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Research Paper

Computer simulations to maximise fuel efficiency and work performance of agricultural tractors in rotovating and ploughing operations

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This study was conducted to investigate the effects of five control variables of a tractor: ballast, tyre inflation pressure, transmission gear, engine speed, and work load on three fuel efficiency parameters: fuel consumption per work hour (FC), fuel consumption per tilled area (FCA) and specific volumetric fuel consumption (SVFC). This was done for moldboard ploughing and rotovating operations by computer simulation. A tractor model was constructed with four sub-models: engine and power train, fuel consumption, tractive performance, and draught and power requirement. The simulated fuel efficiency values were in a range of 3.3–6.5% error in average when compared with those obtained from field experiments carried out in a paddy field under the same operational conditions. Based on these results, the tractor model was considered acceptable for simulations to find a general relationship between the fuel efficiency parameters and the control variables.

Using the tractor model, 162 simulations were performed under the various combinations of the control variables on the basis of a full factorial design. The simulation results were used to develop linear regression models from which strategies can be established to maximise fuel efficiency. The best strategy reduced FC, FCA, and SVFC by 81.3, 61.1, and 52% under ploughing, and by 58.9, 75.7 and 28.6% under rotovating operations, respectively, when compared with those for the worst strategy.

1. Introduction

The tractor is one of the largest fuel consumers among agricultural machines. In Korea, agricultural tractors consumed 329,000 kL in 2010 which was about 17% of the total tax-free fuel allocated for agricultural use. This consumption was a 4% increase compared to 2009 (NACF., 2010). The tractor population is growing continuously and the tractor power also appears to increase in recent years. This trend is expected to continue and so is tractors' fuel consumption in Korea. In addition, tractors should meet emission standards both in domestic and overseas markets. In response to such circumstances, tractor manufacturers are required to develop technologies to increase fuel efficiency of tractors and at the same time to reduce their emissions without any power loss.

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Nomenclature

a	Acceleration of tractor, m s^{-2}
A, B,C	Constants depending on implement types
A_r	Vertical projected area of implement, m^2
b	Unloaded tyre section width, m
B_n	Mobility number
CI	Cone index, kPa
C_r	Specific draught torque, Nm m^{-2}
d	Unloaded tyre diameter, m
e_i	Longitudinal offset of soil reaction to wheel ($i = r$ for rear, f for front), m
F_d	Draught of implement, N
G_i	Speed reduction ratio of ith gear, decimal
GTR	Gross traction ratio
h	Unloaded tyre section height, m
H	Gross traction force, N
h_z	Ground clearance of implement, m
K_i	Soil texture parameter ($i = 1$ for fine, 2 for medium and 3 for course soils)
L_1	Longitudinal distance between rear axle and mass center of implement, m
L_2	Longitudinal distance between mass center of tractor and rear axle, m;
L_3	Longitudinal distance between mass center of tractor and front axle, m
L_4	Longitudinal distance between front axle and mounting position of ballast, m
MRR	Motion resistance ratio
m_t	Tractor mass, kg
N_t	Rotational speed ($i = e$ at engine, R at rear tyre, F at front tyre), RPM
P_L	Tractor power, kW
P_r	PTO power, kW
P_w	inflation pressure of tire, Pa
r_i	Rolling radius of tyre ($i = r$ for rear tyre, f for front tyre), m
r_s	Unloaded radius of tyre, m
s	Slip of driving tyres, decimal
T	Ploughing depth, m
T_i	Torque ($i = e$ at engine, R at rear tyre, F at front tyre), N m
V	Tractor velocity, km h^{-1}
v_a	Actual velocity of tractor, m s^{-1}
v_t	Theoretical velocity of tractor, m s^{-1}
W_b	Weight of ballast, N
w_i	Width of tillage implement, m
W_i	Weight of implement, N
W_j	Vertical tyre load ($j = r$ for rear, f for front), N
w_k	Weight acting on the axle in % of total weight ($k = R$ for rear axle, F for front axle), %
W_t	Total tractor weight, N
δ	deflection, m
η	Transmission efficiency, decimal
ω	Rotational speed of rotovator shaft, rpm

Abbreviations

Ba	Ballast
CG	Center of gravity
DF	Degree of freedom
Es	Engine speed
FC	Fuel consumption in, L h^{-1}
FCA	Fuel consumption per tilled area, L ha^{-1}
FE	Fuel efficiency parameters
SVFC	Specific volumetric fuel consumption, L kW^{-1} h^{-1}
Ti	Tire-inflation pressure
Tr	Transmission gear ratio
Wl	Work load

Various studies have been conducted to improve fuel efficiency of tractors. Gear up and throttle down (GUTD) is a well-known operational technique to reduce fuel consumption of tractors in field operations, particularly during ploughing and transportation.

Grisso and Pitman (2001) analysed the effects on tractor's fuel consumption of engine speed and gears at the same drawbar power using performance test data published by the Nebraska Tractor Test Laboratory. They realised that 5–30% of fuel can be saved if the engine speed is reduced by 20–30% and the drawbar is loaded within 75% of the maximum engine power. Peça et al. (2010) analysed the effects of engine speed and gear on the overall power efficiency in tractor operations. They reported that the overall power efficiency increased by 10–20% when the engine speed was reduced from 2200 to 1750 rpm. Proper adjustments of tyre inflation pressure and ballast also contributed to improving fuel efficiency of tractors (Serrano, Peça, Marques da Silva, & Márquez, 2009). Gee-Clough, Pearson, and McAllister (1982) found that if a tyre is loaded in a range of 70–140% of the optimum dynamic load, the tractive force would not be significantly reduced relative to the maximum traction. Lancas, Upadhyaya, Sime, and Shafii (1996) reduced fuel consumption by 6–20% and increased productivity by 4.6–7.5% by maintaining proper tyre inflation pressure during stubble-disking operations in tilled moist clay soils. Casady (1997) developed guidelines for the management of tyre inflation pressure and ballast to maximise tractive efficiency, to minimise soil compaction and to increase the life of a tractor's drivetrain and profitability. A variety of educational materials have been developed to help tractor operators increase fuel economy (Fulton, Raper, McDonald, & Tyson, 2006; Firestine, Furrey, Aslin, Crivella, & Sautter, 2007). Tractor manufacturers also developed and commercialised information and support systems such as ‘ACET’ of Renault, ‘INFORMAT’ of Steyer, ‘ECOplus’ of Kubota, ‘ECOTRONIK’ of Steyr, and ‘Efficient Technology’ of Fendt to improve fuel efficiency.

Park et al. (2010a) developed an eco-driving system to help tractor operators select the proper gear and engine speed according to the work loads. They reduced fuel consumption by an average of 69% in ploughing and 54% in rotovating operations with the aid of the system. Lee, Kim, Kim, and Choi (2011) conducted field experiments under various soil conditions and found that proper adjustment of tyre inflation pressure