On the Feasibility of Electrification for Large Mobile Cranes

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Abstract—Trends towards vehicle electrification to reduce dependence on fossil fuels and increase drive train efficiency have led vehicle manufacturers to seek out paths towards gradual hybridization. For heavy duty construction vehicles, electrification consists of two principle components: electric hybridization of the vehicle carrier and the vehicle’s auxiliary function. Economic and physical feasibility for the transition to electrical replacements for critical system components is important for the gradual development of electrified systems. In this paper, we present an investigation into multiple pathways for the hybridization of mobile cranes paired with simulations that analyze the feasibility of system electrification. ADVISOR was used to compare the feasibility of hybrid topologies for the vehicle carrier of a crane using approximate emissions, fuel economy, and efficiency. Analysis of the feasibility of transitioning to an electric motor for the crane’s auxiliary function was performed using ANSYS TwinBuilder. Issues concerning satisfying the current draw of electric motors for both simulations point to currently available energy storage systems as the main factor hindering the electrification of mobile crane systems without significant redesign due to the initial cost, upkeep, and lack of energy density.

Index Terms—Electrification, hybrid vehicles, power train electrification, hybrid power train, heavy truck, all-terrain cranes.

I. INTRODUCTION

Vehicle electrification has become a popular trend in the face of climate change and with the increasing popularity of all-electric vehicles. Electrification, defined as the transition to electricity as the primary energy source, reduces our dependency on carbon based fuels through increased energy efficiency and benefits from reduced emissions using renewable energy generation [1]. To acquire share in the growing electric vehicle market and reduce greenhouse gas emissions, manufacturers are searching for pathways to convert their current products to function via electrical energy, which are both functionally and economically feasible [2]–[4].

Heavy-duty construction vehicles are no exception but have to deal with the added design problems related to their necessary auxiliary functionality. As it stands, a variety of heavy-duty construction vehicles use internal combustion engine (ICE) driven hydraulic hybrid systems to transmit the power necessary to handle large dynamic loads with control coming from the throttling of valves [5]. For this reason, the full electrification of heavy-duty construction vehicles consists of a transition to electric drives for traditional combustion vehicle drive trains as well as the auxiliary hybrid hydraulic-combustion systems [2], [6]. A mobile crane is conventionally defined as a construction vehicle, which is able to move between locations and move heavy objects by suspending them from a projecting beam. Mobile cranes come in varying types ranging from treded “crawlers” and all-terrain vehicles to truck mounted and floating cranes [7].

This paper analyzes the potential electrification of an all-terrain mobile crane, which can be moved quickly to and from urban or rural sites while being able to lift heavier loads than truck mounted cranes [7]. To do this, an all-terrain crane, such as the example shown in Fig. 1, combines a heavy truck with a lifting crane upper arm, which are both mated through a turn table that allows rotation. One ICE is utilized to drive a complex system of hydraulic pumps that runs the various functionalities of the crane necessary for effective use in the upper and another ICE is utilized to run the vehicular carrier as is shown in Fig. 2.

The full electrification of heavy-duty vehicles face the primary difficulty of energy dense electricity storage as they require very large batteries to provide the necessary current draw for their functionalities [6], [8]. Considering that electric machine size increases with rated torque, which is high for crane applications, and the cost, reliability, and maintenance issues for large capacity battery systems, a full transition into purely electric power schemes is not recommended [5]. While an example of an all-electric all-terrain crane does exist in the Zoomlion ZTC250N-EV, the crane’s structure was specially made with a focus on it’s electric systems and required significant research and design that isn’t possible at smaller manufacturers [3].

A gradual progression for the electrification of heavy-duty construction vehicles based on the various levels of essential functionality allows for the development of electrification technologies while compensating for the lack of current energy storage and electric motor energy density [5], [9]. Transition of the heavy truck system’s traction engine or of the crane’s upper arm to deal with dynamic loads to electric power can be performed separately or in parallel while maintaining effectiveness [8].
II. ELECTRIFICATION OF HEAVY TRUCK FOR CRANES

Concerning the heavy truck systems, electrification consists of a conversion from an ICE to electric propulsion. As a target for full electrification, there are multiple potential hybrid topologies whose performance should be compared to establish whether it is feasible to effectively transition to electric propulsion systems [10]. For this objective comparison, we utilized NREL’s ADVanced Vehicle SimulatOR, code named ADVISOR to estimate fuel economy, energy usage, and compare relative emissions for example model vehicles [11]. Using empirically derived data sets and basic physics, this software has been used in numerous recent papers for quick analysis of example model hybrid vehicle compositions [10], [12].

Using a set of constant parameters, a conventional and various hybrid topologies were simulated to compare fuel economy and emissions ranging from a series hybrid to a full electric vehicle. The mass of the example design vehicle was selected as 55 metric tons, which is comparable with a crane such as the one shown in Fig. 1 and a typical urban heavy duty vehicle driving cycle usage was implemented, shown in Fig. 5. The input motor was an experimental version of the most powerful motor available in the simulation that was modified to emulate having two motors attached to the same axle. To allow for the increased current draw of having a second motor, the battery pack’s module count was doubled. The change in state of charge (SOC) or the energy available within the system’s batteries is recorded for all vehicles with an battery powered electric system as shown in Fig. 5.

Critical mission results were extracted from the simulations, including emissions, fuel economy, and approximate drive train efficiency of each example model vehicle. Recorded emissions are assumed to be the direct result of fuel consumption and the fuel economy is approximated in terms of energy to it’s gasoline equivalent. Nitrogen oxide emissions are used as a comparison because it is targeted for reduction within recent regulation created by the EPA targeting future heavy-duty vehicles developed in 2021-2027 [13]. As shown in Table I, the example series vehicle outperformed the other vehicles in terms of approximate gasoline fuel economy while also sporting one of the lowest nitrogen monoxide rates outside of the all-electric vehicle.

In terms of physical space, there was a question of whether or not a battery pack of the size simulated in ADVISOR would be able to be physically accommodated on the all-terrain crane. For this reason, we removed the optional mass from the crane, 5 tons, and simulated the example series topology with a following trailer, taking increased rolling resistance into account as a result. As shown in Table I, there was a marginal efficiency and fuel usage increase over the regular series topology. For all of the hybrid electric vehicles, the SOC, shown in Fig. 5, faced drastic drops of 20-40% through the 5.5 mile long drive cycle, which would necessitate exponentially larger costs, economically and physically, to allocate for bigger energy storage systems and allow for greater range.

III. ELECTRIFICATION OF CRANE UPPER ARM

For the upper crane subsystem, the development of hybrid hydraulic-electric systems allows for greater control flexibility through electric drives while benefiting from the power density of hydraulic systems [5], [9]. For example, the SK487-AT3 City Boy is a hybrid electric crane with a diesel engine for the carrier and a motor powering the upper [4] but is restricted to urban environments by range and deals with smaller loads than all-terrain cranes. One of the known challenges for the replacement of auxiliary functionality is sizing of the electric machine for hydraulic pump drives [8], [14]. ANSYS TwinBuilder [15] was used in this study to perform multi-physics analysis of an electric machine system was used in this study following the procedures described here [16].

As shown in Fig. 6, the example model hydraulic-electric hybrid consists of a permanent magnet synchronous machine, 3 phase inverter drive, and closed loop PID control similar to the implementation seen in [14]. A traditional upper system works by selectively activating certain pumps while the ICE is running but duty cycle data for function operation isn’t publicly available. Without this information, the shaft’s speed was compared with a representative driving cycle’s speed to test the machine’s torque and speed output in the worst case scenario. To ensure the electric machine could replace the current ICE, the ICE’s torque-speed curve was used to mimic...
the hydraulic system’s load on the pump drive. A set of real, publicly sold motors were found that had approximately equivalent power output to the original ICE to input their parameters into the simulated electric machine model as well as the system’s voltage.

The main crane upper simulation results were the current draw from the energy storage system, the machine’s speed and its response to the torque load of the system. To be economically feasible, the electric network had to be physically possible without being overly large or heavy, extremely costly, or hard to maintain. However, the average current draw of the system was larger than current large modular battery systems can supply without large changes to the physical construction of the mobile crane, large upfront cost for modules, and with the number of failure points increasing with each inter-module connection. To coincide with these findings, the real electric machines had similar average current draws to what the simulation predicted would be necessary to drive the full hydraulic load.

Alternative electrification methods for the crane upper include micro hybrid AC electrification, which allow for a gradual insertion of electrical power into the current product line without significant financial and physical investment needed and addresses the second biggest fuel consuming system [17]. Recent papers concerning an alternative Hybrid Hydraulic-Electric Architecture (HHEA) proposed using a hydraulic system for power transmission and a network of small distributed electric machines as a method of control [5], [18].

IV. CONCLUSION

In this paper, multi-physics simulation models were employed to assess the feasibility of mobile crane electrification. The results reinforce the understanding that energy storage systems are one of the major obstacles concerning the electrification of heavy duty construction vehicles [2], [6], [14], [19]. Simulations were conducted for the electrification of both the heavy truck and the crane upper arm.

The heavy truck crane simulation included an example hybrid vehicle model of the approximate mass and size of an
all terrain crane and underwent drastic drops in the battery’s SOC. If the example vehicles underwent these driving cycles, they would have run out of battery power within two or three more driving cycles, 5 to 10 miles, or would not have been able to travel the range necessary for rural environments.

For the crane upper arm simulations, the worst case scenario current draw of the motor would have proved too heavy a cost for currently available energy storage systems without significant upfront investment in space and money. Because of these results, the cost, size, and reliability of current energy storage systems may not feasibly allow for a traditional implementation of crane systems without a redesign of the fundamental structures, which they are based upon.

Alternative design methodologies exist when considering the electrical system implementation of the crane. The gradual introduction of electrification could also be implemented in cranes through micro hybrid systems, for example, the introduction of electric motors that run parallel to the heavy truck section [9]. Another recent topic, which focuses on the integration of hydraulic and electric systems is the design of motors directly coupled to hydraulic pumps, which may minimize connection energy transfer inefficiencies while exhibiting high power densities [14], [19]. Both concepts combine hydraulic and electric systems to benefit from the power density of hydraulics along with the flexibility and efficiency of electric motors while keeping the electrical system’s size modest.

Table I

<table>
<thead>
<tr>
<th>Topology</th>
<th>Drive Train Efficiency</th>
<th>Fuel Usage (mpg)</th>
<th>Emissions (NOx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>15%</td>
<td>2.6</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>18%</td>
<td>4.8</td>
<td>24</td>
</tr>
<tr>
<td>Series (Trailer)</td>
<td>20%</td>
<td>4.9</td>
<td>23</td>
</tr>
<tr>
<td>Parallel</td>
<td>16%</td>
<td>3.4</td>
<td>58</td>
</tr>
<tr>
<td>EV</td>
<td>34%</td>
<td>4.3</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 6. Simulation model for the electrification of the crane upper arm in ANSYS TwinBuilder. Model includes electric machine used to drive the load torque profile of that seen in hydraulic pumps, power electronic inverter, and control algorithms.

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REFERENCES


