The Ohio State University College of Engineering

SMART@CAR

Project report

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EXECUTIVE SUMMARY

Nearly 10 years ago, the Center for Automotive Research (CAR) at The Ohio State University launched the Sustainable Mobility – Advanced Research Team (SMART@CAR) consortium to provide a comprehensive research and development program focused on plug-in hybrid electric vehicles (PEVs), electric vehicles and intelligent charging. It was a multi-industry and multi-academic collaborative research program emphasizing the development of pre-competitive understanding of the impacts of plug-in electric vehicles.

SMART@CAR offered utility companies and smart charging equipment suppliers an opportunity to work with members of the CAR Automotive Consortium to explore aspects of the impact of electric and hybrid-electric vehicles to their industries. Member organizations participated collaboratively in setting the research agenda and project direction. They had direct access to all research developments as results were achieved.

Research projects provided valuable industry and economic insights for generators of power, distributors of power, and automotive interests as the PEV industry moved from pre-competitive exploration 10 years ago to an integral part of vehicle fleets driven by government agencies, private industry and consumers today.

SMART@CAR research projects utilized data collection, data analysis, simulation, modeling and optimization, and experimentation. Projects studied problems related to the development, manufacturing, deployment, and application of PEVs.

Research projects were focused on four main areas:

- PEV (virtual) fleet study projects
- Multiple PEV charging
- PEV battery second use
- PEV technology adoption and vehicle-grid interaction modeling

BACKGROUND

For more than 25 years, the interdisciplinary Center for Automotive Research (CAR) at The Ohio State University College of Engineering has advanced progress and technology in the automotive industry through collaborative research programs. Led by Director Giorgio Rizzoni, PhD, Ford Motor Chair in Electromechanical Systems and professor in the Departments of Mechanical and Aerospace Engineering, and Electrical and Computer Engineering, CAR research projects explore the technological aspects of mobility, from energy efficiency and environmental impact to vehicle intelligence, autonomy and safety.

Throughout CAR's history, organizations with an interest in automotive research have been invited to participate in collaborative research through the CAR Automotive Interests Consortium. Private automotive industry members and government partners have the power to engage CAR scientists in original highly-leveraged precompetitive research in automotive and transportation systems. Members have exclusive access to the results of the projects.

In support of these and other research programs, CAR offers laboratory facilities, including an electronics lab and machine shop. Currently, programs are focused on advanced propulsion systems, fuel economy, vehicle safety, connectivity and autonomy, and advanced driver assistance systems.

In addition to its technological advancements, CAR strives to position mobility within social and behavioral contexts. As a result, the center's automotive engineers have formed relationships with Ohio State faculty and researchers that specialize in city and regional planning, health sciences, transportation systems, geography, business and public policy. In addition, research projects lead to new knowledge that enable scholarly achievements for faculty, staff and students at Ohio State through publications in peer-reviewed journals and presentations at national and international conferences.

An industry advisory committee to CAR provides insight into coming industry disruptions. These insights enable CAR to plan for research that explores future-looking issues that will need to be addressed. These insights and programs keep CAR and its partners at the forefront of providing industry solutions and economic value to members of the consortium and contribute to industry advancements.

In 2008, the Center for Automotive Research (CAR) launched a new consortium to provide research for the automotive and electric utility companies that were exploring Plug-in Electric Vehicles (PEVs) and their impact on the power grid: the Sustainable Mobility – Advanced Research Team, or SMART@CAR consortium

While CAR traditionally had been focused on optimizing the engineering inside vehicles, the SMART@CAR program focused on what happened outside the vehicle. From 2008 through 2014 research groups, which included Ohio State faculty, research specialists, graduate students and undergraduate students, studied the impacts of electric and hybrid-electric vehicles on the electricity distribution network.

SMART@CAR consortium members and affiliated partners included: American Electric Power (AEP), Dayton Power & Light (DP&L), Duke Energy, Electric Transportation Engineering Corporation (ETEC), First Energy, Juice Technologies, LLC/Plugsmart, Buckeye Power, Inc., BottomLine Resource Technologies, LLC, CleanFulesOhio, Renault, PJM, TE Connectivity, Recharge Power, Inc., and Vanner, Inc.

The CAR automotive industry research consortium includes: Caterpillar, Eaton, Ford Motor Company, General Motors, Hitachi, Oshkosh Corporation, Honda America, and the Transportation Research Center, Inc. (TRC).

In addition to Rizzoni, SMART@CAR faculty personnel included:
Yann Guezennec, Department of Mechanical Engineering and Aerospace
Ramteen Sioshansi, Department of Integrated Systems Engineering (energy policy, renewable energy, power systems economics, optimization, decision science, game theory)
J. Wang, Department of Electrical and Computer Engineering (electric power systems, power electronics)
M. Roberts, AEDE, (risk management, validity and value of technical analysis

Ümit Özgüner, Department of Electrical and Computer Engineering (control of large scale systems)

Research personnel included:
Vincenzo Marano, program manager and research associate
S. Potter, senior evergy advisory, Ohio State Institute of Energy and the Environment
J. Neal, research engineer (battery aging lab)
J. Shively, electronic technician,
Numerous graduate student researchers

SMART@CAR RESEARCH PROJECT AREAS

Understanding societal impact and viability of PEVs required studying the technologies of these vehicles, the predicted interaction of the users (drivers) of these vehicles, and impacts across all relevant industries including vehicle manufacturers, battery makers and finally the power grid from distribution networks to potential charging locations. The research projects studied during SMART@CAR centered on one or more of those interactions. The interconnected nature of the industries often resulted in shared data collection and analysis from one project that would inform other studies. Several of the program categories changed focus as questions were answered and new issues and questions came to light.

At the end of the program, research projects were focused primarily on four main areas:

- PEV (virtual) fleet study and impact on the distribution network, which looked at the impact of market penetration on the electric transmission and distribution grids
- Electricity distribution issues, including transformer size and aging
- Battery aging for grid storage (PEV battery second use), which examined implications for secondary market use
- PEV technology adoption and vehicle-grid interaction modeling, which included optimal public charging station locations

PEV VIRTUAL FLEET STUDY

Driving patterns, charging patterns and PEV impact at distribution level

In order to predict driving patterns that would occur as PEVs gained market penetration, a study was conducted using a limited number of cars owned and used by employees of a local electric utility. They provided data from their actual commutes. The data collection process leveraged both time-based and event-based charging statistics collected from their employer and Blink meters at charging stations installed at employees' houses, around their work facilities, and in some shopping centers in the Columbus area. All the vehicles were identified when they accessed a charging station, which allowed actual driving and charging behavior data to be collected from the participants.

A virtual fleet of vehicles was developed to exploit the data through the use of Monte Carlo simulations considering different scenarios in both business and residential sectors. One of the key points of the simulation was the velocity generation model. This sub-model generated stochastic velocity profiles, simulating real driving situations with different driving patterns and estimated the energy usage of vehicles in each scenario.

Project leaders utilized university expertise applied to the questions of use and access. For example, the Department of Integrated Systems Engineering research group uses mathematical modeling tools to make systems better. One of their projects studied the patterns of consumer purchase of hybrid electric vehicles across the state of Ohio by Census tract.

Since the hybrid electric vehicle market was more mature than the plug-in electric vehicle market, the group could utilize demographic and socioeconomic data of hybrid electric vehicle adoption. They studied hybrid electric vehicle adoption across the state of Ohio at a fairly aggregated level – the level of census tracts, or about 5,000 to 6,000 people.

Ultimately, they developed a model for establishing public charging locations. Based on registration data of the electric vehicles in Ohio, they examined driving patterns and driving behavior. They considered range anxiety for a driver using an electric vehicle. They looked at usability patterns and the user experience, including departure and destination times. They also considered the micro- and macro implications of charging a vehicle at a public charging location. While fast chargers continue to advance, a 15 to 20 minute time commitment is not insignificant to the average busy person.

They considered various locations, like a coffee shop or even a big box retailer that might be interested in providing this convenience for their customers. They also considered the optimal number of stations that could benefit the largest number of vehicle owners using them, and the maximum amount of energy recharged into the battery.

With all of this data – owners, average driving distances, charging times, and potential locations – they developed an optimization mathematical model to determine the optimal locations for charging stations.

PEV Impact at Distribution-Level

Consortium members believed that unregulated PEV (Plug-in Electric Vehicle) charging would have great impact on the existing power grid system and especially on the distribution transformer system. For this reason, a home charging case study was considered to describe the impact of PEV charging on the loss of life of a residential distribution transformer. This required the development of both an improved transformer loss-of-life model and a smart charging strategy.

The transformer thermal model developed was calibrated and validated by means of a testing program performed on an off-the-shelf distribution transformer. The novelty of this experimental approach consisted of measuring the oil temperature while simulating the high voltage AC environment with a low voltage DC current. This technique allowed measuring the temperature through thermocouples.

The objective of the proposed PEV smart charging control strategy is to minimize the residential distribution transformer's loss of life by using the transformer thermal model. Aging distribution transformers must be considered when evaluating smart charging of PEVs. Since the relationship between winding insulation temperature and transformer loss of life is exponential, measuring the winding hot-spot temperature as precisely as possible is critical. So a transformer aging model was integrated with a dynamic thermal model in order to predict the transformer hot-spot temperature.

The proposed smart charging control strategy leverages the prediction of residential base loads. An autoregressive moving-average model trained with ambient temperature and prior load data was used to predict the future base load. The optimization objective is pursued by means of a tradeoff between the minimization of the transformer loss of life and the maximization of the charging service quality. The service quality is based on customer satisfaction with respect to the requested level of the final State Of Charge (SOC). The smart charging strategy can be essentially described as a two-step process: first, the total charging loads requested by all the PEV's are collected, and then the optimal charging patterns are distributed to every PEV. The smart strategy was first tested through simulations and finally was validated in a case study of a distribution transformer that was servicing six households in a neighborhood. The case study used Hardware-In-the-Loop experiments in which an environmental chamber was employed to reproduce climate changes.

MULTIPLE PEV CHARGING

One of the research projects developed and conducted by CAR Associate Fellow Shawn Midlam-Mohler's research group looked at the effect of plug-in hybrids on local distribution networks. The group took both a high-level view while gathering data at the neighborhood and even individual home level. They eventually constructed a mathematical model for electricity usage that included climate data and other variables, and then were able to simulate multiple vehicles.

Midlam-Mohler, associate professor of Practice, Mechanical & Aerospace Engineering explained that the model allowed the group to answer many hypothetical questions about transformer overload and wear. They learned that application of the smart grid can lead to acceptable charging times to provide consumers with their anticipated level of service, while at the same time maintaining an acceptable transformer life, even given the current way electricity distribution companies size transformers.

They also demonstrated that poor charging leads to reduced transformer life contrasted with smart charging, which leads to acceptable transformer life. Power companies planning to build infrastructure in new neighborhoods, or replacing transformers in established neighborhoods, can use the model to include planning for PHEV and EVs.

This project led to additional scientific applications as well. Other CAR research groups have been able to apply the mathematical transformer model for projects in related fields: fuses and plugs and hybrid vehicle design.

PEV BATTERY AGING AND SECOND USE

Giorgio Rizzoni explained that one area of discussion at regular consortium meetings became a focus of research during the program: Battery life.

Power companies wondered about borrowing power from car batteries during high peak time. Aging experiments were critical in demonstrating that batteries will age more rapidly if they are charging and discharging regularly, so utility companies were dissuaded from using batteries as a means of grid storage while the battery is in service in a vehicle. SMART@CAR projects included testing batteries from cell to module level, as well as battery aging and management, in order to develop control strategies on performance, fuel economy, range and battery life.

Aging Campaign Design

The Aging Campaign project assessed the value of the secondary usage of automotive Li-ion batteries in grid storage applications such as Community Energy Storage (CES) units. When the project began, literature related to secondary usage was limited primarily to research projects on secondary usage conducted by national laboratories such as Argonne National Laboratory (ANL), Sandia National Laboratories (SNL), National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Oak Ridge National Laboratory (ORNL). The studies are difficult to conduct because both CES and Li-ion battery technologies are still new, and few batteries have reached the end of their automotive lives. Thanks to the CAR Industrial Consortium, the project was able to leverage results from previous studies of Li-ion battery aging over multiple years in automotive applications. The extensive equipment and personnel capabilities of the Energy Storage System Laboratory at CAR then utilized Li-ion cells which have aged under automotive usage scenarios up to their effective end of life, which is characterized by a decrease of capacity and/or power capability of 20 percent. The aging characteristics of the batteries were evaluated during secondary usage in CES applications. The CES data obtained by participating utility members depended on the experimental procedure and aging protocols considered to be representative of usage patterns in CES applications. The CES data were analyzed to define electrical and thermal secondary aging cycles.

Aging Experiments

The project devoted two battery cyclers functioning 24 hours per day, seven days per week to gather data on aging. An aging campaign typically consisted of sustained (accelerated) aging periods for several weeks, interspersed by periodic (one simulated month) evaluation periods to monitor the battery degradation. Depending on accelerated aging factors, the tested batteries either reached practical end of life in this secondary usage (criteria to be defined by members) or project the estimated remaining life based on the measured rate of degradation.

1. **Battery Characterization:** an initial assessment and HPPC test (hybrid pulse power capacity) at various SOCs (20% to 90%) and temperatures (-10°C to 50°C).

2. **Development of an Aging Profile:** an aging profile was engineered (current sequences of discharges and charges) based both on real data (when available) and results from other SMART@CAR projects. The effects of temperature fluctuations (on

battery capacity, and charging/discharging efficiency) were taken into account starting from public weather data. One value of average temperature is considered for each week (52 values for 1 year).

3. Aging Tests: based on the aging profiles presented in point **2**, two different channels were used for aging assessment.

- *Channel 1*: one battery was exercised at a current profile that was 3 times× the current profile defined in **2:** every 56 hours the temperature of the testing equipment is updated, thus representing one week of real world data at the given temperature.
- *Channel 2*: one battery was exercised at a current profile that is 5 times the current profile defined in **2:** every 26 hours the temperature of the testing equipment is updated, thus representing one week of real world data at the given temperature.

In this way, testing time can be reduced by three and five times, respectively (ca. 120 and 73 days to analyze a 1-year period).

4. Periodic Aging Assessment: experiments were periodically interrupted in order to assess battery characteristics.

- *Channel 1* [3×]: every 10 days (representing one month of real world data) the aging tests were interrupted and a capacity, pulse test was performed.
- *Channel 2* [5×]: every six days (representing one month of real world data) the aging tests are interrupted and a capacity, pulse test is performed.

Depending on factors for accelerating aging factors, the test batteries either reach practical end of life in this secondary usage or we extrapolate the estimated remaining life based on measure rate of degradation. During all tests, current, voltage, and temperature data were constantly measured and archived.

PEV TECHNOLOGY ADOPTION AND VEHICLE-GRID INTERACTION MODELING

Impact of PEV Charging on Grid (Economics and Emissions)

Refined simulation cases were conducted to examine the impact of secondary uses of electric vehicle batteries on the distribution system. The refined battery model fixed some weaknesses in the previous experimental models, such as the assumption of the PJM regulation market, and transformer-aging cost was quantified so that secondary uses wouldn't cause unexpected transformer failures. Also, various combinations of battery and transformer sizes were tested to find the optimal combination that maximized secondary use benefits.

Economic Value of PEV Batteries (Second Life) for Grid Applications

PEV batteries will generally deteriorate due to age and usage. This deterioration will result in a reduction in the amount of energy that the battery can store. Current design proposals call for PEV batteries to be used for driving purposes until the energy storage capacity has fallen below 80 percent of the rated capacity of the battery, at which point the battery will be removed from the vehicle. Although batteries that have deteriorated to this point are unusable in PEVs, they can have secondary uses as power system energy storage devices. Energy storage can provide a number of valuable services, among which are: energy arbitrage, ancillary and capacity services, deferral of transmission and distribution investments, and distribution-level islanding.

Models were developed for this project to optimize the usage of discarded PEV batteries as energy storage devices and to evaluate these secondary uses. The optimization of PEV battery use is inherently complex, because of their multiple potential uses and because of the effect of battery usage on future battery cycling capabilities. For example, using the battery for energy arbitrage purposes will require the battery to discharge when energy is resold to the grid. As such, the battery cannot provide reserve energy at the distribution level in case of a system service interruption until the battery is recharged. Similarly, if the battery is scheduled to provide ancillary services and energy sales, the battery may not be able to feasibly deliver its energy sales if the ancillary services are deployed in real-time. Thus, the optimization framework must account for the likelihood of these contingencies, and the associated cost.

An additional source of complexity stemmed from the cycle-life of the battery. Because cycling energy through the battery will cause battery deterioration, there is an opportunity cost associated with using the battery for energy storage purposes that must be accounted for. The optimization model will be formulated to trade off the costs associated with different battery uses (e.g. energy arbitrage will necessarily incur a cycling cost, but ancillary services will only incur a cycling cost if the capacity is deployed in real-time). The models focused on a small distribution-level storage device.

Optimal EVSE Location

This subtask was designed to identify future location demand for electric charging infrastructure in metropolitan areas and to understand the relation between PEV penetration levels and the impact on planning charging station locations and electrical distribution. A general model that optimizes the PEV charging station locations was developed, and simulations were run to examine the impact of budget and PEV penetration on the selection of station locations.

Technology Adoption Models

Demographic data was utilized to understand the patterns in PHEV and EV purchases and identify future target areas for an increase in consumer purchases, including the extent to which early adopters influenced an increase in area purchases, i.e. to what extent PHEV adoption is clustered. Using registration data from the Ohio Bureau of Motor Vehicles, vehicle purchases and dates of purchase were indexed by census block. The aggregate demographic data collected by the US Census Bureau and available at the census block level is used to estimate a model of the probability of purchase based on income, age, and other potentially influencing characteristics.

Previous purchases of vehicles by consumers in the same or adjoining blocks was considered an important characteristic because they indicate future purchases made by neighbors. This clustering is particularly important in understanding the potential effect of PHEV vehicle purchases on the local power delivery infrastructure. Because PHEV availability and purchase numbers were small at the time, the study investigated the purchases of HEVs such as the Toyota Prius and Honda Insight, and Volkswagens with turbo diesel drivetrains. The HEVs were chosen because their purchasers were demographically comparable to PHEVs purchasers, and there were a significant number available. Volkswagen turbo diesel vehicles were analyzed because they appeal to both fuel-cost conscious consumers and they are more limited in their refueling options. Data on retail fueling locations was used as an additional predictor of the purchase of the Volkswagen TDI models.

CONCLUSION

The Center for Automotive Research provides members of the CAR Automotive Consortium unique pre-competitive research that offers the automotive industry and related businesses the opportunity to thoroughly and economically prepare for future disruptions.

Nearly 10 years ago, CAR launched the Sustainable Mobility – Advanced Research Team (SMART@CAR) Consortium to provide utility companies and smart charging equipment suppliers an opportunity to work with members of the CAR Automotive Consortium to explore a multi-industry and multi-academic collaborative research program emphasizing the development of pre-competitive understanding of the impacts of plug-in electric and hybrid-electric vehicles to their industries.

Member organizations set the research agenda and project direction and enjoyed exclusive access to all results. From secondary battery use to the market penetration of plug-in electric vehicles focused on consumer behavior and expectations, SMART@CAR members acquired proprietary information to prepare their industry for a changing automotive landscape. Their strategic plans were directly informed by these studies, enabling them to better plan for projects like neighborhood transformer placement and potential upgrades, new housing developments, placement of consumer charging stations, and the future development of smart charging capabilities.

The SMART@CAR research program provided valuable industry and economic insights for generators of power, distributors of power, and automotive interests as the PEV industry moved from pre-competitive exploration 10 years ago to an integral part of vehicle fleets driven by government agencies, private industry and consumers today.

Comprehensive research universities like Ohio State innovate through interdisciplinary and systematic investigation that leads to a deeper understanding of challenges and solutions for society and the world. Industry and academic partnerships like SMART@CAR lead to new technologies and economic advancement, simultaneously advancing scholarly achievement and training the next generation of engineers and researchers.

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