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Evaluation of Hybrid, Electric and Fuel Cell Powertrain Solutions for Class 6-7 Medium Heavy-Duty Vehicles

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Abstract

Electrification of heavy-duty trucks has received significant attention in the past year as a result of future regulations in some states. For example, California will require a certain percentage of tractor trailers, delivery trucks and vans sold to be zero emission by 2035. However, the relatively low energy density of batteries in comparison to diesel fuel, as well as the operating profiles of heavy-duty trucks, make the application of electrified powertrain in these applications more challenging. Heavy-duty vehicles can be broadly classified into two main categories; long-haul tractors and vocational vehicles. Long-haul tractors offer limited benefit from electrification due to the majority of operation occurring at constant cruise speeds, long range requirements and the high efficiency provided by the diesel engine. However, vocational applications can realize a significant benefit from electrified powertrains due to their lower vehicle speeds, frequent start-stop driving and shorter operating range requirements.

As the heavy-duty industry deals with solving challenges around the application of electrified powertrains, there are multiple pathways that can be explored to meet future regulatory requirements. This paper is the second part of a two-paper series that focuses on evaluating electrified solutions for Class 6-7 medium heavy-duty vehicles in the 2027 and beyond time frame. Using a model-based approach, this paper presents a comprehensive analysis that compares the baseline diesel powertrain against multiple alternative powertrain configurations. These configurations include, an optimized parallel diesel hybrid, all-electric, diesel range extender, gasoline range extender, Compressed Natural Gas (CNG) range extender, and fuel cell range extender; which are evaluated on the basis of cost of ownership, fuel efficiency, emissions, payback period, lost payload opportunity, range, and battery life. The analysis shows that for a near-term less-disruptive scenario wherein the conventional diesel powertrain layout is preserved, a 48V P3 parallel hybrid vehicle configuration is the most cost-effective solution, while for a near-term more-disruptive scenario, the Internal Combustion Engine (ICE) based Range Extender Electric Vehicles (REEVs) have the most potential to reduce greenhouse gas emissions while achieving lower cost of ownership than the baseline vehicle. For a longer-term and more-disruptive scenario, the all-electric vehicle configuration can achieve parity with the baseline vehicle cost of ownership provided the vehicle driving range requirement is limited to 100-150 miles. The analysis further highlights that the overall benefit of an all-electric powertrain solution depends significantly on the future battery technology advancements and vehicle range requirements.

Introduction

While medium and heavy-duty vehicles comprise of only 5% of all vehicles on the road, they are responsible for 23% of all transportation related greenhouse gas emissions and 6.7% of all greenhouse gas emissions in the United States (US) [1]. The trend is similar in Europe, where 5% of all greenhouse gas emissions are produced by heavy-duty vehicles [1, 2]. Furthermore, with the continued growth of shipping, delivery, and the e-commerce industry, the overall truck freight in the US is expected to increase by at least 1% annually for the next 25 years [1]. Therefore, vehicle technology improvements on medium and heavy-duty vehicles offer a significant opportunity to have a large impact on the effort to reduce greenhouse gas emissions emitted from on-road vehicles.

Considering this opportunity to significantly reduce GHG emissions, the US Environmental Protection Agency (EPA) implemented a Phase 2 of the greenhouse gas emission standards for medium and heavy-duty vehicles in 2017, which requires 22-25% reduction in vehicle CO_2 emissions by 2027 [3]. Similarly, in 2019, the European Union also implemented regulations requiring selected categories of heavy-duty vehicles to reduce CO_2 emissions by 30% in 2030, with respect to the 2019 baseline [4]. However, the most aggressive regulations for reducing on-road emissions from heavy-duty vehicles were recently implemented by California's Air Resource Board (ARB) in June 2020. This regulation, termed Advanced Clean Trucks (ACT) [5], requires truck manufacturers to sell an increasing share of Zero/Near-Zero Emission Vehicles (ZEV/NZEV) beginning in 2024. By 2035, the ACT rule will require

Conclusions and Future Work

In this study, a validated baseline vehicle model for a Class 6-7 urban vocational application with conventional diesel powertrain was modified to develop representative models for five alterative powertrain configurations, including an all-electric, three downsized engine range extenders (Diesel/Gasoline/CNG) and a fuel cell range extender. The electrified powertrain specifications for the different vehicle configurations were then optimized through a DoE process in the FEV-XCAL tool. The optimized vehicle configurations were finally compared on the basis of fuel consumption reduction, CO_2 reduction, freight efficiency improvement, increased weight, payback period, and cost of ownership. The following conclusions can be drawn from the analysis results:

1. For the less-disruptive near-term scenario, a 48V P3 parallel hybrid would be the most suitable electrification technology for a Class 6-7 urban vocational application. The technology predicts 17% reduction in vehicle on-road CO_2 emissions from the baseline vehicle, which would significantly reduce the gap between vehicle CO_2 emissions and 2027 GHG standards. Compared to baseline vehicle, the technology also predicts a 6% reduction in cost of ownership with a payback period of less than one year.
2. For the more-disruptive intermediate-term scenario, ICE based REEVs are expected to dominate for vehicle range requirement of more than 100 miles. Among the ICE REEVs, a clear advantage was observed with the CNG REEV due to lower fuel price and lower fuel carbon mass fraction. In comparison to baseline, the CNG-REEV vehicle configuration was able to reduce on-road CO_2 emissions by 54% with a payback period of 3 years and a 0.5% reduction in cost of ownership. It should be stated however that while the on-road CO_2 emissions were reduced with the CNG REEV, the impact of natural gas leakage on net greenhouse gas emissions during storage, transfer and extraction were not considered in this analysis.
3. For the more-disruptive long-term scenario, ultimately both the BEVs and the FC REEV are expected to dominate depending on the range requirement. For a vehicle range of less than 150 miles the BEV offers a significant advantage with a predicted freight ton efficiency increase of 294% on the ARB transient cycle while achieving a similar cost of ownership as the conventional diesel powertrain (advanced battery assumption). For a longer range requirement of up to 350 miles, the FC REEV helps offset the trade-off between vehicle range and lost payload opportunity cost, while maintaining zero on-road CO_2 emissions. Even with the higher fuel cost for hydrogen, the FC REEV enables a 144% increase in freight ton efficiency and a similar cost of ownership when compared to the conventional diesel powertrain (advanced battery assumption). While the net cost benefit of the BEV and FC REEV will strongly depend on the advancement of battery technology and hydrogen fuel cost in the future, the market penetration of these vehicle configurations are expected to be driven more by the stringent CO_2 emission regulations [5].

Overall, the analysis shows a significant opportunity for electrification in Class 6-7 urban vocational applications to increase energy efficiency and reduce on-road CO_2 emissions at a similar or even reduced cost of ownership. Two pathways for electrification of heavy-duty powertrains, less-disruptive and more-disruptive, have been presented to help navigate the 'Messy Middle'. The less-disruptive parallel hybrid configurations offer a cost-effective pathway for a more conventional powertrain layout while meeting CO_2 standards in 2027-2030 timeframe, while the more disruptive BEV and REEV configurations offer the advantage of significant reduction in on-road CO_2 emissions along with an easier transition to the ultimate future of zero on-road emission heavy-duty vehicles [6].

One specific near-term alternative powertrain solution that was not discussed in this study is the hydrogen internal combustion engine (H2-ICE). While the fuel conversion efficiency of a fuel cell is far superior than that of a H2-ICE, H2-ICEs can be applied relatively quickly to existing heavy-duty powertrains to achieve zero on-road CO_2 emissions. The technology has the potential to significantly reduce on-road CO_2 emissions until the fuel cell systems become cost-effective and durable for application in medium and heavy-duty vehicles. Future work will include more detailed investigations on hydrogen based alternative powertrain solutions.

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Definitions/Abbreviations

ARB - Air Resources Board
ACT - Advanced Clean Trucks
BEV - Battery Electric Vehicle
BSFC - Brake Specific Fuel Consumption
CAN - Controller Area Network
CNG - Compressed Natural Gas
CO2 - Carbon Dioxide
DC - Direct Current
DoE - Design of Experiments
EPA - Environmental Protection Agency
EV - Electric Vehicle
FC - Fuel Cell
GEM - Greenhouse Gas Emissions Model
GHG - Greenhouse Gas
GR - Gear Ratio
GT - Gamma Technologies
GVW - Gross Vehicle Weight
GVWR - Gross Vehicle Weight Rating
H2-ICE - Hydrogen Internal Combustion Engine
HDFTP - Heavy Duty Federal Test Procedure
HDUDDS - Heavy Duty Urban Dynamometer Driving Schedule
HHD/HD - Heavy Heavy Duty
HHDDT - Heavy Heavy-Duty Diesel Truck
HVAC - Heating, Ventilation and Air Conditioning
ICE - Internal Combustion Engine
LTO - Lithium Titanate Oxide
MG - Motor Generator Unit
MHD/MD - Medium Heavy Duty
MPG - Miles per Gallon
MPGe - Miles per Gallon Equivalent
NHTSA - National Highway Traffic Safety Administration