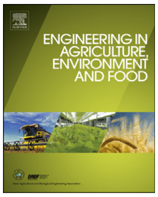
Engineering in Agriculture, Environment and Food 9 (2016) 171–178

Contents lists available at ScienceDirect

Engineering in Agriculture, Environment and Food

journal homepage: http://www.sciencedirect.com/eaef



Research paper

Energy consumption in agriculture transportation operations

T. Jokiniemi [a, *], A. Suokannas [b], J. Ahokas [a]

[a] *Department of Agricultural Sciences, University of Helsinki, Koetilantie 5, P.O. Box 28, FI-00014, Finland*
[b] *LUKE Natural Resources Institute Finland, Vakolantie 55, FI-03400, Vihti, Finland*

ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form
12 October 2015
Accepted 13 November 2015
Available online 18 November 2015

Keywords:
Agriculture
Transportation
Tractor
Truck
Energy efficiency
Fuel consumption intensity
CAN-bus

ABSTRACT

Fuel consumption intensity in agricultural transportation tasks was examined by theoretical assessments as well as practical test runs in laboratory and on road. A theoretical model for the fuel consumption intensity was created on the basis of basic equations and the results were compared to the measured figures. The results indicated that the model was working reasonably well. However, several variables included in the model require assumptions and estimations, and thus a good feel about the related issues is needed to use the model. The overall results from the study indicated that the key factors considering the energy efficiency in transportations are the rolling resistance, engine loading and payload to dead weight -ratio. With appropriate management, the energy efficiency of an agricultural tractor can be close to that of a truck. Additionally, the accuracy of the fuel consumption data captured from the tractor CAN-bus was examined. It was concluded that it was accurate enough for purposes such as energy analysis, but not for applications that demand high absolute accuracy.

1. Introduction

Energy efficiency and energy saving possibilities in agriculture have recently been targets of intensive research. This trend, affecting all industry sectors as well as private life, is driven by the general concern about the climate change scenarios and depletion of fossil energy resources. System analysis provides tools to examine the energy use in the production system and hence to reveal the inefficiencies. In order to do this, the information of energy consumption in subsystems is needed.

Agricultural internal transportations are often disregarded in the energy analysis, as they are relatively complex and difficult to estimate. The geographical layout of each farm is different, which means that universal figures cannot be given, but the energy consumption has to be estimated individually. Additionally, there is lack of information about the energy consumption in agricultural transportation operations. Until now these have usually been conducted by tractor-trailer combinations with numerous variations, and the figures given for the highway traffic cannot hence be used. However, as the size of the farms continues to grow, the internal transportation operations are becoming increasingly important for both the energy consumption and economy of the farm (Bernhardt et al., 2008). This is particularly evident in relation to large livestock units, where great amounts of feed and manure are transported between the animal shelters and fields. According to Bernhardt and Weise (2001), transporting of manure and silage or grass comprises over 50% of all agriculture transportations.

Present study focused on the complexity of the transportation operations in agriculture, having several targets. By theoretical assessments, a simple universal method to estimate the fuel consumption intensity was developed, and the energy consumption of transportations was evaluated for an agriculture tractor as well as for a truck. Replacing tractors by trucks has often been suggested to improve the transportation efficiency in agriculture. For example Götz et al. (2011) examined the efficiency and performance of tractors and trucks in several combinations, concluding that there was a clear benefit for trucks but it was not tremendously high.

In the experimental part of the study, the energy consumption and fuel consumption intensity were measured in a practical on-

---

Abbreviations: c_d, Aerodynamic drag coefficient, decimal; f, Coefficient of rolling resistance, decimal; f_t, Coefficient of rolling resistance for tractor, decimal; f_w, Coefficient of rolling resistance for trailer, decimal; E_i, Fuel consumption intensity, $\mathrm{l\,t^{-1}\,km^{-1}}$; F_L, Aerodynamic drag, N; F_{Ro}, Rolling resistance, N; F_{St}, Climbing force, N; m_c, Mass of the payload, kg; m_t, Mass of the tractor, kg; m_v, Combined mass of tractor and trailer, kg; m_w, Mass of the trailer, kg; μ_e, Engine efficiency, percent or decimal; μ_{tm}, Transmission efficiency, percent or decimal; μ_{tr}, Traction efficiency, percent or decimal.

* Corresponding author.
E-mail addresses: tapani.jokiniemi@helsinki.fi (T. Jokiniemi), antti.suokannas@mtt.fi (A. Suokannas), jukka.ahokas@helsinki.fi (J. Ahokas).

http://dx.doi.org/10.1016/j.eaef.2015.11.001
1881-8366/

road situation with various loads and two tyre inflation pressures, and the relationship between engine load and efficiency was examined. The results received from the theoretical model were also compared to the measured fuel consumption figures. Additionally, the applicability and accuracy of the fuel consumption data received from the tractor CAN-bus (Controller Area Network) was evaluated. The tractor bus traffic includes lot of different data and some of it could be utilized by the farmer as well as by research. For example Udompetaikul et al. (2011) concluded that the fuel consumption data received by monitoring the tractor CAN-bus was reliable enough for research purposes. Also Schutte et al. (2004) collected the fuel consumption data from the tractor bus without additional sensors. In this study, the reliability of the CAN-bus fuel consumption data was evaluated by a series of laboratory runs that preceded the transport test runs on road.

2. Materials and methods

The structure of the study was divided in two parts. Theoretical inspection was made on the basis of the basic motion equations, the definition of fuel consumption intensity and a typical agricultural transport work pattern. The aim of this part was to create a simple model for the fuel consumption intensity in typical agricultural applications. The model results were used to estimate the energy consumption of transport operations with an agricultural tractor and a truck. The experimental part included the laboratory test runs as well as transport test runs on the road, and the aim was to validate the results of the theoretical model, and also to examine the reliability of the fuel consumption data captured from the tractor CAN-bus. Additionally, a reduced top speed was tested to evaluate the practical effect of the top speed on the energy consumption and transport performance.

2.1. Theoretical inspection

When a vehicle is in constant motion, the required force is equal to the sum of all forces resisting the motion. Energy required for a certain distance can then be calculated by the product of the applied force F and the travelled distance s. The resistive forces are the rolling resistance F_{Ro}, aerodynamic drag F_L and the climbing force F_{St}. The rolling resistance force can be estimated by the coefficient of rolling resistance f and the normal force $N = mg\cdot \cos\alpha$, where m is the total mass of the vehicle, g is the gravitational acceleration (9.81 m s^{-2}) and α is the slope angle. In case of an agricultural tractor the aerodynamic drag is relatively small compared to the rolling resistance due to the low top speed. If the aerodynamic drag is ignored and the situation is examined on a level surface ($F_{St} = 0$), the energy requirement is then received from Eq. (1):

$$E = F_{Ro}s = fmgs \tag{1}$$

The fuel consumption intensity is denoted as consumed fuel in litres per ton-kilometres (l t^{-1} km^{-1}). When energy unit is used instead of fuel, the fuel consumption intensity E_i can be calculated as a quotient of used energy and the product of total mass and distance:

$$E_i = \frac{E}{ms} = \frac{fmgs}{ms} = fg \tag{2}$$

According to the Eq. (2), the fuel consumption intensity depends only on the resistive forces, when the total mass of the vehicle is considered. While the mass of the payload m_c is only part of the total mass, the consumed energy can be allocated to the payload by Eq. (3):

$$E_i = \frac{E}{m_c s} = \frac{fmgs}{m_c s} = \frac{m}{m_c} fg \tag{3}$$

It is obvious that the higher is the mass of the payload with respect to the total mass, the smaller is the energy consumption per payload unit.

The rolling resistance depends on the surface properties, tyre type and size, load and driving speed. According to Renius (1999), an increase in the tyre size does not have any remarkable effect on the rolling resistance on a hard surface above the diameter of about 1 m, and a rough value of 0.02 for the rolling resistance coefficient can be used for a tractor tyre. According to Wong (2001), the rolling resistance coefficients for truck tyres varies between 0.006 and 0.010, meaning that the rolling resistance for a truck is about half or less compared to that of a tractor. However, the rolling resistance of a tractor trailer tyre is closer to that of truck, and the trailer is carrying most of the load. This can be taken into account by calculating a single rolling resistance coefficient for the whole combination. When the rolling resistance coefficient for the tractor is f_t and for the trailer f_w, the rolling resistance of the whole combination is then:

$$f = f_t \frac{m_t}{m_t + m_w} + f_w \frac{m_w}{m_t + m_w} = \frac{f_t m_t + f_w m_w}{m_t + m_w} \tag{4}$$

Where m_t is mass of the tractor and m_w is the mass of the trailer. It must be noted that masses used in the Eq. (4) are the axle loads, as the tractor often carries part of the trailer mass trough the drawbar. When a two axle tipper-type trailer is used, there is no weight transfer from the trailer to the tractor, and the sole vehicle weights can be used.

Eqs. (1)–(3) handle only the work needed to move the vehicle and the payload. In addition to this, the losses in the engine, transmission and in the draft work must be considered. The engine efficiency is denoted by μ_e, transmission efficiency by μ_{tm} and traction efficiency by μ_{tr}. The traction efficiency depends on the rolling resistance and the wheel slip. The rolling resistance is already considered in the previous equations. The wheel slip in on-road transportations is only a few percents, and it may be disregarded. The Eq. (3) can then be written as:

$$E_i = \frac{mfg}{m_c \mu_e \mu_{tm}} \tag{5}$$

The engine efficiency can be calculated from the brake specific fuel consumption (BSFC) of the vehicle. According to Kim et al. (2005), the average BSFC for the maximum PTO power of tractors tested in the Nebraska Tractor Test Laboratory in 2002 was 0.236 kg kWh^{-1}. While the lower heating value of the fuel is 43 MJ kg^{-1} (~12 kWh kg^{-1}), the average efficiency of tested tractors is thus 1/(0.250 × 12) = 0.35. The specific fuel consumption, however, is affected by the engine load and -speed, and it is constantly changing. The BSFC of diesel engines is at the lowest ca. 200 g kWh^{-1}, which corresponds to efficiency of 0.42 (Hewood, 1988). When the engine is idling, the BSFC is infinitely large, since no output power exists. The engine efficiency varies therefore between ca. 40 and 0 per cent, depending on the operating conditions, and an estimation of the average engine efficiency must be used in the analysis. This can be given on the basis of the resistive forces and the engine specific fuel consumption map. As the legislation limits the total mass and hence the payload for the trucks as well as tractors, and the power reserve is also needed to climb the hills, the average engine load in the transportation tasks cannot be extremely high on a level surface. The engine speed for a given running speed can be reduced, and the load increased