

Multi-Domain Simulation Model of a Wheel Loader

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ABSTRACT

Wheel loader subsystems are multi-domain in nature, including controls, mechanisms, hydraulics, and thermal. This paper describes the process of developing a multi-domain simulation of a wheel loader. Working hydraulics, kinematics of the working tool, driveline, engine, and cooling system are modeled in LMS Imagine.Lab Amesim. Contacts between boom/bucket and bucket/ground are defined to constrain the movement of the bucket and boom. The wheel loader has four heat exchangers: charge air cooler, radiator, transmission oil cooler, and hydraulic oil cooler. Heat rejection from engine, energy losses from driveline, and hydraulic subsystem are inputs to the heat exchangers. 3D CFD modeling was done to calibrate airflows through heat exchangers in LMS Amesim. CFD modeling was done in ANSYS FLUENT® using a standard $k - \epsilon$ model with detailed fan and underhood geometry.

Critical wheel loader drive cycle inputs into the model have been obtained from testing and have been used to validate the system response and cycle fuel consumption. Predicted engine speed, pump pressures, machine ground speed, and cycle fuel consumption were found to correlate with the test results. An energy distribution study shows energy losses in the respective subsystems. The model has been effectively used to identify improvements in system efficiency in terms of fuel consumption and productivity.

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INTRODUCTION

The construction industry is undergoing evolution in terms of increasing demands from customers for machine productivity, fuel efficiency, and driver comfort. Along with creating a competitive landscape in the global market for better efficiency, tighter emission requirements necessitate the introduction of electronics controls in the machine [1, 2]. Challenges of the traditional method of designing off-highway machines are discussed by Prabhu [3]. Due to the increasing number of interactions between the machine subsystems (hydraulics, mechanical, thermal, electrical, and controls), design analyses at the component level proved to be insufficient; however, the use of multidomain system simulation early in the design stage of a new machine is key for reducing the number of physical prototypes and experiments. This conclusion could have a profound effect on designing optimized machines, especially in the area of construction [4, 5, 6]. System efficiency can be achieved by component level loss reduction, optimizing system interaction, and de-coupling systems [7]. System level simulation is critical for system level optimization.

The common types of wheel loader drivelines vary depending on their operating weights. For example, large wheel loaders in mining applications use diesel-electric drivelines, while small wheel loaders use hydrostatic transmissions for better drive control; however, the majority of wheel loaders in the industry have a power-shift transmission with a torque converter. The torque converter in a transmission is the major cause of wheel loader inefficiency. Driveline efficiency is key for improving fuel efficiency. The construction industry and some researchers have studied improving different architectures for improvement in driveline efficiency [8, 9, 10, 11, 12].

This paper is organized into the following sections. The first section describes the wheel loader's drive cycle and presents a general description of its subsystems. The following section, Model Outline, presents an overview of the model of the machine, engine, hydraulics/mechanism, cooling system, and definition of task based cycle. Model Validation presents the validation of the model. Finally, Results and Discussion presents the energy distribution of the model wheel loader and identifies fuel savings potential.

WHEEL LOADER DRIVE CYCLE AND SUBSYSTEMS

A typical wheel loader's operation is considered in the study. This operation is typically cyclical in nature and includes the following phases:

- Phase 1 Approaching load pile: The empty wheel loader moves toward the pile.
- Phase 2 Digging: The machine starts digging into the pile.
- Phase 3 Reversing back to original position: The loaded wheel loader reverses and reaches origin position.
- Phase 4 Approaching dumping area: The wheel loader moves toward the pile to dump the load and lifts up the boom.
- Phase 5 Dumping and reversing back to original position: The wheel loader is stopped for dumping and reverses while lowering the boom.

Due to the path of the operation, the cycle is called the I-drive cycle and is considered for the study shown in Figure 1. Driveline and hydraulic subsystems compete for power from the engine simultaneously during some segments of the working cycle [13].

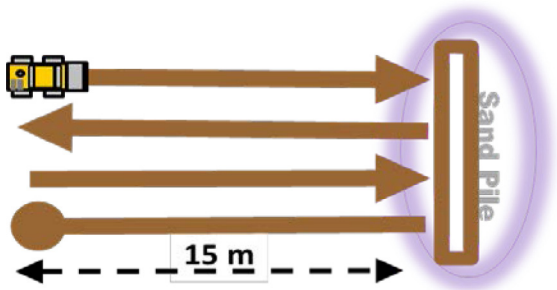


Figure 1. Typical I-test cycle

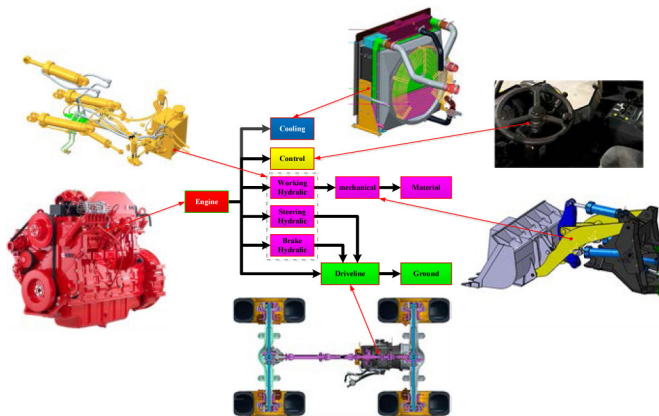


Figure 2. Critical wheel loader subsystem

Wheel loader subsystems, shown in Figure 2, include the driveline subsystem and hydraulic subsystem. The driveline subsystem consists of a diesel engine and power-shift transmission with a torque convertor with forward and reverse gears. The hydraulic subsystem includes steering, working, and cooling hydraulics. Detailed modeling of the working and steering systems of the wheel loader is beyond the scope of this paper. Soil tool interaction during the process of digging the loader bucket into the pile is very complex,

and modeling it is also beyond the scope of the project. Digging forces and machine velocity are used to capture the digging process during the short I-drive cycle.

MODEL OUTLINE

LMS Imagine.Lab Amesim is an advanced multi-domain simulation and analysis software, which allows users to model multiple physics, including thermal, mechanical, electrical, and fluids, in a single platform. It offers comprehensive physics-based libraries and a wide variety of model fidelities based on the modeling need [14]. The wheel loader model is based on Liugong's 5-ton capacity bucket as shown in Figure 3. It is equipped with Cummins' Tier-2 8.9 L displacement engine. This machine has an engine driven fan and a fixed hydraulic pump.

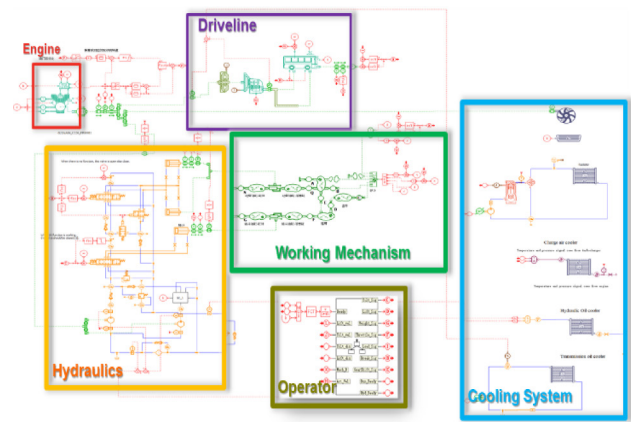


Figure 3. Wheel loader model outline in LMS Amesim

Engine Model

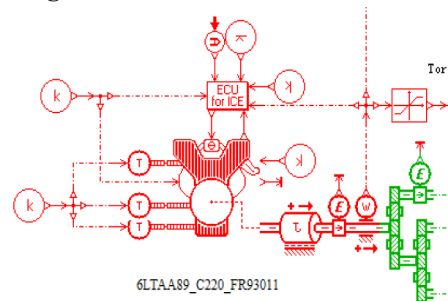


Figure 4. IFP-drive engine model in LMS Amesim

Figure 4 shows a simplified, map based model, used for the diesel engine, which includes the relevant properties such as full-load and friction curves. This model can capture engine dynamics due to inertia as well as speed lugging under load. Fuel consumption map from test cell is also an input of this engine model and is used to predict the fuel consumption. This model is from IFP-Drive library in LMS Amesim [14].

Advanced engine models like Mean Value Engine Model (MVEM) must be considered for machines with cyclical application like wheel loaders [11,15]. These models can capture the air handling dynamics of the engine and can impact machine performance and fuel consumption for the drive cycle. The authors have experienced

significant reduction in CPU time, along with other subsystem models. Thus, time response in the engine model is tuned to match the response of Mean Value Engine Model to enhance computation efficiency.

Working Hydraulics and Mechanism Model

Detailed modeling of working hydraulics using LMS Amesim was done by Park et al. [16]. Figure 5 presents working hydraulics and working mechanism of a wheel loader. Thermal hydraulics and planar mechanical libraries are used for modeling. Contacts between the boom/bucket and bucket/ground are also captured in the model. Digging forces and torque obtained from tests are inputs to the model. Variable weight and inertia of both empty and loaded buckets are also considered in this model. All steering flows are assumed to be going to a working circuit. System level hydraulics are considered for the model.

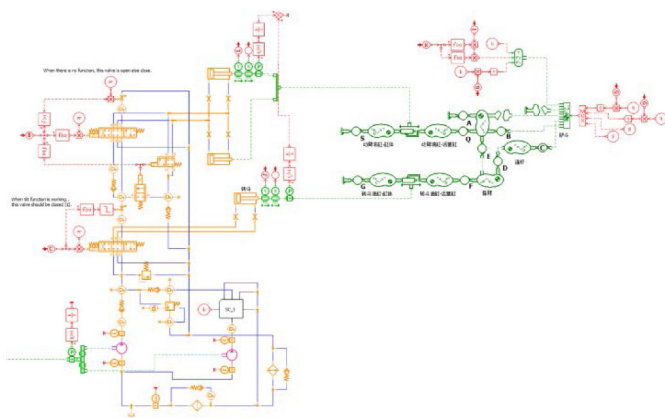


Figure 5. Hydraulics and wheel loader working mechanism model

Steering hydraulics and mechanism are not considered in the model because steering during the test included cycle to cycle variability, and steering loads are usually difficult to characterize. Component level details of the hydraulic system are not considered because of the availability of component level data and computational efficiency.

Powertrain Model

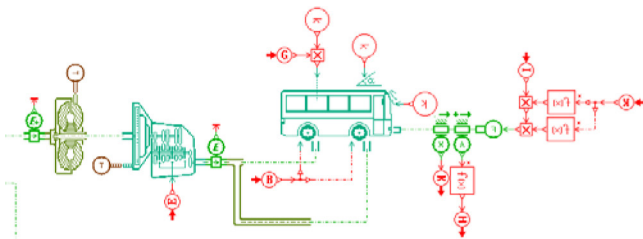


Figure 6. Driveline model

A typical wheel loader driveline consists of a torque converter and gearbox in series which propel the tires. Torque converters are used in construction applications for operational smoothness, robust design, high reliability, and lower price. Figure 6 shows a driveline model used in the system model. The model can capture additional weight of the machine and input of digging forces.

Cooling System Model

This wheel loader has four heat exchangers: 1) Radiator to dissipate engine coolant heat, 2) Charge Air Cooler (CAC) to cool boost air from engine compressor outlet, 3) Hydraulic Oil Cooler (HOC), and 4) Transmission Oil Cooler (TOC). Radiator, CAC, and HOC are arranged side by side, and TOC is in front of the stack shown in Figure 7. Heat exchanger characteristics are provided by suppliers and modeled using the NTU regression tool in LMS Amesim. The fan is modeled using fan performance and efficiency curve. The engine coolant circuit is modeled with thermostat and radiator. The engine heat rejection from coolant used is from reference tables obtained from the engine test cell. CAC inputs are compressor outlet temperature and mass flow rates, and these are also obtained from the engine test cell. The TOC circuit has a separate pump to circulate transmission oil, which will cool the transmission oil from torque converter and transmission losses. These are obtained from the driveline subsystem. Similarly, the hydraulic oil is heated due to friction and throttle losses in the hydraulic circuit which is cooled by HOC. LMS Amesim offers a 1D cooling tool which applies the air flow in only one direction, so air flow must be calibrated in the 1D model. Airflows must be obtained from physical tests or 3D CFD model. During the time of modeling work, no physical test data was available, so the authors used FLUENT to carry out 3D CFD model to obtain airflows.

ANSYS FLUENT is used to solve steady-state Navier-Stokes equations based on k- ϵ turbulence model [17] with standard wall function employed to model the turbulence characteristic. This model consists of detailed fan and underhood geometry. The rotation of the fan is modeled by the Multiple Reference Frame Model (MRF). The heat exchangers are represented by regularly shaped cell zones with porous medium coefficients based on Darcy's law.

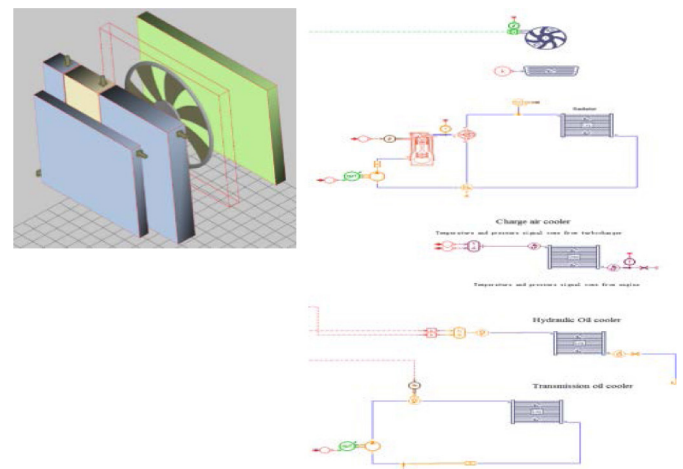


Figure 7. Cooling system model of wheel loader and view of heat exchanger arrangement

Figure 8 shows the air flow rates obtained from 3D CFD and 1D LMS Amesim model at given engine speed. It can be concluded that the LMS Amesim air side restriction is adjusted to match air flow rates through heat exchangers from 3D CFD. Now this model can accurately predict air flow at different fan speeds.