Control Engineering Practice 48 (2016) 1–9

Contents lists available at ScienceDirect

Control Engineering Practice

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

Wheel loader operation—Optimal control compared to real drive experience

V. Nezhadali [a,*], B. Frank [b], L. Eriksson [c]

[a] Vehicular Systems, Electrical Engineering Department, Linköping University, SE-581 83 Linköping, Sweden
[b] Faculty of Engineering, Lund University, 118 S-221 Lund, Sweden - Volvo Construction Equipment, SE-631 85, Eskilstuna, Sweden
[c] Vehicular Systems, Electrical Engineering Department, Linköping University, SE-581 83 Linköping, Sweden

ARTICLE INFO

Article history:
Received 13 November 2014
Received in revised form
9 November 2015
Accepted 14 December 2015
Available online 24 December 2015

Keywords:
Optimal control
Modeling for control
Powertrain modeling and simulation
Trajectory optimization

ABSTRACT

Wheel loader trajectories between loading and unloading positions in a repetitive loading cycle are studied. A wheel loader model available in the literature is improved for better fuel estimation and optimal control problems are formulated and solved using it. The optimization results are analyzed in a side to side comparison with measurement data from a real world application. It is shown that the trajectory properties affect the operation productivity. However, efficient trajectories are not the only requirement for high productivity operation and all major power consuming sources such as vehicle dynamics, lifting and steering have to be included in the optimization for productivity analysis. The effect of operator steering capability is also analyzed showing that development of autonomous vehicles can be envisaged especially for repetitive cycles.

1. Introduction

Wheel loaders (WL) are categorized as construction machines with frequent application in mining and other construction environments. Due to the fact that the capacity of a WL bucket is limited and usually smaller than the total amount of load to be displaced, WL loading and unloading operation is repeated several times. In such high frequency application, investigating how fast WLs can perform a loading operation or how much fuel can be saved during the operation is a common point of interest for both WL owners and manufacturers. The productivity of WL operation can be described according to the fuel consumption and operation duration for transfer of certain load while lower values of both time and fuel correspond to higher productivity. However these two objectives are contradictory and minimizing one, results in the increase of the other, thus encouraging to obtain an efficient compromise between the two. The analysis of different solutions to increase WL productivity can be performed via different experimental operations and measurements or by mathematical optimization of suitable WL models. Since performing measurements with WLs is by far more costly and time consuming, manufacturers favor methods which can replace the measurements yet producing reliable results.

Short loading cycle (SLC), is a typical operating cycle for WLs and is illustrated in Fig. 1. WL loading cycles are highly transient operations during which various components in steering, lifting, and powertrain subsystems interact to perform the loading process while operating in different ranges of efficiency. There are also workplace parameters such as the placement of the load receiver with respect to the WL, different loading conditions at each loading occasion or the road surface condition which add up to the size of the optimization problem when analyzing WL operation efficiency. This paper presents an example where such optimization problems can be solved using optimal control (OC) while the implemented methodology and the results are insightful considering the growing interest for development of autonomous vehicles or operator assist systems (Dadhich, 2015).

Different studies are carried out for quantification, control and simulation of various subsystem properties and dynamics during the WL operation. In Fales, Spencer, Chipperfield, Wagner, and Kelkar (2005) the focus is only on the lift hydraulics and linkage dynamics and a controller is designed for bucket leveling. In Nilsson, Fröberg, and Åslund (2012) optimized engine transients for fuel efficient operation are calculated without including the lifting and steering dynamics. Efficient operator and machine interactions during WL operation are analyzed in Filla (2011, 2005) with emphasis only on the influence of the human operator in the dynamic simulations. A WL model including steering and lifting hydraulics while representing the diesel engine with an electric motor is presented in Carter and Alleyne (2003) aiming at powertrain controller evaluation. In Prasetiawan (2001) and Zhang,

* Corresponding author.
E-mail addresses: vaheed.nezhadali@liu.se (V. Nezhadali), bobbie.frank@volvo.com (B. Frank), larer@isy.liu.se (L. Eriksson).

http://dx.doi.org/10.1016/j.conengprac.2015.12.015
0967-0661/

Nomenclature

ω_e	system state, engine speed
p_{im}	system state, intake manifold pressure
ω	system state, angular speed of lift arm
θ	system state, angle between lift arm and horizontal axes
V	system state, vehicle speed
X	system state, WL position
Y	system state, WL position
β	system state, heading angle of WL
δ	system state, steering angle
u_f	control input, fuel mass injected per combustion cycle
u_p	control input, lift cylinder pressure
u_s	control input, steering angle time derivative
u_b	control input, braking force
J_e	engine inertia
$P_{e,load}$	engine load
T_e	engine torque
P_{lift}	lifting power
P_{steer}	steering power
P_{trac}	traction power
F_w	traction force at wheels
τ_p	time constant in pressure dynamics
p_{stat}	stationary intake manifold pressure
F_{roll}	rolling resistance force
M_{tot}	mass of WL+load+rotating inertia equivalent
T_{buc}	torque on lift arm due to bucket load
$T_{arm,w}$	torque on lift arm due to its own weight
R_{turn}	WL turning radius
m_f	fuel mass
ρ_f	fuel density
F_{buc}	bucket and load weight
M_{buc}	mass of load in the bucket
H_{buc}	bucket height
θ_1	bent angle of lift arm
F_{cyl}	lift force
α	angle between lift force and lift arm
r_1, r_2, R	lift arm dimensions
y_g	height of the hinge between body and lift arm
$F_{arm,w}$	lift arm weight
Q	mass flow rate into lift cylinders
A_{lc}	lift cylinder cross section area
n_{lc}	number of lift cylinders
η_{lift}	lift system efficiency
ϕ	speed ratio over torque converter
γ	gear ratio
r_w	wheel radius
P_{pump}	power on engine side of torque converter
P_{turb}	power on wheel side of torque converter
η_{TC}	torque converter efficiency
c_{st}	steering load constant
T	short loading cycle duration

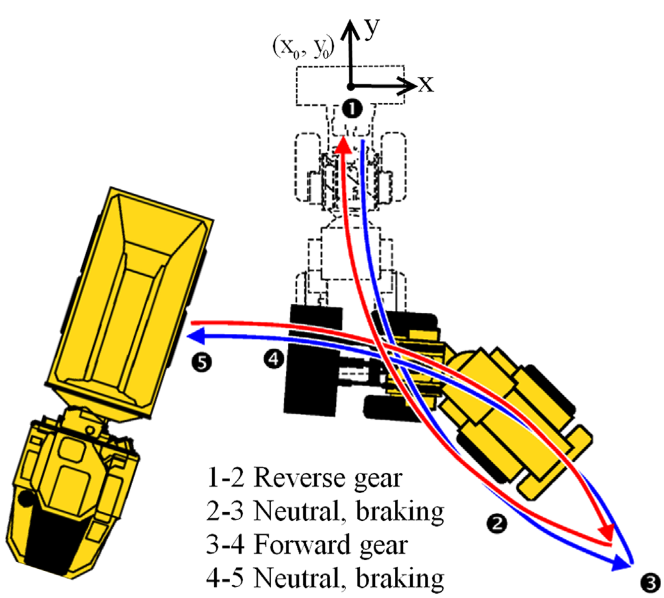

Fig. 1. Typical WL trajectory and choice of gears in a SLC operation. Point 3 will be referred to as `reversing point` since WL moving direction switches from backward to forward at this point. Picture from Filla (2013).

Alleyne, and Prasetiawan (2002) modeling, simulation and control are at the center with no trajectory optimization in the loop. Geometrical analysis of optimal WL trajectories is also performed in numerous works as Filla (2013), Takahashi and Konishi (2001), Sarata, Weeramhaeng, and Tsubouchi (2005, 2006), and Frank and Fröberg (2014) where the diesel engine and lifting dynamics are not included.

The contribution in this work is that in addition to including major dynamics of diesel engine, lifting hydraulics and steering system in the model, trajectory planning and optimization of the complete system transients are also considered in the analysis of WL operation in the SLC. The novelty in this paper is that a WL model available in the literature (Nezhadali & Eriksson, 2014) is improved such that despite the nonlinear properties of certain components and the presence of discontinuous gear shifts during the WL operation, it can acceptably predict fuel consumption and component transients during a loading cycle and more importantly is compatible with optimal control problem formulation requirements. The key contribution is a side to side comparison of measured WL trajectories and results from OC while showing how OC can be used to analyze and improve the performance in such industrial applications.

1.1. Paper outline

Section 2 of the paper describes the details of the measurement setup and how the SLC operation is performed by operators of different skill level while component transients are measured. The measurements are later used to define the boundary values for the OC problem formulation. First in Section 3, new models are developed and parametrized for diesel engine, lifting hydraulics and torque converter (TC) such that the complete WL model can fairly well approximate the measured fuel consumptions when following the measured speed, lifting, steering and WL trajectories.

Later in Section 3, OC problems representing the SLC properties such as payload and driving distance similar to the measurements are formulated and solved using the developed model.

The results from optimizations and measurements are compared and analyzed in Section 4. Candidate cycles from measurements are selected and path constraints are defined in the OC problem formulation such that the same trajectories are followed while optimizing the rest of transients. Also, for these sub-optimal trajectories the trade-off between fuel and time objectives is calculated and compared to the OC obtained trade-offs. Finally, the effect of operators' capability in fast WL steering on the WL trajectory and operation productivity is investigated.