Off-Road Vehicle Energy-Saving Potential

Energy Systems Division

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1 Background

The U.S. Department of Energy's (DOE's) Vehicle Technology Office (VTO) has played a critical role in enabling electrification and reducing fuel consumption in the automotive sector. However, the off-road vehicle sector accounts for 8% of transportation fuel, and that share is likely to increase over time as on-road vehicles move towards electrification. DOE can again play a key role in the off-road vehicle market by providing tools that can be used by academia and the industry to evaluate the impact of advanced technologies. The need for a pre-competitive simulation tool was also identified during a 2019 DOE-led workshop at Argonne National Laboratory that included OEMs and suppliers to this market.

Autonomie, a powerful and robust system simulation tool for vehicle energy consumption and performance analysis, was developed by Argonne National Laboratory in collaboration with General Motors. Its application covers energy consumption and performance analysis throughout the entire vehicle development process by leveraging its plug-and-play powertrain and vehicle model architecture and development environment.

2 Project Objectives

The objectives of this project are to:

- Provide a pre-competitive simulation platform to OEMs, suppliers and academia to evaluate technologies
- Quantify the potential fuel savings of selected applications resulting from electrification
- Facilitate collaboration within the industry

While Autonomie has traditionally been used for on-road vehicles, we are now developing features, models and processes to facilitate the modeling of off-road vehicles. This work focuses on wheel loaders and excavators with the intention of building model capabilities that could be used to simulate a wide variety of off-road applications.

3 Approach

Currently, Autonomie [1] is centered on models of on-road vehicle powertrains that move a vehicle forward along a defined vehicle speed profile. This project expands those capabilities by adding models that represent the multiple functions that off-road vehicles can perform using the power generated by the powertrain. More specifically, we are adding fluid power system models to simulate the duty cycles of hydraulic systems used to extend arms, rotate cabins, and extend buckets. The project focuses on new vehicle control and powertrain architectures that can provide fuel savings over current architectures.

We partnered with the University of Helsinki [2, 3] to integrate models into Autonomie. University of Helsinki has a long history of modeling off-road applications.

3.1 Choice of Applications

The construction and agriculture markets are respectively the number 1 and number 2 energy consumers in off-road vehicle applications. In the construction market, excavators and wheel loaders are respectively the number 1 and number 2 biggest energy consumers. In this project, we model excavators and wheel loaders as baselines to develop off-road modeling capabilities in Autonomie.

3.1.1 Excavators

While no standard exists to classify the different types of excavators (Figure 1), the market can broadly be defined by the size of the machine:

- Mini excavators: 1–10 tons
- Small excavators: 11–18 tons
- Medium excavators: 20–35 tons
- Large excavators: 36–90 tons

OEMs such as Komatsu, Hitachi, and Caterpillar have developed hybrid versions of baseline excavators, some of which have become commercial products, that are either medium excavators or on the lower end of large excavators. Each OEM has pursued a different technology pathway, but most have focused on the electrification of the cabin rotation. While there can be significant variations in the power required to move the arm, bucket or boom, the power and duty cycle required to rotate the cabin is relatively constant and makes that motion a good candidate for electrification. Komatsu has electrified the motion using an electric machine and capacitors. Hitachi originally used capacitors and then switched to lithium-ion (li-ion) batteries. Caterpillar kept the hydraulic system but decoupled it from the engine and uses gas accumulators to recover some of the energy when the cabin slows down. It is important to note that customers' primary requirements are reliability and productivity. Carbon footprint and fuel savings, while important, remain secondary.

While the intent of this project is not to model in detail any specific excavator model, we loosely used the Caterpillar 336 excavator as a baseline, as it is one of the best-selling excavators in the U.S. and is available with a hybrid option. The Cat 336 is a 49.5 ton (37,200 kg) vehicle equipped with a 9.3 L diesel engine.

Figure 1. An excavator (<https://pixabay.com/photos/excavator-shovel-1937151/>)

3.1.2 Wheel Loaders

Wheel loaders are typically characterized by the load they can carry and/or the size of the bucket. They can be divided into four categories:

- Compact: 40–100 HP & 1 to 2.5 cubic yards
- Small: 115–180 HP & 2.5 to 6.5 cubic yards
- Medium: 230–400 HP & 3.75 to 15 cubic yards
- Large: Up to 1800 HP & 30+ cubic yards

Electrification efforts in the wheel loader market (Figure 2) have been very limited so far. John Deere offers the 944K hybrid wheel loader series architecture, which does not include a storage device. Large wheel loaders (the 944K is a 536 HP machine) have electric drive systems that are more cost effective than mechanical transmissions. John Deere also offers the 644L hybrid wheel loader, a modification of the 644L that has a torque converter and a 4 speed transmission. The hybrid version replaces the torque converter with an electric machine to reduce losses in the transmission. The 644L does not have a battery to capture energy during slow down. John Deere and Caterpillar are the two best-selling wheel loader brands in the U.S. The John Deere 644 is used as the baseline for this study.

There have also been prototype demonstrations including a PHEV wheel loader from Huddig, a 150 kW machine using an 80 kWh battery, and a hybrid LX01 wheel loader from Volvo; however, none of these is currently in production.

Figure 2. A wheel loader (<https://pixabay.com/photos/wheel-loader-wheel-cat-938m-heap-2580470/>)

3.2 Duty Cycle

While the passenger car market is split into defined categories (i.e., compact, SUV, pickup truck, etc.), the off-road vehicle market is loosely defined, with each OEM defining categories based on its own offerings, and while standardized drive cycles exist to evaluate the fuel consumption of passenger cars, no standardized vehicle level duty cycles exist to define off-road applications. In addition, the multitude of moving parts makes it difficult to define a complete vehicle level cycle. The U.S. Environmental Protection Agency (EPA) defines engine-only duty cycles for wheel loaders, excavators, and other applications, but does not specify how the engine power is used in the vehicle [4]. The Japan Construction Mechanization Association [5] provides a detailed outline of an excavator duty cycle that can be used to determine fuel consumption. Working with an OEM that has run and collected data on such a test to validate the duty cycle and component behaviors would be a possible next step for this project.

3.2.1 Excavator Duty Cycle

Through a literature review, a representative duty cycle was identified for the excavator. An excavator duty cycle can be broken down into four independent motions:

- Arm motion
- Bucket motion
- Boom motion
- Cabin motion

A duty cycle can be identified for each independent motion for a typical excavator job: loading up material from one location and dumping it at another location. The actual motion of the vehicle itself is not considered in this study, as typically the excavator is not moving and little energy is spent in vehicle motion.

Figure 4 shows the duty cycle as a function of time, and Figure 5 shows the total duty cycle power demand repeated over time.

Figure 3. Excavator duty cycle

Figure 4. Excavator duty cycle

3.2.2 Wheel Loader Duty Cycle

While there is no standardized and regulatory vehicle level duty cycle for wheel loader and off-road machines in general, a wheel loader duty cycle commonly used to assess vehicle level fuel consumption is the V-cycle, which describes the repetitive back and forth vehicle motion carried out as the vehicle loads material in the bucket and dumps it in a truck. Such a cycle is visually defined in Figure 6.

Figure 5. Wheel loader V-cycle and hydraulic functions

A synthesized vehicle speed profile for the V-cycle is shown in Figure 7.

Figure 6. V-cycle vehicle speed profile

Hydraulic power is then defined for the lift and tilt functions as shown in Figure 8 [6,7,8].

Figure 7. Lift and tilt power profile

3.3 Excavator Modeling

Modeling off-road vehicles in Autonomie poses a few challenges. A primary input to Autonomie is a vehicle speed profile that serves as the base to determine powertrain power demand. In the case of an excavator, the vehicle is at a standstill while vehicle functions are executed by an arm, a boom, a bucket and a rotating cabin.

A baseline model of the excavator was implemented in Autonomie and exercised over the selected duty cycle (Figure 3). Hydraulic components such as hydraulic cylinders, valves, pumps and motors were also implemented in Autonomie. The driver model was modified as the driver does not just follow a vehicle speed trace but also runs stationary functions. The model uses a 9.3 L diesel engine (232 kW) and a centralized hydraulic system.

Figure 9 highlights how the four hydraulic functions were implemented (cabin rotation and arm, boom, and bucket motions). A predefined load was used to determine the force required from the hydraulic cylinders. The cylinder models then determine pressure, flow and position.

Figure 8. Hydraulic component implementation in Autonomie

Engine power, speed and torque to support the hydraulic functions are shown in Figure 10. The engine power closely follows the hydraulic power. The current engine control in Autonomie shows relatively high engine speed fluctuations, which could be higher than what is actually seen in a traditional excavator. Working with OEMs and having access to field data would be necessary to validate and adjust the engine speed control.

Figure 9. Engine power, torque and speed

The excavator was hybridized by electrifying the cabin rotation. The hydraulic system used for the cabin rotation in the conventional system is replaced by an electric machine and a 4 kWh 540V li-ion battery. When the cabin slows down, regenerative energy is captured through the electric motor and stored in the battery. Figure 11 highlights the power of the four hydraulic functions. The amount of energy recovered remains relatively small compared to the overall energy spent, and the fuel savings in this example is approximately 5%.

Figure 10. Arm, boom, bucket and cabin power profile in the hybrid excavator

3.4 Wheel Loader Modeling

Autonomie was originally designed to move a vehicle along a predefined speed profile without obstacles. The modeling of the penetration of the bucket into a pile of material is of particular interest as it is akin to modeling a vehicle running into an obstacle, a case study that never occurs in the modeling of light-, medium-, and heavy-duty on-road vehicles. This power required to load up the bucket could not be accounted for in the way the driver model was originally set up and required modifications. The extra loading force itself is modeled in the vehicle loss model where other losses are accounted for (tires, grade, aerodynamics).

The hydraulic component models used to represent the lift and tilt motion are similar to the hydraulic components used in the excavator model. The conventional powertrain uses an automatic transmission with a torque converter (Figure 12). The hybrid version developed in this project replaces the torque converter with an electric machine geared to the transmission input as well as a clutch to mechanically connect the engine to the gearbox. We used a high voltage li-ion battery as a storage device.

Figure 11. Wheel loader schematic in Autonomie

The combination of reduction in torque converter losses, the capture of regeneration energy, and the change in engine operations provides a 15% reduction in fuel consumption over the cycle. Figure 13 highlights how the hybrid powertrain engine operates in an area of higher engine efficiency compared to the conventional powertrain.

Figure 12. Wheel loader engine operations

4 Conclusion

In this project, we developed Autonomie models for excavators and wheel loaders. For each machine we developed a baseline version (conventional powertrain) as well as a hybrid version that provides fuel savings compared to the baseline. Hydraulic models were developed and integrated into Autonomie to support the modeling of the working functions of the machines. Those models include hydraulic pump, valve, actuator, and cylinder models.

Early in the project, we presented our research at the Center for Compact and Efficient Fluid Power (CCEFP) 2020 Summit. While our results were limited at the time, feedback was positive, and participants highlighted the benefit of a public tool to quantify the benefits of electrification.

Wheel loaders and excavators cover a very wide range of functions, duty cycles and power requirements, and the lack of standards make it difficult to accurately represent the machines. The lack of publicly available data is such that models cannot be easily validated. Engagement with the industry would be required to continue this effort and to increase the level of fidelity in the models and their predictions.

Future work could focus on other ways to reduce energy consumption. While an electrical system may not always be able to replace a hydraulic system, decoupling the hydraulic system from the engine offers opportunities for further energy savings. For example, a hydraulic pump that is continuously tied to the engine will spin and generate losses even when it does not need to generate hydraulic power. Also, fuel cell battery hybrid systems could replace engine-based powertrains in large machines where full electrification may not be feasible due to the large energy requirement.

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