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CALTRANS DIVISION OF RESEARCH, INNOVATION AND SYSTEM INFORMATION

TRANSFORMING IDEAS INTO SOLUTIONS

Research Results

Battery Technologies for Current and Future Heavy-Duty and Transit Electric Vehicles

Develop a guide to better understand the current and future battery technologies for heavy duty vehicles and transit vehicles.

Modal

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Project Title: Battery Technologies for Current and Future Heavy-Duty and Transit Electric Vehicles

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DRISI provides solutions and knowledge that improves California's transportation system.

WHAT WAS THE NEED?

California Air Resources Board (CARB) mandated the Innovative Clean Transit (ICT) regulation. CARB's ICT regulation requires transit agencies to purchase 100% zero-emission vehicles (ZEV) by 2029, with ZEVs required to comprise increasing percentages of annual new bus purchases until then and fully convert their fleets to ZEVs by 2040. California transit agencies are therefore spending hundreds of millions of dollars on purchasing such ZEVs, which today cost approximately twice as much as their Compressed Natural Gas (CNG) counterparts. These vehicles are run on battery and hydrogen fueling systems that are constantly evolving, seeing new and exciting technologies invented at a rapid pace. Some of these technologies are steady state batteries and other forthcoming advances could extend vehicle range, lengthen battery life, and shorten charging times sufficiently to make battery-electric buses a feasible option for a broader range of transit services, such as routes that are longer or traverse hilly terrain. At the same time, the cost of hydrogen has plateaued after years of falling prices. Transit agencies therefore are facing a lot of uncertainty to which type of bus to purchase, with this choice deciding how substantial amounts of funding will be spent and having a significant impact on the future of their services.

WHAT WAS OUR GOAL?

The goal of this research was to provide a summary of the role of advanced batteries in the design, operation and charging, and cost of heavy-duty trucks from 2025 through 2040. The research was going to also address how the new advanced battery technologies impact the versatility and costs of each vehicle type, and which types of heavy-duty vehicles will benefit most from and be more suitable for use of the advanced batteries.

WHAT DID WE DO?

This research focused on the development of advanced batteries with high energy density (>400 Wh/kg) and their role in the electrification of buses, vocational trucks, and construction machinery. Both vehicle and machinery electrification, along with advancements in battery technology, are actively progressing. Therefore, the key objective of this study was to assess the status of advanced battery development and its impact on the further commercialization of these electrified systems.

For advanced batteries, an extensive literature review and evaluation of ongoing research and development on advanced lithium-ion and sodium-ion batteries were conducted to determine the current state of development and the challenges associated with commercializing the various battery technologies. The modeling of advanced battery technologies predicts that batteries with specific energy of approximately 500 Wh/kg and energy density of 1,000 Wh/L will likely be developed and then commercialized in 7-12 years. These batteries are expected to enable the development of electrified construction vehicles and machinery with performance equal to or exceeding that of diesel-engine products currently available in the market.

Technology	***Advantages***	***Challenges***	***Application Scenarios***	***Electrode***
Ternary lithium-ion battery	*High energy density, long cycle life, low self-discharge*	*Cost, thermal stability, safety concerns*	*Long-range transport, high-utilization transport*	*NCM /Graphite*
Solid-state batteries	*Improved safety, higher energy density, longer lifespan*	*Manufacturing complexity, cost, scalability*	*Long-range transport, high-utilization transport*	*NCM /Li-metal or Si*
Sodium-ion batteries	*Abundant raw materials, lower cost*	*Lower energy density, shorter cycle life*	*Low-cost transport*	*Sodium-based cathode/Hard carbon anode*
Lithium-metal batteries	*Extremely high energy density, lightweight*	*Safety concerns, dendrite formation, high cost*	*Long-range transport, high-utilization transport*	*NMC or Sulfur/Li-metal*
Silicon-based batteries	*Higher capacity, energy density*	*Volume expansion, cycle life, manufacturing complexity*	*Long-range transport, high-utilization transport*	*NCM/Si*

Image 1: Overview of Advanced Battery Technologies

WHAT WAS THE OUTCOME?

Based on both academic and market literature and publicly available news releases, it is evident that the electrification of construction trucks, machinery, transit buses, and inter-city buses is progressing, primarily utilizing conventional lithium-ion batteries and electric drive components originally developed for passenger cars, SUVs, and medium- and heavy-duty trucks. In the case of buses, electric models are commercially available and gaining traction in an expanding global market. For construction trucks and machinery, there have been successful demonstrations and implementations of various types of electrified equipment in real-world construction projects in the United States, China, and Europe.

Market trends indicate a growing shift toward electrification, driven by regulatory policies and industry-led innovation. In the United States, federal and state subsidies, along with increasingly stringent emissions regulations, are accelerating adoption. However, the pace of market expansion will depend on advancements in battery technology, economies of scale, and infrastructure development. Manufacturers recognize the potential benefits of electrification and are investing in research and development to address existing limitations.

A key enabler of widespread electrification is the development of next-generation lithium-based batteries with higher energy density without compromising other critical performance metrics, such as cycle life and fast-charging capability. However, battery health remains a significant challenge, as aging and capacity fade are inevitable over time. Despite advancements in material design and battery management strategies, capacity degradation continues to impact long-term usability and the economic viability of Electric Vehicles. Significant progress has been made in both mechanistic studies and AI-driven battery diagnostics to bridge the gap between laboratory research and real-world performance but further understanding of battery cycle life and calendar life, as well as improvements in cell-level performance from material sciences, are necessary to enhance the longevity and reliability of advanced battery systems.

Battery safety, on the other hand, is not an inevitable issue but remains a critical concern due to the potential for catastrophic failures such as thermal runaway. Unlike gradual capacity fade, safety incidents can occur suddenly and have severe consequences. Advances in mechanistic investigations and early fault detection using specialized deep learning methods are helping mitigate these risks, but safety failures still pose a major barrier to widespread adoption. Beyond increasing energy density, ensuring the highest levels of safety is essential for the viability of advanced batteries in high-power applications, such as construction machinery. If these advancements are realized, electrified heavy-duty vehicles could achieve or surpass the operational performance of conventional diesel-powered models while offering lower long-term operating costs. In addition, the inherent benefits of electrification – such as reduced noise pollution and improved air quality in work environments—could further incentivize adoption.

Solid-state battery developers have set ambitious targets for commercial production by 2030, a milestone that could significantly enhance the competitiveness of electrified construction equipment and other industrial vehicles. However, the scalability and cost trajectory of solid-state battery technology remain uncertain. Its successful integration into mainstream applications will require overcoming challenges related to manufacturing efficiency, material availability, and cost reduction

WHAT IS THE BENEFIT?

Based on the findings of this study, Caltrans can procure electrified versions of most, if not all, of the trucks and construction machinery they require from established manufacturers. Initially, these vehicles and equipment will rely on conventional lithium-ion batteries, like those used in battery-electric cars and trucks in California. Charging infrastructure will be available from multiple manufacturers, though construction equipment may require significantly higher power levels – potentially in the megawatt range – necessitating further technological advancements. For heavy-duty vocational trucks, achieving a balance between high energy density, rapid charging capability, durability, and cost-effectiveness is critical to meeting demanding operational requirements. Integrating these vehicles with megawatt-scale charging infrastructure and advanced battery management systems will be essential to enhancing efficiency, minimizing downtime, and enabling large-scale electrification of vocational fleets. Although the current cost of electrified construction machinery remains high, precise cost projections are challenging due to various influencing factors beyond the relative costs of diesel engines, batteries, and electric motors. Nonetheless, this presents a strategic opportunity for Caltrans to begin electrifying its work vehicles and machinery. Early adoption would provide valuable operational experience with advanced battery technologies, potentially before 2030. The findings of this report may offer valuable guidance to other California agencies, such as CARB and the California Energy Commission (CEC), in shaping future electrification strategies.

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