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FUEL CONSUMPTION MODELS FOR TRACTOR TEST REPORTS

M. F. Kocher, B. J. Smith, R. M. Hoy, J. C. Woldstad, S. K. Pitla

ABSTRACT. *Five models for estimating fuel consumption for agricultural tractors with partial drawbar loads were compared. Data were collected from eight John Deere tractors, JD 7230R (e23), 7250R (e23), 7270R (e23), 7290R (e23), 8320R (16 speed), 7290R (IVT), 8345RT (IVT), 8370R (IVT), on the drawbar test track at the Nebraska Tractor Test Lab. The tractors were tested with seven load levels per speed at three different travel speeds as close as possible to 7.5, 10, and 13 km h^{-1}. The IVT tractors were operated in auto mode, and the geared tractors were shifted up three gears and throttled back to the same travel speeds as obtained with the original gear (before shifting up) at maximum drawbar power. The seven loads were selected at 30%, 40%, 50%, 60%, 70%, 75%, and 80% of the drawbar pull at maximum power and rated engine speed at the selected travel speed. Model 1 (fuel consumption as a linear function of drawbar power on concrete), currently used in OECD Code 2, Section 4.4.8, resulted in a separate equation for each speed tested. When regression mean square errors were used for statistical comparison of the five fuel consumption models, model 5 (fuel consumption as a linear function of drawbar power and travel speed on concrete, and engine speed) was not significantly different from the model currently used in OECD Code 2, Section 4.4.8 (model 1, fuel consumption as a linear function of drawbar power on concrete, with separate equations specific to the three speeds tested). The simplest model (model 2), which used a single equation for fuel consumption as a linear function of drawbar power on concrete over the range of speeds tested, had significantly higher regression mean square errors compared to model 1 for half of the eight tractors tested. Model 5 (fuel consumption as a linear function of drawbar power and travel speed on concrete, and engine speed) was determined to be the best of the five models for estimating fuel consumption, with a single equation applicable over the range of speeds tested. Model 3 (fuel consumption as a linear function of drawbar power and travel speed on concrete) provided a statistically equivalent fuel consumption estimate to model 5 without the drawback of requiring an input value for engine speed.*

Keywords. *Drawbar power, Engine speed, Fuel consumption, Model, Partial drawbar loads, Tractors, Travel speed.*

According to the U.S. Department of Energy (USDOE, 2016), energy efficiency is one of the easiest and most cost-effective ways to combat climate change, improve air quality, improve the competitiveness of our businesses, and reduce energy costs for consumers. The agricultural industry in the U.S. is a significant consumer of energy, particularly from petroleum products. Reduction in the use of petroleum products and increasing efficiency of equipment has been a major focus since the inception of petroleum-powered machinery.

The agricultural sector is the largest consumer of off-highway diesel, accounting for 5.4% of the total use in the U.S. in 2010 (Hoy et al., 2014). Considering that tractors are the primary power unit for most mechanized agricultural operations, much of the focus on increasing efficiency has been directed toward tractors.

Currently, there are two main approaches to fuel conservation when considering tractor power transmission systems and operation: continuously variable transmissions (CVT) and the shift up throttle back (SUTB) methodology, also known as gear up and throttle down (GUTD) (Grisso et al., 2014). CVT transmissions use computer-controlled technology to select the optimal combination of engine speed and gear ratio to supply the power necessary, while still maintaining the desired travel speed with high fuel efficiency (Renius and Resch, 2005). The SUTB methodology is used when less than full power is required (Grisso et al., 2014). The operator controls the transmission and throttle so the tractor operates in as high a gear and as low an engine speed as practical while still delivering the required power at the desired travel speed with high fuel efficiency.

The Nebraska Tractor Test Lab (NTTL), following OECD Code 2 (OECD, 2016) mandatory test procedures, mainly tests the efficiency of tractors at full power, and only a small amount of data is collected at partial drawbar loads where the higher fuel efficiency of CVT transmissions and SUTB would be obtained. However, many operations do not require maximum power from the tractor. The actual power demands vary from field to field, from operation to operation, and within the field during almost all operations. Given the interest in reducing fuel consumption, more information collected during OECD Code 2 tractor tests on the fuel savings that could be obtained as a result of CVT transmissions and SUTB operation would be welcomed.

An optional test in OECD Code 2 Section 4.4.8, Fuel consumption test at varying drawbar loads, outlines a test pro-

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cedure for collecting data on fuel consumption at varying drawbar loads at less than maximum power using SUTB or CVT transmissions (OECD, 2016). This test includes three travel speeds (7.5, 10, and 13 km h^{-1}) and five drawbar loads (30%, 40%, 50%, 60%, and 75% of the pull at maximum power) for each travel speed as was determined during the official testing for maximum power, with the tractor unballasted, front drive engaged (if applicable), and at rated engine speed. This approach presents a separate equation for estimating fuel consumption at each travel speed tested. Reporting fuel consumption estimation equations for specific speeds limited the usefulness of the equations. A tractor fuel consumption model applicable over the range of speeds for which a particular tractor was tested would be preferred over three models, each applicable only at a specific speed. The usefulness of these models is limited by the need for reasonable estimates of the required input data for the models. The primary value of these models may be in using the tractor test reports to allow comparison of fuel consumption estimates for different tractors under the same operating conditions. These comparisons may be performed by those considering the purchase of a tractor.

LITERATURE REVIEW

Several models for tractor fuel consumption are available in the literature. ASABE Standard EP496.3, clause 6.3.2.1.1 (ASABE, 2015a) presents the following equation to estimate average annual gasoline consumption by tractors, and notes that diesel consumption on a volumetric basis is approximately 73% of gasoline consumption:

$$Q_{avg} = 0.305 \times P_{pto} \tag{1}$$

where

Q_{avg} = average gasoline consumption (L h^{-1})

P_{pto} = maximum PTO power (kW).

This model is suggested for estimating average gasoline (or diesel) consumption by a tractor for a whole year, not for estimating consumption for a particular operation. Clause 6.3.2.2 in EP496.3 points to ASABE Standard D497.7, clause 3 (ASABE, 2015b) for estimating fuel consumption for a specific operation. It is interesting to note that the last test of a tractor fueled with gasoline conducted at the NTTL was performed in 1978. The equations for diesel tractor engines in D497.7 clause 3.3.3 can be shown as equivalent to equations 19 and 20 in Grisso et al. (2004) based on over 20 years (1979 through 2002) of NTTL reports. ASABE Standard D497.7 presents two definitions and two equations for determining fuel consumption of engines at specific loads, and with the engine at rated speed, or less than rated speed. The two equations are given below:

$$X = \frac{P}{P_{rated}} \tag{2}$$

where

X = fraction of equivalent PTO power available

P = equivalent PTO power required by current operation (kW)

P_{rated} = rated PTO power available (kW).

$$N = \frac{n_{PT}}{n_{FT}} \tag{3}$$

where

N = ratio of partial throttle engine speed to full throttle engine speed at operating load

n_{PT} = partial throttle engine speed (rpm)

n_{FT} = full throttle engine speed (rpm).

An equation for a partial throttle multiplier (PTM) is used to account for changes in fuel consumption when using the SUTB approach to reduce fuel consumption:

$$\text{PTM} = 1 - (N - 1) \cdot (0.45 \cdot X - 0.877) \tag{4}$$

The following equation from ASABE Standard D497.7 is specifically for diesel fuel, for estimating the specific fuel consumption on a volume basis (SFC_v) in units of L kW^{-1} h^{-1}:

$$\text{SFC}_v = \left(0.22 + \frac{0.096}{X}\right) \cdot \text{PTM} \tag{5}$$

Clause 6.3.2.2 in ASABE Standard EP496.3 provides an equation for estimating the fuel use for a specific operation and notes that a fuel consumption of 15% above that for Nebraska Tractor Tests is included for loss of efficiency under field conditions. That equation, written with the variables defined above, is as follows:

$$Q_i = SFC_v \cdot X \cdot P_{rated} \tag{7}$$

where Q_i is the fuel consumption for a specific operation (L kW^{-1} h^{-1}).

Grisso et al. (2008) extended the work of Grisso et al. (2004) and developed a method to determine specific coefficients from data in the NTTL report for a fuel consumption model for a specific tractor. The model that Grisso et al. (2008) developed was as follows:

$$Q = (aX + b) \cdot [1 + (cXN_{red} - dN_{red})] \cdot P_{rated} \tag{8}$$

where

Q = fuel consumption (L h^{-1})

a, b, c, d = coefficients determined from results in the NTTL report for the specific tractor

X = ratio of equivalent PTO power to rated PTO power (decimal)

N_{red} = engine speed reduction from rated speed (%)

P_{rated} = rated PTO power for the tractor (kW).

Using variable definitions from equation 3 above, N_{red} can be determined as follows:

$$N_{red} = (1 - N)\ 100\% \tag{9}$$

These forms of models for fuel consumption of tractors performing specific operations included terms for the load power and engine speed.

Coffman et al. (2010) compared the fuel consumption of a tractor with a CVT transmission operating at a single speed with partial loads ranging from 50% to 90% of full power in manual and auto mode. They concluded that there was a reduction in fuel consumption when the tractor was operated in auto mode at loads of 78% or less of the pull at maximum power, compared to operation in manual mode at full throttle. The model used for fuel consumption (mass rather than volumetric) was linear, with a coefficient of determination (r^2) of 0.99, with intercept and slope values for the auto mode and different intercept and slope values for the manual mode at full throttle.

Howard et al. (2013) expanded the testing of fuel efficiency of tractors at partial load to include both CVT tractors in auto mode and geared tractors in SUTB mode. Their study included two tractors, a John Deere 8295R IVT (CVT transmission) and a John Deere 8295R PowerShift (geared transmission), tested at three speeds between 5 and 11 km h^{-1}. Six loads were tested from 30% to 80% in 10% increments of the pull at maximum power at the selected travel speed. For each transmission operating mode (CVT, gear transmission at full throttle, and SUTB), the model developed had fuel consumption as a linear function of drawbar power, with a separate equation determined for each speed. Examination of the fuel consumption models reported by Howard et al. (2013) suggested that within each transmission operating mode, the slopes of fuel consumption with power appeared to be similar, and the intercepts appeared to be linearly related to travel speed.

OECD Code 2 Section 4.4.8, Fuel consumption test at varying drawbar loads (OECD, 2016) used the same model to report tractor fuel consumption as Howard et al. (2013). For each tractor tested, reporting a separate fuel consumption estimation equation for each of the three test speeds limits the usefulness of the equations. A single tractor fuel consumption equation applicable over the range of speeds tested would be preferred to three equations, each applicable for a specific speed.

Smith (2015) studied fuel consumption measurements from eight tractors at partial drawbar loads from 30% to 80% of maximum drawbar power at rated engine speed with speeds of approximately 4, 7.5, 10, and 13 km h^{-1}. Three models for fuel consumption were compared: fuel consumption as a linear function of drawbar power with a separate equation for each speed, fuel consumption as a linear function of drawbar power and travel speed, and fuel consumption as a linear function of drawbar power and engine speed. The model with fuel consumption as a linear function of drawbar power with a separate equation for each speed was slightly more accurate than either of the other models. The other two models had an advantage in that a single equation was applicable over the range of speeds tested, rather than a separate equation for each speed, applicable only for the speed tested. For six of the eight tractors, the slope of fuel consumption with travel speed (second model) was significant, and coincidentally, for six of the eight tractors, the slope of fuel consumption with engine speed (third model) was significant. There were no significant differences among the fuel consumption estimations between the second and third models.

These references indicated that tractor fuel consumption is strongly related to power. Howard (2010), Howard et al. (2013), and Smith (2015) indicated that there was also an effect of travel speed on tractor fuel consumption. The ASABE Standards (ASABE, 2015a, 2015b), Grisso et al. (2004, 2008), and Smith (2015) indicated that there was an effect of engine speed on tractor fuel consumption.

OBJECTIVES

The overall objective of this study was to determine an accurate model of fuel (diesel) consumption that can be reported for a tractor tested with the OECD Code 2 optional fuel consumption test at varying drawbar loads. The model would preferably result in one equation applicable over the range of speeds included in the test. The specific models evaluated were:

1. Linear relationship of fuel consumption with drawbar power on concrete, with a separate equation for each speed.
2. Linear relationship of fuel consumption with drawbar power on concrete.
3. Linear relationship of fuel consumption with drawbar power and travel speed on concrete.
4. Linear relationship of fuel consumption with drawbar power on concrete and engine speed.
5. Linear relationship of fuel consumption with drawbar power and travel speed on concrete, and engine speed.

MATERIALS AND METHODS

Eight tractors were used in this study. The selection was based on availability and collaboration by the manufacturer, as these particular models were already at NTTL for official testing. Deere & Company (Waterloo, Iowa) donated the use of tractors, and company test engineers for these additional tests, and NTTL donated the use of the test car, additional load tractors, NTTL test engineers, and fuel. All tractors were normal production models in all respects, as required by OECD Code 2. The eight tractors used for this study are listed in table 1, along with their corresponding reference letters used throughout the rest of this article. In accordance with the required sections of OECD Code 2 (OECD, 2016), the tractors were all tested unballasted.

TEST DESIGN

Data were collected for the geared transmission tractors using the SUTB methodology. The tractors were operated in as high a gear and as low an engine speed as practical while delivering the required power at the desired travel speed with a high fuel efficiency. This resulted in shifting up three gears from the gear at which maximum power at rated engine speed was obtained closest to the desired travel speed. The tractors with CVT transmission were set to auto mode and used their control technology to select the optimal engine

Table 1. Test tractor models and transmissions.

Tractor	Make and Model	Transmission[a]
A	John Deere 7230R	PowerShift (e23, geared)
B	John Deere 7250R	PowerShift (e23, geared)
C	John Deere 7270R	PowerShift (e23, geared)
D	John Deere 7290R	PowerShift (e23, geared)
E	John Deere 8320R	PowerShift (16-speed, geared)
F	John Deere 7290R	IVT (continuously variable)
G	John Deere 8345RT	IVT (continuously variable)
H	John Deere 8370R	IVT (continuously variable)

[a] e23 is the Deere & Company designation for a transmission option described as having 23 forward and 11 reverse gears.

speed and gear ratio to supply the power necessary while still maintaining the desired travel speed.

Smith (2015) used four travel speeds as close as possible to 4, 7.5, 10, and 13 km h^{-1} and indicated that the lowest speed did not fit the purpose of the test. Operations at that low speed would normally be used only when maximum pull was required, typically requiring close to maximum tractor power. This did not match the purpose for the test of using partial drawbar loads suited to SUTB and CVT operation with reduced fuel consumption. In addition, the high pull required at those low speeds often resulted in slip on the test track, exceeding the 15% limit in Code 2, before the engine speed decreased to rated speed and maximum drawbar power was developed. Consequently, only results from the 7.5 km h^{-1} (speed 1), 10 km h^{-1} (speed 2), and 13 km h^{-1} (speed 3) travel speeds were used.

Seven loads were selected at 30%, 40%, 50%, 60%, 70%, 75%, and 80% of the drawbar pull at maximum power and rated engine speed for the selected travel speeds. These loads represented the range of power necessary for most common tractor drawbar power loads.

The order of loading was not randomized, as all measurements were obtained after the loads reached steady state. When Coffman et al. (2010) randomized the application of loads and obtained measurements after the loads reached steady state, they did not observe any significant differences as a result of the order in which the loads were applied. Data were collected for the first travel speed at 80% load, and then the load was reduced to 75%. The next load was 70%, and then the loads were reduced in the order of 60%, 50%, 40%, and 30% of drawbar pull at maximum power and rated engine speed for the selected speed. The same loading pattern was used for the remaining speeds, resulting in a total of 21 data points (seven loads at each of three speeds) for each tractor used in the analyses. Additional details regarding this research are provided by Smith (2015).

TEST LOCATION

All testing took place at the NTTL in Lincoln, Nebraska. This facility satisfies all the requirements of OECD Code 2 (OECD, 2016) for drawbar testing with a clean, flat, concrete surface. A diagram of the test track is shown in figure 1 (Howard et al., 2013).

INSTRUMENTATION AND DATA ACQUISITION

Measurements were obtained using instrumentation that met the requirements of the OECD Code 2, section 3.4.2 (OECD, 2016).

LOAD CONTROL

The load applied to the tractor being tested was controlled through the NTTL test car. The test car is a Caterpillar articulated dump truck that was modified to fulfill the needs of OECD Code 2 official testing. The test car is outfitted with two National Instruments controllers for data acquisition, load control, and data logging. The exterior-mounted controller is a NI CRIO 9073 (National Instruments, Austin, Texas), and the controller inside the cab is a NI PIX1042Q. The software interface is LabVIEW version 12.0F3 with custom coding written by NTTL test engineers, which is in compliance with the requirements of OECD Code 2.

TEST PROCEDURE

Due to the larger loads exceeding the maximum load generation capability of the NTTL test car, additional load units were towed behind the test car when necessary (fig. 2). The additional load units were modified tractors, with either a valve between the exhaust manifold and exhaust stack that could be closed to increase the exhaust back pressure in the engines, or an eddy current brake retarder attached to the PTO to add additional load beyond that created by the engine. In the case of load units braked by restricting the exhaust, the operator of each additional load unit selected the gear appropriate for the travel speed, closed a valve in the fuel line to stop fuel flowing to the load unit engine, and released the clutch. This resulted in the wheels of the load unit powering the engine, which acted as an air compressor since no fuel was supplied to the engine. The eddy current brake retarder could be excited to whatever degree required within its range by engaging the tractor PTO and selecting an excitation voltage. As the load requirement decreased, the load unit transmissions were shifted to neutral to minimize the load they applied. As necessary, the additional load units were unhooked from the test car if their weight alone caused the load to exceed the target load. The loads were applied in a manner that conformed to the requirement of OECD Code 2 (OECD, 2016).

Data were collected over a 61 m travel distance (minimum). Due to the length of the straightaways, it was possible to collect two datasets per straightaway. A minimum of four datasets per treatment was collected. The information included in a dataset was one measurement of each of the quantities required by OECD Code 2. The NTTL test engineer observed real-time output for key data (power, fuel con-

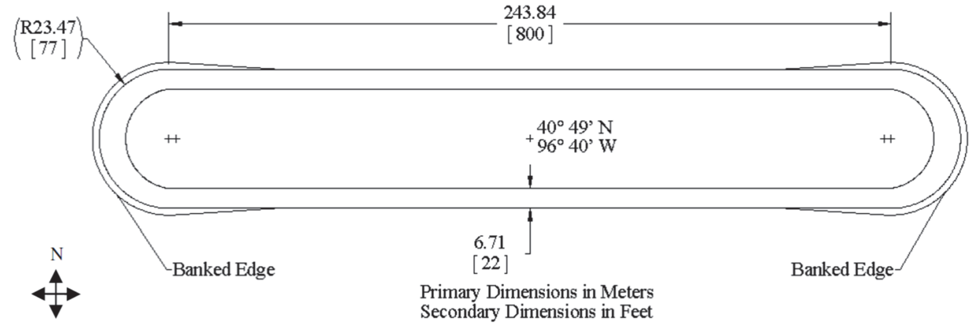

Figure 1. Diagram of track at the Nebraska Tractor Test Lab (from Howard, 2013).

Figure 2. John Deere 8345RT during tests with the NTTL Test Car and three additional load units on the test track at the Nebraska Tractor Test Lab on 4 November 2014.

sumption, and load) for consistency. When the NTTL engineer saw the key data values reach a relatively steady state, data collection began. If any of the key indicators were outside of an acceptable range, additional datasets were collected until the requirements were met. The same test engineer collected data for all of the tractors for consistency.

The loads for each speed were adjusted on the go, without requiring the tractor to stop. The NTTL test car adjusted the controller to vary the load, and the additional load units were shifted into neutral as required to reduce load.

DATA ANALYSES

Model 1: Fuel Consumption as a Function of Power, by Speed

The approach developed by Howard et al. (2013) used the following regression model (eq. 10), which could be divided into separate fuel consumption equations for each of the three test speeds (model 1) of a particular tractor. The regression analysis with this model (including all three test speeds) for each tractor had 15 degrees of freedom for the error sum of squares:

$$\begin{aligned}\hat{Q}_{M1ijk} &= b_{M10i} + b_{M11i} \cdot VI_1 + b_{M12i} \cdot VI_2 \\ &\quad + m_{M1P0i} \cdot P_{ijk} + m_{M1P1i} \cdot VI_1 \cdot P_{ijk} \\ &\quad + m_{M1P2i} \cdot VI_2 \cdot P_{ijk}\end{aligned} \tag{10}$$

where

Q_{M1ijk} = model 1 estimated fuel consumption for tractor *i*, speed *j*, and load *k* (kg h^{-1})

b_{M10i} = model 1 intercept term 0 for tractor *i* (kg h^{-1})

b_{M11i} = model 1 intercept term 1 for tractor *i* (kg h^{-1})

b_{M12i} = model 1 intercept term 2 for tractor *i* (kg h^{-1})

VI_1 = velocity index 1 ($VI_1 = 0$ for speeds 1 and 3, $VI_1 = 1$ for speed 2)

VI_2 = velocity index 2 ($VI_2 = 0$ for speeds 1 and 2, $VI_2 = 1$ for speed 3)

m_{M1P0i} = model 1 slope with power term 0 for tractor *i* (kg kW^{-1} h^{-1})

m_{M1P1i} = model 1 slope with power term 1 for tractor *i* (kg kW^{-1} h^{-1})

m_{M1P2i} = model 1 slope with power term 2 for tractor *i* (kg kW^{-1} h^{-1})

P_{ijk} = drawbar power (on concrete) for tractor *i*, speed *j*, and load *k*.

Use of model 1 with the data from this experiment resolved to the following equations for fuel consumption of each tractor for speeds 1, 2, and 3:

For speed *j* = 1, $VI_1 = VI_2 = 0$:

$$\hat{Q}_{M1i1k} = b_{M10i} + m_{M1P0i} \cdot P_{i1k} \tag{11a}$$

For speed *j* = 2, $VI_1 = 1$, $VI_2 = 0$:

$$\begin{aligned}\hat{Q}_{M1i2k} &= \left(b_{M10i} + b_{M11i}\right) \\ &\quad + \left(m_{M1P0i} + m_{M1P1i}\right) \cdot P_{i2k}\end{aligned} \tag{11b}$$

For speed *j* = 3, $VI_1 = 0$, $VI_2 = 1$:

$$\begin{aligned}\hat{Q}_{M1i3k} &= \left(b_{M10i} + b_{M12i}\right) \\ &\quad + \left(m_{M1P0i} + m_{M1P2i}\right) \cdot P_{i3k}\end{aligned} \tag{11c}$$

Model 2: Fuel Consumption as a Function of Power

Coffman et al. (2010) and Howard et al. (2013) showed that a model with fuel consumption as a linear function of drawbar power alone had high coefficients of determination (r^2 values) and worked well. Model 2 was proposed to allow determination of whether this simple model was sufficient to provide accurate estimations of fuel consumption. The regression analysis with this model for each tractor had 19 degrees of freedom for the error sum of squares. Model 2 was proposed with fuel consumption as a linear function of drawbar power on concrete as follows:

$$\hat{Q}_{M2ijk} = b_{M2i} + m_{M2Pi} \cdot P_{ijk} \tag{12}$$

where

Q_{M2ijk} = model 2 estimated fuel consumption for tractor *i*, speed *j*, and load *k* (kg h^{-1})

b_{M2i} = model 2 intercept for tractor i (kg h^{-1})
m_{M2Pi} = model 2 slope with power for tractor i (kg kW^{-1} h^{-1})
P_{ijk} = drawbar power (on concrete) for tractor i, speed j, and load k.

Model 3: Fuel Consumption as a Function of Drawbar Power and Travel Speed

Examination of the fuel consumption models reported by Howard et al. (2013) suggested that the slope of fuel consumption with power for each transmission operating mode appeared similar among the speeds. Smith (2015) determined that about 79% of the model 1 slopes with power among the 7.5, 10, and 13 km h^{-1} speeds were not significantly different for the eight tractors tested. The regression analysis with this model for each tractor had 18 degrees of freedom for the error sum of squares. Model 3 is a revised version of model 1, using the same slope of fuel consumption for all travel speeds and including travel speed as an independent variable rather than restricting the model to the specific travel speeds tested. Model 3 was proposed to estimate fuel consumption for each tractor from drawbar power and travel speed on concrete as follows:

$$\hat{Q}_{M3ijk} = b_{M3i} + m_{M3Pi} \cdot P_{ijk} + m_{M3Sti} \cdot S_{tijk} \qquad (13)$$

where
Q_{M3ijk} = model 3 estimated fuel consumption for tractor i, speed j, and load k (kg h^{-1})
b_{M3i} = model 3 intercept for tractor i (kg h^{-1})
m_{M3Pi} = model 3 slope with power for tractor i (kg kW^{-1} h^{-1})
P_{ijk} = drawbar power (on concrete) for tractor i, speed j, and load k
m_{M3Sti} = model 3 slope with travel speed for tractor i (kg km^{-1})
S_{tijk} = travel speed (on concrete) for tractor i, speed j, and load k (km h^{-1}).

Model 4: Fuel Consumption as a Function of Drawbar Power and Engine Speed

The ASABE Standards (ASABE 2015a, 2015b), Grisso et al. (2004, 2008), and Smith (2015) suggested there is an effect of engine speed on fuel consumption. The regression analysis with this model for each tractor had 18 degrees of freedom for the error sum of squares. Model 4 was proposed to estimate fuel consumption for each tractor from drawbar power on concrete and engine speed as follows:

$$\hat{Q}_{M4ijk} = b_{M4i} + m_{M4Pi} \cdot P_{ijk} + m_{M4Sei} \cdot S_{eijk} \qquad (14)$$

where
Q_{M4ijk} = model 4 estimated fuel consumption for tractor i, speed j, and load k (kg h^{-1})
b_{M4i} = model 4 intercept for tractor i (kg h^{-1})
m_{M4Pi} = model 4 slope with power for tractor i (kg kW^{-1} h^{-1})
P_{ijk} = drawbar power (on concrete) for tractor i, speed j, and load k
m_{M4Sei} = model 4 slope with engine speed for tractor i (kg min h^{-1} rev^{-1})
S_{eijk} = engine speed for tractor i, speed j, and load k (rev min^{-1}).

Model 5: Fuel Consumption as a Function of Drawbar Power, Travel Speed, and Engine Speed

Smith (2015) noted that fuel consumption for some tractors was better estimated by drawbar power and travel speed, while fuel consumption for other tractors was better estimated by drawbar power and engine speed. Model 5 was proposed with the idea that a model including both travel speed and engine speed would work well for both of those sets of tractors and incorporate the fuel-conserving concepts of both CVT and SUTB. The regression analysis with this model for each tractor had 17 degrees of freedom for the error sum of squares. Model 5 was proposed to estimate fuel consumption for each tractor from drawbar power and travel speed on concrete, and engine speed as follows:

$$\begin{aligned}\hat{Q}_{M5ijk} &= b_{M5i} + m_{M5Pi} \cdot P_{ijk} \\ &\quad + m_{M5Sti} \cdot S_{tijk} + m_{M5Sei} \cdot S_{eijk}\end{aligned} \qquad (15)$$

where
Q_{M5ijk} = model 5 estimated fuel consumption for tractor i, speed j, and load k (kg h^{-1})
b_{M5i} = model 5 intercept for tractor i (kg h^{-1})
m_{M5Pi} = model 5 slope with power for tractor i (kg kW^{-1} h^{-1})
P_{ijk} = drawbar power (on concrete) for tractor i, speed j, and load k
m_{M5Sti} = model 5 slope with travel speed for tractor i (kg km^{-1})
S_{tijk} = travel speed (on concrete) for tractor i, speed j, and load k (km h^{-1})
m_{M5Sei} = model 5 slope with engine speed for tractor i (kg min h^{-1} rev^{-1})
S_{eijk} = engine speed for tractor i, speed j, and load k (rev min^{-1}).

EVALUATION OF MODELS

The coefficients for the fuel consumption models and the regression statistics were obtained using linear or multiple linear regression for each of the models with each of the tractors. The mean square errors of the regressions (sums of squares for residuals divided by the degrees of freedom for error) for each fuel consumption model were determined and used for comparison of the errors among the models for each tractor. As the mean square errors were analogous to variances, F-tests were used to compare the mean square errors among the models within each tractor. Making all possible comparisons among the five fuel consumption models resulted in a total of ten comparisons per tractor. To ensure that the family-wise alpha error was maintained at approximately 0.05, the alpha value for individual comparisons was fixed at 0.005.

RESULTS AND DISCUSSION

The r^2 values for each of the fuel consumption models with each tractor are shown in table 2, and the mean square

Table 2. Coefficients of determination (r^2) for each of the fuel consumption models with each tractor.

	Fuel Consumption Model[a]							
Tractor	Model 1, All Speeds	Model 1, Speed 1	Model 1, Speed 2	Model 1, Speed 3	Model 2	Model 3	Model 4	Model 5
A	0.999340	0.9990	0.9995	0.9995	0.9944	0.9988	0.9946	0.9992
B	0.997913	0.9977	0.9984	0.9976	0.9871	0.9975	0.9882	0.9976
C	0.986733	0.9930	0.9851	0.9812	0.9826	0.9850	0.9910	0.9932
D	0.994668	0.9996	0.9986	0.9834	0.9854	0.9915	0.9900	0.9916
E	0.998133	0.9981	0.9977	0.9986	0.9884	0.9957	0.9963	0.9964
F	0.997600	0.9965	0.9972	0.9993	0.9946	0.9946	0.9975	0.9977
G	0.998319	0.9985	0.9986	0.9978	0.9769	0.9972	0.9868	0.9974
H	0.996913	0.9986	0.9966	0.9955	0.9939	0.9965	0.9956	0.9974

[a] Model 1 = fuel consumption as a linear function of drawbar power on concrete by speed (with speeds 1, 2, and 3); model 2 = fuel consumption as a linear function of drawbar power on concrete; model 3 = fuel consumption as a linear function of drawbar power and travel speed on concrete; model 4 = fuel consumption as a linear function of drawbar power on concrete and engine speed; and model 5 = fuel consumption as a linear function of drawbar power and travel speed on concrete, and engine speed.

Table 3. Regression mean square errors ($kg^2\ h^{-2}$) with the comparisons for each of the fuel consumption models with each tractor.

	Fuel Consumption Model[b]				
Tractor[a]	Model 1, All Speeds	Model 2	Model 3	Model 4	Model 5
A	0.025632 a	0.171802 b	0.037421 a	0.173832 b	0.026647 a
B	0.096510 a	0.472315 b	0.094705 a	0.453907 b	0.097927 a
C	0.711001 a	0.735573 a	0.672002 a	0.401690 a	0.321629 a
D	0.283918 a	0.612895 a	0.375541 a	0.442271 a	0.394204 a
E	0.114675 a	0.562500 b	0.221951 ab	0.187897 ab	0.192709 ab
F	0.167855 a	0.297326 a	0.313435 a	0.148022 a	0.143541 a
G	0.143877 a	1.563161 b	0.203009 a	0.940279 b	0.199401 a
H	0.340777 a	0.531217 a	0.321319 a	0.402685 a	0.254241 a

[a] Within each tractor, mean square error values followed by the same letter are not significantly different.

[b] Model 1 = fuel consumption as a linear function of drawbar power on concrete by speed (with speeds 1, 2, and 3); model 2 = fuel consumption as a linear function of drawbar power on concrete; model 3 = fuel consumption as a linear function of drawbar power and travel speed on concrete; model 4 = fuel consumption as a linear function of drawbar power on concrete and engine speed; and model 5 = fuel consumption as a linear function of drawbar power and travel speed on concrete, and engine speed.

errors for each of the models with each tractor are shown in table 3. The comparison of model 2 with model 1 for tractor A presents an example of the procedure used for the comparisons. The regression mean square error from model 2 (0.171802) was divided by the regression mean square error from model 1 (0.025632), giving a value of 6.703. This value was greater than the F table upper value (alpha = 0.9975, df model 2 = 19, df model 1 = 15) of 4.474, so the model 2 regression mean square error was determined to be significantly greater than the model 1 regression mean square error. If the larger of the two mean square errors was in the denominator (e.g., model 3 MSE divided by model 2 MSE for tractor A), the ratio of the mean square errors was compared to the F table lower value (alpha = 0.0025) and was determined to be significant if the ratio of the mean square errors was less than the F table lower value.

Looking at the trends in the regression mean square error values (table 3), model 2 had the largest mean square error (least accurate fuel consumption prediction) for six (B, C, D, E, G, and H) of the eight tractors tested. Model 1 had the smallest mean square error (most accurate fuel consumption prediction) for four (A, D, E, and G) of the eight tractors tested. Model 5 had the smallest mean square error for three tractors (C, F, and H), and model 3 had the smallest mean square error of regression for the remaining tractor (B).

Considering the statistical analyses (table 3), there were no significant differences among the fuel consumption models for tractors C, D, F, and H (half of the tractors tested). For these tractors, the predictions of fuel consumption, which included speed as well as drawbar power (models 1, 3, 4, and 5), were not significantly different from the predictions obtained when using drawbar power alone (model 2).

For the other half of the tractors tested (tractors A, B, E, and G), model 1 had significantly lower regression mean square error (more accurate fuel consumption predictions) than model 2, indicating that, overall, using separate equations for each travel speed improved the fuel consumption predictions. Three of these tractors, (A, B, and G) had the same significant differences among the fuel consumption models. For these tractors, there were no significant differences among models 1, 3, and 5, and no significant differences among models 2 and 4. In the comparison between these two groups of models, models 1, 3, and 5 had significantly smaller regression mean square errors (more accurate fuel consumption predictions) for these three tractors than models 2 and 4. For tractor E, model 1 was significantly better than model 2, and models 3, 4, and 5 were not significantly different from model 1 or model 2. For the tractors for which statistically significant differences existed (tractors A, B, E, and G), model 1 was significantly better than model 2, and models 3 and 5 were equivalent to model 1.

Overall, model 1 appeared to be the best fuel consumption model, although it has the drawback of being applicable only to the specific travel speeds tested. Because model 5 has the widest applicability (for any travel speed within the range tested), includes the most factors that tend to affect fuel consumption (drawbar power, travel speed, and engine speed), and had the smallest regression mean square error for the most tractors (out of models 3, 4, and 5), it was determined to be the best overall fuel consumption model. However, model 5 has the drawback that it requires three input values (drawbar power and travel speed on concrete, and engine speed) to obtain an estimate of fuel consumption. Of those three required inputs, the engine speed value is likely

Table 4. Coefficients of model 5 for the tested tractors.

Tractor	b_{M5i} (kg h^{-1})	m_{M5Pi} (kg kW^{-1} h^{-1})	m_{M5Sti} (kg km^{-1})	m_{M5Sei} (kg min h^{-1} rev^{-1})
A	20.15	0.2367	0.1764	-0.01391
B	6.373	0.2348	0.2706	-0.003987
C	33.59	0.2101	0.1171	-0.01946
D	-4.696	0.2164	0.1773	0.005192
E	-2.369	0.2037	0.07468	0.004842
F	-4.681	0.1887	0.04788	0.008110
G	-1.469	0.2069	0.4642	0.003416
H	-2.962	0.2001	0.1722	0.005463

Table 5. Coefficients of model 3 for the tested tractors.

Tractor	b_{M3i} (kg h^{-1})	m_{M3Pi} (kg kW^{-1} h^{-1})	m_{M3Sti} (kg km^{-1})
A	1.656	0.2348	0.1519
B	1.083	0.2342	0.2621
C	1.793	0.2366	0.1209
D	1.969	0.2169	0.2079
E	2.675	0.2047	0.2508
F	2.408	0.2419	0.008471
G	0.8741	0.2289	0.5045
H	0.9092	0.2312	0.2024

the least well known. For practical use in situations where an appropriate value for engine speed is not known, model 3 provided a statistically equivalent alternative to model 5. Model 5 was determined to be the best of the five models compared for estimating fuel consumption with a single equation over the range of speeds tested. The coefficients obtained with model 5 for each of the tractors tested are shown in table 4. The regression mean square errors with model 5 (table 3) for the eight tractors tested ranged from 0.027 kg^2 h^{-2} (tractor A) to 0.394 kg^2 h^{-2} (tractor D).

In situations where the value for engine speed is not known, model 3 (the revised version of model 1) provides a means of estimating fuel consumption that was statistically equivalent to model 5 (and model 1). The coefficients obtained with model 3 for each of the tractors tested are shown in table 5. The regression mean square errors with model 3 (table 3) for the eight tractors tested ranged from 0.037 kg^2 h^{-2} (tractor A) to 0.672 kg^2 h^{-2} (tractor C).

All testing for this study was done within an ambient temperature range of 12°C to 32°C. Many tractors these days have cooling systems with variable-speed fans that consume significantly higher parasitic power at higher temperatures. The fuel consumption models presented in this article do not account for ambient temperature and therefore would have higher errors at higher ambient temperatures. Another limitation of these models is that all output power during the tests was drawbar power. Many implements require PTO power and/or hydraulic power in addition to drawbar power. To use these models to estimate fuel consumption for tractors with such implements, the drawbar power equivalent of the PTO and/or hydraulic power output would have to be determined and added to the drawbar power requirement. Errors in determining the drawbar power equivalent of PTO and/or hydraulic power would increase the error in using these models to estimate tractor fuel consumption.

CONCLUSIONS

For half of the eight tractors tested (tractors C, D, F, and H), there were no statistically significant differences among the five fuel consumption models compared. For the other half of the tractors tested (tractors A, B, E, and G), the fuel consumption model used by Howard (2010) (i.e., model 1, fuel consumption as a linear function of drawbar power on concrete with separate equations specific to the three speeds tested) was significantly better than model 2 (fuel consumption as a linear function of drawbar power on concrete alone). For three of these tractors (tractors A, B, and G), models 1, 3, and 5 had significantly smaller regression mean square errors than models 2 and 4. Model 1 has the drawback of being applicable only to the specific travel speeds tested. Because model 5 was not significantly different from model 1, has the widest applicability (for any travel speed within the range tested), and includes the most factors that tend to affect fuel consumption (drawbar power, travel speed, and engine speed), it was determined to be the best overall fuel consumption model. For practical use in situations where an appropriate value for engine speed is not known, model 3 provided a statistically equivalent alternative to model 5 for determining fuel consumption.

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