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Donovin Lewis
University of Kentucky, donovin.lewis@uky.edu

Damien Lawhorn
University of Kentucky, damien.lawhorn@uky.edu

Dan M. Ionel
University of Kentucky, dan.ionel@uky.edu

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On the Feasibility of Electrification for Large Mobile Cranes

Donovin Lewis, *Student Member, IEEE*, Damien Lawhorn, *Student Member, IEEE*, and Dan M. Ionel, *Fellow, IEEE*

SPARK Laboratory, Department of Electrical and Computer Engineering,
University of Kentucky, Lexington, KY, USA
donovin.lewis@uky.edu, damien.lawhorn@uky.edu, dan.ionel@ieee.org

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: hybridization of the vehicle carrier and transitioning towards increased electrical power of the auxiliary function of the vehicle. Transition from traditional combustion to electrical powered systems is difficult in part due to the learning curve and complexity associated with electric power systems, especially concerning energy storage. 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 electrification of mobile cranes paired with simulations that analyze the feasibility of introducing electrical systems. 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 from an engine for the crane's auxiliary function was performed with 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 preventing 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, integration, 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]. 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 [3]. 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], [4].

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 treaded ”crawlers” and all-terrain vehicles to truck mounted and floating cranes [5]. This paper analyzes the potential electrification of an all-terrain mobile crane, a mixture of truck mounted and rough crane types, which can be moved quickly to and from locations, unlike rough terrain cranes, as well as lift heavier loads than truck mounted cranes [5]. To do this, an all-terrain crane combines a vehicular carrier called a lower with a lifting component known as an upper which are mated through a turn table which allows the upper to rotate. 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.

The full electrification of heavy-duty vehicles face the primary difficulty of a high price tag for battery costs as they require vary large batteries to provide the necessary current draw for their functionalities [4], [6]. 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 [3]. While an example of this 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 [7]. For these reasons, it is reasonable to consider a gradual strategy or progression for the electrification of heavy-duty construction vehicles as it allows for the development of electrification technologies while compensating for the lack of current energy storage and electric motor energy density [3], [8]. A procedural strategy can be developed for vehicular electrification based on the various levels of essential functionality. Transition of

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Figure 1. Photo of an all-terrain mobile crane courtesy of Link-Belt Cranes.

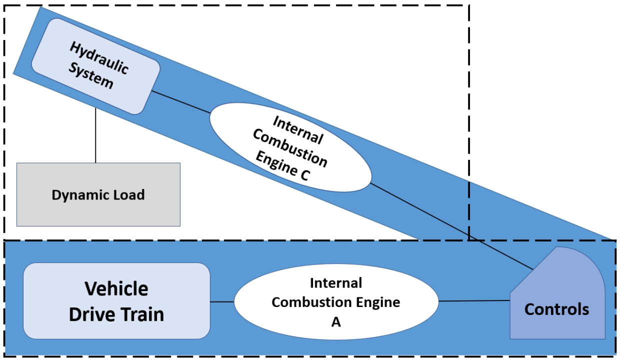

Figure 2. Systems summary of a conventional all-terrain mobile crane

the traction engine in the lower to move the vehicle across the road or of the upper to power implements, in this case a hydraulic load, to electric power can be performed separately or in parallel while maintaining effectiveness [6].

II. CRANE LOWER ELECTRIFICATION SIMULATION

Concerning the main carrier or lower of the crane, electrification would mean 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 see which would be most effective for the current situation [13]. A comparison between the fuel economy, drive train efficiency, and emissions of conventional vehicle and hybrid topologies establishes whether it is feasible to effectively transition to electric propulsion systems. 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 theoretical vehicles [14]. Using empirically derived data sets and basic physics, ADVISOR has been used in numerous recent papers for quick analysis of theoretical hybrid vehicle compositions [13], [15].

A conventional vehicle was simulated to establish a standard to compare the theoretical hybrid vehicles. Using a set of constant parameters, we then simulated various hybrid topologies to compare fuel economy and emissions ranging from a series hybrid to a full electric vehicle. The total mass was input as 55 metric tons based on an approximate mass of an akin all-terrain crane and an urban driving cycle based on typical heavy duty vehicle usage was utilized, shown in Figure 4. The input motor was an experimental version of the most powerful motor available in ADVISOR which was modified to simulate 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) for all vehicles with an battery powered electric system is recorded using the maximum effort possible from the electric machine to satiate the set drive cycle as shown in Figure 4.

After running the simulations, ADVISOR outputs the emissions, fuel economy, and approximate drive train efficiency of each theoretical vehicle. Assumptions are made in the evaluation of both as 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 [16]. As shown in Table I, the theoretical 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 theoretical 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 Figure 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. CRANE UPPER ELECTRIFICATION SIMULATION

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 [3], [8]. An example of this exists with the SK487-AT3 City Boy, a hybrid electric crane with a diesel engine for the carrier and a motor powering the upper [9] 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 [6], [10]. ANSYS TwinBuilder [11] was used in this study to perform multi-physics analysis of an electric machine system as seen in [12].This approach provides feasibility analysis of the proposed hybrid electric-hydraulic system which utilizes an electric machine, drive and energy storage in lieu of the conventional ICE, similar to the implementation seen in [10].

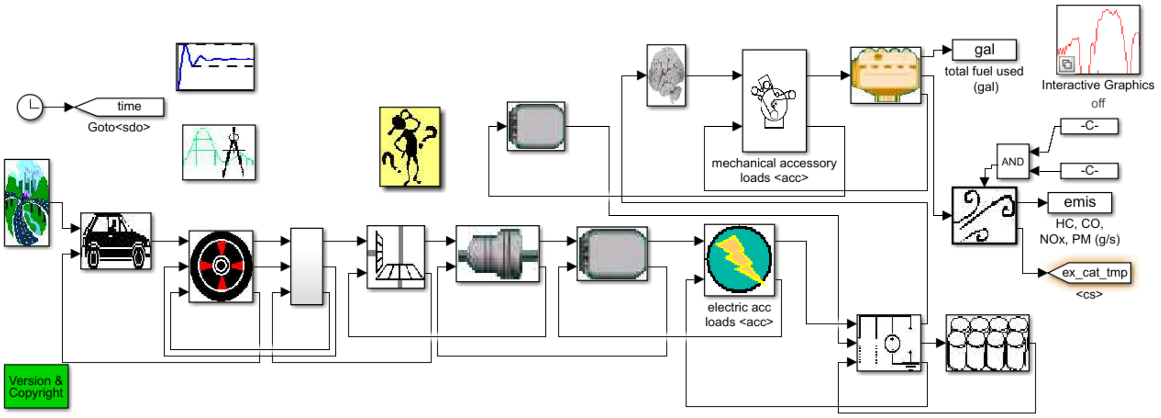

Figure 3. Block diagram of a series topology simulation in ADVISOR

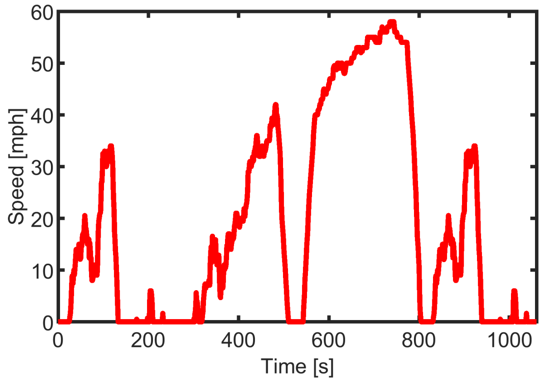

Figure 4. Urban heavy duty vehicle driving cycle

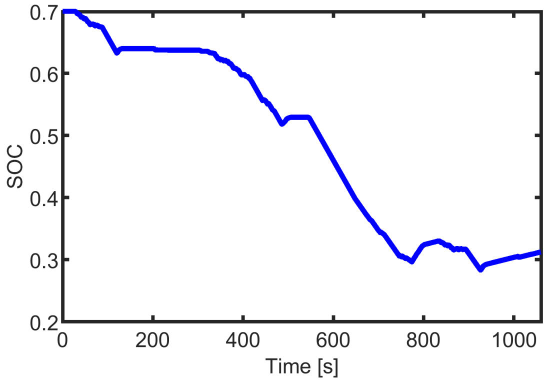

Figure 5. Series topology SOC under UDDSHDV driving cycle

As shown in Figure 6, the theoretical hydraulic-electric hybrid consists of a permanent magnet synchronous machine, 3 phase inverter drive, and closed loop PID control. To ensure the electric machine could replace the current ICE, it's torque-speed curve was implemented to mimic the hydraulic system's load on the pump drive. A traditional upper system works by selectively activating certain pumps while the ICE is running but we did not have duty cycle data for function operation. Without this information, the shaft's speed was compared with a representative driving cycle's speed, created to test the machine's torque and speed output in the worst case scenario. 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 outputs of the TwinBuilder simulations were the current output from the energy storage system, the machine's speed and it's 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 and large upfront cost for modules with the number of failure points increasing for each inter-module connection. To coincide with these findings, the real electric machines had similar average current draws as the simulation predicted to run at the power needed to drive the full hydraulic load.

Table I
THE RESULTS OF ADVISOR TOPOLOGY ANALYSIS

Topology	Drive Train Efficiency	Fuel Usage (mpg)	Emissions (NOx)
Conventional	15%	2.6	103
Series	18%	4.8	24
Series (Trailer)	20%	4.9	23
Parallel	16%	3.4	58
EV	34%	4.3	0

IV. CONCLUSION

In this paper, multi-physics software ADVISOR and Twin Builder was used to access the feasibility of mobile crane electrification and reinforced the understanding that energy storage systems are one of the major obstacles concerning

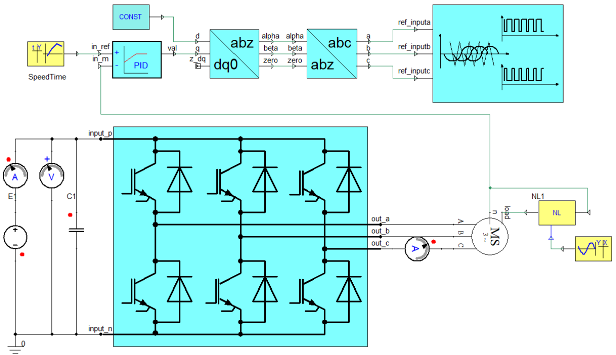

Figure 6. TwinBuilder Upper Electrification Simulation

the electrification of heavy duty construction vehicles [2], [4], [10], [17]. The ADVISOR simulations running a theoretical hybrid vehicle of the approximate mass and size of an all terrain crane underwent drastic drops in the battery's SOC. If the theoretical vehicles underwent these driving cycles, they would have run out of battery power within two or three more driving cycles, 20 to 30 minutes, or would not have been able to travel the range necessary for rural environments. In the Twin Builder 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 do 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 do exist when keeping electrical system implementation in mind throughout the crane's design process. The gradual introduction of electrification could also be implemented in cranes through micro hybrid systems, for example, the introduction of electric AC that run parallel to the vehicle section [8]. These micro hybrid systems allow for a gradual insertion of electrical power into the current product line without significant financial and physical investment needed for larger electrical systems and addresses the second biggest fuel consuming system [18]. 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 [3], [19]. Another recent topic for the integration of hydraulic and electric systems include designs for motors directly coupled to hydraulic pumps which would minimize connection energy transfer inefficiencies while maintaining high power densities [10], [17]. Both ideas mesh hydraulic and electric systems to benefit from the power density of hydraulics along with the controllablity and efficiency of electric motors while keeping the electrical system's size modest.

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