Alternative Fuels to Decarbonize Long-haul Trucking

by

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ABSTRACT

Decarbonizing road transport is one of the most urgent and complex challenges in global climate action. In particular, heavy-duty trucks account for roughly 7% of total US emissions, and their share is expected to grow as freight demand rises. A wide variety of fuel and powertrain options (e.g., battery electric, gaseous hydrogen, and renewable diesel) are being explored to reduce the climate impact of long-distance trucking. Yet there is no clear replacement for diesel fleets, which has slowed investment and the development of policies to support the transition to cleaner options. This has been in part because existing comparative analyses of alternative fuels rely on inconsistent assumptions that make "apples-to-apples" comparisons difficult, and because options that suit some business cases well may not suit others, given the operational diversity of U.S. trucking. This thesis addresses that gap by comprehensively assessing the portfolio of strategies for long-distance trucking using an integrated framework that combines a physics-based vehicle model, fuel production and distribution cost model, well-to-wheel emissions analysis, and total cost of ownership calculations, all under a consistent set of assumptions grounded in real-world duty cycles.

First, battery electric long-haul trucks are evaluated under overnight depot charging in the United States. A fleet replacement model grounded in the U.S. Vehicle Inventory and Use Survey quantifies payload penalties, finding that battery electric fleets require approximately 1.3 times as many vehicles to deliver equivalent cargo capacity as a diesel fleet, a factor that substantially increases capital and operating costs and has been systematically underestimated in prior work. This work finds that battery electric trucks are not well-suited for representative long-distance operations at a 600-mile range under today's conditions. However, their competitiveness as a replacement for diesel fleets is expected to improve over time as battery energy densities increase, retail electricity prices decline through greater asset utilization, and the electric grid becomes cleaner. A break-even analysis further identifies cases under which long-haul battery electric trucks can achieve cost parity with diesel, encompassing key variables such as unit electricity and battery costs, aerodynamic truck design, and alternative operating strategies including intermediate charging and battery swapping.

Second, a comprehensive cost and emissions analysis is conducted for alternative fuels, including renewable diesel, biomass-derived Fischer-Tropsch (FT) diesel, biomass-derived methanol, liquid organic hydrogen carriers (LOHCs), and green ammonia transported as

a liquid at 15 bar. Among these options, biomass-derived methanol reported the be the lowest-cost decarbonization option at \$125/tonne CO_2 avoided, followed by FT diesel (\$238), green H_2-LOHC (\$455), and green ammonia (\$647). Further scenario analyses show cost reductions of \$80 and \$175 per tonne of CO_2 avoided for LOHC and ammonia, respectively, when using blue hydrogen as a near-term bridging option. In the long run, biomass resource constraints and declining clean hydrogen production costs are expected to favor zero-carbon fuel pathways. Liquid organic hydrogen carriers in particular show promise as a long-term solution for long-distance trucking, leveraging existing liquid fuel logistics infrastructure to reduce capital investment. However, LOHCs remain one of the least explored fleet options, with no real-world demonstration at scale to date, though prototyping contributions have been made separately from this work.

Third, recognizing the wide operational heterogeneity of U.S. trucking, the analysis is extended to a broader range of duty cycles representative of short-haul, regional, and long-haul operations. The objective is to identify the most cost-effective decarbonization strategies for each operational context and the variables driving the cost. Battery electric trucks show the most sensitivity to operational range, with abatement costs below \$200/tonne CO_2 in local delivery rising to above \$600/tonne CO_2 for routes exceeding 600 miles. Compressed renewable natural gas achieves abatement costs below \$200/tonne CO_2 across all duty cycles and benefits from existing natural gas vehicle infrastructure, though network density for flexible long-haul routes remains limited. Gaseous hydrogen has high abatement costs, largely due to fuel costs at the pump driven by distribution and refueling infrastructure, both of which are highly sensitive to scale and asset utilization.

Finally, the analyses presented so far for cost, life-cycle emissions and infrastructure needs are extended to the Taiwanese transport sector, evaluating decarbonization pathways across scooters, passenger vehicles, light and heavy trucks, and buses. The analysis found that achieving Taiwan's national target of 3.3 million metric tonnes of CO_2 avoided by 2050 will require stronger policies, particularly for trucks, and cleaner electricity generation beyond current government projections.

Together, these projects combine methodological contributions with rigorous quantitative analysis to support informed decision-making for fleet operators, infrastructure providers, and policymakers, both in the United States and in countries where national decarbonization strategies for heavy-duty transport are taking shape.

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