Automation in Construction 69 (2016) 89–101

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Gear ratio and shift schedule optimization of wheel loader transmission for performance and energy efficiency

Kwangseok Oh [a], Seungjae Yun [a], Kyungeun Ko [b], Sunghoon Ha [b], Panyoung Kim [b], Jaho Seo [c], Kyongsu Yi [a,*]

[a] School of Mechanical and Aerospace Engineering, Seoul National University, 599 Gwanangno, Gwanak-Gu, Seoul, 151-742, Korea
[b] Hyundai Heavy Industries Co., Jeonha1-dong, Dong-gu, Ulsan, 682-792, Korea
[c] Korea Institute of Machinery and Material, 156 Gajeongbuk-ro, Yuseong-gu, Daejeon, 305-343, Korea

ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form 23 May 2016
Accepted 3 June 2016
Available online 11 June 2016

Keywords:
Torque converter (T/C)
Automated manual transmission (AMT)
Dual clutch transmission (DCT)
Driver model
V-pattern working cycle

ABSTRACT

This paper presents gear ratio and shift schedule optimization strategies to improve energy efficiency for the dynamic simulation of a wheel loader equipped with dual clutch transmission (DCT) and automated manual transmission (AMT). A conventional wheel loader uses torque converter (T/C) based automotive transmission, and the torque converter causes heavy energy loss during the V-pattern working cycle. To improve fuel economy while maintaining working performance in the V-pattern working cycle, automated manual transmission (AMT) and dual clutch transmission (DCT) have been suggested to substitute the clutch for the torque converter. In addition, the optimization strategies for the gear ratio and shift schedule for AMT and DCT have been proposed for improving fuel economy. Gear ratios have been determined by a nonlinear optimization method based on the standard V-pattern working cycle which is obtained from experimental test data by a skilled driver. Then, the gear-shift schedule for clutch-type transmission has been derived by using a determined gear ratio and optimization strategy. Simulations have been conducted to investigate working performance and energy efficiency by using three developed wheel loader simulation models equipped with T/C, AMT, and DCT, respectively, with the driver model for the V-pattern working cycle. Simulation results show that AMT- and DCT-based wheel loaders are more fuel efficient for the V-pattern working cycle than the T/C-based wheel loader.

1. Introduction

Wheel loaders constitute one of the most important heavy vehicles in construction sites since they can exhibit high performance for transporting materials, and are a key factor for improving construction efficiency. Wheel loaders consume a large amount of fuel to conduct V-pattern work, which is a typical function of wheel loaders since wheel loaders are typically exposed to harsh environments and deliver heavy materials. Therefore, many researches to improve working performance and lower emissions in construction machines have been performed, and various methods for enhancing fuel efficiency have been applied to construction machinery. The wheel loader that is the subject of this study is shown in Fig. 1.

M. Worley et al. [1] presented a subscale dynamic model, which isolates the boom and bucket manipulator systems of the front-end loader for the purpose of design load characterization. The proposed model includes state equations governing the hydraulic dynamics across the control valves and in the cylinders, as well as soil-tool interaction loads at the bucket cutting-edge. R. Filla et al. [2] presented the initial results for a simulation model of a human operator. Rather than allowing the operator model to follow a pre-defined path with control inputs at given points, it followed a collection of general rules that together describe the machine's working cycle in a generic way. R. Filla et al. [3,4] also presented some results of an approach to an event-driven simulation model of a human operator and a holistic approach to wheel loaders as complex energy conversion systems. K. Pettersson et al. [5] analyzed two known concepts of multi-mode power split transmissions suitable for the wheel loader application and compared the solutions based on energy efficiency. J. Sun et al. [6] reviewed different types of automotive transmissions to improve fuel economy and explained their unique control characteristics.

In this study, clutch-type automotive transmissions have been applied to the torque converter based wheel loader for improving fuel efficiency during V-pattern working. Applied clutch systems are either automated manual transmission (AMT) or dual clutch transmission (DCT), which are both well known for high energy-efficiency. Required components to apply the clutch-type transmissions to the wheel loader have been analyzed and modeled in the Matlab/Simulink environment. Energy loss caused by fluid friction in the torque converter in the automotive transmission of the wheel loader can be prevented by replacing the torque converter with a clutch. When the wheel loader does not

* Corresponding author.
E-mail address: kyi@snu.ac.kr (K. Yi).

http://dx.doi.org/10.1016/j.autcon.2016.06.004
0926-5805/

Fig. 1. Wheel loader.

need to transfer engine torque to wheels during V-pattern working, unnecessary energy loss can be prevented efficiently by disengaging the clutch.

The clutch control strategy has been proposed and applied to the wheel loader simulation model with a driver model for V-pattern working. In addition, an optimization strategy of gear ratio and shift schedule for clutch-type automotive transmission has been proposed based on standard V-pattern working cycle in this paper. The standard V-pattern working cycle has been obtained from experimental test data by a skilled driver. A five-ton class wheel loader simulation model has been used to analyze the working performance and energy efficiency of V-pattern working. The used driver model and simulation model in this paper were developed in the Matlab/Simulink environment. Simulation results show that the clutch-type automotive transmission is more fuel-efficient than the torque converter based automotive transmission, while producing satisfactory working performance. It is expected that the presented analysis and optimization strategies for the wheel loader can be applied in the design stage for improving fuel efficiency and reducing the emissions of construction equipment.

2. Modeling and analysis of wheel loader

The basic function of any type of automotive transmission is to transfer the engine torque to the wheel smoothly and efficiently for high driving-performance. To achieve high driving-performance and transfer the engine torque efficiently, the torque converter has been generally used in the powertrain system. However, torque converters involve a loss of energy due to fluid friction when the engine is transferring torque to wheels or idling. The wheel loader that is the subject of this study also utilizes a torque converter for automotive transmission. Moreover, it is analyzed that the energy loss by fluid frictional force in the torque converter is dominant by using the wheel loader simulation model with a driver model based on typical V-pattern working [23]. The used simulation model for analysis has been constructed in the Matlab/Simulink environment and validated from experimental test data [7].

2.1. Conventional wheel loader and driver model

The developed and used wheel loader simulation model in this paper consists of the driver model, the wheel loader dynamic model, and the load model. All constructed simulation models have been modeled in the Matlab/Simulink environment based on vehicle dynamics and multi-body dynamics [8]. The overall simulation model schematic is shown in Fig. 2.

The mechanical and hydraulic powertrain models consist of an engine, torque converter, transmission, pumps, valves, and cylinders. One part of the power from the engine is transmitted to the wheel through the mechanical powertrain for driving, and the remaining part of the power is transmitted to cylinders for working and steering. The pump is connected to the engine with a torque converter directly in order to transmit power from the engine to the hydraulic system. Fig. 3 describes the overall mechanical and hydraulic powertrain of a wheel loader. Each component of the powertrain has been presented in Fig. 3, and the dashed line indicates power transmitters, such as the torque converter, single-clutch, and dual-clutch.

Engine speed is calculated based on the following equation:

$$J_e \frac{d\omega_e}{dt} = T_e - T_{T/C\_P} - T_{Hyd\_P} \tag{1}$$

where ω_e, J_e, T_e, T_{T/C_P}, and T_{Hyd_P} are engine speed, engine inertia, engine torque, torque converter pump torque, and hydraulic pump torque, respectively. The torque converter input (turbine) and output (pump) torque can be determined by using Eqs. (2) and (3):

$$T_{T/C\_P} = CF(r_s) \times \omega_e{}^2 \tag{2}$$

$$T_{T/C\_T} = TR(r_s) \times T_{T/C\_P} \tag{3}$$

where CF and TR are the capacity factor and torque ratio, respectively, that can be determined by using speed ratio (r_s) from torque converter experimental data. The capacity factor indicates the ability of the converter to absorb or to transmit torque, which is proportional to the square of the rotating speed [9]. Fig. 4 shows an efficiency map and torque ratio of the torque converter, which is derived from experimental data.

In order to calculate clutch torques, such as T_{sc} and T_{dc} in Fig. 3, the clutch dynamic model should be considered. Therefore, the simplified

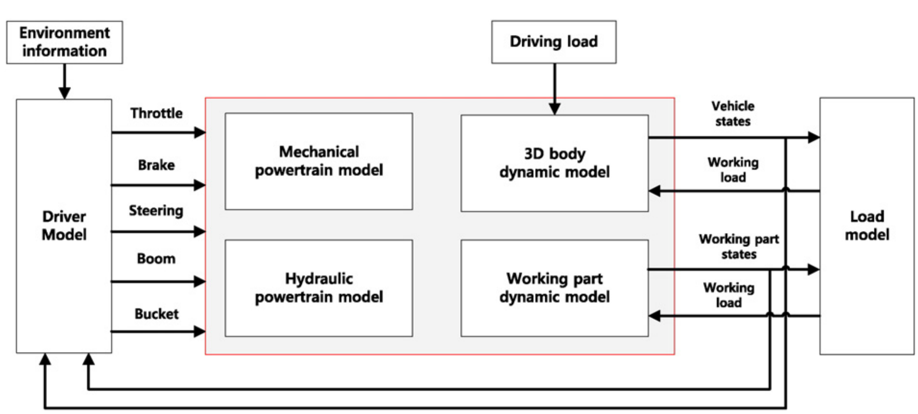

Fig. 2. Simulation model schematic.