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DEVELOPMENT AND VALIDATION OF A TRACTOR DRAWBAR FORCE MEASUREMENT AND DATA ACQUISITION SYSTEM (DAQ)

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TECHNICAL NOTE:

DEVELOPMENT AND VALIDATION OF A TRACTOR DRAWBAR FORCE MEASUREMENT AND DATA ACQUISITION SYSTEM (DAQ)

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ABSTRACT. *Matching agricultural tractors to implements towed by the drawbar is one of the important aspects of machinery management for ensuring optimum performance and fuel cost savings. A field deployable tractor draft force measurement and data acquisition system was developed and evaluated as part of this research project. A drawbar instrumented to measure draft force in field operating conditions was developed and statically calibrated. The drawbar was calibrated by applying loads from 4.45 to 134 kN using a hydraulic cylinder connected to a 444.8 kN load cell. Testing was conducted with the drawbar installed on a tractor on a concrete track. The Nebraska Tractor Test Laboratory (NTTL) load car was used for applying draft loads to evaluate the instrumented drawbar. The track test consisted of seven loads corresponding to maximum power in seven gears. The draft forces as measured by the drawbar were compared to the draft measurements recorded by the load car. The error between draft force measurements of the instrumented drawbar and the load car measurements ranged from 0.21 kN (0.27%) to 0.99 kN (2.88%).There were no statistically significant differences between drawbar and load car measurements confirming that the drawbar force measurement and data acquisition (DAQ) system developed as part of this research can be used for field use.*

Keywords. *Data acquisition, Draft load, Drawbar, LabVIEW, Strain gages, Tractor.*

The tractor drawbar is the most widely used method of towing an implement. An accurate robust method to measure the draft load developed by a towed implement had been a critical industry need for some time. Tractor tests were conducted as far back as 1908 in the Winnipeg Tractor Trials (Ellis, 1913). Some approaches for draft force measurement have included: attaching a strain gage load cell to the drawbar; or a hydraulic cylinder acting as a load cell (used by the Nebraska Tractor Test Laboratory (NTTL) for official drawbar draft measurements until being replaced by load cells in 2011); installing an instrumented drawbar pin (Zoerb et al., 1983); or instrumenting the drawbar itself (Grevis-James and Bloome, 1982). A primary benefit of these types of sensors was to minimize alterations to the tractor components while determining the amount of force generated by a towed implement. Fastening a load cell to the end of the drawbar was discounted, as such a system created a cantilevered load that affected the tractive efforts of the tractor (Zoerb et al., 1983). In addition, the load cell needed to be rigidly mounted to prevent excessive lateral movement during turning or stopping. The result was potential damage to the load cell and the tractor, as well as an unacceptable risk of personal injury to the operator. A design complication of using a load cell that would not pivot was that the load cell would prove less effective in measuring lateral loads as seen in contour or headland operations. Another method of integrating the load cell into the drawbar (proof-ring) was to permanently alter the drawbar which required a replacement drawbar to be installed after data collection was complete (Kheiralla and Yahya, 2001). Drawbar pin instrumentation was previously accomplished (Zoerb et al., 1983), but created an unacceptable level of physical noise in the data due to the often large tolerances between the drawbar hole, the pin, and the implement tongue. Another approach was to apply strain gages to the pin where the load on the drawbar transferred to the rear axle housing. This approach was suitable to reduce the noise due to narrower tolerances. A disadvantage of this method was that since the pin rotated freely, a directional strain error

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was generated. To avoid this error, minor design steps were required to ensure that the pin could not rotate during data collection. A pin of this design required additional development time and testing to ensure proper strain and alignment when compared to other alternatives.

Previous studies have tried to determine the amount of power required to pull an implement via the drawbar (Wendte and Rozeboom, 1981; Grevis-James and Bloome, 1982; and Graham et al., 1990). These studies developed data acquisition systems (DAQs) that were capable of measuring the amount of force applied to the drawbar by an implement and ground speed of the machinery with wheel slip. Graham et al. (1990) used a hydraulic load cell attached to the end of the drawbar, while others used a modified drawbar instrumented with strain gages. All of these studies modified the tractor drawbar to measure the tractive efficiency with their main purpose being to determine draft loads and wheel slippage for tillage and planting operations. Calibration procedures, if listed, generally included a two point calibration linear scale. Other research related tire velocity, inflation pressure, and ballasting (Upadhyaya et al., 1988; Zoz and Grisso, 2003; Taghavifar and Mardani, 2013) to draft forces and tractive efficiency.

This research presents a different approach for calibrating an instrumented drawbar and verifying the draft force of a towed implement in a laboratory using The Organisation for Economic Co-operation and Development (OECD) Code 2 test procedures (OECD Code 2, 2016). This research approach also minimized alterations to components supplied with the tractor by using a replacement drawbar for instrumentation, which could be mounted onto multiple tractors of similar size with limited modifications.

Objectives

The goal of this project was to develop a portable draft measurement and data acquisition system. This system measured the draft force applied by an implement on a tractor drawbar. Specific objectives were to:

- Calibrate the instrumented tractor drawbar, and
- Use OECD Code 2 tractor drawbar power test procedures and the Nebraska Tractor Test Laboratory load car to determine if there was any difference in draft measurements between the instrumented drawbar and the load car.

Materials and Methods

An instrumentation system to measure and record draft force on the drawbar was developed. This system consisted of a drawbar instrumented with strain gages and DAQ hardware. The drawbar draft force measurement system was connected to a load cell integrated into the hitch of the Nebraska Tractor Test load car for evaluating the measurement accuracy.

Measuring Devices

For an initial prototype design, an instrumented drawbar was deemed an appropriate component of the device under test. The ideal location to minimize vertical loading in the strain gage measurement was as close to the front drawbar support as possible (see fig. 1a). Material was milled from the surface of the drawbar to increase the sensitivity and provide a smooth surface to mount the strain gages (fig. 1a). A 90° strain rosette (Micro-Measurements EA-06-125TQ-350, Vishay Precision Group, Inc., Wendell, N.C.) was mounted on each side of the drawbar with one strain gage parallel with the length of the drawbar (fig. 1b) to measure the axial load and the perpendicular strain gage to compensate for temperature in the negligible loading direction. The wiring and the strain gages required protection from debris, so a cross-drilled hole provided a raceway between the rosettes for the sensor wires to be routed safely (fig. 1b). The strain gages on the rosettes were wired in a full-bridge configuration for temperature compensation (fig. 1c). The drawbar was interfaced using a National Instruments (NI) compact DAQ (NI 9174, National Instruments, Austin, Tex.) with a universal analog module (NI 9219, National Instruments, Austin, Tex.) which was capable of providing the excitation voltage of +2.5 VDC and ground required for the strain gage transducer (fig. 1d).

DAQ Hardware and Software Program

An NI 9174 cDAQ is a portable 4-slot DAQ chassis for use with NI C series I/O modules. The chassis has the capability to handle multiplexed analog I/O signals, thermocouples, and digital I/O signals, in the same chassis. A NI 9219 universal analog module, capable of measuring analog voltages from strain gages bridges, thermocouples, load cells, and other analog sensors, was utilized. The full-bridge temperature compensated drawbar strain measurements were performed using the NI 9219 module for both calibration and testing purposes. The full-bridge mode of the NI 9219 uses the internal voltage excitation to return voltage reading proportional to the excitation level allowing the mV/V output of the load cell to be used in our calibration equation.

Separate LabVIEW programs were utilized for the drawbar calibration and the drawbar testing on the NTTL test track. The LabVIEW graphical user interface (Front Panel) was the indication and control panel for the user. The LabVIEW program used for calibration was the current version of the NTTL load car hitch calibration program used with a NI compact reconfigurable I/O (cRIO) DAQ board. This program was configured to measure 3 load cells simultaneously at a sampling rate of 50 Hz, so it was necessary to reconfigure the Front Panel to measure 2 load cells (calibration fixture and drawbar). The user was required to setup channels in NI Measurement and Automation Explorer (NI MAX) to be called in the calibration program via a task. Push button control logic allowed elements to be hidden on the Front Panel of the NTTL load car hitch calibration program which were unused in this calibration application. Data were logged to a file for later use to determine the calibration equation.

The LabVIEW program for NTTL track testing that was developed displayed drawbar pull in real-time, and test setup information (fig. 2) on the Front Panel. The *Get Data* push button control allowed the user to log the raw data for a specified test duration. To write the accumulated data to a file

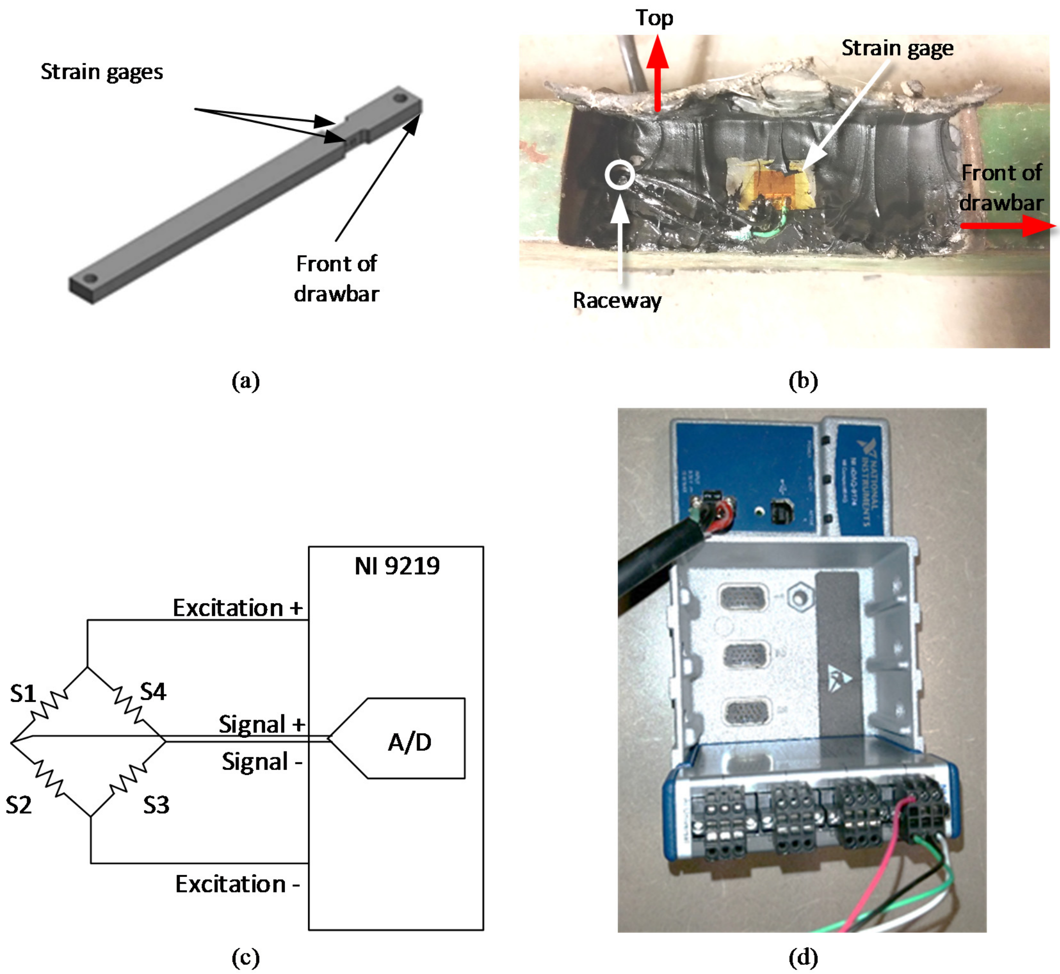

Figure 1. (a) Drawbar illustrating sensor location, (b) focused side view where strain gage rosette was placed on drawbar, (c) circuit diagram illustrating the bridge configuration as attached to DAQ module, (d) NI cDAQ with NI 9219 module wired as a full-bridge design.

after testing was completed, the *Write Data* push button control was used before stopping the program.

A block diagram in LabVIEW included visually represented nodes analogous to statements, functions, etc. in text-based programming languages. The drawbar track testing program block diagram (Appendix I) was created utilizing similar nodes to the NTTL load car hitch calibration program. Tasks setup in NI MAX for calibration were used in the same capacity in the drawbar track testing program.

Test Setup

The drawbar was mounted on an AGCO Allis tractor (9695, AGCO Corporation, Duluth, Ga.) in the standard centered position (tractor in fig 3). The NI DAQ board used for drawbar draft force data acquisition was connected to a laptop situated inside the tractor cab. The LabVIEW program previously described was used to record the drawbar data.

During the track testing, the NTTL load car (figs. 3a, 3b, 3c) was used to apply a constant force in the plane of the drawbar with minimum vertical and transverse loading. The hitch position was set to maintain a constant distance above the ground to avoid vertical loading, which was compensated by the full-bridge strain configuration. The load car used two Interface load cells (1232ALD-100K-B, Interface, Inc., Scottsdale, Ariz.) connected in series and attached to the hitch to measure the draft force under tension. Draft forces were measured in the first load cell while the second load cell was used to verify the load measurement (fig. 3c). The load cells on the NTTL load car were calibrated bi-annually using the independent calibration fixture in figure 4. The drawbar test was performed on the NTTL test track, utilizing the two 244 m (800 ft) straight lengths of concrete surface.

The NTTL provided calibration fixture (fig. 4) consisted of an Interface Gold Standard (IGS) Calibration load cell (1632AJH-100K, Interface, Inc., Scottsdale, Ariz.) sent back to Interface, Inc. for calibration triennially to primary standards at NIST. The IGS was a 444.8 kN (100 klb$_f$) load cell with a static error of ± 0.017% full scale. A hydraulic cylinder utilizing a double-acting hand pump applied a tension load to the load cell while the other end of the load cell was attached to a steel plate connected to the drawbar. The calibration fixture frame used a spacing-block to keep the tractor frame equidistant from the calibration fixture frame so that the entire system was static.

Calibration and Test Procedure

The drawbar was attached to the calibration fixture (fig. 4), which uses a 444.8 kN (100 klb$_f$) IGS listed previously that conforms to NIST primary standards and has a

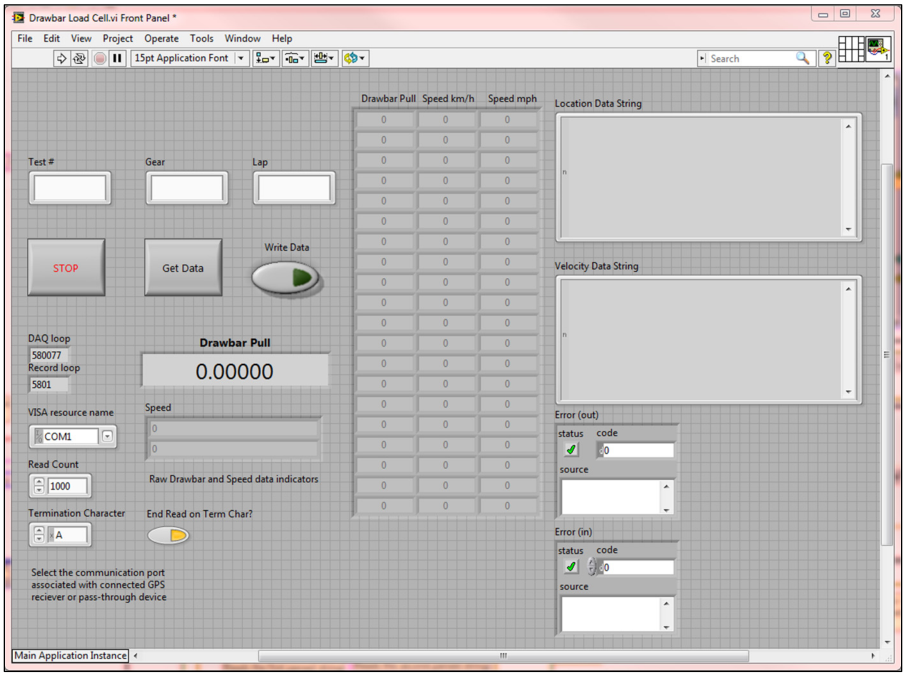

Figure 2. LabVIEW Front Panel for drawbar testing on the NTTL test track.

static error of ±0.017% full scale. One end of the IGS was attached to a hydraulic cylinder which developed the tension load, whereas the other end was attached to a steel plate connected to the drawbar (fig. 4). The calibration procedure began with anticipated physical loads of 4.45, 8.90, 13.3, 22.2, 44.5, 66.7, 89.0, 111, and 134 kN (1, 2, 3, 5, 10, 15, 20, 25, and 30 klb_f) as measured by the IGS. It was assumed that any load under 4.45 kN (1 klb_f) occurring during field use would be highly variable due to being either transport or a headland turn. Loads over 133 kN (30 klb_f) occurring during field use were assumed to be from heavy tillage equipment used by heavily ballasted >224 kW (>300 HP), track laying, or 4WD tractors using a higher category drawbar size. The bridge output voltage corresponding to the strain values from the drawbar were recorded for three replications near the anticipated IGS physical loads and converted to match the respective IGS physical load values (table 1).

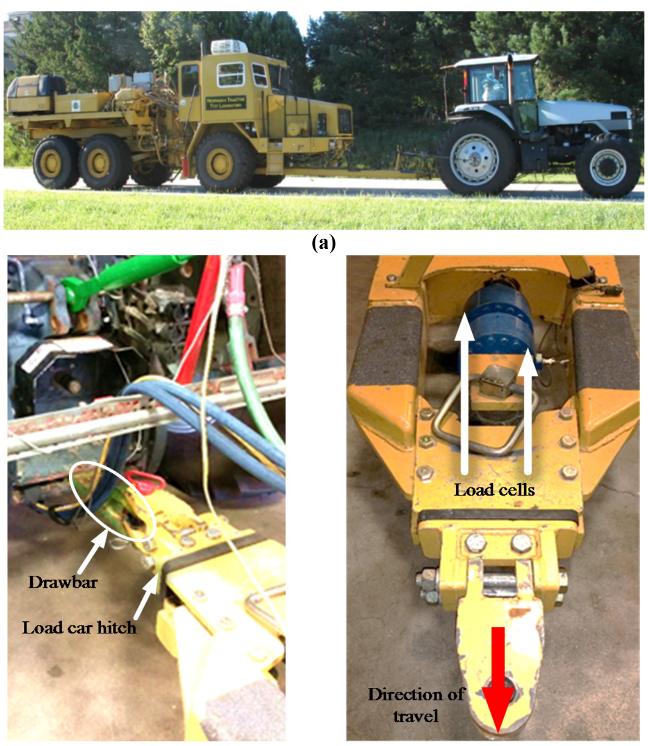

Figure 3. (a) AGCO Allis 9695 pulling NTTL load car for track testing, (b) detail of AGCO Allis 9695 coupled to the test car, (c) test car hitch with serial load cells.

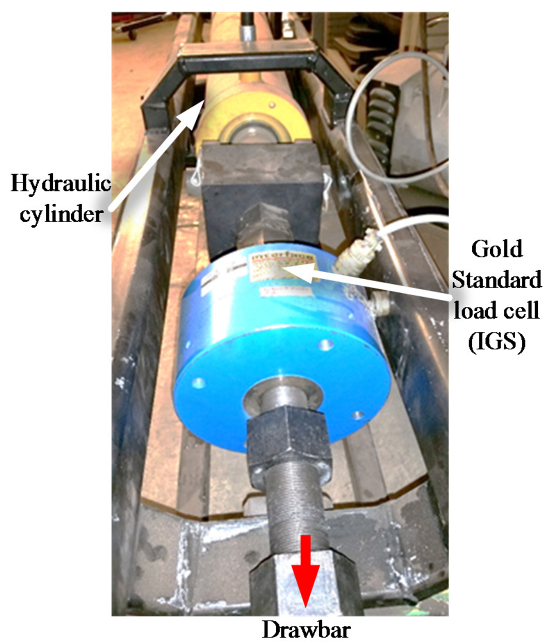

Figure 4. Calibration stand using a hydraulic cylinder to apply load to the drawbar.

Table 1. IGS force versus the Wheatstone bridge output for the instrumented drawbar.

IGS Physical Force (kN)	Drawbar Electrical Value (mV/V)
2.22	0.6979
4.45	0.7046
8.90	0.7185
13.34	0.7320
22.24	0.7559
44.48	0.8302
66.72	0.9038
88.96	0.9774
111.21	1.0493
133.45	1.1242

Using the summarized IGS physical force and drawbar electrical values in table 1, an iterative process was performed to ensure repeatable measurements within 0.67 kN (150 lbf). The resulting final drawbar force values and the electrical values from the iterative process are summarized in table 2. These resulting drawbar force and electrical values were used for the final calibration.

The calibration plot can be seen in figure 5 and the calibration equation is presented in equation 1.

$$\text{Calibrated Force} = 307.99*\left(output\right) - 211.77 \quad (1)$$

where
Calibrated Force = drawbar physical force (kN),
output = wheatstone bridge output (mV/V).

After the determination of the calibration equation of the drawbar, testing was accomplished using section 4.4.2.1 of the OECD Code 2 (OECD, 2016). According to this section of the OECD code, the speed settings required are: the gear/speed setting giving a travel speed immediately faster than the maximum power developed down to the gear/speed setting giving a travel speed immediately slower than the maximum drawbar pull developed. These operating points are further limited by Nebraska Tractor Test Board Action No. 6 (NTTL, 1998) to include only typical field operating speeds. The Nebraska Tractor Test Board requires that the maximum drawbar power shall be determined:

(a) in all gears which produce less than 15% slip and a nominal (unloaded) speed of less than 12.9 km·h^{-1} (8 mph) at rated engine speed,
(b) the gear below the slowest run from part (a) with the load adjusted to produce slip near 15%, and
(c) a gear producing a nominal (unloaded) speed between 12.9 and 16.1 km·h^{-1} (8 and 10 mph) at rated engine speed.

The tractor was tested in seven gears corresponding to maximum power in each gear (gears 6 to 12) (NTTL, 1995) for typical field operating speeds. The first gear in each repetition was selected at each end of the range of gears used, but due to the load car's limited transmission ranges, the subsequent gears were selected in ascending or descending order to reduce the need to adjust the load car's transmission. For example, one of the replications gear sequence was 12, 11, 10, 9, 8, 7, and then 6. Each treatment consisted of four straight runs of 152.4 m (500 ft) on the concrete track in each of the seven gears. Measurements were obtained for three complete replicates of treatment combinations. Tests were carried out with the governor set to maximum engine speed. Wheel slip was measured to verify that the loading was such that none of the loads caused mean wheel slip to exceed 15% as required by OECD (section 4.4.1.7) (OECD, 2016). Other data recorded by the NTTL load car were engine speed, hydraulic temperature (to verify that steady state operating conditions were achieved before beginning data collection), draft force, and ground speed. The drawbar DAQ recorded the drawbar strain.

The draft forces from the four runs were averaged to determine the means of each treatment (gear). Differences were determined for each treatment combination: the difference between the draft force as measured by the drawbar and the draft force measured by the load car. Student's t-tests, using an alpha level of 0.025 were used to determine which

Table 2. Final drawbar force calibration values.

DUT Physical Value (kN)	Drawbar Electrical Value (mV/V)
4.25	0.6979
4.94	0.7046
9.53	0.7185
13.41	0.7320
20.49	0.7559
43.48	0.8302
66.76	0.9038
89.82	0.9774
111.33	1.0493
134.35	1.1242

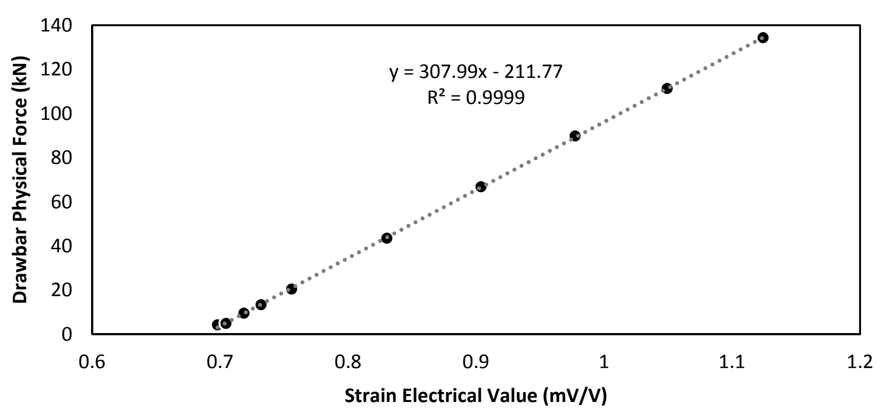

Figure 5. Final drawbar force calibration curve.

(if any) of the differences in treatment means were significantly different from zero (drawbar different than load car measurement (H_0 = 0 kN)). A table value (t = 4.303) was obtained given a probability value of 0.05 corresponding to a 95% confidence interval and 2 degrees of freedom (three repetitions) for a two-tailed test. OECD Code 2 required the force measurements to be within ±1.0% (section 3.4.2, OECD Code 2, 2016). As field conditions vary more than laboratory conditions, draft measurements within ±2.0% were considered optimal, but an accuracy of ±2.5% was considered satisfactory for farm use (Grevis-James and Bloome, 1982).

Results and Discussion

Calibration Verification

The table below (table 3) shows a comparison between the final calibrated drawbar force values and IGS force values. IGS values were the result of the final drawbar calibration curve replicated three times and then averaged to verify calibration repeatability within our calibration tolerances of 0.67 kN. The largest difference of the verification was at the 89 kN force with a difference of 0.53 kN (119 lbf, 0.60%).

The calibration verification (fig. 6) shows the slope of the given linear regression by the instrumented drawbar was near a slope of 1.0 with relation to the force applied through the IGS. Loads below 22.24 kN (5000 lb_f) had more variability due to the smaller measurement range between treatment loads. Additional calibration below this level was unnecessary due to loading and measurement time requirements and was within procedural tolerances.

Table 3. Final calibration verification.

Drawbar Calibration Value (kN)	IGS Force (kN)	Average Force Difference (kN)	Average Force Difference (%)
4.25	4.16	0.09	2.12
4.94	4.75	0.19	3.85
9.53	9.48	0.05	0.52
13.41	13.42	-0.01	-0.07
20.49	20.48	0.01	0.05
43.48	43.62	-0.14	-0.32
66.76	66.48	0.28	0.42
89.82	89.29	0.53	0.59
111.33	111.35	-0.02	-0.02
134.35	134.57	-0.22	-0.16

Track Test

The tractor equipped with the instrumented drawbar and the data acquisition system was tested on the concrete track using the NTTL load car. Data obtained during the test were averaged for each tractor gear. Student's T-tests were used to determine if there was a significant difference between the instrumented drawbar and the load car draft force measurements (H_o = 0 kN). Draft force differences were not statistically significantly different from zero in any of the tested gears, leading to acceptance of the null hypothesis. In gear 12, the instrumented drawbar measured an average of 2.55% less force than measured by the load car which was out of the 2.5% accuracy range. Gears 6 through 11 draft force difference averages were within 2% draft force accuracy difference (table 4). Using the OECD tolerance of 1.0% for force measurements (section 3.4.2, OECD Code 2, 2016), gears 6 through 10 satisfied this tolerance.

Figure 7 shows the correlation between the force measured by the load car and the force measured by the instrumented drawbar. The trend of this line (m = 1.0233) was close to the calibration curve with a strong coefficient of determination (R^2 = 0.9982) between the instrumented drawbar and the load car force measurements.

The largest average draft force difference (0.99 kN, 2.88%) was in gear 12 whereas, the largest range of draft force values were in gears 6 and 7 (fig. 7).

Summary and Conclusions

Development of an agricultural tractor drawbar measurement and data acquisition system was accomplished. Static calibration was successful with the instrumented drawbar

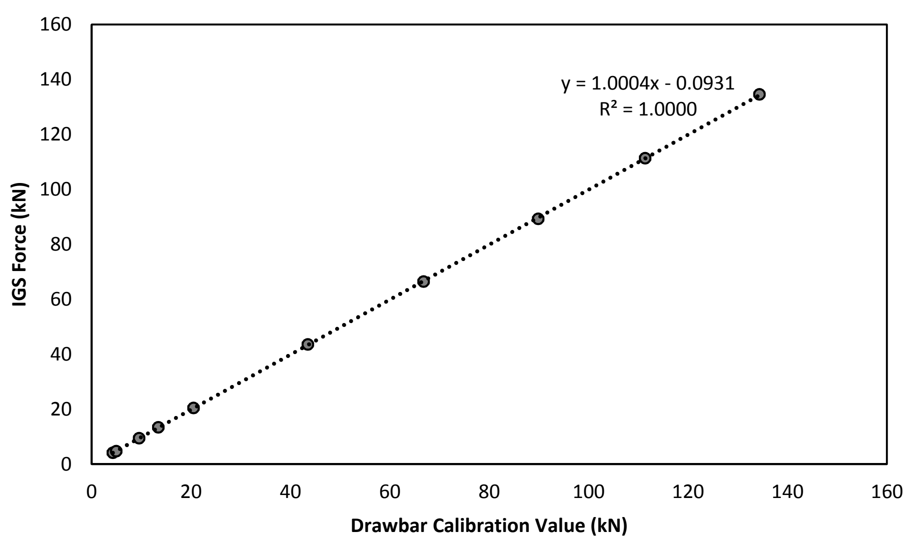

Figure 6. Calibration verification.

Table 4. Average draft force results of the load car and DUT in corresponding gears.

Gear	Speed (km h^{-1})	Average Load Car Force (kN)	Average Drawbar Force (kN)	Average Force Difference (kN)	Average Force Difference (%)	Force Difference Standard Deviation
6	4.95	81.31	81.98	-0.6713	-0.83%	0.91
7	6.10	77.00	76.79	0.2103	0.27%	0.10
8	6.88	72.82	72.30	0.5150	0.71%	0.69
9	7.84	62.71	62.17	0.5415	0.86%	0.55
10	9.17	54.42	53.98	0.4478	0.82%	0.44
11	10.89	45.71	45.01	0.7044	1.54%	0.53
12	12.80	38.67	37.68	0.9857	2.55%	0.34

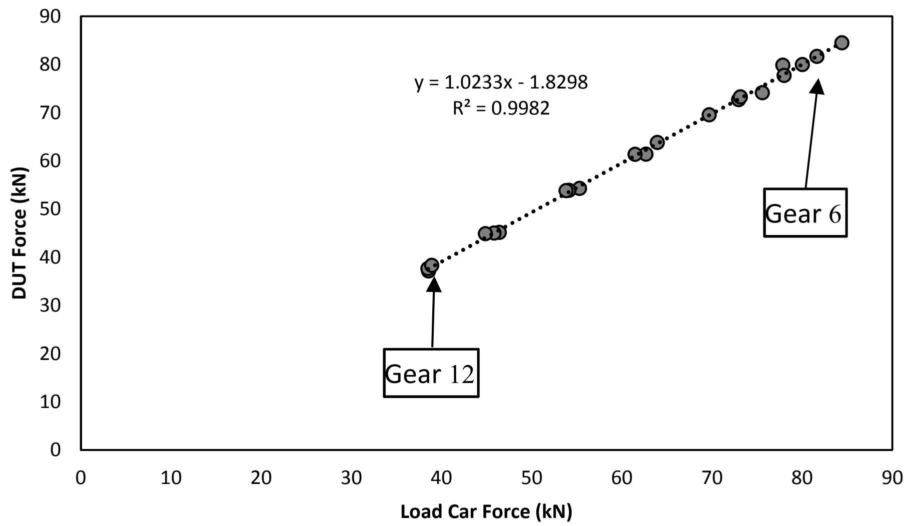

Figure 7. Average draft force comparison between load car and drawbar for all replications of the test.

yielding repeatable force values within 0.67 kN of the IGS force values after the final calibration was applied. Using OECD Code 2 and Test Board Action No. 6 as test procedures, the drawbar force was evaluated in select gears used for typical draft implement field operating speeds. Differences in draft forces between the instrumented drawbar and the load car (Ho = 0 kN) were not statistically significant based on the two-tailed Student's T-test using an alpha value of 0.025 leading to the acceptance of the null hypothesis. Draft force differences ranged from 0.21 kN (0.27%, gear 7) to 0.99 kN (2.55%, gear 12). Most gears provided an accuracy of less than 2.5% error, while gear 12 was the only gear to fall outside this margin. Gears 6 through 10 were the only gears to meet the OECD force measurement tolerance of 1.0%. However, as the OECD tolerances are possible in laboratory conditions, they are not necessarily representative of plausible field measurement tolerances leading to the higher acceptable tolerances of 2.5%. These results indicate draft force measurements for field use are achievable with the drawbar draft force measurement and data acquisition system.

Acknowledgements

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APPENDIX I – LABVIEW BLOCK DIAGRAM

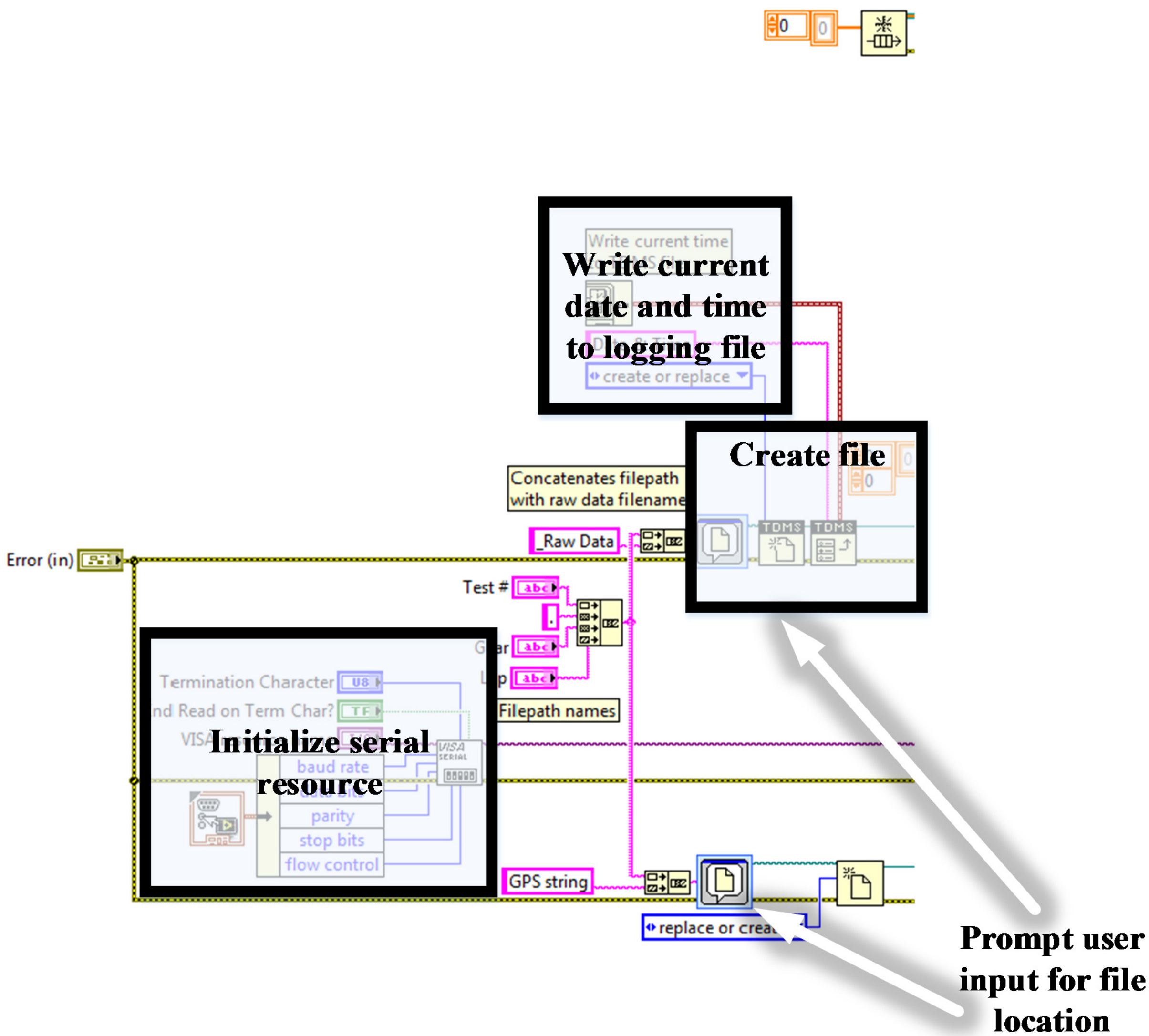

Figure 8. Block Diagram of LabVIEW program. Illustrates dialogue and file path names, and how the serial resource is initialized.

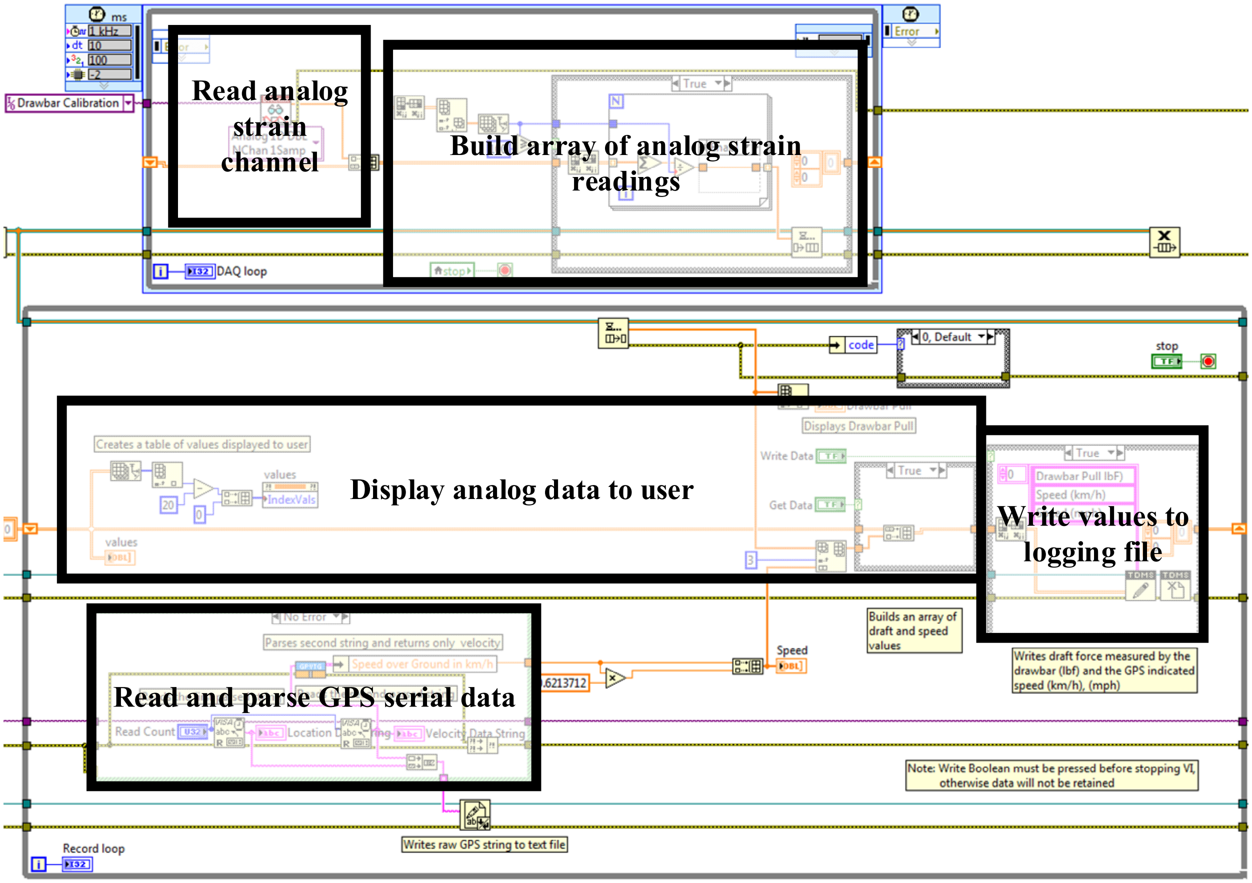

Figure 9. Block Diagram of LabVIEW program. Illustrates the reading and logging of the data.