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Rule-Based Power Distribution in the Power Train of a Parallel Hybrid Tractor for Fuel Savings

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Most parallel hybrid tractors are conceptualized as a motor which serves as an auxiliary power source that handles loads which an engine does not cover. However, the development of hybrid tractors for better traction performance does not show greatly improved fuel consumption compared to conventional tractors, meaning that different means of controlling- the power source is needed for hybrid tractors. In this study, improving fuel consumption in a parallel hybrid tractor is demonstrated through power split ratio strategy after devising a simulation model of a power train. Initially, the simulation of the power train in a parallel hybrid tractor needs to assess the following actual traction performance factors: the engine, the wheels, and the PTO speed. PTO is the abbreviation of Power Take Off, which is any of several methods for taking power from a power source. Rule-based power distribution strategy depending on the optimal control then changes fuel savings while working over wide land areas. Finally, vehicle performance values which include certain operating points and fuel consumption between a case of the hybrid and a case of control of the traction power source for traction improvement are compared and analysed.

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NOMENCLATURE

M = Vehicle mass (kg)
g = Gravity (m/s^2)
θ = Incline (%)
ρ_{air} = Air density (kg/m^3)
C_d = Coefficient of air resistance
A_f = Frontal area (m^2)
V = Vehicle velocity (m/s^2)
f_r = Coefficient of rolling resistance
T_{eng} = Engine torque (Nm)
T_{mot} = Motor torque (Nm)
F_{mg} = Wheel resistance of Incline (N)
F_{aero} = Wheel resistance of air (N)
F_{fr} = Wheel resistance of ground (N)
I_g = Transmission gear
r_f = Final ratio
r_t = Tire radius (m)
ω_{eng} = Engine speed (rpm)
ω_{mot} = Motor speed (rpm)
ω_{target} = Engine target speed (rpm)
T_{req} = Required torque of vehicle (Nm)
F_t = Vehicle wheel load (N)
I_{veh} = Inertia of the vehicle (kg m^2)

1. Introduction

The vehicle industry at present faces problems related to petroleum. International oil pricesare expected to increase due to reduction of petroleum production by International organizations and political instability in the Middle East. The vehicle industry faces greater restrictions on exhaust gases. which cause environmental pollution. This international situation has led to their emphasis on eco-friendly manufacturing steps to create cleaner and more efficient. One such result is the hybrid vehicles, which has two or more power sources in the drivetrain. There are many different types of hybrid vehicles although only the gasoline-electric hybrid is currently commercially available. Hybrids are classified according to the division of power between the power sources; both sources may operate in parallel to provide acceleration simultaneously, or they may operate in series with one source exclusively providing acceleration and the second being used to augment the first's power reserves. The sources can also be used in both series and parallel as needed, with the vehicle being primarily driven by one source but with the second capable of providing direct additional acceleration if required.

Current hybrids use both an internal combustion (IC) engine and a battery/electric drive system to improve fuel consumption, emissions, and performance. Electrically assisted pedal bicycles are a form of hybrid drive. Other combinations of energy storage and conversion are possible although not yet in commercial production.[1]

Following this developmental stream of hybrid vehicles, the agricultural mechanics industry is now developing hybrid tractors. However, unlike general vehicles, tractors require considerable amounts of traction power given their need for auxiliary operating power to work with crops. Crucial in this area is a technology known as PTO, which stands for Power Take Off. The PTO component, which refers to a secondary transmission and a clutch to handle heavy loads, is located between the engine and the main transmission. In some cases, a tractor which uses an engine as a traction power source alone is not capable of operating under a heavy load in an agricultural field.[2] This explains why hybrid tractors now have large PTO components. In general, parallel hybrid tractors use a motor as a secondary power source in charge of loads. However, unlike hybrid vehicles, the power sources of hybrid tractors are not operated by electronic control machines or by an algorithm. This implies that a different means of controlling the power sources of hybrid tractors is needed for better performance. In this study, improving fuel use by a hybrid tractor is demonstrated by power split ratio (PSR) of dynamic programming (DP) after the modeling of the power train. The powertrain simulator of the parallel hybrid tractor needs verification through actual data and enforcement of rules-based power distribution control using the optimal control, DP. The results suggest that controlling the power source electronically is possible when operating parallel hybrid tractors. The operational points with regard to control of the traction power source for traction and improving the fuel consumption are also compared and analyzed.

2. Parallel Hybrid Tractor

The parallel hybrid tractor in this work has a 50 kw engine and 9 kw motor as its power sources. The motor is the auxiliary power source, which covers traction power. A 15 kw Battery supplies power to the traction motor. The manual transmission, which is located between the power sources and the rear wheels has sixteen gears.

2.1 Power Train Structure

The power train structure is shown in Fig. 1 was created using the simulator in the MATLAB software program. It usually works by engine only, but if it takes a big load to the PTO is working, it is in a hybrid mode, operated as a motor to support the engine. In the end the engine and the motor provides power to the wheel against the load of driving, and to the PTO working machine against PTO load applied between the power source and the manual transmission. The battery provides power to the motor and it is charged by the engine after the end of the PTO operation.[3]

The power source modules show the performance data of the engine, motor and battery. Specifically, the engine and motor speed are synchronized to deliver more power to the wheels and the PTO.

The PTO module includes the necessary power for auxiliary components, such as the rotor, plow, mower, and bailer. The manual transmission module includes gear ratios and the value of the final gear ratio. The values which represent the rolling, air, and ground resistance, all related to the required power, are calculated in the vehicle module.

$$T_{eng} + T_{mot} = I_{veh}\dot{\omega}_{veh} \quad (1)$$

$$T_{eng}\omega_{eng} + T_{mot}\omega_{mot} = T_{veh}\omega_{veh} \quad (2)$$

$$(T_{eng} + T_{mot})I_g r_f = F_{req} r_t \quad (3)$$

2.1.1 Power Source Modules

Figs. 2 to 4 show the performance data of the power sources. The values of the required torque as calculated by the PID control, are transferred to those modules and have an effect on the calculation of the power source speed. OOL is an abbreviation which stands for the optimal operating line, which refers to the optimal fuel savings line of the engine. It is the set of points which have the lowest fuel quantity against the values of the engine power given the engine speed and power displacement. It can be obtained by the experiment data and also one of the power distribution criteria.

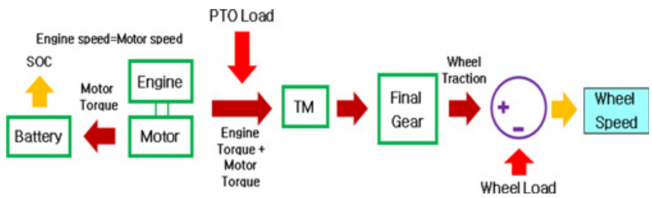

Fig. 1 Power train system of hybrid tractor

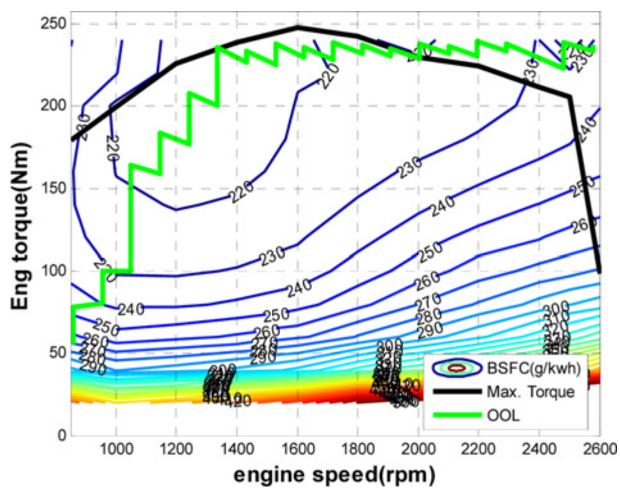

Fig. 2 Engine data of 50 kw

2.1.2 PTO (Power Take Off) Module

Fig. 5 shows the PTO rotary power data under operation by auxiliary devices to handle agricultural work. The PTO power can be measured at the spot between the power sources and the transmission. It is the input of the PTO module in the simulator, while the output is the PTO speed (rpm). The PTO serves as the vehicle load in the simulator.

It is actually used in the PTO module in the simulator. Its unit is Nm, same as torque.

2.1.3 Transmission Module

The gears of the manual transmission have sixteen values. These gear values are much greater than those of general hybrid vehicles due to the high level of power required for work.

2.1.4 Vehicle Module

The vehicle module calculates the values of the resistance which is operates on the rear wheels. These values are calculated by the Eq. (4)

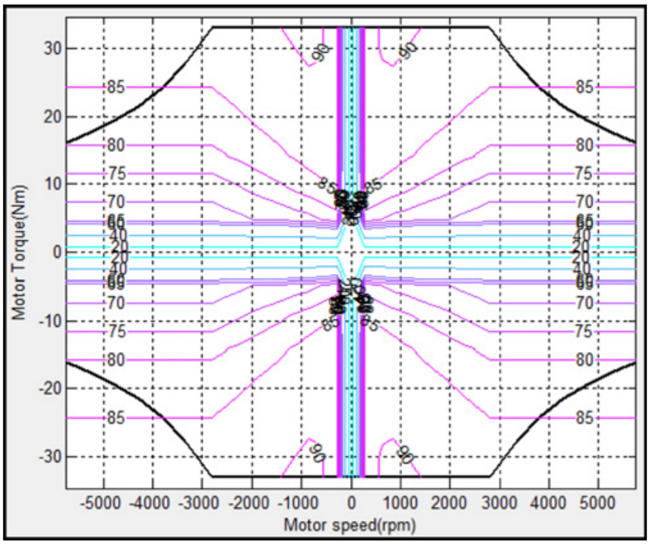

Fig. 3 Motor of 9 kw

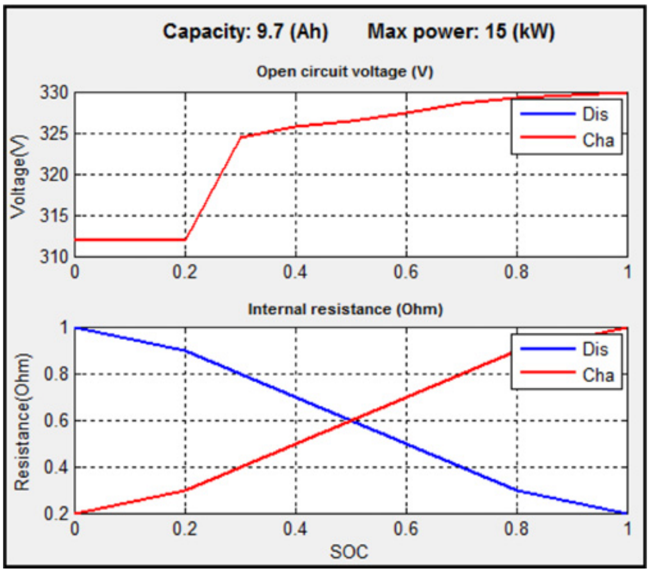

Fig. 4 Battery of 15 kw

as shown below.

$$F_t = F_{mg} + F_{aero} + F_{fr} = Mg\sin\theta + \frac{1}{2}\rho_{air}C_dA_f(V-V_w)^2 + Mgf_r\cos\theta \quad (4)$$

Table 1 shows the information of object hybrid tractors. Those item values are used to calculate required torque of traction power sources.

3. Distribution Traction Power

3.1 PID Control

The power required by the hybrid tractor can be calculated by the PID control. Equation for calculating required torque of engine as shown below.

$$T_{req} = P(\omega_{target} - \omega_{eng}) + I\int(\omega_{target} - \omega_{eng})dt \quad (5)$$

PID stands for proportional-integral-derivative, which refers to a control-loop feedback mechanism. It is widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. This controller attempts to minimize the error by adjusting the process through use of a manipulated variable. The PID controller algorithm involves three separate constant parameters, and is accordingly sometimes called a three-term control method. They are the proportional, the integral and the derivative values, denoted respectively as P, I, and D.[4]

In this study, the engine speed is adjusted by this PID action. The required torque can be calculated from the difference between the target

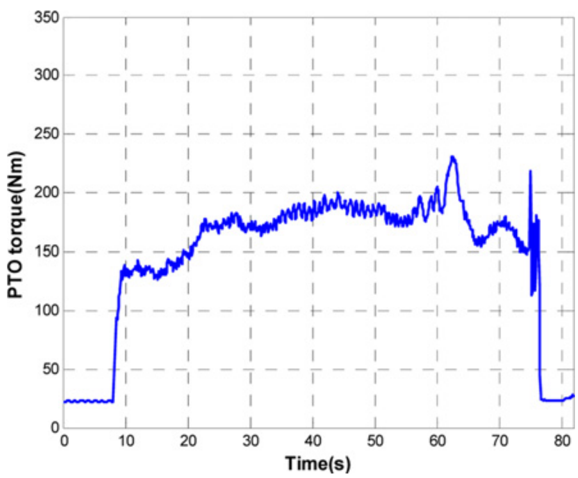

Fig. 5 Applied PTO load

Table 1 Tractor information

Item	Value
Vehicle mass (kg), M	2570
Tire radius (m), r_t	0.64
Vehicle frontal area (m^2), A_f	3.2
Air density (kg/m^3), ρ_{air}	1.204
Rolling resistance co-eff., C_d	0.035
Aerodynamic drag co-eff., f_r	0.023

engine speed and the simulated engine speed of the tractor. This difference is reflected for calculating the required torque in the drive model of the simulator to minimize errors in the result. Most tractors are used to move materials and work within a particular engine speed region.

3.2 Distribution Strategy

In hybrid vehicles, the distribution strategy for the power on sources is determined by a rule-based control or optimal control method. Rule-based control is one of the power distribution strategies used by hybrid vehicles. This method is used in the driver model of the power train simulator of hybrid tractors. The distribution strategy of hybrid tractors simply consists of three cases. The engine is always on when the tractor is working in the field. If the tractor needs more traction due to a heavy load, the traction motor comes on. When the battery SOC is a lot of enforcement falls by jammed PTO load, the engine charges the battery. This mode is started after the PTO operation. It can provide the supplemental power not delivered by the engine. Fig. 6 shows the power distribution of hybrid tractors, emphasizing traction performance in suburban field.[5]

3.3 Proposed Strategy of Hybrid Tractors

The proposed distribution strategy for a hybrid tractor considers the traction and fuel consumption performance through power split ratio strategy. Points of the power split ratio of total required power are calculated by dynamic programming (DP) which is one of the optimal controls of hybrid vehicles for optimal fuel saving and sustaining of battery SOC. The powertrain of parallel hybrid tractors also can be applied to dynamic programming for the optimal driving.

3.3.1 Dynamic Programming

In order to solve a given problem, using a dynamic programming approach, we need to solve different parts of the problem, then combine the solutions of the sub-problems to reach an overall solution. Often when using a more naive method, many of the sub-problems are generated and solved many times. The dynamic programming approach seeks to solve each sub-problem only once, thus reducing the number of computations: once the solution to a given sub-problem has been computed, it is stored or memorized: the next time the same solution is needed, it is simply looked up. This approach is especially useful when the number of repeating sub-problems grows exponentially as a function of the size of the input.[6]

Dynamic programming applied to the hybrid tractor in this study consists of N stages of time step, conditional parameter x in k stage of N, and control parameter u. Optimization is defined as shown below.

$$x(k+1) = f(x(k), u(k)) \tag{6}$$

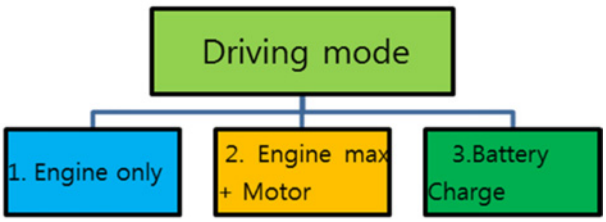

Fig. 6 Power distribution for the parallel hybrid tractor

$J_{k,N}(x(k))$ is the optimal route from k stage to final stage. The dynamic equation as shown below.

$$J_{k,N}(x(h)) = \min\{L(x(k), u(k)) + J_{k,N+1}(x(k+1))\} \tag{7}$$

Above equation expresses dynamic programming which is solved by backward way. If the optimal route form k+1 stage to final stage is known, the optimal route from k stage to final stage can be calculated. from the dynamic equation. Cost function J is the function of fuel economy and battery SOC change in the view of the power distribution problem of the hybrid tractor. Control parameter u is the battery power in each time step.[7]

3.3.2 Distribution of Power Split Ratio Values

The control strategy of power split ratio is the power distribution strategy of the hybrid vehicle in analyzing driving data by optimal control, targeting optimization of fuel saving performance. It is used to calculate engine required power given total required power in the power train simulator. Power split ratio is the ratio between total required power and engine required power as shown below.

$$PSR = \frac{P_{d\_cmd}}{P_{ref}} \tag{8}$$

Driving mode can be changed by PSR values. If PSR is bigger than 1, the engine charges the battery to increase SOC. It means that the engine required power is bigger than total vehicle required power.

If PSR is bigger than 0 and smaller than 1, the engine and motor are operated by hybrid traction. In the case of 0, the vehicle is operated as electric vehicle (EV). Regenerative braking can be applied to the vehicle under 0. However, regenerative braking is not appropriate to be applied to tractors. Speed of wheels is too slow compared to hybrid vehicles and drivers do not use the brake pedal as frequent as general hybrid vehicles during PTO work. Regenerative braking is not considered to calculate engine operating points by dynamic programming.[8]

However, battery charge from the engine must be included in the power distribution strategy because sustaining battery SOC is related to fuel saving performance. Battery SOC needs to be recovered to original condition after heavy PTO work where battery charge from the engine does not happen.

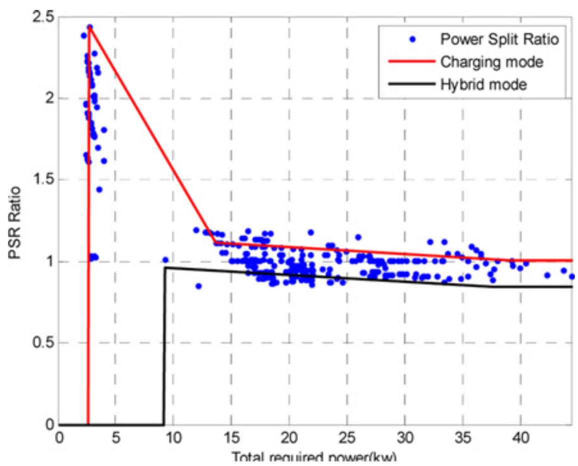

Fig. 7 Power split ratio of the parallel hybrid tractor

Power split ratio can be calculated by operating points of the engine from dynamic programming. Operating points of the parallel hybrid tractor are shown below.

It is the tendency that the power split ratio is decreased according to total required power. This means that high total required power mainly shows hybrid traction and low total required power mainly shows battery charging mode. This tendency is also advantageous for sustaining battery SOC and saving fuel amount. PSR of the battery charging and hybrid mode from dynamic programming is applied to the power train simulator of the hybrid tractor. Total required power is calculated from PID control and PSR values make a decision of the engine required power.[9]

4. Results and Conclusions

4.1 Simulation Result of Hybrid Tractors

The results of the power train simulator of the hybrid tractor must be compared to actual data. Figs. 8 to 10 show the engine speed, the PTO speed and the wheel speed in both the actual situation and the simulation. The engine operating points are mostly located in the range of 2300 to 2500 rpm. These results show that the simulation outcome approximates the actual data correctly. The hybrid tractors simulator also shows accurate results with regard to the actual performance.

Fig. 11 is the change of the battery state of charge, which started at 0.6. There is no regenerative braking in the hybrid tractor, thus the SOC only drops during rotary work. Battery SOC of PSR strategy drops more faster than the case of PID control. It means that proportion of engine required power is less than that of PID control.

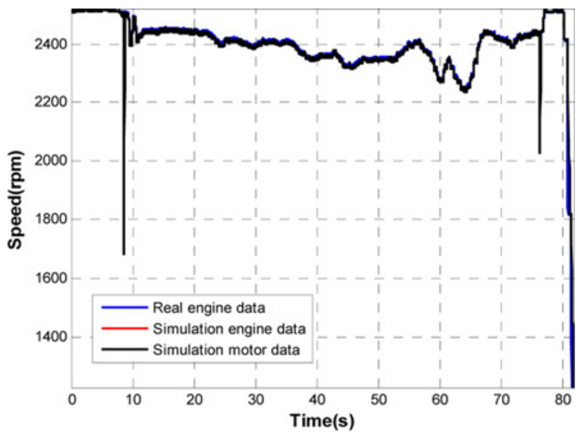

Fig. 8 Engine and motor speed

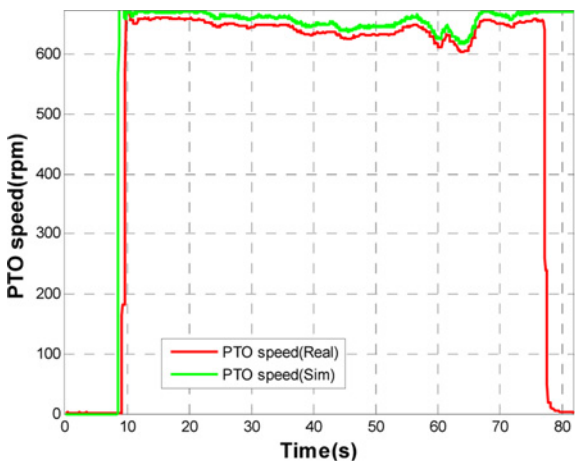

Fig. 9 Tractor PTO speed

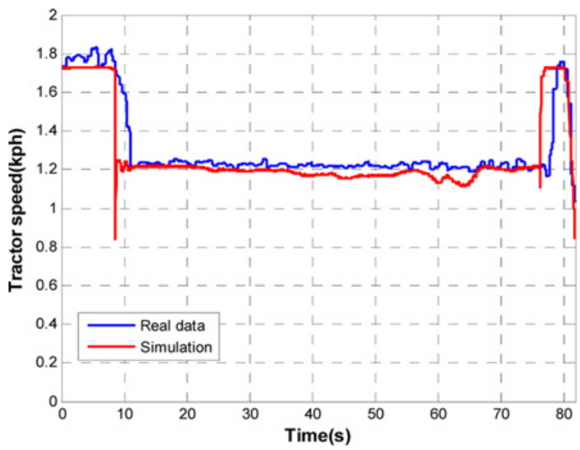

Fig. 10 Tractor wheel speed

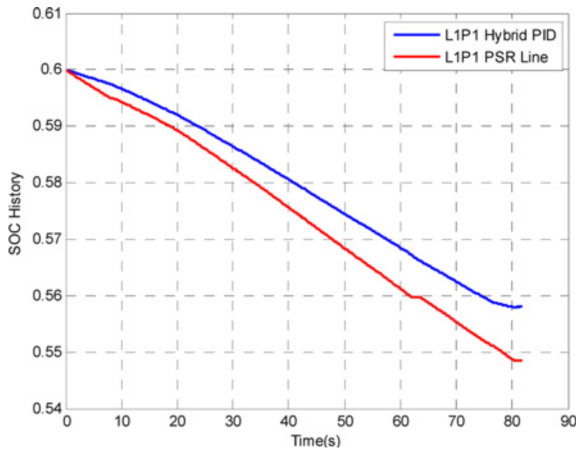

Fig. 11 Change of battery SOC

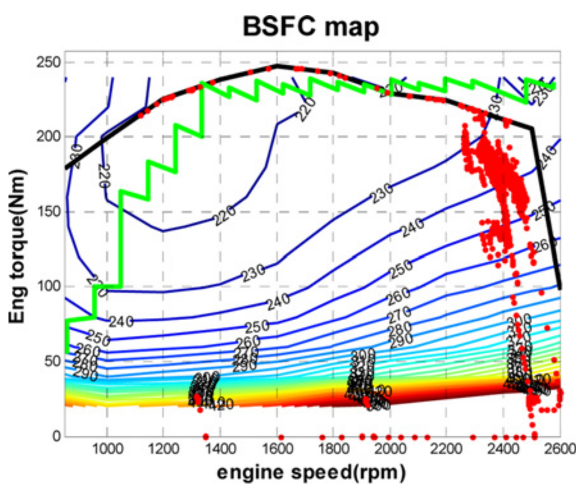

Fig. 12 Engine operating points of the conventional tractor

4.2 Simulation Result of Engine Control

Figs. 12 to 14 show the operating points of the engine in the conventional tractor, PID hybrid and the proposed strategy. Green line stands for optimal operating line.

The operating points of the engine in the proposed strategy are similar to those of the original parallel hybrid tractor.

However, operating points of the engine in the conventional tractor are completely different from those of the hybrid tractor and proposed strategy. They have much higher torque compared to other cases. This indicates that hybrid tractors show better fuel consumption performance compared to conventional tractors.

The fuel consumption of the three cases including a case of the conventional tractor are shown below. Fuel consumption when using the proposed power distribution strategy in the parallel hybrid tractor is less than in the original case.[10] Fuel saving improvement between conventional and PID hybrid tractor is much bigger than that between PID hybrid and proposed case.

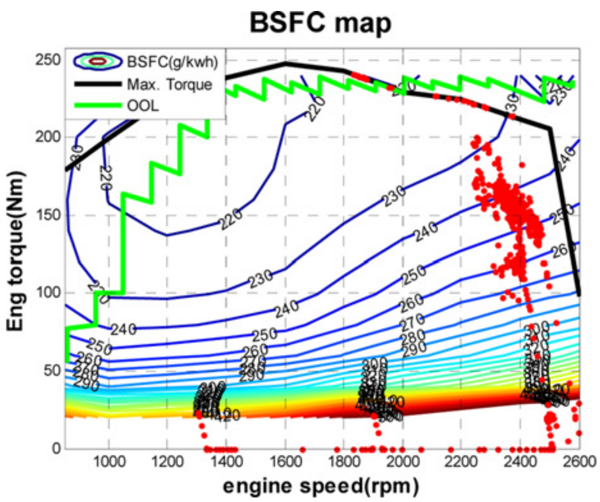

Fig. 13 Engine operating points of the parallel hybrid tractor

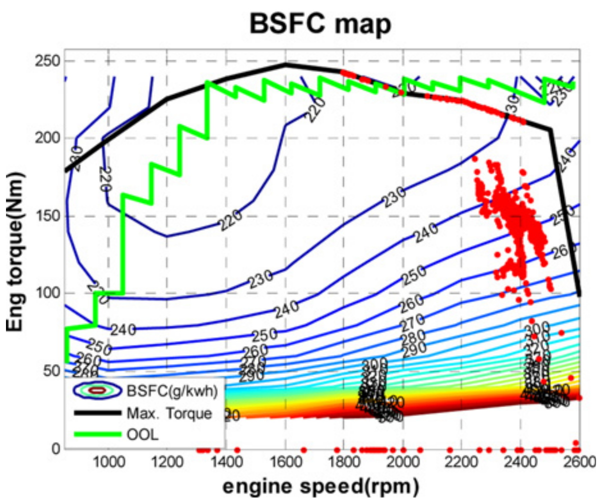

Fig. 14 Engine operating points by the proposed strategy

Table 2 Values of fuel consumption

PTO	Conventional	Hybrid tractor	Proposed case
Rotary	208.81 g	184.22 g	180.75 g

The engine fuel efficiency improvement rate of the conventional tractor and the hybrid is 11.78%. Hybrid side is of course higher than conventional because the motor support the engine for dealing with total load. The fuel efficiency improvement rate of the proposed strategy is 1.88% compared to the hybrid. This value does not achieve the fuel efficiency improvement rate between the engine and hybrid tractor. However, increase of the 1 - 2% fuel efficiency improvement of the same powertrain and the driving environment is great achievement.

Therefore the proposed power distribution strategy is proved by the simulation to be effective for improved fuel consumption performance by aparallel hybrid tractor. This can serve as an useful strategy for the control of parallel hybrid tractors if they are operated using electric power source management system.

ACKNOWLEDGMENTS

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REFERENCES

1. Ehsani, M., Gao, Y. M., and Emadi, A., "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design," CRC Press, 2nd Ed., pp. 459-469, 2010.
2. Jeong, J., Lee, D., Shin, C., Jeong, D., Min, K., et al.,"Comparison of the Fuel Economy of Series and Parallel Hybrid Bus System Using Dynamic Programming," The Korean Society of Automotive Engineers, Vol. 21, No. 1, pp. 92-98, 2013.
3. Tritschler, P., Bacha, S., Rullière, E., and Husson, G., "Energy Management Strategies for an Embedded Fuel Cell System on Agricultural Vehicles," Proc. of International Conference on Electrical Machine, pp. 1-6, 2010.
4. Zheng, C., Cha, S. W., Park, Y.-I., Lim, W. S., and Xu, G., "PMP-Based Power Management Strategy of Fuel Cell Hybrid Vehicles Considering Multi-Objective Optimization," Int. J. Precis. Eng. Manuf., Vol. 14, No. 5, pp. 845-853, 2013.
5. Hofman, T., Steinbuch, M., Van Druten, R., and Serrarens, A., "Rule-Based Energy Management Strategies for Hybrid Vehicles," International Journal of Electric and Hybrid Vehicles, Vol. 1, No.1, pp. 71-94, 2007.
6. Kessels, J. T., Koot, M. W., Van Den Bosch, P. P., and Kok, D. B., "Online Energy Management for Hybrid Electric Vehicles," IEEE Transactions on Vehicular Technology, Vol. 57, No. 6, pp. 3428-3440, 2008.

7. Jeong, J., Lee, D., Kim, N., Park, Y.-I., and Cha, S. W., "Fuel Economy Analysis of a Parallel Hybrid Bus Using the Optimal Control Theory," Proc. of IEEE Vehicle Power and Propulsion, pp. 1-5, 2011.

8. Zheng, C. H., Park, Y. I., Lim, W. S., and Cha, S. W., "Fuel Economy Evaluation of Fuel Cell Hybrid Vehicles Based on Optimal Control," International Journal of Automotive Technology, Vol. 13, No. 3, pp. 517-522, 2012.

9. Kim, N. W., "Energy Management Strategy for Hybrid Electric Vehicles Based on Pontryagin's Minimum Principle," Ph.D. Thesis, Department of Mechanical Aerospace Engineering, Seoul National University, 2009.

10. Bernard, J., Delprat, S., Büechi, F. N., and Guerra, T. M., "Fuel-Cell Hybrid Powertrain: Toward Minimization of Hydrogen Consumption," Transactions of IEEE Vehicular Technology, Vol. 58, No. 7, pp. 3168-3176, 2009.