

Battery Swapping May Meet Range and Reliability Needs for Certain EVs

Swappable EV batteries have been much talked about but rarely implemented in North America. But China has made a big commitment to the technology and changing market dynamics could make swappable batteries a more compelling option.

In [China, swappable EV batteries](#) have moved from concept to cornerstone — especially for commercial fleets. Companies like NIO and CATL have built nationwide networks where taxis, delivery vans, and ride-hailing vehicles can swap batteries in minutes, slashing downtime and boosting productivity. It's a system tailor-made for high-utilization fleets.

Meanwhile, the U.S. fleet sector is playing catch-up. With [fewer swap-ready vehicles](#) and almost no nationwide infrastructure, American fleets still rely on plug-in charging, which ties up vehicles—and time. As federal EV subsidies shrink, U.S. operators face mounting pressure to maximize ROI. Fast, modular battery swaps could be the answer. For fleets that can't afford to wait hours to charge, China's model is looking less exotic and more essential.

The U.S. may be late to the battery-swapping game, but the technology pieces are falling into place. Emerging players like Ample are leading the charge with modular, autonomous swap stations designed to retrofit a wide range of EVs — no redesign required. The company claims its robotic systems can swap a depleted battery for a fresh one in under 10 minutes, with growing pilots in cities like San Francisco and Madrid. For fleet operators, this could be a game-changer.

The path forward in the U.S. involves two major thrusts: standardization and modularization. SAE International has begun drafting protocols for swappable batteries, while component suppliers are developing universal high-voltage connectors, smart BMS modules, and quick-connect thermal interfaces. The Department of Energy has also been

funding research into adaptable EV platforms that support modular battery architecture.

Electronic Design Challenges of Supporting Battery Swapping

Designing an electric vehicle (EV) that allows for battery swapping when needed — whether manually or at a swapping station — introduces a range of electronic design challenges centered around safety, compatibility, communication, and power management. Unlike hot swapping (which implies zero downtime), this model allows for controlled shutdown or idle states yet still requires a robust and flexible electronic architecture.

There are also standards and compliance factors to consider. Familiarity with some of the more obvious standards and regulations is a good beginning. For example, compliance with safety and communication standards is especially critical if you're engineering for public swap stations.

On the design side, aim for compatibility with ISO 15118, IEC 62196, and any regional battery swap protocols, such as NIO's specifications that are relevant in China.

[ISO 15118](#) is an international standard that defines communication between electric vehicles (EVs) and charging stations, enabling features like smart charging and Plug & Charge for a more convenient and efficient EV charging experience. It facilitates bidirectional power transfer (vehicle-to-grid or V2G) and ensures secure communication between the EV and the charging station.

[IEC 62196](#) is a set of international standards that define

Method	How it works	Advantages	Disadvantages	Best Use
Voltage-based	Measure terminal voltage, maps to SoC curve	simple, low cost	Inaccurate under load, sensitive to temperature and age	Backup / Full-Empty detection
Current integration (Ah counting)	Adds up current in/out from full charge	real-time tracking, intuitive	Drifts over time, requires periodic calibration	Sort-term tracking with reset
Kalman filtering	Sensor fusion: voltage + current + battery model	Highly accurate, handles noise and drift	Complex, needs detailed battery model	Advanced EV battery management
Coulomb counting	Calculates charge in/out using current over time	Fast response, cycle-capable	Drift from offset, needs accurate capacity info	Mid-to-high end battery management system (BMS)

Each of the four methods of estimating state of charge (SOC) described — voltage based, current integration, Kalman filtering, and Coulomb Counting — have strengths and weaknesses. However, in general, the sophistication of Kalman filtering provides advantages for swapping applications.

the requirements for plugs, socket-outlets, vehicle connectors, and vehicle inlets used in conductive charging of EVs. These standards ensure interoperability and compatibility of EV charging components.

Electrical system testing would likely need to meet [UN-ECE R100](#), [SAE J1772](#), and [UL 2202](#).

Design Challenges of Incorporating Swappable Batteries

The design challenges of swappable batteries are mostly those of any EV but with some important additions, mostly centered on issues of monitoring and control:

High-Voltage Connector Safety and Lifecycle

Main EV batteries typically operate at 400 to 800 V DC and high current. Typically, connections are all but permanent. With swappable batteries, the more frequent connect/disconnect cycles raise safety and durability concerns.

Designers can address this challenge via [EV pre-charge circuits](#) to avoid inrush current, adopting high-durability connectors rated for thousands of mating cycles and, preferably, incorporating sequenced contact design (e.g., control, ground, power last). Other considerations include arc suppression and contact wear monitoring.

Electrical Isolation and Interlocking

Extremely critical for both equipment longevity and the safety of humans in the vicinity of the equipment is ensuring that the system is de-energized and electrically isolated before battery removal. Again, where this might have occurred a once or twice in a vehicle's lifetime with traditional non-swappable batteries, swapping makes it a central design requirement.

That means incorporating isolation detection circuits (e.g., an insulation monitoring device — IMD — that can

monitor the insulation resistance in an electrical system to prevent faults and ensure safety.). In addition, an extra layer of safety can be obtained by incorporating interlock loops that disable high-voltage relays unless all mechanical and electrical conditions are safe, as well as ground fault detection with logic lockout.

Battery Recognition and Compatibility

One of the points of resistance to battery swapping is the vehicle owner concern that a swapped-in battery might be defective, thus failing to provide sufficient range and power or even causing damage to the vehicle. Published reports suggest this concern has had validity in China. Thus, the swap-capable system must detect the installed battery and verify it's safe and compatible quickly and reliably.

This goal can be achieved with the help of battery ID chips, EEPROMs, or RFID for version control; digital handshake protocols (e.g., CAN, ISO 15118); and if possible, the vehicle control unit must validate chemistry, capacity, and voltage range that can be inferred.

Modular Battery-Management System (BMS)

Integration

The BMS of a swapped-in battery must communicate seamlessly with the vehicle. That can be easier said than done given the potential variations in hardware and software out there.

So, to meet swappable requirements, the design should include firmware on the vehicle side that's flexible and can support multiple BMS variants. Real-time error detection and fallback states should also be incorporated in case of miscommunication.

Realigning State of Charge (SOC)

EV systems have typically been optimized to function

with a specific battery pack, one that may have aged in predictable ways or developed weaknesses in some cells. Since the swapped battery may have a very different SOC than the value present in the prior battery pack, recovery capabilities need to be incorporated that can quickly assess and adapt. Designers typically rely on four main methods of SOC determination (*see table*).

That means a design should support rapid SOC initialization and correction logic, logging, and analytics to detect abnormal SoC transitions, and, optionally, load prediction and power ramp-up delay for voltage stabilization.

Thermal Monitoring and Interface Validation

Just as a swapped battery is likely to have unique electrical characteristics, the thermal properties of a swapped battery are also going to be unique. Thus, the challenge is to ensure that the battery thermally integrates with the vehicle's cooling/heating system.

That means incorporating sensors for real-time monitoring of battery inlet/outlet temperatures, fault detection to quickly identify if cooling interfaces aren't operatives, and, likely, software-controlled HVAC adaptations to manage different thermal demands.

Mechanical and Sensor Feedback for Physical Interconnection

Large, unwieldy battery assemblies, often requiring placement in hard-to-reach positions, must nevertheless be safely secured and properly placed. The vehicle must be able to confirm physical alignment and secure latching before energizing circuits.

While specific choices will vary with design challenges, likely candidates for adoption include redundant limit switches, Hall sensors, or load cells, unambiguous lock-in confirmation before contactor closure, and, perhaps, visual diagnostic cues for service technicians showing state of connection and of physical lock-in.

System Power Management During Swap

A Catch-22 of battery swapping is that keeping many core vehicle electronic functions available during the operation is very important. Or, at a minimum, these functions should quickly reboot and recover after a swap.

This goal can be addressed through a number of means, such as providing temporary auxiliary power via low voltage (e.g., 12 V) or EV [supercapacitor](#) backup during battery swap.

In addition to those hardware choices, swap activities can be further assisted by incorporating a fast boot architecture for power electronics and vehicle control units, as well as so-called graceful shutdown/startup sequences for drive inverter and DC-DC systems.

Software and Diagnostics

Software is a last (but certainly not least) consideration. Obviously, the system must accommodate battery-swap sce-

narios in its logic, UI, and diagnostics. This may take some effort to determine and incorporate.

Optimal design requirements could include fault-tolerant software layers that can respond appropriately to loss-of-battery conditions. Also consider combining those features with onboard event logging, error reporting, and user notifications as well as [over-the-air \(OTA\) update](#) infrastructure for BMS and vehicle software compatibility.

As noted early in this article, North America is far behind China in adopting battery-swapping technology. And because of the different regulatory and economic factors in North America, it may not end up "catching up." So, in the more limited scenarios for which battery swapping may be a good fit, most of these suggestions will be useful, but perhaps not all.

References

[Battery Swapping Station](#)

[Design of an Automatic Battery Swapping Station for Electric Vehicles](#)