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The battery designer's challenge — satisfying the ever-increasing demands of vehicle electrical systems

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Abstract

The automotive battery designer of the 1990s and beyond will encounter an unprecedented array of complex challenges imposed by consumer desires, governmental mandates, and vehicle manufacturers' specifications. It is predicted that enhanced feature content in the areas of safety, convenience, performance, and guidance will result in a three- to six-fold increase in electrical power consumption in vehicles by the year 2000. In the absence of major breakthroughs in vehicle electrical systems, these new loads will significantly modify the duty cycle to which the battery is subjected. The micro- and macro-environment in which the battery must survive will significantly impact the product's design and material specifications. Severe weight and size limits will be imposed on batteries in an attempt to meet mandated Corporate Average Fuel Economy (CAFE) requirements and additional pre-start electrical loads may be introduced to reduce objectionable emissions. Finally, quality and reliability levels of vehicles and their component parts must undergo continuous improvement. In order to respond to these diverse and sometimes contradictory demands, the battery designer must participate as an integral part of the vehicle electrical system development team. Design considerations for the future must include elevated and multiple voltages, multiple batteries per vehicle designed for specific functions, and further improvements in power and energy density, as well as cycle-life.

Origin of the challenge

Understanding the factors driving automobile design is necessary in order to make sense of the demands being made on the automotive battery. Certainly the primary mission of the vehicle is to provide a personal transport function to the end-user and passengers. But as design and manufacturing technology have progressed, the primary mission has become almost secondary to the objective of building sales volume by providing customers (end-users) with additional features to make his or her travel more enjoyable. The areas of focus have been diverse, just as the tastes and desires of individual customers are diverse. But they can be broadly categorized as being oriented toward performance, comfort and convenience, safety or guidance. Marketing groups within the automobile companies apply their resources to the task of assigning a monetary value to proposed features and determining how many of their customers would purchase them, or be influenced to purchase the car because of them. The results of this process

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are seen in the increasing vehicle 'content' available to the consumer. Also influencing the vehicle design goals are the external or environmental mandates of governments with respect to fuel economy, exhaust emissions and safety. Interwoven throughout the design objectives are the goals of minimizing cost and maximizing vehicle reliability.

The history of the impact of these various driving forces on automotive battery design has been documented [1, 2] and can be summarized as being greater energy storage and power in a smaller volume with longer life at a lower cost. And the industry, through its creative efforts and hard work, has responded. The past is not the subject of this paper; it is reflective, however, of the general direction of battery performance and design demands for the future. The progression of electrical load demands has followed the general course outlined by Rivard [3] in 1986. Present loads are approaching 2 kW and are projected to reach 3 to 6 kW, or even 8 kW, by the end of the decade [3, 4] (Fig. 1). Specific battery needs are identified as: higher energy density; tolerance of many duty cycles (high cycle-life); high reliability; and most likely, higher voltage — in the range of 24 to 48 V. Being part of the battery industry and as result being more informed about battery technology, let us take a look at the future from our own perspective.

The new electrical power loads will come from the basic areas mentioned above: performance features, comfort and convenience features, guidance features, safety features and government mandates in emissions, safety and economy [5]. Examples are given in the partial list shown in Table 1. The timing of production implementation of specific devices to provide these features or functions will be dependent upon legislation and cost/benefit (profitability) estimates. Legislation will be responded to in a manner designed to minimize the cost of providing the function in the timeframe

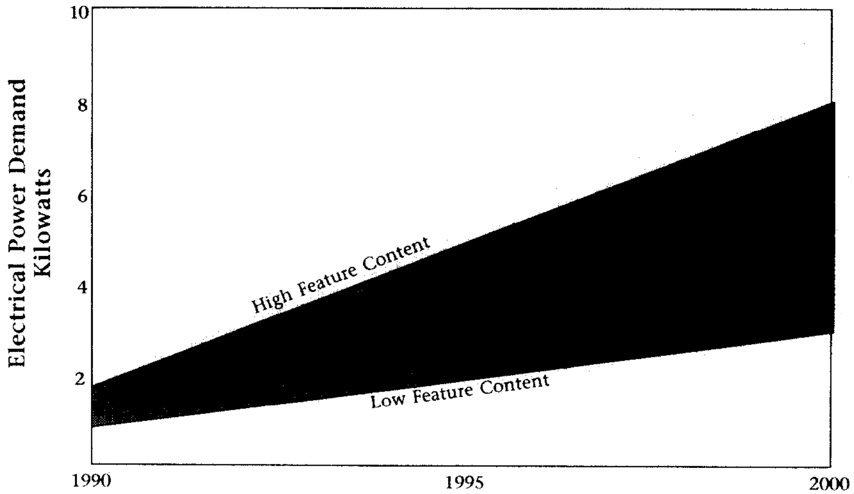

Fig. 1. Projected automobile electrical load demand in North America.

TABLE 1

Future automobile electrical power loads

Performance	Economy and emissions
Electronic fuel injection	Electric powered water pump
Electronic distributorless ignition	Electrically heated catalytic converters
Electronic valve actuation	Advanced powertrain control
Electric power steering	System and component diagnostics
Advanced powertrain control	Electronic fuel injection
Electric all-wheel steering	Electronic distributorless ignition
Active suspension	Electronic valve actuation
Traction control	Electric power steering
Electric powered air conditioning	Electric powered air conditioning
Convenience	Safety
Memory seats	Anti-lock braking
Supplemental 'instant' electric heat	Electric all-wheel steering
Electric powered air conditioning	Active suspension
Zone adjustable climate control	Traction control
Electrochromic glass	Collision avoidance
Digital audio	Blind-spot sensors
Navigation aids	

required. History says initial components or systems selected to provide the function will not be optimized with respect to energy efficiency, cost, size or weight. After the function is achieved in production, the engineers will then go back and optimize, perhaps integrating with other mandated or desired functions or features to achieve lower cost and greater packaging efficiency. The original equipment vehicle manufacturers (OEMs) will not, however, provide features that are not end-user desired unless they are legislated. The key to predicting phase-in of electrical power loads due to this driving force is in monitoring legislative and administrative rule-making activities and the technologies available to meet the mandates. In the U.S.A. for example, the California Air Resources Board is proposing emission requirements that are much more restrictive than the remainder of the country [6]. The California regulations may require electric vehicles in a manufacturer's fleet as well as electrically heated catalytic converter technology for internal combustion engine vehicles. The latter may be in addition to other known means for emission reduction, including modified fuels.

Past and present direction in vehicle fuel economy (energy efficiency) in the U.S.A. is to mandate fuel economy goals while making inexpensive fuel available, as opposed to the European and Japanese approach of taxing fuel and taxing vehicles on some size or power basis somewhat related to fuel economy. Increased fuel economy goals are expected to be legislated in the U.S.A. within months. Furthermore, given the current situation in the Mid-East, some shorter-term action may be put in place which produces a rapid market emphasis on fuel economy. Either will accelerate the electrification of some of the existing mechanical engine loads such as power steering and electric coolant pumps [4], as well as spread electric radiator fans to all vehicles not presently using them. The incentive to provide smaller, lighter batteries with greater energy capacity will also increase. The development and design of more efficient alternators and electrical load management [4] will also be accelerated by this form of legislation. Again, the degree and timing of implementation will depend on the legislated goals and the penalties for non-compliance balanced against cost and the market demand for fuel efficient vehicles and specific vehicle features conflicting with that objective.

An effect of fuel economy goals already observed in practice is the change induced in the battery's micro-environment: the rise in battery operating temperature seen in late-model vehicles. Under-the-hood temperature has risen significantly as unoccupied volume has decreased and open frontal area has decreased [1–4]. Amplifying this effect is the decline in battery volume, increase in surface to volume ratio, and decrease in heat capacity. These factors have resulted in more rapid battery temperature rise and higher peak operating temperature. The outcome is deterioration of battery service life in warm climates. In addition to laboratory data, proof of the temperature effect in vehicle service is evident from other data [7]. It has also been found that battery design, material and manufacturing improvements have resulted in overall improvements in battery service life in the U.S.A. [7, 8]. But caution is advised in projecting that trend into the future because of the large percentage of replacement batteries in the sample and the older vehicles they represent, as well as the industry mastery of 'maintenance-free' battery design and manufacturing during the eight years between failure mode studies. In addition, the fundamental temperature-dependent failure modes are exponentially dependent on temperature, making it reasonable to expect that incremental improvements in battery resistance to thermal effects can be more than eliminated by a very small rise in average operating temperature.

Perhaps the most far-reaching factor that is part of the macro-influence on battery design, manufacture and distribution is the inevitable increase in the legislated requirements for environmental control of lead. Laws have been proposed in the U.S.A. to raise the recycling percentage to greater than 95%. In the extreme, legislation has been introduced to ban lead/acid batteries entirely, regardless of whether technological or economic alternatives exist [9]. Given the lack of ready alternatives and the recycling capacity already in place, lead/acid batteries are not likely to be banned outright, but environmental rules may increase the cost of lead/acid batteries enough to make other electrochemical systems appear more attractive in future years.

In addition to the macro-trends imposed on the automotive and battery industries and the market driven feature trends within the automobile industry (Fig. 2), there are a number of other forces at work having impact on future battery needs, both in terms of product and service. Most have as

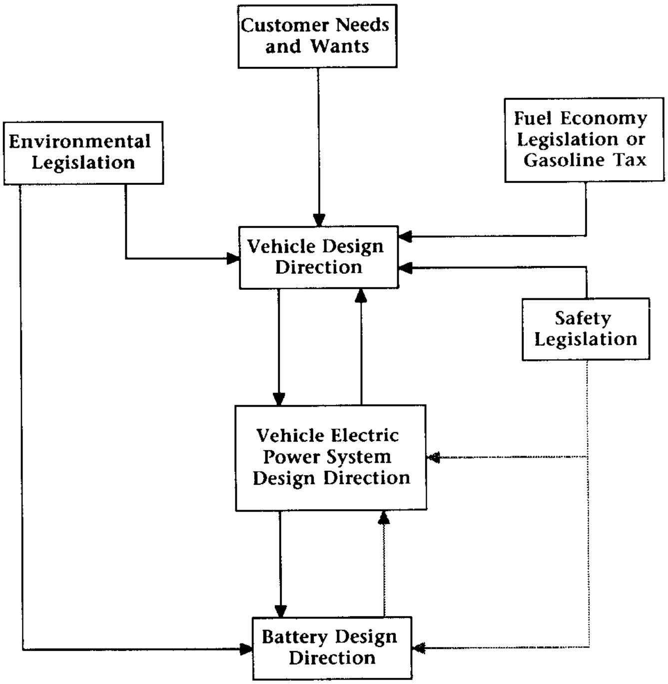

Fig. 2. Battery design direction influences.

their source the original equipment vehicle manufacturers' changing methods of doing business. Some of the changes are responding directly to competitive market actions and have been in progress for some time: examples being increased quality and long-term reliability objectives, shortened development and vehicle design timeframes, and worldwide design and manufacturing. The less visible change is the movement toward system design and optimization methodologies as opposed to the historical component optimization approach [4, 10]. This is proving to be a slow and difficult transition for most vehicle manufacturers because of its effect on organizational communication and structure, as well as design process procedures. However slow, change is occurring and will have significant impact on battery companies with original equipment business.

The challenge

Defining the challenge to the battery designer in detail requires a great deal of conjecture, but some overall trends appear clear. Electrical accessory power loads will increase by a factor of three to six. Vehicle manufacturer design engineers will adopt a systems design approach to reliably supporting

TABLE 2

Electric power systems of the future

Architecture	dual/high voltage
Generation	integral starter/generator
Charge regulation	advanced electronic control
Distribution	conventional and multiplexed power buses
Loads	partitioned by power level, function, duty cycle controlled by energy management system
Storage	dual batteries, high and low voltage (12 V)

those loads. Likely elements of the new electrical power systems will be high voltage and dual-voltage system architectures, integral starter/generators, refined battery recharge control, and electrical load management [4, 11, 12] (Table 2). The mission of battery designers will be much more complex than it has been. No longer will it be sufficient to meet the automaker's specification. Battery designers will be required to provide quantitative information on their component's characteristics in the vehicle application (both real-time operational response and long-term reliability response), and interactively work with system designers to help evaluate design options effectively and generate entirely new sets of functional requirements for the system's individual components, including the battery(ies). This will require resources to generate levels of application information never before required of battery makers. Decisions will need to be made on the trade-offs involved in designing for power versus capacity versus cycling capability versus temperature resistance versus charge acceptance versus.... And those decisions will require hard data in order to meet the quality, reliability and warranty goals of the automobile manufacturers.

OEM focus has historically been optimization of components. For the battery, this has translated into requests for longer life (cycle-life), better resistance to high temperature, better charge acceptance at low temperature, ability to withstand complete discharge (lot stand), higher power and energy density, lighter weight, reduced water loss, etc. Certain of these are conflicting desires relative to the fundamental characteristics of the lead/acid system. Battery designers have been and should continue to work on improving the performance and life of their products, but the system designer has to take the fundamentals into account in the system design and optimize its performance without requiring individual components to operate in opposition to their fundamental characteristics. Examples of the old approach can be seen in new vehicle battery warranty performance reports. Year after year, the twelve-month warranty data have shown a slight improvement in battery warranty. Detailed examination shows that the reductions are due to improved battery quality and vehicle assembly plant procedure changes. The greater majority of the battery warranty is due, however, to system design inadequacies, most specifically the failure to provide sufficient generation capacity to recharge the battery, or high vehicle inventory residence time.

The battery designer can work feverishly and quite successfully to improve cycle-life and energy density and charge acceptance, but cannot solve an energy imbalance in the system design. But that is why, with the changes coming in system design, battery designers, in their own self interest and in their customer's, need to be an integral part of the system design process; because it represents an opportunity to break out of the old ways of doing things to create more effective and reliable electrical power system designs.

Specific battery requirements of the future will be determined by power system design. Anticipated needs (Table 3) are dependent on the three basic functions of the battery(ies) in the system:

(i) cranking and starting, plus required accessories;
(ii) load levelling, providing power when generation is inadequate;
(iii) standby power, in the event of charging system failure.

Cranking and starting. Battery power delivery requirements are determined by the cranking and starting system power needs. No significant change in cranking power requirements is expected in the short run. Long term, it may be possible to reduce cranking power needs significantly by the addition of variable valve timing to the control already available for engine fuel delivery and ignition timing. As indicated earlier, strict emission regulations requiring electrically heated catalytic converters could add a battery supplied power load greater than most existing cranking loads. Cranking system voltage is likely to rise to the 36 to 48 V range in the long term. Continued desire for higher battery power density, i.e., smaller package size, will be seen.

Load levelling. The battery performs a significant electrical system load-levelling or 'peak-shaving' function to meet power and energy requirements when generation is not sufficient to do so. The future will see electrical accessory loads rise as the level of cost-effective generation capacity rises. A balance will be reached where the total cost to supply electrical power for features will match up to the value of the features to end-users. Part of the equation will include an assessment of the amount of power and energy to be supplied by the battery while maintaining life, weight and cost goals. The battery designer's concerns throughout the future decade are two-fold. First, how many of these proposed electrical devices are actually going to see production, and when? Second, how are the vehicle manufacturers going to

TABLE 3

Future battery requirements

1. Increased power density
2. Increased energy density
3. Higher voltage
4. Increased cycle-life
5. Higher temperature operating capability
6. Improved reliability

modify their electrical power systems to deal with the increased loads; and what will these changes mean in terms of the performance and reliability required from the vehicle battery or batteries? The answers to these questions will in turn require active involvement and detailed application information from battery designers. As the component characteristics are factored into the system design options, specific battery development and design needs and direction will be brought more clearly into focus.

On the system side, higher voltage is likely to be one of the most inexpensive methods of getting additional generation capacity while simultaneously improving generation and distribution energy efficiency. When system power consumption approaches the power levels required for cranking and starting, integral starter/generators will be used [12]. One of the obvious attractions will be the elimination of the cost, weight and volume of one rotating electromechanical device. Another implication is that battery power requirements may be dictated by the load-levelling function as opposed to the starting function.

Generator and battery capacity sizing will be done using a set of criteria developed through load classification, detailed drive-pattern distribution studies and system computer modelling. Classification of the loads can be done in a number of ways, but the method having most utility for battery designers is by power and energy consumption and by duty cycle. The most significant contributors to vehicle electrical power and energy consumption and battery energy input/output are the very high power level, intermittent, and medium-to-high power continuous-use devices. An example of a very high power device might be an electrically heated catalytic converter, with power requirements of 3 to 5 kW for 10 s or more, each time the engine is started, plus a lesser sustained load for as long as the engine exhaust components take to come up to operating temperature. This, of course, is in addition to the normal cranking power requirements of the vehicle. Given the large sensitivity of automotive battery life to depth-of-discharge, this could have a significant impact on battery service life. High power, continuous-use devices would include electrically powered air-conditioning compressors and blower motors, heated windshield, heated side windows and rear windows, as well as auxiliary passenger compartment heat. Some of these might not ordinarily be thought of as continuous, but from a design viewpoint they must be treated as continuous because of specific users' driving habits. Even the intermittent use devices, which have been moving toward electrification for fuel efficiency reasons, consume power when in the standby condition. All this adds to the base electrical load, i.e., the amount of power required to maintain basic vehicle function.

The rise in total electrical power consumption will promote the concept of passive and active electrical load management to achieve maximum feature content for a given power system capacity and vehicle fuel economy target, i.e., engine power consumption for electrical power generation and total vehicle electrical power system weight.

The long-term increase in system power level combined with use of the battery in a load-levelling function increases the need to achieve conflicting battery design objectives of maximizing energy density, power density and cycle-life. Although system designers would like to design systems with zero net battery discharge at idle, system economics and the desire for electrically powered features will make it unlikely and battery cycling will occur. Cycle-life breakthroughs would certainly be welcomed by system designers to allow use of more battery power. In the case of a simple system design, however, the severity of short-term cycling is limited by the need to maintain an operational state-of-charge level in the long term under adverse drive patterns. Charge management strategies designed to maximize fuel economy would have a much greater use for enhanced cycle-life. The frequency and depth of excursions into the negative charge regime will be controlled by the amount of excess generation capacity available and the opportunity charging strategies employed. Ultimately, the price OEMs will be willing to pay for cycle-life improvements is limited unless they perceive a customer feature with identifiable value such as greatly improved fuel economy or a battery that will last the life of the car.

Standby power. As base electrical loads increase, the amount of power required to maintain vehicle function upon alternator failure will increase proportionately. Since battery size and weight will be minimized to maximize vehicle interior volume and fuel economy, the likely outcome is a reduction in time available to the vehicle operator to drive to a service location. The counterpoint is that increased system reliability and system prognostics (failure prediction as opposed to after the fact diagnosis) will decrease the importance of the standby power function for the battery. This could mean capacity, size and weight reduction for the battery if the load-levelling function can be met with lower capacity batteries, or a second battery.

Responding to the challenge

Battery designers face a very challenging decade in the 1990s. Many different goals are achievable through different system and battery design approaches. Those most likely to be implemented will depend upon the vehicle market segment. Different segments will value different features. The latter might range from reliability (i.e., the long life, maintenance-free car) to performance to luxury to economy. And each may require different characteristics from the battery and all will certainly require a close working relationship with the vehicle system designer to define the right product for the right application.

Most segments of the vehicle market will require the energy efficiency improvement available from higher electrical system voltage. The battery designer's challenge will be to develop higher voltage batteries having higher power and energy density than today's 12-V units.

The issue, which will not change appreciably over the next ten years, is the need for greater reliability — whether the system operates at 12, 24, 36 or 48 V. Reliability improvements will be required to reduce product defects from parts per hundred or thousand to parts per million. Reliability in its broader definition will also have to be improved. Battery cycling performance (i.e., life) will have to be improved and life expectancy at elevated operating temperature will also have to increase.

In addition to developing new product designs and processes, this will require battery manufacturers to apply resources to generate application information and battery response to the application characteristics that were never before required of them. Automobile manufacturers will have to understand that not every battery company can provide what is needed under this changed design environment. Those battery companies willing to invest in the generation of this vital information will be successful in the original equipment market, but only if the automobile companies are willing to pay for the technology. If they are not willing and persist in treating batteries as a low-tech commodity, they will not receive the quality information that is necessary in order to respond to the market desires for end-user features in a rational, cost-effective, energy efficient manner.

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