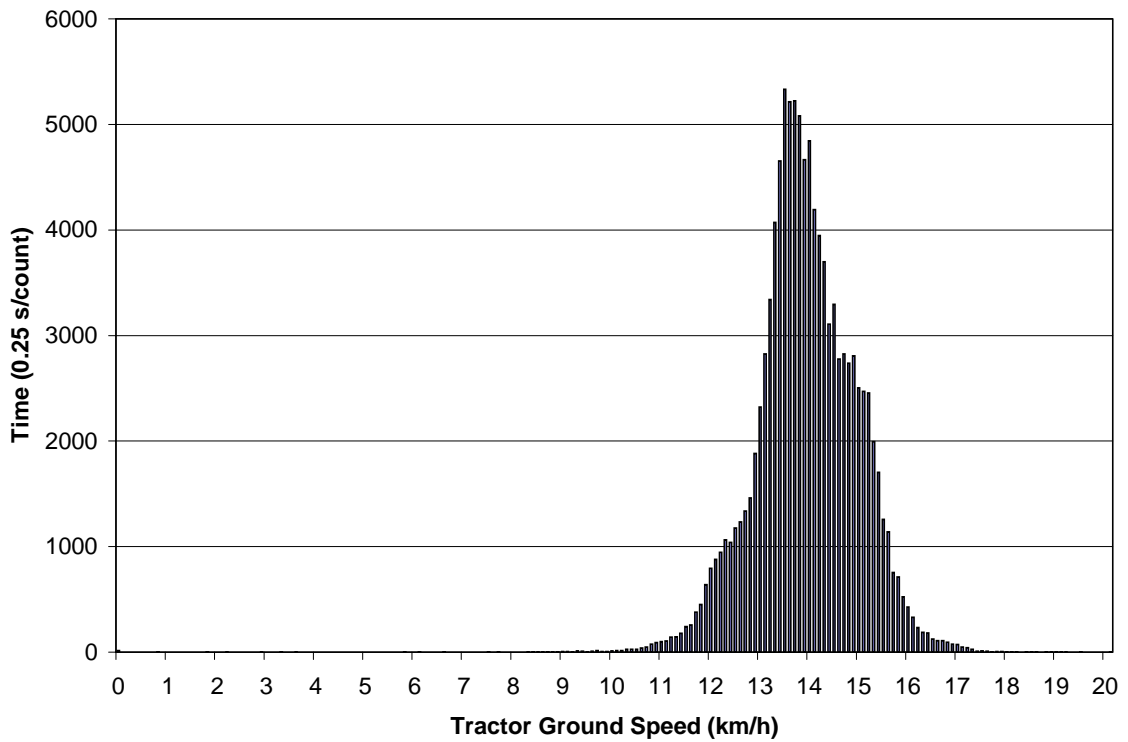


Figure 15. Histogram of E Diesel tractor ground speed while cultivating .

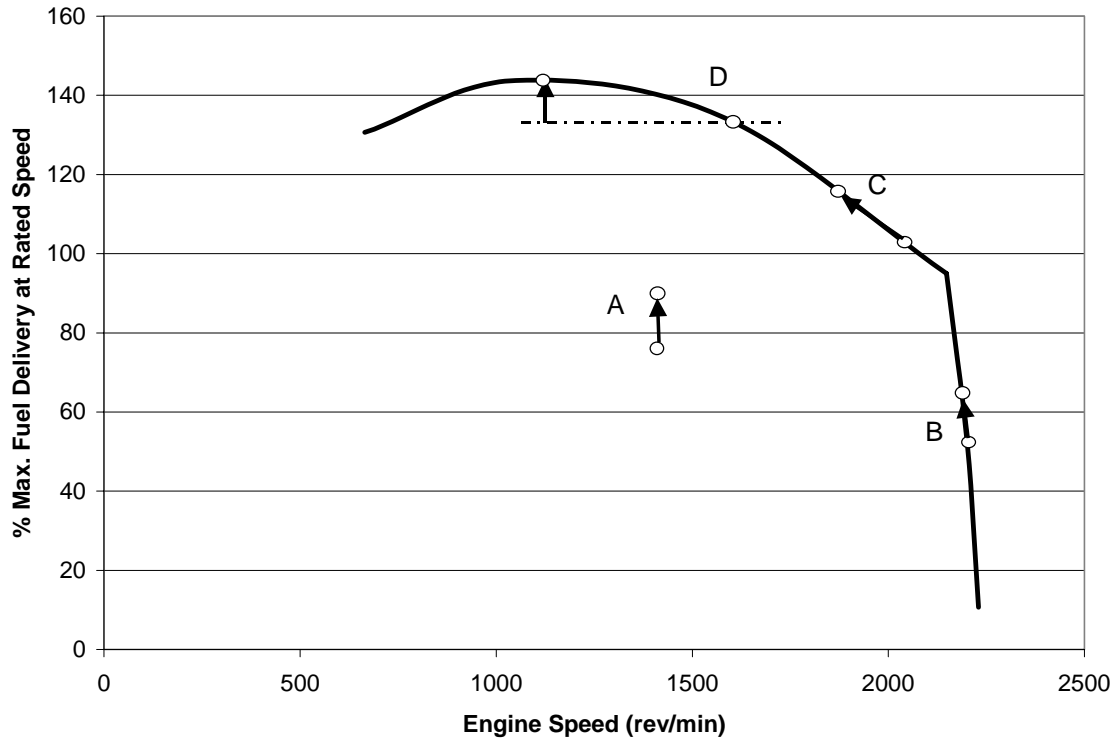


Figure 16. Schematic illustrating the shift in fuel delivery at different points in operating range of the engine when fueled with E Diesel as compared to diesel.

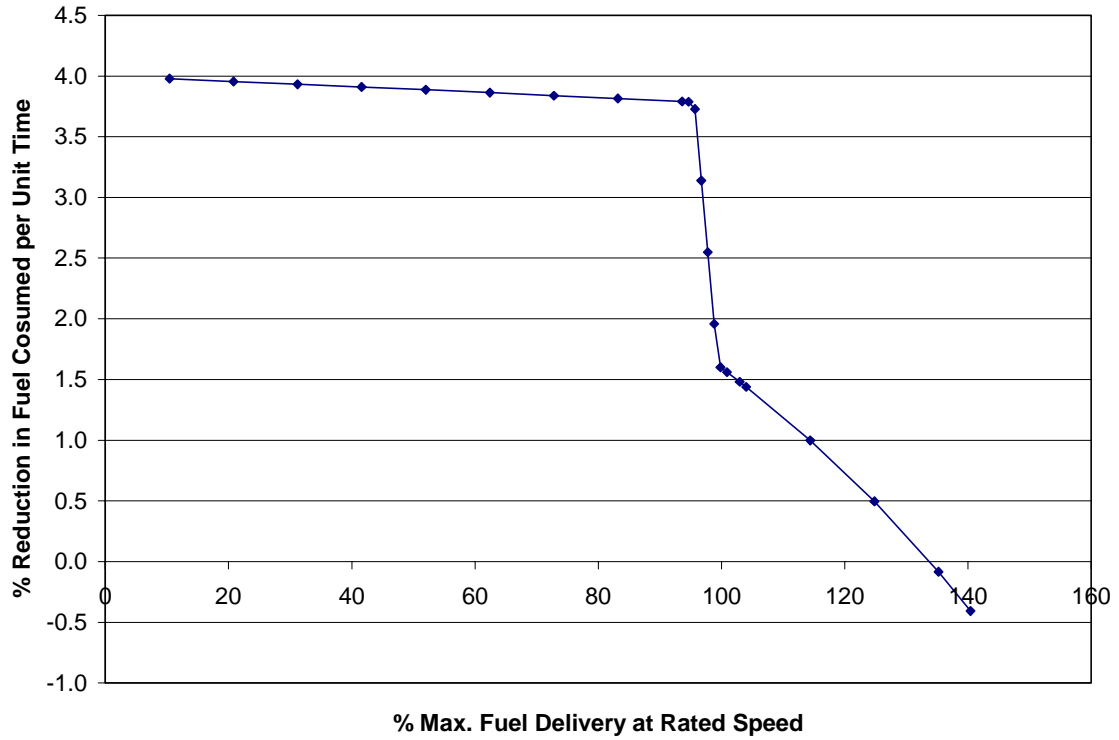


Figure 17. Percentage reduction in fuel consumed per unit time relative to the fueling level of the engine.

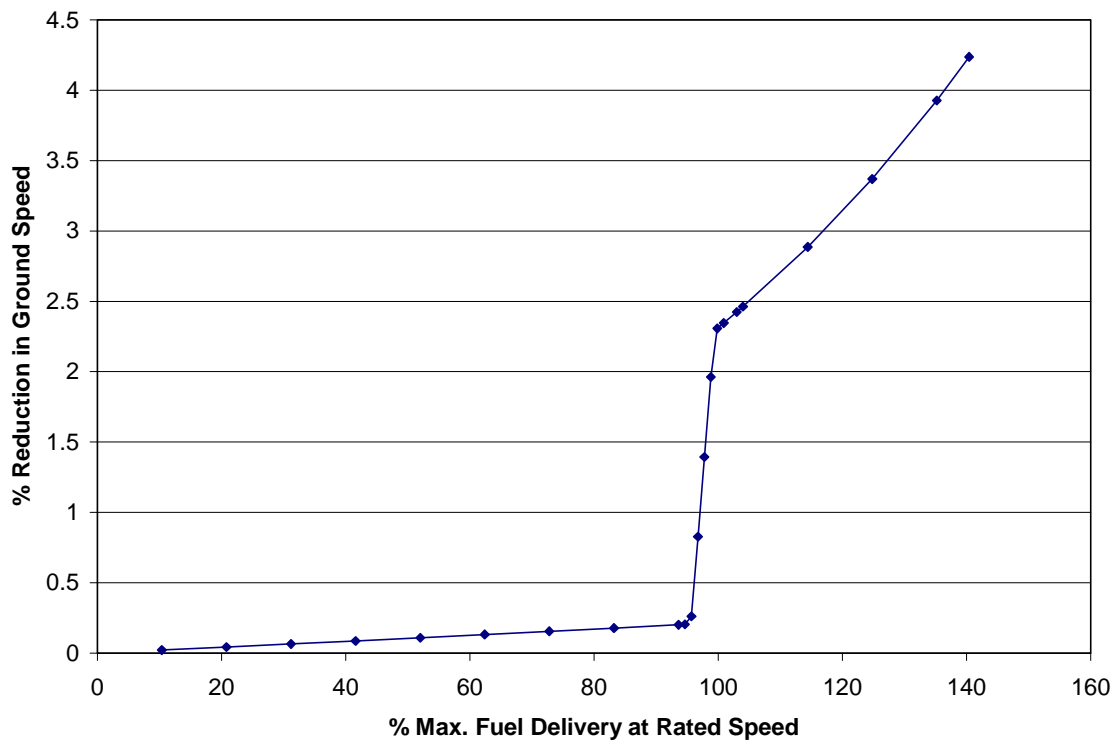


Figure 18. Percentage reduction in ground speed relative to the fueling level of the engine