THE NASCENT INDUSTRY OF ELECTRIC VEHICLES

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An electric vehicle (EV) is a vehicle that operates solely using electricity and can plug into the power grid to recharge. This connectivity with the grid poses a unique set of challenges, as the new EV charging infrastructure must be compatible with the existing power infrastructure and the grid must be able to support the growing fleet of EVs. Of particular interest to operations researchers are an assortment of pricing and planning problems, many of which are still ill defined due to the youth of today's EV industry and the uncertainties that accompany it. In this chapter, the needs of the growing EV industry are addressed, and some of the key issues that will be faced over the next several years are identified.

Key words: electric vehicles; charging infrastructure; charging stations; vehicle-to-grid; smart grid; battery swapping

INTRODUCTION

Although electric vehicle (EV) technology has existed since the mid-1800s, gasoline-powered automobiles with internal combustion have largely overshadowed EVs because of their lower costs, higher speeds, and greater driving ranges. Consequently, public interest in EVs has remained low until recently, when the 2000s energy crisis and subsequent recession sparked consumer demand for sustainable transportation. This heightened interest is not transient. As automakers race to bring mass-produced consumer EVs to market and policy makers provide incentives for both the producers and end users of these vehicles, the public's attitude towards sustainable transportation will be solidified as EV adoption rates increase.

To facilitate adoption of EVs, public and private sector organizations are teaming up to provide charging infrastructure at both the local and national levels. In addition to the United States, other places such as Canada, Australia, the European Union, Israel, China, and Japan have begun laying the groundwork for new EV fleets [1]. The teams responsible for such infrastructure seek to maximize the convenience of owning and operating an EV, and through collaboration with power utility companies, they can ensure the reliability and energy efficiency of their systems.

The time is ripe to begin planning for the rollout of EVs and their supporting infrastructure, and research opportunities abound for those versed in analytics and operations research. In this chapter, the features of EVs which distinguish them from the ubiquitous gasoline-powered vehicles are outlined, and the various types of charging infrastructure are described. A series of open issues to be addressed by operations researchers is also presented to demonstrate the vast potential for new research and to map out future paths of study.

WHAT IS AN EV?

An EV is a vehicle that operates solely using electricity. It has an electric motor and stores energy in an internal battery, which can be recharged by plugging the vehicle into an outlet or charger. Because EVs do not use any gasoline, they are also known as zero-emission vehicles since they do not produce tailpipe emissions. Indirectly, though, they are still responsible for a share of the greenhouse gases emitted by the coal-burning generators which produce the electricity for their operation, but the net carbon footprint of an EV is only about 40% of that of a comparable gasoline-powered vehicle [2].

One major concern with EVs is their limited driving range as compared with regular gasoline-powered vehicles. This factor increases the likelihood of depleting the battery completely while on the road, and because recharging can take several hours at standard voltages, the inconvenience to a stranded driver is significant. For this reason, some drivers prefer the concept of a plug-in hybrid EV (PHEV). PHEVs retain most of the same traits as pure EVs, but they also utilize an internal combustion engine fueled by gasoline. Depending on the make, a PHEV may either maximize overall energy efficiency by reverting to its all-electric mode for city driving and switching to gasoline power for highway driving, or minimize gasoline usage by utilizing the combustion engine only after the battery is depleted.

Hybrid EVs (HEVs), which have gained popularity over the last several years, differ from PHEVs because they have no external outlet and thus cannot draw power from the electrical grid. Instead, their electric power comes from an internal generator driven by the combustion engine, or is restored via regenerative braking, in which kinetic energy from deceleration is recaptured rather than dissipated as heat. While this characteristic does offer improved fuel efficiency over regular vehicles, the efficiency is still less than that provided by PHEVs and pure EVs [3].

INFRASTRUCTURE REQUIREMENTS

The key feature of EVs is their ability to draw power from the electrical grid. In order for them to experience widespread adoption by the public, they must be able to connect to the grid efficiently and effortlessly, and operations research can aid in the development of solutions for accomplishing this goal. The three main types of EV charging infrastructure include at-home charging methods, public charging stations, and battery swapping concepts.

At-Home Charging

Current EV charging takes place almost exclusively in private garages (both residential and commercial), which are expected to continue to be the primary charging location as EVs gain popularity. Therefore, it is important for at-home charging solutions to be as convenient and reliable as possible.

The most common method of charging EVs at home is by conventional (Level I) charging. It involves plugging an EV into a standard 120V wall socket. Charging the battery completely can take approximately eight to fourteen hours [4]. This solution suffices for the majority of EV owners since they can plug in their vehicle at the end of the day, let it charge overnight, and wake up the next morning to a fully charged vehicle. The system also works for the power companies because charging takes place during off-peak hours when demand for electric power is low. For drivers hoping to get the most mileage out of their EVs, however, the long time required for a complete recharge is a serious drawback. Once the battery is fully depleted, the vehicle is effectively out of commission until the following day.

An alternative to Level I charging has been termed "opportunity charging," or Level II charging, which is designed to fully recharge EV batteries in four hours or less [5]. To achieve the faster charging time, the outlet voltage is increased to around 240V. Level II charging is intended to extend the daily mileage of EVs by allowing a greater number of excursions per day, since drivers can plug in their vehicles during meals or other downtime and make another trip only hours later. Given that very few drivers return home with a fully depleted battery, the actual time necessary to recharge can be much less than four hours if the battery still carries a partial charge. This also extends the length of outings occurring later in the day because drivers do not have to worry about limiting their range due to a partially depleted battery.

Several different pricing models for the electric power used to fuel EVs have been considered. Current EV owners who charge their vehicles at home pay for electric power in the same way that they do for power used by other appliances. A feasible alternative would be to meter electricity used by EVs separately, either within at-home charging units or on-board the vehicles themselves, and charge a different rate for EV electricity usage. Some studies have examined the effects of imposing a per-mile tax on gasoline-powered vehicles as opposed to a per-gallon tax ([6], [7]), and a similar pricing mechanism could be considered for EVs.

Dynamic pricing schemes may be necessary to attenuate peak loading on the electrical grid. Some research has already been done to study the impact of EV charging on the grid ([8], [9], [10]), and consideration of time of use pricing, critical peak pricing, and nodal pricing will help the utility companies to optimize loading on their systems. Empirical research on managing EV charging behavior will become important as EV adoption rates rise and more data becomes available.

Public Charging

Despite the importance of at-home charging, the ability to recharge EVs while away from home will be critical to their success. PHEVs will still be able to utilize the existing network of gasoline stations in case their batteries become depleted while on the road, but pure EVs will need to be able to access the grid wherever they are. This will allow EV drivers to commute both short and long distances without needing to own a spare, gasoline-powered (or hybrid) vehicle.

So far, only a handful of charging stations in the United States have been installed and made accessible to the public, and their primary purpose is to generate publicity, spread awareness, and encourage the use of EVs. They are all centrally located at sites such as community centers and major-chain supermarkets, but the eventual goal is to have one charging station per parking spot rather than one station per site. As the rate of EV ownership increases, multiple drivers will want to plug in and charge their vehicles at the same time. One way to accomplish this is by outfitting parking lots and garages with sufficient charging infrastructure so that drivers can plug into the grid wherever they park.

It is expected that most drivers who plug in away from home will be working, shopping, or participating in some other activity that will last only a few hours. Therefore, Level II charging capability will likely be the standard for public charging stations. For drivers in need of a more expedited recharge, however, Level II charging may be insufficient. Level III charging, which requires less than ten minutes for a full recharge (approximately the same amount of time necessary to fill a tank with gasoline) [11], is instead seen as a viable solution for when time is of the essence. It remains to be seen whether Level II or Level III charging will be most popular among EV drivers, but it seems certain that a mix of the two will persist since both types have their advantages (Type III is faster, but Type II requires lower voltages and less specialized hardware).

An open area of research for operations researchers is the pricing of charging services. Previous studies on gasoline station pricing serve as a starting point ([12], [13]), but the fact that electricity is a utility poses new challenges. Currently, EV drivers must first purchase a membership in order to utilize a company's public charging stations, and then they are required to purchase a subscription plan. Subscribers can pay as they go (i.e., pay a flat fee each time they recharge), purchase a monthly or annual quota, or buy an unlimited plan that allows them to recharge as frequently as they wish. In each case, the number of recharges is measured by the number of times an EV is plugged in and unplugged. An alternative to consider would be metered charging, where rates are determined by the amount of power used rather than the total number of recharges. This option would be more attractive to drivers who do not deplete their batteries before recharging and require only a partial recharge.

To better understand pricing models of EVs and charging stations, demand modeling is necessary. A consumer's decision to purchase an EV depends heavily on the cost and convenience of recharging. If recharging is expensive or if charging stations are inconveniently located, a highly priced EV will be difficult to sell. Or, if a driver has already purchased an EV, the cost and convenience of recharging could influence his or her driving behavior. There may also be a bandwagon effect, where consumers will purchase an EV because they observe that their friends and neighbors already own one, as well as peer pressure from those who are especially concerned about the environment. Knowing how all of these factors influence individuals' attitudes towards EVs and, ultimately, their decision to purchase (or not to purchase) an EV will be instrumental in determining the optimal pricing of EVs and charging stations.

Discrete choice modeling, a popular and widely accepted technique in transportation demand modeling, is a natural fit to model the demand for EVs. It has already been used in several studies examining the demand for EVs ([14], [15], [16]), but further research using more recent data will be required as the public becomes more informed about EVs. Predictive models that capture trends in the demand for EVs will also be necessary to fully understand the EV market.

Battery Swapping Stations

An alternative to Level III charging stations is battery swapping stations. Rather than recharging the battery, an EV driver can simply swap out a depleted battery for a fully charged one. The process is not only slightly faster than recharging, but it is also fully automated. It has already been successfully tested in Japan, and takes less than one minute from beginning to end [17].

Unlike charging stations, which have minimal spatial requirements and can be installed in home garages or parking spaces, battery swapping stations are comparable to gasoline stations and thus need dedicated plots of land. The capital costs of acquiring the land, constructing a facility, and maintaining an inventory of batteries are much greater than the cost of installing a charging station, so the swapping stations will be less prevalent than charging stations, especially during the early phases of EV adoption. Before battery swapping stations are made available to the public, their primary users will be companies that operate large EV fleets, such as taxi, shuttle, and delivery services.

Battery swapping has a number of issues that have yet to be resolved. In order to ensure that a driver is able to swap batteries, there must be a sufficient number of charged batteries in inventory. Because of the spatial requirements needed for storing EV batteries, it is neither practical nor cost effective to carry a large surplus. On the other hand, it would be unacceptable for a driver to be unable to swap for a fully charged battery. The number of chargers at the station for recharging the depleted batteries would also need to be kept to a reasonable level to satisfy service requirements without incurring excessive cost. Also, since batteries have a limited lifetime (measured in charging cycles), a swapping station would need to manage its inventory by recycling or discarding worn out batteries and replacing them with newer ones. This task is complicated by the fact that the station has little control over the incoming stock of depleted batteries. Some sort of safeguard would need to be established to protect the station from handling too many incoming batteries that have reached the end of their lifetime.

If a swap station decides to recycle its used batteries, it faces the decision of when to withdraw those batteries from its inventory. A used battery has salvage value because it can still store electric charge, enough for some applications beyond EVs, although this value decreases with the age of the battery. Similarly, the swap station may choose to purchase used batteries to replace the stock it recycles, especially since these batteries will eventually be swapped out with incoming ones. Determining the appropriate purchasing price of a used battery is yet another optimization problem to solve.

Since a proof-of-concept of battery swapping for EVs was only recently demonstrated, the literature is barren with regard to optimal swapping station management. A team from Japan has used queueing systems to analyze the operation of a single swapping station [18], but their model relies on simplistic assumptions (such as Poisson arrival and processing times) and does not take into account the presence of other battery swapping stations. Further research utilizing more sophisticated modeling techniques with more realistic assumptions is warranted.

Smart Grid Applications

The future of the EV infrastructure will be greatly enhanced by the development of the smart grid for delivering electric power to consumers. Presently, most power distribution systems provide electric power to customers without any controls to curtail wasteful usage or to reallocate unnecessary peak-hour consumption to off-peak hours. (A few systems and utilities do employ real-time controls and time of use pricing ([19], [20], [21]), but these efforts are still in their infancy.) By incorporating such controls into their systems, power utility companies can better match supply and demand, thereby reducing costs, conserving energy, and improving reliability. The ability to optimize distribution in real time is especially important when utilizing renewable energy sources, such as wind and solar, which are intermittent.

EV charging would directly benefit from the presence of the smart grid. For drivers who charge their EVs overnight, the smart grid would ensure that the cost of recharging would be minimized by delaying charging until off-peak hours. Collecting data on a driver's driving activity and patterns would permit an even greater degree of charging optimization, especially for Level II charging, which is more likely to occur during peak hours. For example, if a driver's daily commuting distance is 30 miles and the EV's battery has enough charge left for 20 miles, the smart grid might decide to only recharge a portion of the battery – enough for the driver to return home, plus a buffer – and then complete the remainder of the recharge later during off-peak hours. There could always be manual overrides, of course, if the driver plans to deviate from his or her normal activities, but intelligent recharging would benefit both the power company and the customer.

As much as the smart grid could optimize energy distribution, the addition of vehicle-to-grid (V2G) technology would improve the efficiency of the grid even more. With V2G, not only can the grid provide power to EVs and other electrical appliances, but the EVs can also provide power back to the grid. Some papers have considered the potential benefits of V2G ([22], [23], [24]), but further analysis will be required once data becomes available. EV batteries can serve as spare energy resources during peak hours, when demand for electric power is greatest, and later draw power back from the grid during off-peak hours. Normally, during peak hours, the power companies must operate additional generators to satisfy demand, and these generators are much more expensive than the primary baseload generators. Utilizing a network of EV batteries plugged into the grid would provide a greener and more efficient alternative to satisfying customers' power needs.

To encourage EV owners to plug in their vehicles and discharge power back to the grid, monetary incentives could be offered based on the amount of power discharged. The net difference between the incentive for discharging power during peak hours and recharging during off-peak hours would translate directly into a rebate for the EV driver, and over time, this rebate would help to offset the initial investment into the EV itself. V2G would operate in conjunction with the smart grid to ensure that the amount of power discharged during the day does not inconvenience a driver by prohibiting additional travel, and manual thresholds could be established based on the driver's personal preferences.

In order for V2G to be truly effective, the grid must know to what extent it can draw power from an EV. If it drains an EV's battery completely, and the EV is parked at its owner's workplace, then the owner cannot return home and likely will not discharge power to the grid again. However, if the owner needs to commute five miles to return home and the grid leaves the battery with twenty miles of charge, both parties benefit. The same considerations hold for charging EV batteries as well. Consider the previous example, except the battery is completely discharged and the owner plugs it in to recharge. If the owner only needs enough charge for a five-mile commute, it would not make sense to fully charge the battery, especially during peak hours when the cost of power is greatest. Instead, the grid should only recharge enough for the commute, plus a buffer (e.g., an additional ten miles of charge).

OTHER OPEN ISSUES

Because EVs have only recently experienced a resurgence in popularity, there are still a number of open issues that have either been insufficiently addressed or overlooked completely, hence plenty of opportunities for academic research to facilitate the transition to EVs and sustainable transportation. Many of these issues, including those introduced in earlier sections, involve topics which fall in the realms of operations research, management science, and analytics. Advances in EV design and battery technologies have led to several automakers announcing plans to market EV and PHEV models, but a lack of supporting infrastructure and business models threatens to delay the EV transition.

Much of the existing literature on EVs has dealt with great amounts of uncertainty regarding the technological requirements and capabilities of EV infrastructure. The lack of data on driving behavior with respect to EVs further hampers the ability to draw conclusions and ultimately provide valid policy recommendations. As these items become better understood, though, more quantitative models can be formed and more detailed and rigorous analyses can be conducted.

In the following sections, some additional examples of potential research areas are presented that are of particular interest to industrial engineers with a focus on analytics. The goal is not to offer an exhaustive list, but rather to demonstrate the breadth of topics in need of further study and underscore some of the interrelations between the topics.

EV Pricing

One of the foremost issues for EVs is the pricing of the vehicles themselves. The price of an EV will need to be low enough to entice buyers to make the investment and switch over to sustainable transportation. Even if EVs are priced higher than comparable gasoline-powered vehicles, as long as the perceived benefits are substantial (e.g., fuel cost savings, convenience, image, etc.), consumers beyond the current niche group of EV owners will purchase EVs. Incentives and rebates from the government could also be given to boost EV sales.

Automakers could also offer non-monetary incentives for early EV adopters. For example, they could provide at-home installation of charging hardware to enable Level II and Level III charging. Another possibility is to offer a program that would allow purchasers to borrow, rent, or share a gasoline-powered vehicle for a limited number of days per calendar year, since driving range will be a concern to new EV buyers. Other creative options could be used to help tailor EVs to better fit the needs of consumers.

Infrastructure Deployment

In order to support a vast fleet of EVs, a robust charging infrastructure needs to be in place. An obvious question is where to install charging stations, but the solution is less apparent. Ideally, the charging stations should be centrally located to maximize coverage. Their placement, however, will partially be dictated by the existing infrastructure and access to the grid. If the cost of expanding the grid or installing a dedicated circuit is prohibitive, charging stations may need to be installed in less desirable spots to satisfy consumer demand.

Charging stations in densely populated areas will serve the daily commuting needs of most EV drivers, but they will not benefit drivers who must travel longer distances. One of the goals of the EV charging infrastructure will be to extend the limited driving range of EVs, which will require the strategic placement of charging stations in less heavily populated yet still highly traveled areas. Drivers who regularly commute long distances might invest in an EV with a greater battery capacity, but for those who need the extra range infrequently (e.g., for family vacations), a second vehicle, likely gasoline powered, would be necessary if the existing charging infrastructure were insufficient. The additional cost and inconvenience of owning a second vehicle would not suit the majority of EV drivers.

The establishment of the charging infrastructure for EVs will not occur overnight. It will, in fact, take years, even decades, to grow and expand. To best understand how the infrastructure will evolve over time, models will need to be developed. Important considerations will include consumer demand and charging behavior, which will influence the rate of expansion as well as the prioritization of range extension and coverage, and also the coexistence of the EV charging infrastructure with the existing gasoline station infrastructure. Knowing how consumers affect and react to changes in the EV charging infrastructure will facilitate planning and decision making for charging station locations.

In determining how to build the charging infrastructure for EVs, it will be necessary to determine the source of funding as well. Many of the existing charging stations were funded by the companies that installed them, such as Better Place and Coulomb Technologies, Inc., and those companies collect a fee when the charging stations are used. Other charging stations, paid for by city councils, are free to use. As EVs increase in popularity, the decisions to install charging stations will become more complex as the number of stakeholders increases. An important question is also how to regulate private charging station providers. They can be considered as utilities or distributors in a deregulated market and thus regulated by the public commissioners, or, as such operators prefer, being exempt from regulations governing utilities since they do not constitute an electric plant.

For example, consider a private business that wants to install charging stations in its parking lot. Some of the stakeholders include the business itself, which benefits by providing convenient charging to its patrons; the patrons, who are able to charge their EVs; the charging station manufacturer, which collects a fee each time one of the charging stations is used; and the EV manufacturers (particularly during the earlier phases of EV adoption), whose EVs gain value from the additional infrastructure. The goal is to fairly distribute the cost of the charging stations among the various stakeholders. Such a problem is complicated even further when public funds, which are collected from taxpayers (who may not all own EVs), are used to provide publicly accessible charging stations. Weighing the benefits to individual citizens as compared with society as a whole is both technically and ethically challenging.

As a prototype investigation into a micro-level deployment strategy of charging stations in Chicagoland, approximately 150 charging stations (Level II and III) were to be deployed (estimated cost of around 2 million US dollars). Several modeling and solution methodology approaches have been considered: set covering, max covering, queuing, and combinations based on simulation and optimization. The covering approaches focus on meeting as much demand as possible, while queuing systems focus on the waiting time of EV drivers to recharge their vehicles. Once a targeted segment of customers (e.g., influential parts of the town living in condominiums with an option to install charging stations in garages for overnight charging) or location strategy (e.g., malls and large stores) is selected, the solutions to the

models identified an optimal deployment strategy. A queuing simulation model is then executed to evaluate the waiting times of the users. If these were unsatisfactory, local adjustments were made to the deployment. The demand was extrapolated based on the adoption curve of Prius, the geographical location, demographic data, and the forecasted fuel prices. A demand estimate is drawn for each year and a single covering model solved with the total budget linking the various years. The figure on the left shows a deployment of Level II and Level III charging stations in the Chicago area. The Level 2 stations are deployed at Dominick's grocery stores (labeled in red), which allow for longer charging time during the shopping time of a driver. The Level 3 stations are deployed at gas stations (blue markers).

Vehicle Telematics

Understanding EV driving patterns will be critical to providing effective charging services. Vehicle telematics provides a means of tracking EV road movements as well as monitoring charging behavior, and communications between the vehicles and the charging infrastructure can direct drivers to the nearest available charging stations. There already exists a software application for mobile devices that allows users to locate nearby charging stations and provides them with more advanced details such as the availability of charging stations and the status of a charging session in progress [25].

As more data becomes available from vehicle telematics systems, researchers will be able to better characterize EV driving patterns and identify opportunities to improve the charging infrastructure. Techniques such as data mining and network analysis will prove useful in uncovering patterns of driving and charging behaviors, which can then be applied to simulation studies to perform experiments and gain even deeper insights into the EV charging networks.

FINAL THOUGHTS

A future of EVs and sustainable transportation is no longer a pipe dream – it is imminent. Automakers have announced plans for mass producing their EV models. Charging station manufacturers have successfully demonstrated their products and installed them for public use. The vehicles and infrastructure are ready to go, but there is still plenty of modeling and planning to do before EVs become a major method of transportation. Together with automakers, charging infrastructure companies, policy makers, and the public at large, researchers in the fields of engineering, operations research, and management sciences can help to make sustainable transportation a reality.

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