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In-field fuel use and load states of agricultural field machinery

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ABSTRACT

The ability to define in-field tractor load states offers the potential to better specify and characterize fuel consumption rate for various field operations. For the same field operation, the tractor experiences diverse load demands and corresponding fuel use rates as it maneuvers through straight passes, turns, suspended operation for adjustments, repair and maintenance, and biomass or other material transfer operations. It is challenging to determine the actual fuel rate and load states of agricultural machinery using force prediction models, and hence, some form of in-field data acquisition capability is required. Controller Area Networks (CAN) available on the current model tractors provide engine performance data which can be used to determine tractor load states in field conditions. In this study, CAN message data containing fuel rate, engine speed and percent torque were logged from the tractor's diagnostic port during anhydrous NH_3 application, field cultivation and planting operations. Time series and frequency plots of fuel rate and percent torque were generated to evaluate tractor load states. Based on the percent torque, engine speed and rated engine power, actual load on the tractor was calculated in each tractor load state. Anhydrous NH_3 application and field cultivation were characterized by three distinct tractor load states (TS-I, TS-II and TS-III) corresponding to idle states, parallel and headland passes, and turns, whereas corn planting was characterized by two load states (TS-I and TS-II): idle, and a combined state with parallel, headland passes and turns. For anhydrous NH_3 application and field cultivation at ground speeds of 7.64 km h^{-1} and 8.68 km h^{-1}, average tractor load per tool and fuel use rate per tool of the implement were found to be 7.21 kW $tool^{-1}$, 3.28 L h^{-1} $tool^{-1}$, and 1.31 kW $tool^{-1}$, 0.64 L h^{-1} $tool^{-1}$, respectively. For planting, average tractor load per row and fuel use rate per row were found to be 4.65 kW row^{-1} and 1.70 L h^{-1} row^{-1} at a ground speed of 7.04 km h^{-1}

1. Introduction

Tractors are used for multiple field operations during the entire working season and hence are subjected to varying load demands. Further, for a specific operation, the load demands on the tractor change as a result of ground speed variations, effective implement working widths and depth of operations, field conditions (e.g., soil variability and terrain slope), and machine handling by the operator. When selecting and matching equipment complements, data is readily available for projecting engine load demands of various field operations (ASABE, 2011a). The reference data provides required draft forces at typical working speeds for specific operations (chisel plowing, seeding, etc.), however these power requirements (draft and rotary) of the implements vary within a maximum range of ±50% based on the type of operation (ASABE, 2011a). A more accurate estimation of power drawn by the implements during different tractor loading states such as working periods (e.g., parallel and headland passes) and non-working periods (e.g. field adjustments and repairs) is required. Understanding actual load profiles of the tractor in different working states has the potential to yield true average load conditions. Improved fuel consumption estimation, and better tractor and implement matching are some of the benefits of in-field tractor load state determination.

Tractor performance is currently evaluated using OECD 2 test code (OECD, 2012) where tractors are operated under steady-state conditions, selected engine speeds and torques which are a subset of several field operating conditions. Power take-off (PTO) power, drawbar power, and specific fuel consumption are reported to assess the performance of a tractor under controlled conditions. However, measuring the performance of the tractor under field conditions is central to a more thorough understanding of the actual power consumed by implements for various working phases

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of field operations. Engine speed and load also effect emissions, and hence, accurate load estimation of the tractor will indirectly lead to improved emission calculations and fuel consumption measurements. Thus, determination of in-field tractor load states is essential for improved fuel efficiency, better matching of implements to tractors, and accurate estimation of emissions.

Tractor load state estimation and performance testing has been the subject of many engine development and emission control investigations. More recently, manufacturers have focused their attention on off-highway engine emissions. Specifically, ISO 8178 (ISO, 2006) suggests engine test cycles (e.g. type C1, C2, and D1) for various classes of engines and equipment. These cycles include a sequence of steady-state modes for evaluating engine emission performance. Unfortunately, the test cycle conditions deviate from engine operating conditions experienced in actual field applications. ASABE (2011b) provides practices to follow when estimating fuel use rate and draft power requirements for hitched and other types of equipment loads. However, recommendations are not made for fuel consumption during non-working periods including when the tractor is stopped for field adjustment or repair and maintenance, when the tractor is making end-of-row turns, or when the tractor is operated at reduced speeds to accomplish field border passes.

Efforts are underway to predict off-road equipment emissions. An emission inventory model known as NONROAD was developed to predict emissions based on the equipment use (Harvey, 2003). The model estimates an emission factor which is a function of transient adjustment factors (TAFs). The TAFs are based on engine speeds and loads (both transient and steady-state) of off-road equipment. A load factor of 0.78 was considered for agricultural tractors in predicting the emission factors (Harvey, 2003). This load factor is an approximate indicator of the true load factors of the agricultural machinery, and depending on the type of operation, could have either overestimated or underestimated the engine load factor.

In-field machine performance data acquisition could be of significant value for determining actual load factors and states of tractors. Burgun et al. (2013) conducted a long term data acquisition campaign for evaluating mechanical energy needs of the plowing operation, and suggested dual alternating profile of loads. Further they used steady-state bench test results to predict operational efficiency and field load conditions. Two indicators, time efficiency ($h\,ha^{-1}$) and area specific fuel consumption ($L\,ha^{-1}$) made these predictions possible. Yahya et al. (2009) developed a data acquisition system for use with an agricultural tractor for mapping tractor-implement performance while disk plowing a field. In a similar effort, Al-Suhaibani et al. (2010) instrumented a tractor for measuring performance parameters and the draft forces of various implements at different depths and speeds. The authors found good correlations between measured and predicted values of draft force, which validated the instrumentation methodology. The availability of the Controller Area Network (CAN) bus on the tractors is allowing researchers to obtain tractor performance data (Lin, 2014; Pitla et al., 2013; Darr, 2012). Pitla et al. (2014) obtained tractor fuel use rate messages from the CAN bus to determine field efficiencies of row crop operations based on a threshold fuel use rate methodology. Further, researchers have compared CAN bus fuel use rates of tractors to physical tractor fuel measurements to understand the accuracy of CAN fuel rate data (Cupera and Sedlak, 2011; Marx, 2015; Marx et al., 2015). The study conducted by Marx et al. (2015) concluded that a maximum error of 6.22% between the physical fuel rate measurement and the CAN bus fuel rate measurement is possible. Fuel rate errors were found to be higher at lower fuel rates, whereas for higher engine fuel use rates within the torque curve the errors were found to be closer to ±1% (Marx et al., 2015). Thus, given the utility and availability of CAN bus data on current day machinery, this source of data provides an attractive alternative for tractor performance evaluation. As part of this research, CAN bus data were recorded for estimating true load states of the tractors performing typical row crop production operations.

2. Objectives

The specific objectives of this investigation were to:

(1) Obtain CAN messages related to tractor performance from the communication diagnostic ports of four wheel drive (4WD) and mechanical front wheel drive (MFWD) tractors during row crop production field operations (e.g., anhydrous ammonia (NH_3) application, field cultivation and planting).
(2) Determine actual fuel use rates and power consumption in different load states of the tractors performing NH_3 application, cultivation and planting.

3. Materials and methods

CAN bus data were logged from a 245 kW rated 4WD tractor (JD 9410R, Deere & Co., Moline, IL) and a 127 kW rated MFWD tractor (JD 7200R, Deere & Co., Moline, IL) during field operations. The 4WD tractor (see Fig. 1a) was used to pull an NH_3 applicator (DW 6032, Dalton Ag Products, Lenox, IA) and a field cultivator (JD 2210, Deere & Co., Moline, IL) shown in Fig. 1b.The MFWD tractor (see Fig. 1c) was used for planting corn with a 16 row central-fill planter (JD 1770 NT, Deere & Co., Moline, IL).

CAN data were logged with a Vector™ CAN data logger (CANcase XL log, Vector, Stuttgart, Germany) and CANalyzer software installed on a laptop computer (see Fig. 2). Data were logged from both the implement and tractor channels of the CAN bus. Tractor data from a total of six unique fields were collected. Machinery used for the study, field names, specifications of the implements, and the CAN data bus loads (%) of the tractors are summarized in Table 1. CAN messages logs were imported into Excel for sorting and extraction of machine operating parameters. A screenshot of the CANalyzer interface with CAN messages can be seen in Fig. 3. While all messages were logged, only the SAE J1939 messages were considered for the study as the identifiers and data formats were readily available through the SAE J1939 database (SAE, 2013). The primary messages used in this investigation were the Electronic Engine Controller 1 (EEC1 – $CF00400_{hex}$ – PGN 61444) and Liquid Fuel Economy (LFE – $18FEF200_{hex}$ – PGN 65266), both highlighted in Fig. 3. Data relevant to this investigation included in the EEC1 message were actual engine torque in percent, and engine speed in rpm. The LFE message provided the engine fuel use rate in $L\,h^{-1}$. From Fig. 3, it can be observed that the data in the CAN messages were in hexadecimal format. Contents of the EEC1 and LFE message frame in hexadecimal format and their respective message identifiers is presented in Fig. 4. The hexadecimal data in the messages were converted to engineering units based on the conversion factors and procedures available in the SAE J1939 database (SAE J1939, 2013). The LFE message provided the engine fuel use rate in $L\,h^{-1}$ with a resolution of $0.05\ L\,h^{-1}\,bit^{-1}$, whereas EEC1 message provided actual percent engine torque with a resolution of $1.0\%\,bit^{-1}$, and engine speed in rpm with a resolution of $0.125\ rpm\,bit^{-1}$. As an example, to convert the hexadecimal data of the LFE message, D0 and D1 data bytes of the LFE message (see Fig. 4a) which corresponded to the fuel use rate were converted into decimal numbers and combined to yield bits. These combined bits of D0 and D1 (1123) were multiplied by $0.05\ L\,h^{-1}\,bit^{-1}$ conversion factor to obtain fuel use rate in $L\,h^{-1}$. D0 and D1 data byte values of the LFE message shown in Fig. 4a, yielded a fuel use rate of $56.15\ L\,h^{-1}$. Similar procedure was followed to decode