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Bart A. Coffman
University of Nebraska-Lincoln

Michael F. Kocher
University of Nebraska-Lincoln, mkocher1@unl.edu

Viacheslav I. Adamchuk
University of Nebraska-Lincoln, viacheslav.adamchuk@mcgill.ca

Roger M. Hoy
University of Nebraska-Lincoln, rhoy2@unl.edu

Erin E. Blankenship
University of Nebraska-Lincoln, erin.blankenship@unl.edu

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Testing Fuel Efficiency of a Tractor with a Continuously Variable Transmission

B. A. Coffman, M. F. Kocher, V. I. Adamchuk, R. M. Hoy, E. E. Blankenship

ABSTRACT. *A John Deere 8530 IVT tractor (Waterloo, Iowa) with a continuously variable transmission (CVT) that could be operated in automatic (CVT) or manual (fixed gear ratio) mode was tested for fuel consumption at a setpoint travel speed of 9 km·h⁻¹ with 17 different drawbar loads. Linear regression analysis results showed that with the throttle set to maximum in both transmission modes, operating the tractor with the transmission in the automatic mode was more fuel efficient than operating with the transmission in the manual mode when the drawbar power was approximately 78%, or less, of maximum power. When load transition portions of the data were filtered out, there was no significant effect of load sequencing in the remaining data. On the other hand, there was a noticeable effect of travel direction which could occur due to a minor slope of the test track in the direction of travel. Testing of more tractor models from different manufacturers and at different travel speeds is needed to determine if these results can be applied to different tractor models produced by the same and/or other manufacturers.*

Keywords. Tractor testing, Continuously Variable Transmission (CVT), Fuel consumption, Fuel efficiency, Specific fuel consumption.

Agricultural equipment continues to become more sophisticated with advances in technology. Tractors are now available with continuously variable transmissions (CVTs), which, unlike traditional gear-set transmissions, have continuous gear ratio adjustability over the full range of power. The development of CVT transmissions is described in Renius and Resch (2005). Coupled with intelligent control systems, CVTs have the ability to adjust engine speed and transmission gear ratio together to operate at the point of maximum fuel efficiency for a given travel speed and power requirement. The concept of the engine-transmission control system of CVTs is based on the "shift up, throttle back" approach, also called "Gear Up and Throttle Down" as discussed in Grisso and Pitman (2009). If less than full power is needed, that power can be obtained with higher fuel efficiency at the same travel speed by lowering the gear ratio and reducing the engine speed. The CVT gives the operator the advantage of having the fuel savings of the "shift up, throttle back" operation without having to adjust and "experiment" to find the optimum transmission gear and throttle (operator's engine speed control lever) position every time the load changes in the field.

Standardized testing protocols are an important part of tractor performance evaluation. They ensure that tests done in different locations and/or at different times can be fairly compared. The Organisation for Economic Co-operation and Development (OECD) is one group that oversees the development and maintenance of world-wide tractor testing standards. Currently, tractors from around the world are tested for performance in accordance with the OECD Code 2 standard for official testing of agricultural and forestry tractors (OECD, 2007). However, OECD Code 2 does not have a procedure designed to examine the fuel efficiency of tractors with CVTs. All current CVT-equipped tractor models allow the transmission to be operated in a fixed gear ratio mode, and, therefore, tractors with CVT transmissions tested under OECD Code 2 have been operated in this fixed gear ratio transmission mode. Additionally, the bulk of performance results reported from an OECD Code 2 test are from maximum power tests. At maximum power, CVTs have little, if any, fuel efficiency advantage over traditional gear-set transmissions.

In practice, however, tractors are typically operated at power levels less than maximum, where the CVT tractor models have the potential to operate at higher fuel efficiencies than standard gear-set transmission tractors. Ricketts and Weber (1961) studied engine power output for farm operations. They determined that operations farmers generally called heavy work ranged in power from 97% to 56% of maximum tractor power. Several researchers who mapped soil mechanical resistance in production agriculture fields with corn-soybean rotations using either minimum- or no-till

The authors are **Bart A. Coffman, ASABE Member Engineer,** former Undergraduate Honors Student, **Michael F. Kocher, ASABE Member Engineer,** Associate Professor, **Viacheslav I. Adamchuk, ASABE Member Engineer,** Associate Professor, **Roger M. Hoy, ASABE Member Engineer,** Professor and Nebraska Tractor Test Laboratory Director, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska; and **Erin E. Blankenship,** Associate Professor, Department of Statistics, University of Nebraska-Lincoln, Lincoln, Nebraska. **Corresponding author:** Michael F. Kocher, Department of Biological Systems Engineering, 205 Chase Hall, University of Nebraska-Lincoln, Lincoln, NE 68583-0726; phone: 402-472-3949; fax: 402-472-6338; e-mail: mkocher1@unl.edu.

operations showed maps where the ratio of minimum-to-maximum soil strength values were 0.57 and 0.64 (Chung et al., 2008), 0.5 (Siefken et al., 2005), and 0.45 and 0.55 (Adamchuk et al., 2008). Therefore, a test procedure developed to measure fuel efficiency at power levels less than maximum would provide valuable information to consumers considering the purchase of a new tractor, and would be useful for manufacturers who want to highlight the fuel efficiency of their CVT-equipped tractor models when compared to traditional gear-set transmission tractors.

With the ultimate goal to establish a supplemental CVT transmission test procedure, the objectives of this research were 1) to determine the partial load level below which significant fuel savings occurs, and 2) to investigate the effect of power sequencing and other factors that may influence test outcomes.

MATERIALS AND METHODS

Tractors are used in a wide range of field applications. They provide power through power take-offs, hydraulics, and/or tractive (drawbar) means. Smaller tractors are used more frequently than larger tractors for non-drawbar applications such as stationary power take-off or loader work, while larger tractors are used primarily for drawbar work. With support from Deere & Company (Waterloo, Iowa), a large row-crop tractor [John Deere 8530 IVT (Deere calls their transmission design an IVT (Infinitely Variable Transmission), while the more general term for this transmission type is CVT.)] was used in this investigation. The tractor had a CVT transmission that could be operated in automatic (CVT), or manual (fixed gear ratio) mode, so both transmission types could be tested with the same tractor.

EXPERIMENTAL DESIGN

Since drawbar power is a product of travel speed and drawbar pull, varying either of the two parameters could provide the range of power to be evaluated. In this study, we decided to keep the setpoint travel speed at 9 km·h^{-1}, a common travel speed for crop production operations.

According to the Nebraska Tractor Test report (NTTL, 2006) the tractor used in this research provided 101.30-kN drawbar pull at maximum drawbar power (204.62 kW) when drawbar performance was tested in a ballasted configuration with the front wheel drive engaged and 1800-rpm engine speed. During the official full throttle test, the setpoint travel speed was 9.0 km·h^{-1}, while measured travel speed was 7.27 km·h^{-1}.

Based on this test, 101.30-kN drawbar load was assumed to represent the load for maximum available power. Generalization from soil mechanical resistance mapping research indicates tractors in field operations could easily be working at power levels ranging from 50% to 90% of full power. Therefore, we divided the range of loads between 50.65 and 91.17 kN into 16 equal intervals (2.53 kN or 2.5% of the maximum load), which produced 17 setpoint levels of load and power (assuming constant travel speed). While keeping the setpoint travel speed constant, all 17 load levels were tested according to three random sequences (fig. 1).

During the entire study, the tractor throttle was set to maximum to eliminate confounding between throttle setting and transmission control mode. To avoid operator bias in the experiment, the operator was not allowed to choose a different transmission ratio when there was a major change in drawbar pull. Tests with each of the three random load sequences were conducted with the tractor transmission set in each of the two transmission modes (automatic and manual). As described in more detail by Coffman (2007), the order of the six combinations of transmission modes and load sequences were randomized and the entire test was performed in two travel directions along the same track during two days. The experiment was conducted according to a split-plot design with the combination of transmission mode and load sequence serving as the whole-plot factor and travel direction being considered as the split-plot factor.

The testing was conducted on the west ramp of the Lincoln Municipal Airport. On 14 November 2006, with the tractor transmission set in automatic mode the tractor was tested according to sequence 1 first. Then, sequences 1 and 2 were applied to the tractor with the transmission set in manual mode. Two days later, the automatic transmission mode was
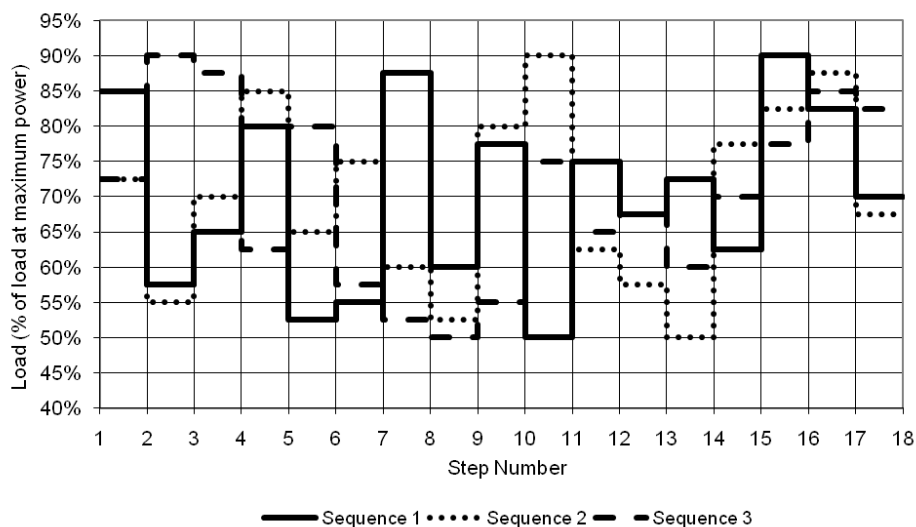

Figure 1. Three randomized load sequences.

tested according to sequences 2 and 3, and finally sequence 3 was applied to the tractor with the transmission set in manual mode.

Since about 1000 data points collected at 20 Hz were thought to be appropriate to assure sufficient time for the tractor engine-transmission to reach steady-state, the track was divided into 122-m long intervals that would take about 49 s to travel if the 9.0 km·h⁻¹ (2.5 m·s⁻¹) travel speed was maintained. Since the track was 732 m long, six different load levels could be applied in one pass. Therefore, the 17 setpoint loads in each sequence were split into three groups (six, six, and five loads, respectively), and applied in both directions when traveling back and forth.

TEST EQUIPMENT

The test was conducted using the NTTL drawbar load car. The load car was equipped with LabVIEW (National Instruments Corp., Austin, Tex.) software for data acquisition and load control. For this study, the software was modified to automatically apply the prescribed drawbar load step changes based on the distance traveled and according to the three randomized loading sequences.

Drawbar load was measured using a hydraulic cylinder in the pull linkage between the tractor and the load car. Travel speed was obtained with an un-powered "fifth" wheel on the load car. The engine speed and tractor wheel speed were recorded as well. The volumetric flow rate of fuel used by the tractor was measured using a positive displacement flow meter and was converted into a mass flow rate with the specific gravity of the fuel (840 g·L⁻¹). In addition, various measurements of temperature were recorded, including: engine oil, engine coolant, hydraulic oil, fuel inlet, fuel return, and intake manifold. The tractor's turbocharger boost pressure was measured and recorded as well.

DATA ANALYSIS

The data from each 122-m long portion of the test track included a transient part immediately following the step load change and a steady-state part. As an example, specific fuel consumption response to a step change of drawbar load is shown in figure 2. Based on preliminary data analysis, it was determined that the transient period varied in length with the magnitude of the load change and variable measured. The longest transition distance observed was 88 m. Therefore data from the last 272 measurements (34 m at 2.5 m·s⁻¹ and
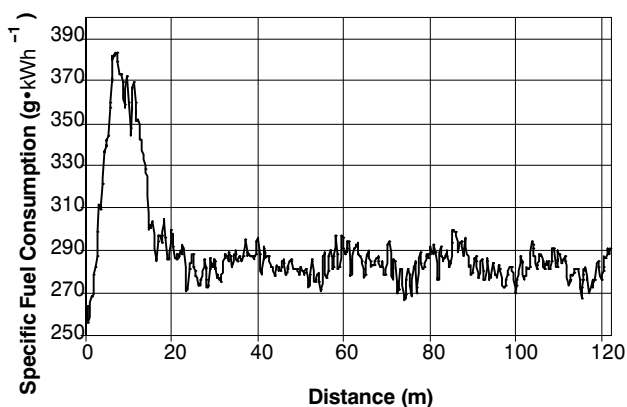
20-Hz sampling rate) for each load setting were averaged to obtain steady-state estimates.

Originally, steady-state average fuel consumption values were to be analyzed using an ANOVA approach according to the experimental design. However, it was noted that the replicated load measurements did not provide exactly the same load settings. Furthermore, there were minor yet significant variations in actual travel speed among the 17 load settings. The average travel speed was 8.62 km·h⁻¹ (maximum of 8.95 km·h⁻¹, minimum of 7.56 km·h⁻¹, standard deviation of 0.206 km·h⁻¹) compared to the setpoint travel speed of 9.0 km·h⁻¹. In addition, the specific fuel consumption is frequently represented as a non-linear function of drawbar power (*ASABE Standards,* 2008) while hourly fuel consumption appears to be proportional to tractor drawbar power. Therefore, the relationship between the steady-state averages of fuel consumption and drawbar power (product of measured values of drawbar load and travel speed) was obtained using a linear regression analysis. The following model was implemented:

$$Q_i = \beta_0 + \beta_1 \cdot P_i + \beta_2 \cdot M_i + \beta_3 \cdot P_i \cdot M_i + \varepsilon_i \qquad (1)$$

where Q = measured fuel consumption (kg·h⁻¹), P = actual drawbar power (kW), M = mode of operation (0 – automatic and 1 – manual), and ε = random error.

This regression model allowed us to analyze the differences between predicted fuel consumption when the tractor was operated in automatic versus manual mode ($\alpha = 0.05$) for each power level observed during this study to determine the power level below which the mode of operation had a significant effect on fuel consumption. In addition, residual analyses were conducted to investigate the effect of travel direction and load sequence on fuel consumption. When evaluating how much the previous load might influence fuel consumption measurements, the first load setpoint within each 6- or 5-point group was omitted to eliminate any turn-around effect.

After the regression analysis was completed, hourly fuel consumption predictions from the regression equations were compared with results from the fuel consumption portion of the drawbar power part of the OECD Code 2 test for the tractor (NTTL, 2006). This use of the prediction equation assumed that fuel consumption was dependent only on drawbar power level, as the tractor weight, travel speed, and load were different for these two tests. The comparison was made for the full power, and 75% of pull at maximum power loads, as the 50% of pull at maximum power load in the unballasted configuration was outside the power range for which the regression equation was developed. Fuel consumption values from the reduced pull tests with full engine speed were compared to predictions using the manual transmission mode as those were corresponding operating conditions. The fuel consumption reported from the reduced pull test with reduced engine speed was compared to a prediction using the automatic transmission mode as those were corresponding operating conditions.

Figure 2. Specific fuel consumption response for a 122-m travel interval.

RESULTS AND DISCUSSION

As shown in figure 3a, regression analysis of the relationship between fuel consumption and drawbar load

produced the following model with a coefficient of determination $R^2 = 0.99$ and a standard error of 0.50 kg·h^{-1}:

$$\hat{Q} = 9.1 + 0.215 \cdot P + 9.9 \cdot M - 0.052 \cdot P \cdot M \qquad (2)$$

where $\hat{Q}$ represents the predicted fuel consumption (kg·h^{-1}). Separating the modes of transmission operation, this model can be rewritten as:

$$\hat{Q} = \begin{cases} 9.1 + 0.215 \cdot P & \text{for CVT transmission in automatic mode} \\ \\ 19.1 + 0.163 \cdot P & \text{for CVT transmission in manual mode} \end{cases} \qquad (3)$$

In this case, shown in figure 3b, predicted specific fuel consumption $(\hat{q})$ was determined as:

$$\hat{q} = \begin{cases} 0.215 + \dfrac{9.1}{P} & \text{for CVT transmission in automatic mode} \\ \\ 0.163 + \dfrac{19.1}{P} & \text{for CVT transmission in manual mode} \end{cases} \qquad (4)$$

Based on the analysis of the difference between fuel consumption with the CVT transmission in manual and automatic modes, fuel performance was similar at high drawbar power levels and the benefit of the automatic CVT mode increased at lower power levels (fig. 4). When comparing the value of the predicted fuel consumption difference ($\hat{Q}$ for manual mode minus $\hat{Q}$ for automatic mode) with the 95% confidence interval for this difference, the automatic mode of the CVT transmission significantly reduced fuel consumption below 160 kW (215 hp), which is 78% of the maximum drawbar power obtained with compara-

ble travel speed and weight (ballasted) during the official OECD test (206.04 kW at 8.96 km·h^{-1}). Using these predicted fuel consumption equations, with the tractor at full throttle and loaded at 100 kW (approximately 50% of full drawbar power) and the transmission in the manual mode, the predicted fuel consumption would be 35.4 kg·h^{-1}. With the tractor at full throttle with the same load and the transmission in the automatic mode, the predicted fuel consumption would be 30.6 kg·h^{-1}, or 13.6% less than with the transmission in the manual mode.

Testing the standard gear-set transmission (CVT in manual mode) with the throttle set at maximum in comparison to the CVT transmission in automatic mode at partial loads determines the maximum difference in fuel use. Operators proficient at using their standard gear-set transmissions with the shift up and throttle back technique save fuel with this technique in comparison to operating with the throttle set at maximum. The fuel savings these operators would experience when switching from their standard gear-set transmissions operated with the shift up and throttle back technique to a CVT transmission operated in the automatic mode would be smaller than the fuel savings determined using the approach described in the previous paragraph.

Table 1 shows fuel consumption predictions from equation 3 compared with the results from the drawbar performance (unballasted) fuel consumption characteristics portion of the report of the OECD Code 2 test (NTTL, 2006). The predicted hourly fuel consumption values were within 2% of the hourly fuel consumption measured during the fuel consumption portion of the drawbar power part of the OECD Code 2 test for this tractor. This indicates good agreement between the results of these two tests, despite the differences in tractor weight, travel speed, and load.

Based on the analysis of the fuel consumption prediction errors (residuals), there was no discernable trend in error estimates with respect to drawbar power (fig. 5a). On the other hand, there appeared to be a difference of 0.54 kg·h^{-1} between average fuel consumption error when traveling North versus South. This was attributed to a slight (about 1%) upward slope from South to North. From a practical
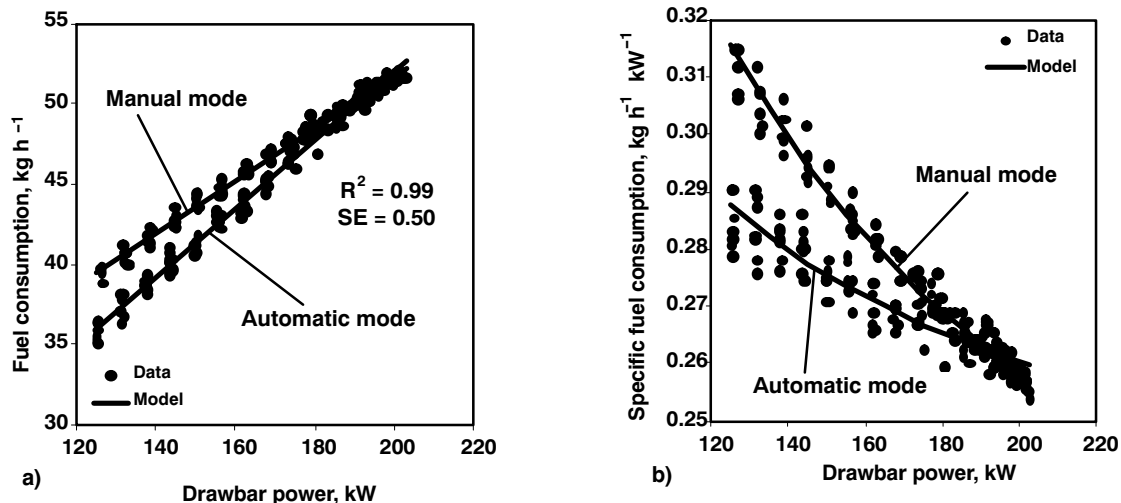
Figure 3. Hourly (a) and specific (b) fuel consumption response to drawbar power for a John Deere 8530 IVT tractor with the transmission in automatic and manual mode.
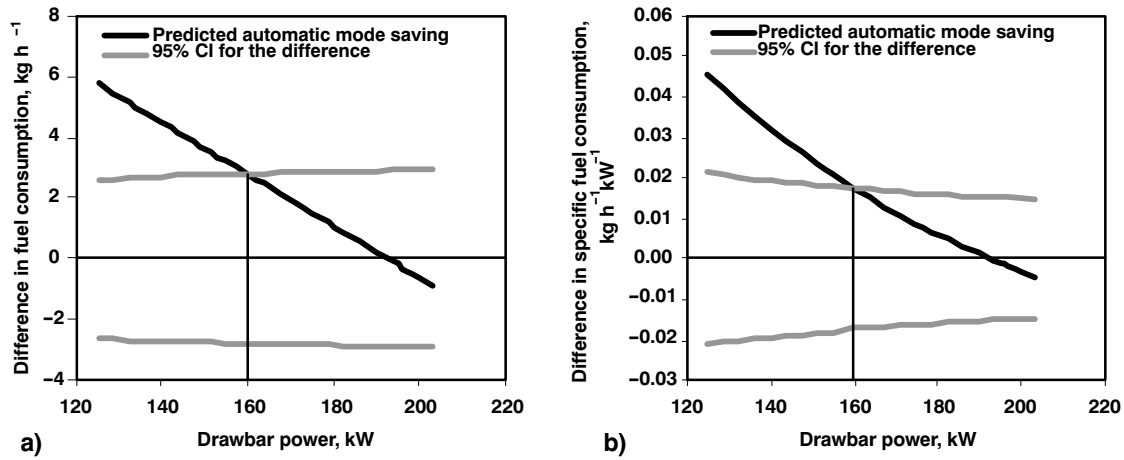
Figure 4. Difference in hourly (a) and specific (b) predicted fuel consumption response to drawbar power between manual and automatic CVT transmission modes. The difference was significant below 160-kW (215-hp) drawbar power.

Table 1. Fuel consumption from the fuel consumption portion of the drawbar power part of the OECD Code 2 (unballasted) test (NTTL, 2006) compared to fuel consumption predictions from the CVT fuel efficiency (ballasted) test.

OECD Code 2 Fuel Consumption Drawbar Performance (unballasted)				CVT Fuel Efficiency Test (ballasted)		
	Power (kW)	Travel Speed (km·h⁻¹)	Fuel Consumption (kg·h⁻¹)	CVT Transmission Mode Used for Fuel Consumption Prediction	Fuel Consumption Predicted from CVT Fuel Efficiency Test (kg·h⁻¹)	Percent Difference of Predicted Fuel Consumption Compared to Code 2 Fuel Consumption (%)
Maximum power	179.23	9.62	48.2	Manual	48.3	0.21
75% of pull at maximum power	139.51	9.98	41.3	Manual	41.8	1.32
75% of pull at maximum power with reduced engine speed	139.24	9.99	38.6	Automatic	39.0	1.21

viewpoint, this suggests the need to assure symmetry (replication in both travel directions) in a future test protocol if there is a terrain feature that could affect tractor performance.

Finally, as shown in figure 5, there was no detectible trend in fuel consumption prediction errors with respect to the change in drawbar power (difference between current and previous drawbar power level). This means that once the
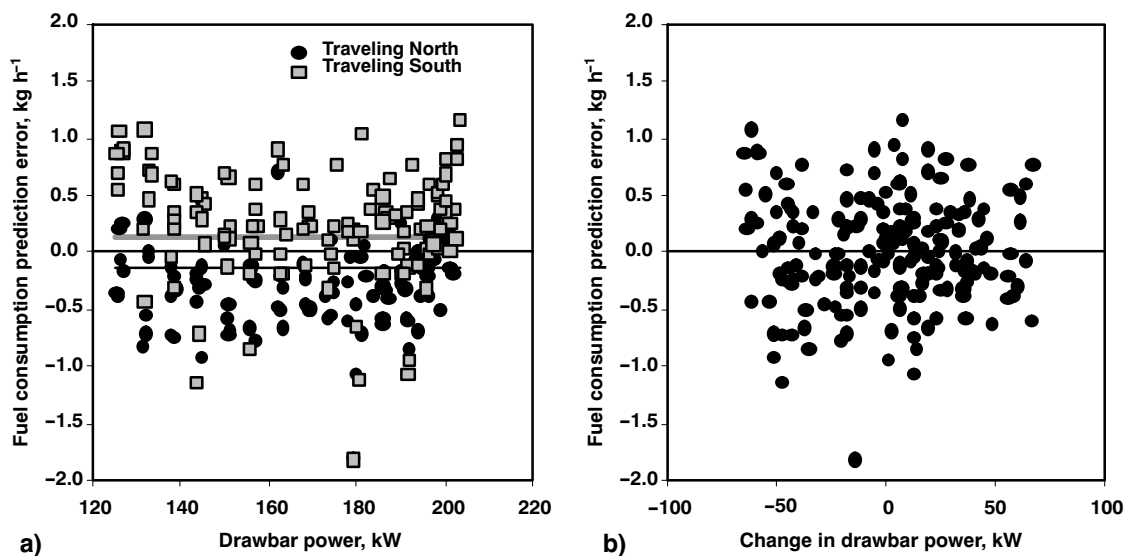

Figure 5. Fuel consumption prediction error analyses with respect to drawbar power and travel direction (a) as well as change in drawbar power (b).

transitional portion of the performance response is removed, the order in which the different load levels are applied does not significantly affect fuel efficiency.

Because the relationship between fuel consumption and drawbar power was linear and there was no significant effect of the order in which the power levels were applied, it appears that the minimum number of power levels required for the test is two power levels representing the range of anticipated field load for each travel speed.

It should be noted that this experiment was conducted at one setpoint travel speed and on one model of tractor. Additional testing of more tractor models from more manufacturers at different travel speeds is needed to determine if these results apply in general, or if they are specific to particular models and/or from specific manufacturers.

CONCLUSIONS

The results indicated that the CVT automatic transmission was more fuel efficient than a standard gear transmission with a finite number of fixed gear ratios when the drawbar power was 78% or less of maximum power and the throttle was set to maximum. This result was expected. When less power is needed, the transmission controller shifts the transmission up and reduces the engine speed to maintain a constant travel speed. This employs the "shift up, throttle back" principle of tractor operation for improved fuel efficiency. Therefore, a test procedure to quantify the fuel efficiency of CVT tractors is a realistic and worthy goal. The lack of statistical significance of load order was encouraging as well. This implies that as long as the test procedure allows determination and use of the steady-state fuel consumption value at each power level, the order in which the specific load levels are used in the test does not affect the final results. While the results of this testing are promising, more work needs to be done. A different tractor, perhaps from a different manufacturer or of a different size, may yield different results. Also, this test only considered a single travel speed, so there is no information on the effect travel speed may have on the fuel efficiency of CVT and gear-set transmissions.

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