Design and Safety Considerations for Automated Battery Exchange Electric Vehicles

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The exchange of the energy storage unit from an electric vehicle is considered as an alternative to in-vehicle battery charging or regeneration. If the exchange process is mechanically assisted or automated, the exchange can be accomplished in much less time than that required for in-vehicle charging. Many means for accomplishing battery exchange have been proposed or attempted, with various degrees of success, from the late 1800's through the present. In recent years, battery exchange methods have not been embraced by the electric vehicle industry, in deference to fast in-vehicle battery charging. Only a small number of semi-automated mechanizations have actually been demonstrated.

The history of electric vehicle battery exchange is reviewed, focusing on innovations and technical lessons learned. Design and deployment considerations are identified for battery exchange in general, and specific embodiments thereof. A technical comparison with fast charging is presented. Possible configurations for automated or assisted battery replacement are reviewed, with advantages and limitations of each discussed. Safety and regulatory considerations, and institutional and technical impediments are cited. The need for battery interface standards is briefly discussed.

KEYWORDS: electric vehicles, battery exchange, interchange, replacement

INTRODUCTION

The development of battery-electric vehicles and related componentry may be best described as an evolutionary process characterized more by incremental engineering refinements than quantum improvements.

The first electric automobiles appeared in the early 1880’s, in France and England. By the turn of the century, “electrics” dominated over steam and hydrocarbon combustion alternatives in the fledgling automotive market, due to their quiet and clean operation, and superior performance. In 1903, the majority of registered automobiles in New York State were electrics, with the Locomobile Company of America alone claiming to have sold over 4,000 vehicles, as reported in a 1903 edition of the periodical “Horseless Age” [1].

It is notable that these early electric automobiles differ little from the present state of the art. The lead-acid storage battery, invented in 1859 by Gaston Plante of France and which powered the first electric automobile in 1881, is still the most commonly used traction battery. Thomas Edison, an active promoter of electric autos, maintained until his death that a better battery is “just around the corner” [2]. Battery-related limitations of EVs, specifically inadequate range and long recharge times, lead to the decline of the electric automobile after 1910 and remain problematic today. The first practical solutions involved various methods of vehicular battery exchange.

Battery exchange involves the physical exchange of the vehicle battery with a charged one, with the aid of some external mechanism. Although many semi-automated means for battery exchange have been demonstrated, we are unaware of any fully-automated mechanism demonstrated to date.

Figure 1, from [3] shows the battery exchange and charging station operated in 1896 by the Morris and Salom Company, servicing a fleet of 200 electric taxicabs in New York City. The visible hydraulic rams on either side of the vehicle serve to precisely position the vehicle for lateral exchange of the battery pack. In 1899, a fleet of over 1000 electric hacks were operated in Paris, serviced by a central battery exchange and charging facility. The French Electromobile hack used in Paris exchanged its lead acid battery pack from the bottom of the vehicle [1].

After 1920, battery-electric propulsion remained popular only in applications for which zero emissions were imperative such as forklifts and mining vehicles, or intermittent or quiet operation was desirable, such as golf cars, milk wagons, and some urban buses [4].

With the first peacetime petroleum shortages in the USA in the early 1970's came the motivation for government funding of electric vehicle research for energy independence and pollution reduction. Interest in battery exchange seems to also have been renewed in the mid-1970’s. A 1978 British study estimated that the total cost of battery exchange would be twice that of petroleum for a given driving distance [5].
A paper presented at the 1983 EVC Expo in Detroit titled "Refueling of Urban Electric Vehicles" [6] discussed the battery exchange option in considerable detail, and assumed that the exchange process would required at least some "skilled labor". The authors envisioned public battery exchange stations, and discussed the issue of battery rental vs battery ownership. They concluded that battery exchange was an inferior solution for private commuter vehicles with range requirements under 50 miles, but was the superior option in all other situations.

Battery exchange to extend the in-service period of transit buses has been considered for some time, and has motivated a number of novel battery interchange solutions. During the period from 1974 through 1981, twenty type SL-E M.A.N. transit buses were converted to battery-electric operation by Gesellschaft für elektrischen Strassenverkehr (GES) using Bosch and Siemens propulsion components and Varta batteries. These were placed in test service in various cities in West Germany. The battery package for this bus was towed on a trailer behind the bus, and replaced by exchange of the battery unit from the trailer using special equipment [7]. Each charged battery unit provided a range of 40km at an average speed of 20 km/hr. Several battery exchanges were necessary during each complete 14 hour service shift, with each exchange reported to take 5 to 8 minutes to complete. It was reported that the 20 test buses were operated successfully a total distance greater than 4.5 million km during the eight year period.

One hundred thirty Mercedes LE-306 and Volkswagen Type II delivery vans were also converted by GES and tested during 1974-81. The Mercedes vans were equipped for battery replacement via a slide-out tray in the underside midsection. In the mid-70's in England, an electric transit bus was constructed by Ribble Motor Services, and the British Dept. of Transportation. It was operated in daily transit service in the city of Runcorn. It carried batteries on a trailer which could be detached and replaced to extend the service range [8].

In Japan, a number of battery-electric transit buses have been constructed and tested which have incorporated some means for battery replacement. Mitsubishi, Hino, and Isuzu have all developed transit buses which operate with automatic battery exchange equipment. Four Mitsubishi ME460 buses were operated in Kobe, Japan along five transit routes, accumulating 322,000 km total mileage between 1975 and 1979. In Kyoto, another Mitsubishi bus services a 23-km route, exchanging batteries several times daily to cover the service day. The Hino BT 900 and Isuzu EV 05 were been deployed in similar service in Nagoya and Osaka respectively [8]. In the USA, an experimental "Battronic" bus was constructed and tested by the Boyertown Auto Body Works in the mid-1970's. It used a side-loading scheme to facilitate manual replacement of the battery pack [9].

Alternative fuels and electric vehicle research languished in the 1980's with the decline in global petroleum prices. Interest in electric transportation was revived again in 1990, following renewed concerns about air quality and instability of the global petroleum market. In 1993, the State of California (USA) passed legislation which required a progressively increasing percentage of new vehicles sold in the state (2% by 1998, 10% by 2003) to be "zero emission vehicles" (ZEVs). However, the provisions of this law were substantially reduced in 1996 and 1998 following appeals by auto manufacturers.

In 1990, the US Advanced Battery Consortium, a group of battery manufacturers and electric utilities, was formed under the auspices of the Electric Power Research Institute (EPRI) and co-funded by the U.S. Department of Energy and the top three U.S. auto makers.

Figure 1. New York City Electric Taxi Charging Station 1896, from Scientific American 1898 by permission.
Historically, provisions for convenient battery replacement in passenger-class EVs appears to have been motivated more by the need to service the batteries, than as a means for extension of the useful vehicle range. Battery installations in trays, which are removable with various degrees of effort, are common. For example, the prototype nickel-iron battery module installed by Westinghouse in the trunk of a small car in 1978-79 was easily replaceable using a specially built cart [8]. The previously mentioned VW Type II “Electrotransporters” tested in West Germany by GES also used the replacement cart approach, with the battery package replaceable as a unit from the side of the vehicle. The placement of batteries inside an axial central tunnel has been adopted in several passenger EV designs. This facilitates extraction of the battery package from either the bottom or one end of the vehicle. Bottom extraction from a central tunnel was employed in the CDA Town Car (1976) [8], the General Motors Impact EV (1991) and the GM HX3 hybrid (1992) [10]. Front access to batteries in a structural tunnel was demonstrated in the ESB Sundancer (1970) using a roll-out tray [4]. In an ERDA-funded computer analysis of traction batteries for EVs in the late 1970’s, a simulated "standard" EV was described with the facility to quickly extract the battery package from the rear of the vehicle [8]. The 1989 Conceptor/GM Van and previous GM van conversions used a battery tray located underneath the midsection of the vehicle, manually exchangeable in approximately 20 minutes with the aid of a specialized battery trolley.

In the Annual Solar/Electric 500 electric vehicle race, sponsored by Arizona Public Service Company from 1990 through the present (now organized by Electric Vehicle Technology Competitions, Inc.), many of the competition vehicles have had provision for battery exchange during pit stops. In races prior to 1997, an unlimited-class one-hour event virtually required the exchange of batteries by pit crews. In 1992, Delco Remy battery testing lab demonstrated the use of an axial central tunnel faciitlates extraction of the battery package from either the bottom or one end of the vehicle. Bottom extraction from a central tunnel was employed in the CDA Town Car (1976) [8], the General Motors Impact EV (1991) and the GM HX3 hybrid (1992) [10]. Front access to batteries in a structural tunnel was demonstrated in the ESB Sundancer (1970) using a roll-out tray [4]. In an ERDA-funded computer analysis of traction batteries for EVs in the late 1970’s, a simulated "standard" EV was described with the facility to quickly extract the battery package from the rear of the vehicle [8]. The 1989 Conceptor/GM Van and previous GM van conversions used a battery tray located underneath the midsection of the vehicle, manually exchangeable in approximately 20 minutes with the aid of a specialized battery trolley.

Battery exchange for electric forklift trucks is well-established. Typically, three batteries complement each vehicle, with two batteries charging while one is in service. Semi-automated transfer equipment is available.

In the field of vehicular battery exchange, inventors have been active, especially after 1970, with over 40 relevant US patents on file. Among the early patents was that issued in 1973 to Paul Hafer covering a means for loading batteries into the sides of a vehicle via a slide-out tray arrangement [9], and a 1974 patent issued to Friedhelm Kappei (FRG), which described a battery box with rollers on its underside, which engaged rails in a side cavity of an electric vehicle [12]. Recognition of the need for battery interface standards appears to have first been cited in a 1992 British patent issued to N. J. Kruschandl for a quick release battery loading/unloading mechanism which used standardized battery power pack(s) coupled with an in-vehicle energy management instrument and information exchange system [13].

For primary (non-rechargeable) batteries, battery exchange may be the only option. Batteries with limited recharge capabilities include zinc-air cells, which have demonstrated energy densities of 440Wh/kg and specific power outputs of 100 W/kg [14].

Range limitations and charging times requirements seem to drive consumer reluctance to purchase EVs, as evidenced by consumer surveys such as the 1995 General Motors “PrEView” campaign in which 72 potential buyers were given the opportunity to drive a GM Impact, considered at the time one of the most advanced EVs available.

**BATTERY EXCHANGE COMPARED WITH FAST CHARGING**

Despite significant advances in electrochemistry, the lead-acid battery still powers the majority of commercially available EVs [15]. Today, as in 1881, typically 30-40% of the mass of a battery-electric vehicle is accounted for by the batteries. Modern deep-cycle lead-acid batteries today are estimated to have only about twice the specific energy density, and provide about twice the vehicle range as their 100-year-old predecessors.

The energy storage density problem is put into perspective when one considers that one U.S. gallon (3.78 L) of unleaded gasoline with a mass of under slightly three kilograms (Kg), contains 34 kilowatt-hours (kWh) of usable energy, a specific energy density of approximately 11,300 Watt-hours per kg (Wh/kg). By comparison, a typical state-of-the-art lead-acid deep-cycle battery contains only about 25 Wh/kg, a factor of 450 less than gasoline. Some improvement to this dismal figure is realized by comparing the relatively poor (typically 25%) energy conversion efficiency of an internal combustion engine (ICE) with the high efficiency of modern electric drive systems (over 90%). In addition, the overall use-cycle efficiency of an EV is superior to an ICE vehicle by a factor of two or more in urban driving, since an ICE must remain idling at stops, and cannot recover braking energy, while an EV is powered only when torque is required, and can recover some energy via regenerative braking. With these factors included, the effective energy density of gasoline compared with a lead-acid battery shrinks to a factor of approximately 62, which is still unattractive. Recently developed advanced battery chemistries have demonstrated specific energy densities over 1000 Wh/kg, but they remain excessively costly or impractical compared with lead-acid batteries.

In the absence of a major breakthrough in battery technology, only two alternatives for extending the range of battery-electric vehicles have actually been deployed: fast charging of batteries in-vehicle, or battery exchange, the complete exchange of a discharged battery pack with a charged one. Hybrid ICE/electric propulsion systems and fuel cells are promising alternatives to battery-electric vehicles, but are not considered in this discussion since they are generally refilled with a hydrocarbon fuel rather than charged from the electric grid.

Normal recharge times for lead-acid batteries vary from 10 hours for golf-cart type lead-acid batteries, to 2-3 hours for the advanced lead-acid batteries in the GM Impact or EV-1. Fast charging implies the accelerated charging of a battery on-board the vehicle, at least to some partial depth of charge. Only within the past decade have successful
EV is charged from a 220VAC supply to 40% capacity. If a typical 20 kWh battery in a small installation, it is worthwhile to consider a single isolated fast-charge charge a fixed vehicle battery. While it would be overly simplistic to consider a single isolated fast-charge installation, it is worthwhile to put the power requirement into perspective. If a typical 20 kVA battery in a small EV is charged from a 220VAC supply to 40% capacity in fifteen minutes with an efficiency of 75%, an RMS current of 194 Amps at 220 Volts, or 42.7 kW, would be required. This is nearly equivalent to the entire capacity of a typical 200 Amp service for a larger new home. The potential impact of the high intermittent demands of fast charging on the utility grid remains to be studied. Transfer of power from a stationary ballast battery overcomes the high utility current demand, but nearly doubles the amortized cost due to the incremental expenditure of the stationary battery, measured in charge/recharge cycles.

Fast charging has advantages in terms of mechanization. It does not constrain the vehicle design to require external access to the batteries; batteries can be placed optimally in the vehicle to best utilize space, rather than contained in a single or a few modules; no external mechanical equipment is required; and the familiar concept of "filling-up" the vehicle is retained. Fast charging technology has been the subject of intense research, with significant improvements reported. For example, Nissan (Japan) report that their "Super Quick Charge System" has the ability to charge NiCd batteries to 40% capacity in 6 minutes, or Pb-acid batteries to the same capacity in 12 minutes [16]. Some advanced batteries are reported to have reduced recharge times. GM reported 15 minute recharge times for nickel-metal hydride EV batteries [15].

While recent reports have suggested new battery construction techniques and charging strategies which permit high charge rates, the large body of data and experience indicates that batteries are generally degraded by quick charging. Energy transfer efficiency drops significantly with increasing rate of charge, partially nullifying the energy efficiency benefits of the EV. Batteries of almost all types which are not specifically designed to accept high rates of charge are overheated or progressively damaged by excessive charge rates.

Batteries designed specifically to accept rapid recharge rates often have compromised cycle life and/or energy density. For example, the (1992) Nissan FEV (Future Electric Vehicle), used specially designed NiCd batteries with reduced internal resistance and provision for cooling during charging [10]. Reduced internal resistance, however, decreases the battery "shelf life" due to internal discharge during non-operational periods.

For comparison, we observe that gasoline flowing through a nozzle into an automobile fuel tank at a flow rate of ten gallons per minute is equivalent to over 20 Megawatts (MW). This recharge rate is equivalent to a substantial portion of the total output of a small electric power plant if delivered as electric power. For battery exchange, a 1000 kg, 48kWh lead-acid battery package for a medium size electric bus, if exchanged in one minute, is equivalent to an energy transfer rate of approximately 2.9 MW. When the aforementioned energy efficiency factors are included, the usable energy transfer rates for gasoline and lead-acid RBI become approximately 2.5 MW and 2.6 MW respectively, nearly the same.

**TECHNICAL FEATURES OF AUTOMATED BATTERY EXCHANGE**

An automated battery exchange process generally requires the mechanization of the following functions:

- Positioning of the vehicle relative to the exchange apparatus, or positioning of apparatus relative to the vehicle.
- Electrical disconnection of discharged battery.
- Disengagement of battery from vehicle receptacle.
- Physical removal of battery.
- Transfer of old battery out of the way of insertion path of replacement battery, into storage/charging queue. Alternatively, vehicle may be repositioned for insertion of battery.
- Dequeuing replacement battery.
- Insertion of replacement battery into vehicle.
- Physical engagement and securing of replacement battery in receptacle.
- Electrical connection of replacement battery.
- Repositioning or securing of exchange apparatus to permit departure of vehicle.

A large number of mechanizations are possible, each imposing some restrictions on the vehicle design and involving specialized off-vehicle equipment. Apparatuses proposed in US and foreign patents vary from crude to almost whimsical in their complexity. Configurations which have actually been mechanized to date have all required some degree of manual assistance by one or more skilled operators. Only a few are amenable to full automation. Figure 2 depicts six configurations which have been demonstrated or conceptually proven.

**A. EXCHANGE FROM BOTTOM OF VEHICLE.**

A removable low-height battery module is secured to the bottom of the vehicle. This method of battery support and replacement was used as early as 1898 for hacks in Paris, as discussed previously. Bottom battery placement is used on many commercial EVs, such as the G-Van, since it minimally intrudes on the interior passenger or payload space. Exchange is accomplished by vertical removal of the exhausted battery package from the bottom of the vehicle. The package is then withdrawn from under the vehicle, or the vehicle is manually repositioned to align with a replacement battery package, which is then inserted underneath the vehicle. Alignment of the vehicle with the exchange equipment is critical, and accommodation of variable vehicle height, with and without the battery payload, have presented significant design challenges.
This exchange approach is applicable to a wide range of vehicles, including automobiles, light trucks and transit buses. One design limitation is the height of the battery pack. This height plus the clearance to the vehicle floor is subtracted from the interior cabin height. The imposition may be severe for a small car or a low-floor bus, but less of a consideration in trucks and transit buses.

B. REAR OR FRONT BATTERY EXCHANGE.

The battery package is removed and replaced from the rear or front of the vehicle. A 1984 patent by Gwyn (rear exchange) and 1994 patent by Swanson (front exchange) suggest means for the extraction and queuing of batteries using this approach [17]. Location of the battery at one end of the vehicle leads to weight distribution challenges in the vehicle design.

C. REPLACEABLE BATTERY TRAILER.

Batteries are stored entirely in a trailer which is towed behind the EV. Exchange is accomplished by replacement of the trailer. This method is most practical for vehicles converted from ICE propulsion, since it minimizes vehicle modifications. Due to the difficulty of exchanging a trailer without some human intervention, a fully automated exchange system based on this method is unlikely. However, variations of this method have been used successfully, such as the previously discussed fleet of GES/MAN SL-E Elektro-Buses in Dusseldorf, FRG. In this case, the trailer remained attached, but the batteries were exchanged from the trailer, which was designed specifically for this purpose [8].

D. SIDE POCKET BATTERY EXCHANGE.

Batteries are located in panners or pockets in the side of the vehicle. This placement is preferred for low-floor transit buses, since it creates a minimum intrusion on the useful interior passenger space. The central battery placement also yields a favorable weight distribution.

Manual exchange from the pockets has usually been implemented using a forklift truck or palette trolley to transfer the batteries. Several current electric bus manufacturers have incorporated provisions for this exchange method, including Specialty Vehicle Manufacturing Corp. in Los Angeles, CA, Bus Manufacturing Corporation in Santa Barbara, CA, U.S. Electricar in Redwood City, CA, and School Buses built by Bluebird and Thomas Built. Fully automated exchange from side pockets is challenging due to the number of different motions needed to exchange the batteries, and the critical alignment requirements.

E. LATERAL EXCHANGE.

The charged battery module is inserted into one side of the vehicle. It can optionally be configured to push out the existing battery with a single motion. Lateral battery exchange is commonly used for electric forklift trucks. This technique was used in New York in 1896 (Figure 1) and in a competition vehicle in the 1993 APS Electrics race. Interference with vehicle drivetrain components or structural frame members of existing vehicles preclude most conversions. Lateral, longitudinal and vertical vehicle alignments with the exchange units are critical.

Figure 2. Battery Exchange Configurations.
F. LONGITUDINAL EXCHANGE.

In an axial exchange configuration, batteries are inserted into the front of the vehicle, and optionally, the existing battery extracted from the rear in a single motion. Batteries may be located in a central longitudinal tunnel. In the pass-through version, either that batteries or vehicle must move axially in the apparatus. A key limitation of this approach is the required full-length unobstructed battery tunnel, which precludes a conventional rear axle or central placement of the motor or transmission. In an automated embodiment, the exchange could theoretically be accomplished at very low speed, without the vehicle actually stopping.

SAFETY AND REGULATORY CONSIDERATIONS FOR EXCHANGEABLE BATTERY ELECTRIC VEHICLES

Vehicles sold in the USA for operation on public highways, regardless of propulsion source, are subject to Federal Motor Vehicle Safety Standards (FMVSS) published by the National Highway Traffic Safety Administration (NHTSA). Similar regulatory agencies and constraints are applicable in most European and Asian countries. Electric vehicles generally pose somewhat different hazards to both the vehicle operator, other vehicles and pedestrians than ICE vehicles. The large mass of batteries usually make EVs heavier than ICE vehicles, degrading both acceleration and braking rates. EV Battery voltages can range from 48 to over 400 volts. Available current up to 1000 amps (or more for larger vehicles) makes possible tremendous energy release in the event of a short circuit. Rupture of a battery case could result in the release of dangerous reactants.

One example of the peculiar hazards associated with batteries occurred in the second annual Solar and Electric 500, April 26, 1992 in Phoenix, Arizona (USA). The race leader, a Solecotia car powered by zinc-bromide batteries, lost coolant and leaked bromine gas, sending the driver and fourteen others to the hospital [18].

Provision for the rapid exchange of the vehicle battery introduces additional safety concerns associated with both the vehicle and the exchange equipment.

SAFETY CONCERNS PERTINENT TO THE VEHICLE

The primary vehicle-related concerns associated with vehicular battery exchange are due to the fact that the provisions which enable the battery to be quickly exchanged inherently require it to be held less securely in place in the vehicle. This includes both the physical battery restraints and the electrical connections to the battery.

Accidental release of the battery module in the event of a collision. If the battery can be exchanged quickly, it is likely to be less securely mounted than a permanent battery installation. Accidental release of a battery module weighing 400 to 500 kg could increase the level of damage and hazard in a collision, especially to the other vehicle.

Battery protection from the elements, and integrity in the event of collision or rollover is also a greater concern with an exchangeable-battery vehicle, since the battery will be more exposed than in a fixed battery installation.

Ventilation of released gases for flooded lead–acid batteries or would probably be a reduced concern for most exchangeable battery configurations, due to the increased exposure of the battery in the vehicle, and well-controlled environment for charging the battery off the vehicle.

Accumulation of road debris, mud, water and snow pose a serious additional problem, especially in the area of the electrical contacts. Rain or slush laden with road salt is an effective conductor, capable of shorting and/or degrading battery and instrumentation contacts.

Electrical connectors that must engage automatically and quickly are likely to be more susceptible to poor contact or accidental short due to misalignment or mishandling. The contactor system must be completely “idiot-proof,” capable of withstanding backward insertion of the battery module, poor alignment, and possibly excessive insertion speed or force.

Provision for fail-safe docking with the automated battery exchange equipment is a nontrivial concern. Depending on the interchange scheme employed, the level and attitude of the vehicle may be critical.

Standardized electrical and mechanical interfaces would be beneficial to facilitate safe attachment of battery modules, and to accommodate electrical connections to instrumentation, auxiliary batteries, and possibly to battery environment control systems (e.g., for high-temperature batteries or external reactant reservoirs). Each additional system increases safety and reliability concerns to some degree.

SAFETY CONCERNS PERTINENT TO THE BATTERY EXCHANGE EQUIPMENT

The battery exchange unit must be easily accessible, but pose no safety hazard to the general public or the EV operators or exchange station maintenance personnel. If
accessible to the public, it must be resistant to vandalism and theft.

Provision must be made for safe dissipation or absorption of the by-products of the charging process. This is especially true if a large inventory of batteries is stored, each in various states of recharge. An explosion hazard exists, which may be a consideration in the location and housing of the exchange and charging apparatus.

Significant electric power may be required if many batteries are concurrently charged at the exchange site. This may require large power handling and distribution equipment. Hazard levels are increased accordingly.

The battery exchange equipment must be designed to overcome docking and alignment problems, preventing to damage to itself and mechanical hazards to the public.

The means for controlling, monitoring and accounting for the battery exchange must be both secure and safe. While not directly a safety issue, security and safety concerns are usually closely linked.

BATTERY EXCHANGE-RELATED PROVISIONS OF THE FMVSS

While electric conversions of existing ICE vehicles often rely (questionably) upon the original vehicle certification prior to conversion, or are granted exemptions based upon limited production, purpose-built EVs generally must comply with all relevant FMVSS passenger car or truck safety standards. Among the first vehicles certified under these standards were the GM/Conceptor G-Van conversion (1989), the Nissan FEV [10] and the Chrysler T-Van [19]. FMVSS regulations specific to EVs are still in the formative stages. An Advanced Notice of Proposed Rule Making (ANPRM) was originally published in the Federal Register in December 1991 (49 CFR Part 571 Docket No. 91-49; Notice 2). In October 1992, the Electric Vehicle Association of the Americas released an executive summary pertaining to FMVSS for EVs [20]. In December 1992, the NHTSA concluded that it would be premature to initiate major rulemaking in this area, and initiated an ongoing fact-finding research program. This research and testing program remains in progress in 1999. In 1998, a special policy exemption was approved for very slow (under 25 mph) vehicles, particularly electric golf cars and electric commuter cars, under 49 CFR Part 571.

Battery charging standards have proceeded ahead of other EV-specific standards. Charging facilities are required to comply with all applicable provisions of Article 625 of the National Electric Code, SAE recommended practice for inductive EV couplers (SAE J1773), and/or SAE proposed recommended practice for conductive EV couplers (SAE J1772). These standards are of relevance to automated battery exchange and charging systems.

For passenger cars, the NHTSA has proposed minor amendments to four existing standards to explicitly address EVs: 1) controls and displays, 2) windshield defrosting and defogging systems, 3) passenger car brake systems, and 4) hydraulic brake systems. Specific provisions of the current FMVSS which are relevant to vehicular battery exchange are discussed below.

Occupant/Driver Collision Protection

General vehicle occupant safety concerns are dealt with in the many subsections of FMVSS 571. These standards apply to EVs but do not specifically address safety problems that EVs, especially those with battery exchange capability, might pose during a collision. Three major areas of specific concern are 1) potential for shock hazard, 2) occupant or bystander contact with electrolytes or reactants, and 3) battery system explosion. All three of these concerns are exacerbated due to the greater exposure and weaker mounting of the battery package in an exchangeable-battery vehicle. The NHTSA considers a disconnect device vital to prevent electric shock resulting from the propulsion battery circuitry shorting to the vehicle chassis. An easily exchangeable battery could be expected to increase the possibility of loss of electrical isolation, because of electrical contacts that can be rapidly disconnected.

Low Speed Front and Rear Collisions

Low speed front and rear collisions are addressed in FMVSS 581. Electric vehicle crashes have been few and little post-accident analysis data exists. Damage analysis following a 30 MPH barrier crash test of a 1990 GM/Conceptor G-Van identified a significant risk of ejection of the bottom-mounted 1200 kg battery pack [21]. Battery securing devices must withstand not only large shocks due to major collisions, but also the cumulative effect of repeated smaller shocks over an extended period. The functionality of the battery must remain unchanged after impact. Certification tests include pendulum, barrier, longitudinal impact, and corner impact tests per FMVSS 581 and SAE J980a.

Side Impact Protection

Regulations regarding side impacts are contained in FMVSS 571.214. In addition to structure concerns, the impact must not expose dangerous electrical wiring or battery fluids to the vehicle occupants or bystanders. An exchangeable battery configuration which loads the battery from the side or bottom of the vehicle would be particularly at risk, since the battery could possibly absorb much the impact of the collision or be ejected.

Roof Crush and Roll Resistance

Regulations regarding vehicle roll-over are addressed in FMVSS 571.216. In such an event, the vehicle occupants and bystanders must be safe from electric power components and battery reactants. Extrapolating from these provisions suggests that the battery receptacle must retain main intact, and the battery must be retained in it.

Battery-Specific Safety Issues

Under FMVSS 571.208 and 571.301, all battery materials must be outside the passenger compartment. Regulations specific to the means by which cells are secured in a vehicle are anticipated. The battery compartment must have ventilation adequate to maintain a concentration of hydrogen below 4% by volume (the minimum flammability concentration) during vehicle operation, charging and maintenance. (This provision would be specific to the battery type.) Batteries with vents shall have flame barriers to inhibit multi-battery explosions. The vehicle shall also have a safety device operable by the
driver to provide positive battery disconnect, which should operate automatically in a collision or rollover.

BATTERY-EXCHANGE SPECIFIC STANDARDS

EV standard setting activities are in progress, especially with regard to charging connectors and systems. The Society of Automotive Engineers (SAE) and Electric Power Research Institute (EPRI) are lead contributors to these efforts. Standards specific to the requirements of battery interchange could contribute significantly to commercial feasibility and user acceptance. While not without additional infrastructure considerations, the standardization of the dimensions, voltages, connectors, and attachment mechanisms for a series of exchangeable battery packs could theoretically make this range-extension method accessible for non-fleet vehicles. It is doubtful that forthcoming EV standards will consider battery exchange, although they will certainly apply to it.

CONCLUSIONS

Vehicular battery exchange methods have been used for over 100 years to overcome the range and charging time limitations of EVs. Past successful deployments have almost all been in transit bus applications. The history of battery exchange automation has included both remarkable innovation and Rube-Goldberg complexity. The key barrier to commercial viability is the dependency upon an infrastructure for battery exchange and off-vehicle charging. However, technical feasibility and effectiveness for range vehicle range extension are concluded to be equivalent to or superior to the only other range-extension alternative, high-rate in-vehicle battery charging.

Safety concerns for exchangeable-battery EVs are greater than for fixed-battery EVs, due to the design provisions for quick battery access. Safety issues related to battery exchange automation equipment must also be considered. Incremental safety concerns appear to be manageable with sound engineering and deployment practices.

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