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Wireless charging in California: Range, recharge, and vehicle electrification

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ABSTRACT

This research evaluated the potential for wireless dynamic charging (charging while moving) to address range and recharge issues of modern electric vehicles by considering travel to regional destinations in California. A 200-mile electric vehicle with a real range of 160 miles plus 40 miles reserve was assumed to be used by consumers in concert with static and dynamic charging as a strict substitute for gasoline vehicle travel. Different combinations of wireless charging power (20–120 kW) and vehicle range (100–300 miles) were evaluated. One of the results highlighted in the research indicated that travel between popular destinations could be accomplished with a 200-mile EV and a 40 kW dynamic wireless charging system at a cost of about $2.5 billion. System cost for a 200-mile EV could be reduced to less than $1 billion if wireless vehicle charging power levels were increased to 100 kW or greater. For vehicles consuming 138 kWh of dynamic energy per year on a 40 kW dynamic system, the capital cost of $2.5 billion plus yearly energy costs could be recouped over a 20-year period at an average cost to each vehicle owner of $512 per year at a volume of 300,000 vehicles or $168 per year at a volume of 1,000,000 vehicles. Cost comparisons of dynamic charging, increased battery capacity, and gasoline refueling were presented. Dynamic charging, coupled with strategic wayside static charging, was shown to be more cost effective to the consumer over a 10-year period than gasoline refueling at $2.50 or $4.00 per gallon. Notably, even at very low battery prices of $100 per kWh, the research showed that dynamic charging can be a more cost effective approach to extending range than increasing battery capacity.

1. Introduction

Fossil fuel based transportation has revolutionized mobility over the past century, catalyzing modernization while simultaneously creating a public health epidemic that continues to threaten people around the globe. With morbidity and premature mortality directly attributable to air pollution from fossil fuel use, a transition to an electrified transport sector is a vital step in reducing the impact of mobility on public health and welfare. Electricity is an attractive transportation fuel because it can be produced from a wide array of renewable and domestically available energy sources and refueling infrastructure is already widespread due to the existing electricity grid. Although hybrid electric and other low-emitting electric vehicle technologies can be beneficial compared to conventional technologies, the magnitude of reductions required to meet climate goals and eliminate tailpipe air pollutant emissions implores the use of zero-emission electric vehicles powered by renewable energy.

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While adoption of electric vehicles is currently hindered by high initial vehicle cost, reduced range, and extended recharging time requirements, this research considers the case of ubiquitous acceptance of battery electric vehicles (BEVs). Accordingly, commercial success is assumed in this research to be predicated on the technologies' ability to satisfy consumer expectations regarding range and refueling (BEV pricing and potential future reductions are outside the scope of this research) relative to gasoline-fueled internal combustion engine vehicles (ICEVs) if it is to gain widespread consumer adoption. While this might not be the only commercially viable path forward for BEVs, it is reasonable to assume that a BEV that is otherwise indistinguishable in all aspects from an ICEV would enjoy similar levels of consumer acceptance.

According to U.S. Department of Transportation (2004), the average person only drives about 40 miles per day; however, this statistic more heavily reflects commuting distances and is not representative of all driving over a year. A one-day, global positioning system (GPS) study of 227 GPS-instrumented vehicles conducted by Gonder et al. (2007) found that an EV with a range of 100 miles could satisfy about 95% of the travel needs of the surveyed vehicles. While this study suggests that current model EVs can serve most average drivers over a typical day, affordable EVs cannot currently serve 100% of all passenger vehicle travel throughout the year. If we impose a strict substitutability requirement that a passenger electric vehicle must satisfy 100% of all vehicle travel in a given year in order to meet current gasoline vehicle expectations, the limitation of using daily mileage averages or a 24-h period snapshot to gauge consumer acceptance of limited-range EVs becomes quite clear. For example, a detailed, one-year, high resolution study of 484 GPS-instrumented vehicles by Pearre et al. (2011) found that an EV with a range of 100 miles would only strictly satisfy (that is be able to serve all driving of a particular driver throughout the year) 9% of drivers; 21% if the EV had a 150-mile range. For 50% of the sample, 313 miles of range was required to fully substitute for a gasoline vehicle during the year. Results reported by California Fuel Cell Partnership (2007) and by Deloitte (2011) from surveys of consumer expectations of alternative fuel vehicles suggest that the vehicle range expectation is at least 300 miles, generally supporting the findings from the year-long survey. Assuming a 2010 Corporate Average Fuel Economy rating for passenger cars of 27.5 miles per gallon (mpg) and an average fuel tank usage of 15 gallons, a modern mid-size ICEV might be expected to travel over 400 miles without refueling. These studies and estimate highlight the fact that current 100-mile BEVs cannot meet general consumer range expectations of 300–400 miles.

In addition to limited range, BEVs are at a disadvantage with regards to refueling duration and public charging infrastructure availability. Access to gasoline refueling infrastructure is widespread with an estimated 130,000 U.S. gasoline stations in 2007 (U.S. Census Bureau, 2011) and, since gas pumps dispense at a rate of 5–10 gallons per minute, refueling only takes a few minutes (EPA, 1996; Clean Energy Fuels Corp., 2007). Current model BEVs have a range of about 80–100 miles and require tens of minutes to hours to recharge, depending on the power level. Even if a 200-mile (80 kWh battery) EV could be affordably deployed, it would strictly satisfy only 30% of surveyed drivers from the study by Pearre et al. (2011) and would require significantly more time to refuel than a gasoline vehicle. In order for a 200-mile (80 kWh) BEV to match gasoline refueling times of 5 min, charging power levels of about 960 kW would be required. Such high power charging, which is infeasible with current battery technology, would allow a 200-mile EV to refuel quickly and presumably satisfy a greater percentage of surveyed drivers, underscoring the fact that advances in range and recharge time are required for EVs to match ICEV expectations.

One possible solution to range and recharge issues of modern electric vehicles is wireless charging, which can be either dynamic (i.e. moving) or static (i.e. stationary). With dynamic wireless charging, the vehicle is inductively charged as it moves along the roadway, extending vehicle range and reducing or even eliminating the need for lengthy stops to recharge. Wireless charging is not a new invention and stationary applications in manufacturing and people movers have been around for years. High power (60–120 kW) static wireless chargers have been demonstrated worldwide on electric transit buses since 2002. For the passenger electric vehicle segment, the first commercially available low power (3.3 kW) stationary wireless chargers became available in 2013.

Relatively little peer-reviewed scientific literature exists on dynamic wireless charging of electric vehicles. The literature that does exist focuses mainly on the technical aspects of wireless charging (see, for example, Systems Control Technology, 1996; Budhia et al., 2013; Onar et al., 2013; Chen et al., 2014; Fei Yang et al., 2015; Liang et al., 2015; Miller et al., 2015). Due to the nascency of electric vehicle wireless charging, only a few papers specifically address practical aspects of system implementation such as potential roadway coverage requirements and range extension expectations. Stamati and Bauer (2013) review basic dynamic charging infrastructure components and use a highway drive cycle to investigate varying dynamic system coverage (10–60 kW charging) and its effect on onboard battery capacity (4.8–24 kWh). They find that a 500 km (310.6 miles) driving range could be achieved for an EV with a 24 kWh battery, 25 kW dynamic charging, and 40% roadway coverage. Chopra and Bauer (2013) simulate battery state of charge over different highway drive cycles to estimate the increased range due to various dynamic charging levels and efficiencies. For an EV with a 24 kWh battery and a 90% efficient dynamic system with 20% road coverage, the expected range extension was estimated to be between 12% (10 kW) and 217% (40 kW), depending on drive cycle.

He et al. (2013) propose two integrated pricing models to analyze electricity and transportation networks coupled by wireless charging. Risch et al. (2014) focus on the material and process perspective, presenting an automated test bench approach to evaluate wireless charging pad fabrication. Their findings highlight the potential but also hurdle of wireless charging system mass fabrication. Deflorio et al. (2015) use a traffic simulation model to analyze the traffic and electric performance of in-motion charging systems for a light van and city car. Chen et al. (2015) present a historical overview of dynamic wireless charging (electrified roadways), a summary of wireless charging technology, several examples of existing demonstration projects, and detail the infrastructure challenges and significance of environmental performance of electrified roads. Kalialakis and Georgiadis (2014) survey the regulatory framework relevant to wireless charging, present technical and safety considerations, and discuss international regulatory activities. Fuller (submitted for publication) reported existing cost estimates of dynamic charging infrastructure, which vary between $2.3 and $3.2 million per lane mile, and presented an original cost estimation of $3.4 million per lane mile. A conservative estimate of $4 million per lane mile was used in a least cost optimization approach along with a representative freeway network in California to analyze the potential of dynamic wireless charging to support all-electric travel throughout the State with a limited-range vehicle. The results showed that a 200-mile BEV could travel to popular destinations around the State (for example Reno, Nevada, Lake Tahoe, Ashland, Oregon, San Diego, Los Angeles, Santa Barbara, Yosemite, and Joshua Tree National Park) with relatively little dynamic charging infrastructure. For 100 kW dynamic charging, approximately 718 miles (9.6%) out of a total of 7275 modeled freeway miles would require electrification (assuming a 200-mile EV is used for travel) at a cost of about $2.8 billion. The paper pointed out that the cost of providing dynamic charging to remote areas of the State was expensive and that costs could be reduced by considering that people stop to rest and eat during long trips. The paper suggested looking at scenarios that did not provide dynamic charging to all extents of California and also integrated static charging during rest stops into infrastructure considerations.

This research builds on the work by Fuller (submitted for publication) by considering the synergistic use of dynamic and static charging to support limited range BEV travel within California. A representative model of the State freeway network and potential pathways traveled by motorists are used in a least cost optimization to evaluate where and to what extent dynamic infrastructure would be needed in California. A scenario representing statewide travel between major cities and popular destination areas within California through the judicious use of en-route dynamic and static charging is presented. System cost is evaluated for varying dynamic charging power level and vehicle range. Consumer side recharging costs are estimated and compared with conventional gasoline ICEV and extended range BEV costs.

2. Data and methods

2.1. California model development

A representative network model of key California freeways suitable for long-distance travel by EVs was developed using the open-source geographic information system (GIS) software QGIS and Caltrans GIS data layers. Each freeway was split into its corresponding north and south or east and west directions, as appropriate, with each direction made up of variable length segments (most were 1 mile or less) that were associated with unique identifiers. The State was considered as two regions, north and south, with each region containing popular cities and leisure destinations along with likely travel routes between respective origin and destination (O–D) pairs. Instead of providing dynamic charging roadway coverage throughout California, it was assumed that drivers would statically charge during rest stops on long trips (such as between San Jose and San Diego, which is about 515 miles). This assumption allowed dynamic charging infrastructure to be minimized while still providing extended coverage throughout the State. The selected O–D pairs listed in Table 1 were associated with either a two-part Tour ID (e.g. sc-cc), signifying that the EV spent the night at the destination and was fully recharged, or a three-part Tour ID (e.g. sc-sf-sc), meaning that the route was completed in one day without any supplemental static charging (such as home, workplace, or public). Table 1 lists only the one-way paths for conciseness; however, the GIS model and all subsequent analyses incorporate the return trip.

The scenario considered in the analysis looked at travel between major cities and a set of key destinations for 39 different O–D pairs on 4891 modeled freeway miles. All two- and three-part Tour IDs in Table 1, along with their return trip, were included in the scenario. En route charging was assumed to be dynamic on the roadways shown in Fig. 1, with travel on "missing" roadways (roads not shown in Fig. 1) by wayside high power static (stationary) charging. Overnight charging was assumed at destinations for two-part Tour IDs. Notably, the scenario assumes travel between Northern and Southern California would be supported mainly through high power static charging. The constructed tours, that is travel between an O–D pair, ranged in distance from 97 miles to 334 miles. Fifteen out of the 39 tours, or just over 38%, totaled 200 miles or more.

Using the GIS model in Fig. 1, travel pathways that approximated the route an EV might take were created between each O–D pair in Table 1. These pathways were then read into a spreadsheet using an original script written in R, an open-source software environment for statistical computing and graphics. The imported paths were ordered and formatted for subsequent use in the optimization portion of the research.

2.2. Optimization model

In order to determine how much dynamic charging infrastructure would be required in California to allow a limited range EV to travel between major cities and popular recreational destinations, optimization techniques were applied to the formulated problem. The objective is to minimize the capital cost of dynamic charging infrastructure that could enable EV travel between key destinations in the state, subject to constraints on battery capacity, reserve mileage requirements, and vehicle charging levels. The problem is essentially a flow-based set covering problem with time and battery constraint requirements. While previous work provides a good foundation for addressing this problem (see, for example, the first Maximal Covering

Table 1
O–D pairs and mileage for California tours.

Origin	Destination	Tour ID[a]	Distance (miles)
Northern California Region			
Santa Cruz	South Lake Tahoe	sc-slt	246
	Reno	sc-reno	262
	Santa Cruz via SF	sc-sf-sc	159
	Santa Rosa	sc-rosa	137
	Redding	sc-red	276
San Jose	Mendocino	sj-men	183
	San Jose via Calistoga	sj-cal-sj	235
	South Lake Tahoe	sj-slt	220
	Reno	sj-reno	237
	Yosemite	sj-yos	173
	San Jose via Monterey	sj-mon-sj	157
	Redding	sj-red	251
	Fresno	sj-fno	186
	San Luis Obispo	sj-slo	181
San Francisco	Yosemite	sf-yos	177
	South Lake Tahoe	sf-slt	190
	Mendocino	sf-men	147
	Reno	sf-reno	206
	San Francisco via Calistoga	sf-cal-sf	172
	San Francisco via Sacramento	sf-sac-sf	188
	San Luis Obispo	sf-slo	238
	Redding	sf-red	221
	Fresno	sf-fno	190
Sacramento	Reno	sac-reno	114
	South Lake Tahoe	sac-slt	97
	Yosemite	sac-yos	155
	Mendocino	sac-men	190
	Sacramento via Calistoga	sac-cal-sac	177
	Santa Cruz	sac-sc	151
	Monterey	sac-mon	196
	Redding	sac-red	162
	Fresno	sac-fno	168
	San Luis Obispo	sac-slo	299
Southern California Region			
Los Angeles	Las Vegas	la-lv	224
	Los Angeles via Santa Barbara	la-sb-la	190
	Los Angeles via San Diego	la-sd-la	275
	Joshua Tree	la-jt	174
San Diego	Joshua Tree	sd-jt	272
	Las Vegas	sd-lv	334

Notes: Return trips are not shown for conciseness.

[a] Two-part Tour IDs such as sd-lv indicate that an EV travels from San Diego to Las Vegas, spends the night in Las Vegas (fully recharging the EV battery overnight), and returns to San Diego the following day (the return leg, lv-sd is not shown for conciseness but is included in all modeling and analysis). Three-part Tour IDs such as la-sd-la indicate that an EV travels from Los Angeles to San Diego and returns to Los Angeles in the same day without using static charging during the day (the EVs use only dynamic charging while traveling between the origin and destination).

Location Problem in Church and ReVelle (1974), the Flow-Capturing Location–Allocation Model of Hodgson (1990), Flow Refueling Location Model in Kuby and Lim (2005), the Capacitated Flow Refueling Location Model of Upchurch et al. (2009), the Flow-Based Set Covering Model of Wang and Lin (2009), and the Flow-capturing location model with stochastic user equilibrium of Riemann et al. (2015)), the main limitation of all prior formulations is that they are node based; refueling occurs at intermediate points between origin and destination where a vehicle stops to refuel. This assumption is invalid for dynamic charging. Not only does dynamic charging require refueling on links instead of at nodes, but it also requires consideration of range and battery capacity. The dynamic charging problem requires an uncapacitated flow-based set covering location model that is link-oriented, based on explicit pathways, and subject to battery capacity constraints. An optimization approach that incorporates missing elements of prior formulations was described in Fuller (submitted for publication), based on work by Wang and Lin (2009), and is used in this research as follows:

$$\text{Minimize} \sum_{i \in L} C_i * W_i \tag{1}$$

Fig. 1. GIS California roadway model with origin–destination pairs.

Subject to:

$$R_{i,t} = \mathrm{R}_{j,t} + A_{j,t} - D_{j,i} * \beta_{j,i,t} \qquad \forall\, j, i \in N, \quad \forall\, t \in T \tag{2}$$

$$O_{i,t} = \kappa - R_{i,t} - E_{i,t} * Z_{i,t} \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{3}$$

$$A_{i,t} = E_{i,t} * Z_{i,t} + O_{i,t} \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{4}$$

$$A_{i,t} + R_{i,t} \leqslant \kappa \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{5}$$

$$\sum_{t \in T} E_{i,t} \leqslant S_i \qquad \forall\, i \in L \tag{6}$$

$$S_i \leqslant U * W_i \qquad \forall\, i \in L \tag{7}$$

$$W_i \in \{0,1\} \qquad \forall\, i \in L \tag{8}$$

$$S_i \geqslant 0 \qquad \forall\, i \in L \tag{9}$$

$$E_{i,t} \in \{0,1\} \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{10}$$

$$O_{i,t} \leqslant 0 \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{11}$$

$$A_{i,t} \geqslant 0 \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{12}$$

$$R_{i,t} \geqslant 0 \qquad \forall\, i \in L, \quad \forall\, t \in T \tag{13}$$

where i, j is the indices for links, t is the index for tours, T is the set of all tour identifications, L is the set of all unique links in the statewide road network, N is the set of all valid link connections making up the statewide road network, $D_{j,i}$ is the distance in miles of link i (the beginning of link i to the beginning of link j), C_i is the cost of installing dynamic charging on link i, $Z_{i,t}$ is the number of miles charged on link i (a function of distance, dynamic charging power level, vehicle energy consumption, and vehicle speed), $B_{j,i,t}$ is the path taken from origin to destination ($\beta = 1$ means that link i is on the path, $\beta = 0$ means link i is the first link in the path, $\beta = 99$ means that link i is not on the path), κ is the range of the vehicle in miles, U is the cardinality of set T, W_i is a binary variable indicating whether dynamic charging infrastructure is located on link i, S_i is an integer variable representing the sum of all tours charging on link i (e.g. if charging occurs on link i on two separate tours, S would equal 2), $E_{i,t}$ is a binary variable indicating whether an EV is recharged on link i, $O_{i,t}$ is a continuous variable representing overage, that is an adjustment term in miles to ensure charging does not exceed battery capacity, $A_{i,t}$ is a continuous variable indicating the amount of added range in miles due to recharging on link i, $R_{i,t}$ is a continuous variable indicating the amount of range in miles remaining after traveling on link i but prior to recharging on the subsequent link.

The objective function (1) as stated is to minimize the capital cost of dynamic charging infrastructure subject to constraints (2)–(13).

Constraint (2) describes the range calculation, which is based on distance traveled, added range, and previous available range. An EV is assumed to begin every tour with a full charge on the first link of a pathway, which is indicated by $\beta_{j,i,t} = 0$. When $\beta_{j,i,t} = 0$, the beginning range is set to κ and the added range $A_{j,t}$ is set to zero. Accordingly, for the first optimization routine iteration of every tour, constraint (2) resolves to $R_{i,t} = \kappa - D_{j,i}$ (the range of the EV minus the length in miles of link i).

Constraint (3) describes the overage calculation, which is needed to ensure that charging does not exceed the battery capacity of the EV. The overage is calculated as the initial EV range, κ, minus the adjusted range from constraint (2), $R_{i,t}$, minus the charge provided to the EV. When the overage is negative, it means that the battery is at full capacity. Positive values indicate how many miles of charge the battery can accept.

Constraint (4) calculates the amount of additional range added to the EV factoring in battery capacity. The overage from constraint (3) is taken to be zero when $O_{i,t}$ is positive (indicating that there is sufficient battery capacity to accept the charge) and $O_{i,t}$ when $O_{i,t}$ is negative (thereby reducing the amount of charge to the vehicle by $O_{i,t}$).

Constraint (5) is a range check to ensure that the added range plus the remaining range does not exceed the total range of the EV.

Constraint (6) checks that the sum of charging events $E_{i,t}$ does not exceed the actual number of possible charging events on a particular link, denoted by S_i.

Constraint (7) assigns which links are used to charge the EV to W_i. Since W_i is a binary variable, it ensures that each charging link is only counted once, which is required for proper calculation of cost in the objective function. Variable U is set to the cardinality of T to account for the possibility of all tours charging on a specific link.

Constraints (8)–(13) simply define the allowable values that the variables can take.

Exogenously set parameters used in the model include: κ = vehicle range, varied between 100 and 300 miles and accounting for an 80% reserve requirement (e.g., for the 300 mile scenario, only 240 miles could be used between origin and destination with 60 miles held in reserve for use at the destination); Z = the number of miles charged on a link, which is calculated by Eq. (14) below and based on a vehicle speed of 65 mph, a vehicle energy consumption rate of 400 Wh/mile (for reference, the midsize 2016 Nissan Leaf EV is rated at 300 Wh/mile while the SUV 2016 Tesla Model X is rated at 380 Wh/mile by the EPA), and a power level (how much power is received by the EV from the roadway wireless pads) between 20 and 200 kW; L = the set of all unique links in the statewide road network; T = the set of all tour identifications; N = the set of all valid link connections making up the statewide road network, D = the distance in miles of each link; and, C = the cost of dynamic charging per mile, which was set to \$4 million per lane mile. Parameter Z was calculated according to the following simplified equation:

$$Z = \frac{\text{power level} * \text{vehicles peed} * \text{link distance}}{3600} * \text{fuel economy} \tag{14}$$

where $3600 =$ number of kJ in 1 kWh, power level = the amount of power, in kW, received by the vehicle from the roadway charging pads; vehicle speed = the speed of the EV in seconds per mile; link distance = the length, in miles, of the link; and fuel economy = the number of miles an EV can travel on 1 kWh (in miles per kWh) assuming an energy consumption rate of 400 Wh/mile.

3. Results and discussion

3.1. Range, vehicle charging power, and system cost analysis

The optimization formulation was coded in A Mathematical Programming Language (AMPL) and the CPLEX 12.4 solver was used to solve the mixed integer problem using the branch and bound technique. The total range of the simulated EV was chosen to be 200 miles, with only 160 miles available for use between the O–D pair. This meant that for purposes of the optimization model, the EV had an effective range of only 160 miles; 40 miles of range was reserved for use at the destination. Dynamic charging power (the amount of power received by the vehicle) was chosen as 100 kW. Power flows onboard the vehicle were not addressed as power could be routed to the motor or stored for later use. The focus of this analysis is the overall feasibility of a system to address range and recharge and its general cost implications. How and to what extent power flows are handled onboard the vehicle is important but the optimal solution has not been devised and should be the focus of more detailed future work. The optimization model was solved and then combined with the GIS model in Fig. 1 to produce the results shown in Fig. 2. Travel beyond listed destinations and on roadways not shown in the figure would be supported by wayside static charging.

Fig. 2 shows that 241 miles (4.9%) out of a total of 4891 modeled freeway miles require electrification if a 200-mile EV is to travel between an O–D pair relying solely on 100 kW dynamic charging. A noticeable missing element is the ability to travel between Northern and Southern California via dynamic charging. Under the proposed scenario, a 200-mile EV traveling from Sacramento to Los Angeles might stop two times for about 27 min each in order to statically charge (wirelessly) at 100 kW; an amount of time conducive to eating and/or resting and sufficient power to provide about 225 miles of additional range. For all other travel within the northern and southern regions, dynamic charging would be sufficient to enable travel between O–D pairs without stopping. To understand how the costs of the statewide dynamic system in Fig. 2 might change for different vehicle charging power levels, the optimization problem was solved for vehicle charging power levels between 20 kW and 200 kW with the results graphed in Fig. 3. It is important to note that the roadside infrastructure in all scenarios does not change, it is based on a power supply capable of supplying 250 kW per 160 m charging section at a cost of $4 million per lane mile. A section could perhaps simultaneously supply 2 vehicles at 100 kW or 5 vehicles at 40 kW. Since each

Fig. 2. 100 kW dynamic wireless charging infrastructure layout (wireless charging segments are highlighted in yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

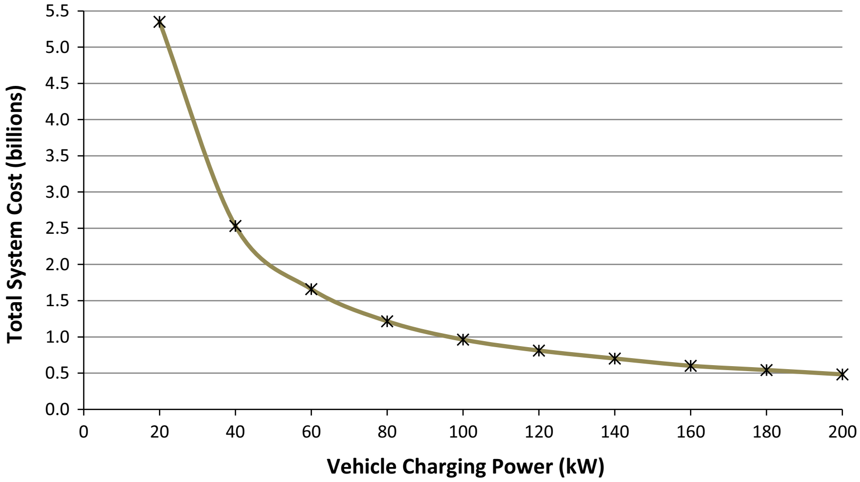

Fig. 3. Statewide system cost vs. vehicle charging power level.

roadway pad is assumed to be rated at 10 kW, power transfer in excess of 10 kW would require multiple pads per vehicle. Each vehicle pad adds weight and cost and so it is important to balance infrastructure and vehicle costs.

While current pad technology used in this analysis is assumed to provide 10 kW, it should be noted that these pads could be rated for 20 kW (Grant Covic, personal communication, December 02, 2012). At 10 kW, the number of pads required for 100 kW charging would exceed the average vehicle length of approximately 5 m; only 6 pads could fit under the vehicle, effectively limiting charging to 60 kW. At a full rating of 20 kW, the 5 pads required for 100 kW charging could be accommodated by the average vehicle length. The weight of all 5 vehicle pads, about 225 lb as estimated by Wu (2012), would dramatically offset any weight increases due to a larger battery. In the presented analysis, a 200-mile EV could travel at least 334 miles (San Diego to Las Vegas) with 100 kW charging (5 pads) at an increased weight of about 225 lb (102 kg). To provide the same 134-mile incremental range via battery energy, an EV consuming 400 Wh/mile would require an additional 53.6 kWh at a weight of 590 lb (268 kg) for current 200 Wh/kg batteries and 295 lb (134 kg) for future 400 Wh/kg batteries. This indicates that dynamic wireless charging could provide additional range with lower onboard weight requirements than possible with current batteries.

Results from the optimization runs indicate a total statewide system capital cost of between $5.2 billion (20 kW) and $484 million (200 kW). While capital cost can be reduced by up to 91% (relative to the $5.2 billion system) by increasing vehicle charging power levels to 200 kW, the graph shows diminishing cost benefits with increasing power. The majority of cost reductions (81%) are realized by increasing power levels to 100 kW, with only 10% additional reduction resulting from doubling the power level to 200 kW.

All of the analyses thus far have been predicated on the assumption that an EV would have a total range of 200 miles; however, it is highly likely that due to cost and consumer preferences, EVs will continue to have varying ranges. To address this likelihood, the optimization was re-run for vehicle ranges between 100 miles and 300 miles for dynamic charging levels from 20 kW to 120 kW. The results from these runs are presented in Fig. 4.

While the graph in Fig. 4 indicates that less dynamic infrastructure is needed as EV range increases (since an increasing percentage of travel can be accomplished on battery energy alone), it is important to keep in mind that this relationship is dependent on assumptions regarding initial state of charge, travel patterns, and energy consumption rate. As seen in the figure, there is a point where the infrastructure cost rate of change begins to diminish with increased range; there is a marked difference between the slope of the line before and after the point where EV range equals 225 miles. This difference arises mainly due to decreased need for the dynamic charging infrastructure and increased consolidation of charging infrastructure that becomes feasible with greater battery range and common route choice.

In California, major population areas are connected to selected destinations by common freeways, which reduce the need for roadway electrification. Out of the 39 one-way trips listed in Table 1, 31 trips can be completed on battery power alone given an EV range of 300 miles (240 miles used on the freeway, 60 miles left in reserve for use at the destination). As battery capacity increases, fewer and fewer destinations require supplemental charging and the dynamic infrastructure can be reduced and consolidated on common freeway corridors. In the Northern California Region, travel originating in San Francisco would require supplemental charging for 13 destinations on 8 different freeways with a 100-mile EV whereas only 4 destinations and 4 different freeways require charging for a 300-mile EV (Redding, Reno, South Lake Tahoe, and San Luis Obispo). Three of the destinations, Redding, South Lake Tahoe, and Reno, are served by a common portion of the I-80 corridor, meaning that roadway electrification can be sited to better serve all three cities as battery range increases. The difference in the rate of change of cost reductions shown in Fig. 4 is reflected by the fact that by 225 miles of range the total number of dynamically charged miles required to reach all trip destinations in Table 1 is reduced by 80%. By 230 miles of

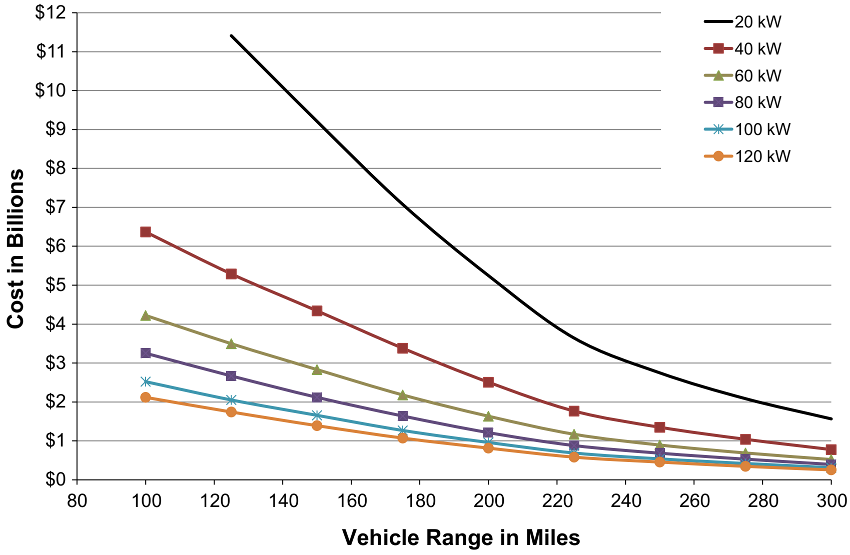

Fig. 4. System cost vs. EV range by vehicle charging power level.

range, the number of dynamically charged miles decreases by 82%. For range increases between 230 miles and 300 miles, there is only an 18% decrease in dynamically charged miles required to reach all destinations. This means that for the selected destinations, stated assumptions, and existing California freeway system, EV range in excess of 225 miles (180 freeway miles, 45 reserve miles) contributes significantly less to overall wireless charging infrastructure cost reduction than increases in range up to 225 miles.

For the power levels and ranges analyzed in the figure, the maximum cost reduction (relative to a 20 kW system) that could be expected for the dynamic system is about 88%. Of that total cost reduction, about 72% occurs by 225 miles of range and about 62% occurs by 200 miles of range. On average, 68% of total cost reduction can be realized by increasing power levels for a given EV range to 60 kW and 52% can be attained by 40 kW. Optimization results indicate a 200-mile EV and a 40 kW dynamic charging system in California would require 626 miles of electrification at a cost of about $2.5 billion; this scenario is used in subsequent analyses.

3.2. Refueling and additional range cost analysis

While upfront capital costs are vital to system adoption, refueling costs must be reasonable as well. In order to estimate dynamic charging refueling costs, the levelized cost of electricity (the price of electricity required for an investment to break even over a specified period of time) over a period of 20 years was used to compare options. The real interest rate was chosen to be 4% and the price of electricity to be $0.1487 per kWh based on data from U.S. EIA (2013) for retail commercial rates in California. This commercial rate is higher than what the transportation sector pays, which was $0.0832 in 2013. Accordingly, the assumed electricity price charged to potential users of a dynamic charging system incorporates about 6 cents per kWh of additional revenue that could be used toward associated operational and maintenance costs. This translates to 2.4 cents per mile (for an EV consuming 400 Wh/mile) or about a 0.4 cent increase relative to current gasoline taxes on a per mile basis (State plus federal gasoline taxes equate to about 2 cents per mile in California as of 2015). The efficiency of the 40 kW dynamic charging system was assumed to be 80% (i.e. 50 kW must be supplied from the electric grid connection in order to provide 40 kW to the vehicle battery terminals), which is the efficiency achieved by the 100 kW system developed by the Korea Advanced Institute of Science and Technology (Jaegue et al., 2014). While the 80% efficiency assumption is the same in all analyses, in reality, varying vehicle pad height will have an impact on system efficiency. It is assumed here that a dynamic charging system would not be deployed for mixed height vehicles unless the system could be built to ensure that it could efficiently serve all traffic. It is assumed pad height would be standardized or a method of accounting for varying heights would be developed prior to deployment. Further work analyzing the impact of 5–10% variations in efficiency would be helpful in understanding any possible constraints regarding system efficiency. The 626-mile, 40 kW dynamic charging system scenario was chosen at a total capital cost of $2.5 billion (at $4 million per lane mile; please refer to Fuller (submitted for publication) for detailed cost estimation). The only operating cost considered in the 20-year LCOE was the cost of electricity. Because the number of EVs using the system is unknown and has a large effect on system payback, EV volume was varied between 25,000 and 1,000,000. The following formula was used for calculating LCOE:

$$\mathrm{LCOE} = \frac{C_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{15}$$

where n is the expected life in years of the charging infrastructure, t is the year, i is the real discount rate, C_0 is the total capital cost of purchasing and installing the charging infrastructure, A_t is the annual cost to operate and maintain the charging infrastructure in year t, and E_t is the total amount of electricity in kWh supplied by the charging infrastructure in year t.

Since the degree to which the dynamic system is used each year is a key determinant of the LCOE, two scenarios were created and analyzed; a low energy consumption (or usage) scenario and a high energy consumption scenario. The high scenario was based on each EV using an average of 138 kWh of energy each year from the 40 kW dynamic system. Out of the tours considered in this research (Table 1), San Diego to Las Vegas is the longest at a distance of about 334 miles and requires 69 kWh of roadway charging energy each way (for a total of 138 kWh) for a 160-mile EV (40 miles reserved for use at the destination). The low scenario was based on findings from Pearre et al. (2011) who, in their 3-year GPS instrumentation study of 484 gasoline vehicles in Atlanta, Georgia, found that the average driver exceeded 150 miles only 9 times out of the year. Assuming similar travel behavior to the Atlanta study subset, EVs were conservatively assumed to take 9 one-way trips per year. On each of those one-way trips the dynamic charging system was assumed to supply the EV with an additional 3 kWh of energy (this scenario would be similar to an EV traveling between Sacramento and Fresno, 168 miles). This meant that each EV was assumed to consume an average of 27 kWh per year for the low scenario.

Under an average energy consumption of 27 kWh per EV per year, the 20-yr LCOE was calculated to be between $218.70 per kWh for 25,000 EVs and $5.61 per kWh for 1,000,000 EVs. For an average consumption of 138 kWh per EV per year over the same period, the LCOE was estimated at $42.90 per kWh for 25,000 EVs and $1.21 per kWh for 1,000,000 EVs. Given the calculated 20-year LCOE values, refueling 27 kWh under the low energy consumption scenario would cost a driver $151–$5905 per year while recharging 138 kWh under the high consumption scenario would cost a consumer $166–$5920 per year. It is highly unlikely that a dynamic charging system would be viable at a volume of 25,000 EVs in either energy scenario due to the high cost of added range (almost $6,000 per year). At EV levels of 1,000,000 vehicles, consumers would be much more likely to use the dynamic system since the added cost per year might only be a couple of hundred dollars. Fig. 5 shows the yearly cost for extending the range of a 200-mile EV by 67.5 miles (27 kWh low energy scenario) and 345 miles (138 kWh high energy scenario).

While both scenarios seem identical in Fig. 5, costs do vary slightly between the 67.5-mile and 345-mile scenarios. Significant cost reduction is apparent at lower volumes; 75% of cost reduction is achieved by a volume of 100,000 EVs and 90% is achieved by 250,000 EVs. At just over 300,000 EVs, the total yearly cost drops below $500. The figure indicates that for a relatively low volume of vehicles (1,000,000) consuming a relatively small amount of dynamic charging energy (27–138 kWh) the yearly cost of additional range could be about $168 per vehicle per year. The main driver of consumer cost is infrastructure cost; a doubling of the electricity rate from $0.1487 to $0.2974 per kWh increases the cost to the consumer by $21 to $189 per year whereas an increase in infrastructure cost of $1 million from $4 million to $5 million per lane mile increases the cost to the consumer by $37 to $205 per year. If all 24 million registered automobiles in California used the dynamic system, the cost of additional range would drop drastically to $10 per year to charge 27 kWh and to $27 per year to charge 138 kWh.

While yearly dynamic charging costs seem reasonable, a comparison between the cost of adding range via dynamic charging and adding it through increased battery capacity is important. To appropriately compare added range costs for dynamic

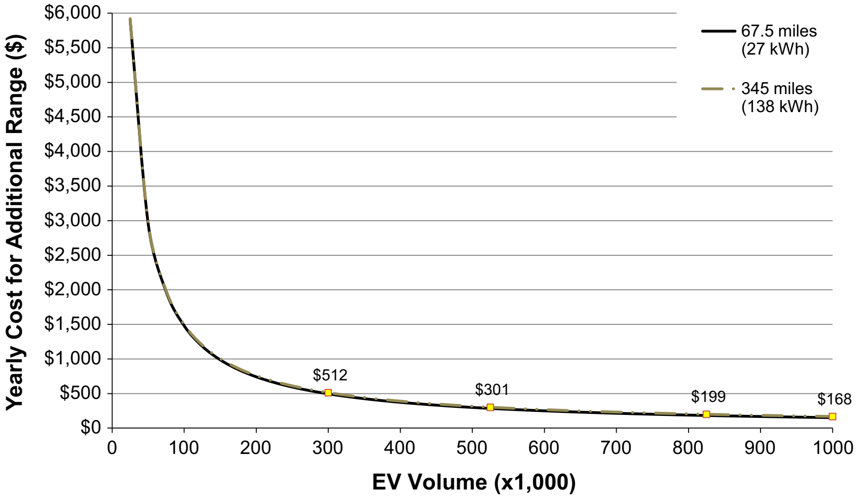

Fig. 5. Yearly cost for additional range via dynamic charging.

charging and increased battery capacity, a driver was assumed to keep an EV for 10 years. Accordingly, battery life was assumed to be 10 years and cumulative dynamic charging costs were calculated over a period of 10 years. The same two energy usage scenarios were used, a low dynamic energy consumption scenario of 27 kWh or 67.5 additional miles and a high dynamic energy consumption scenario of 138 kWh or 345 additional miles. Battery prices were assumed to be $13,800 for the 138 kWh scenario and $2700 for the 27 kWh scenario using a battery price of $100 per kWh. To be conservative, the added cost of accommodating additional batteries on a vehicle was ignored; $100 per kWh is only meant to reflect the purchase price a consumer would pay for additional batteries. The cost of additional range was calculated for EV volumes between 25,000 and 1,000,000 and graphed along with corresponding battery prices in Fig. 6.

As shown in Fig. 6 and 10-yr cumulative dynamic charging costs exceed battery prices at only the lowest EV volumes, reaching cost equivalency with the 138 kWh battery at about 110,000 EVs and with the 27 kWh battery at about 550,000 EVs. This indicates that the dynamic charging system is more cost effective than a battery only approach for longer range travel. For estimated dynamic charging costs and even considering extremely low battery prices, the figure clearly shows that dynamic charging can provide additional range to a 200-mile EV at a lower cost than the corresponding increase in battery capacity.

3.3. Gasoline and electric vehicle annual fuel cost comparison

While dynamic charging is clearly more cost effective at extending range than increasing battery capacity, the large capital costs required to install dynamic charging ($2.5 billion for the 40 kW charging infrastructure network) prohibit competitiveness with current gasoline prices on a per gallon basis at any of the analyzed volumes. For the system to be competitive with $4 per gallon gasoline, either 7.5 million EVs (about 34% of all registered automobiles in California in 2012) consuming an average of 138 kWh of dynamic energy per year would be required or the amount of energy consumed on the system would need to be appreciably increased (for 1,000,000 EVs it would need to be increased to 1100 kWh per vehicle per year – the amount of energy that would be dynamically charged in support of an EV traveling between Sacramento and San Francisco at least 73 times per year). While per gallon gasoline price competitiveness is challenging at analyzed levels, the analysis ignores the fact that the majority of EV drivers may not use dynamic charging on a regular basis. Home charging is assumed to be the main method of charging since it will likely be the most convenient and lowest cost option. Accordingly, a more accurate way to compare fueling costs is to consider total yearly fuel costs for a gasoline vehicle and an EV. Key assumptions of this comparison are detailed in Table 2 while the results of the analysis are shown in Fig. 7.

For the gasoline vehicle, a total annual mileage of 12,000 miles, a fuel economy of 35 mpg, and fuel price of $2.50 and $4 per gallon were assumed. For the EV, 12,000 annual miles, a fuel economy of 400 Wh/mile (2.5 miles per kWh; for reference, the midsize 2016 Nissan Leaf EV is rated at 300 Wh/mile while the SUV 2016 Tesla Model X is rated at 380 Wh/mile by the EPA), a residential electricity rate of $0.1571 per kWh from U.S. EIA (2013), and dynamic 20-year LCOE rates by EV volume from the 138 kWh (345 miles) scenario previously analyzed were assumed. Each EV was assumed to travel 345 miles on dynamic energy with the remaining annual mileage being charged at home.

From the fuel cost analysis graphed in Fig. 7, annual fuel costs for home charging coupled with occasional use of dynamic charging reach cost parity with annual $4 per gallon gasoline fuel costs at a volume of around 240,000 EVs and result in a savings of around $500 per vehicle at a volume of 1,000,000 EVs. If the price of gasoline is relaxed to $2.50 per gallon (average price per gallon in 2006), annual electricity cost parity is not achieved until just over 1,000,000 EVs. While 20-yr dynamic

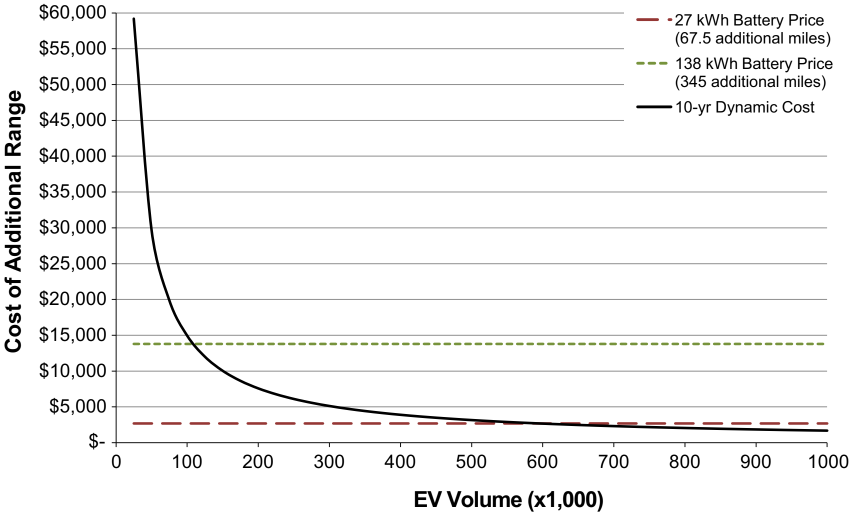

Fig. 6. 10-yr dynamic charging costs vs. increased battery price comparison (battery price of $100 per kWh).

Table 2
Key assumptions for yearly fuel cost comparison.

Vehicle	Fuel economy	Annual miles	Home charging		Public charging[b]	
			Miles	Price[a]	Miles	Price
Gasoline	35 mpg	12,000	–	–	12,000	$2.50 and $4.00 per gallon
Electric	2.5 miles per kWh	12,000	11,655	$0.1571 per kWh	345 (dynamic)	$1.21–42.90 per kWh

[a] Residential electricity rate from U.S. EIA (2013).

[b] Public charging for gasoline vehicle is at a gasoline station while for the EV it is via dynamic charging. Dynamic charging prices are 20-year LCOE prices for the 138 kWh high scenario previously analyzed.

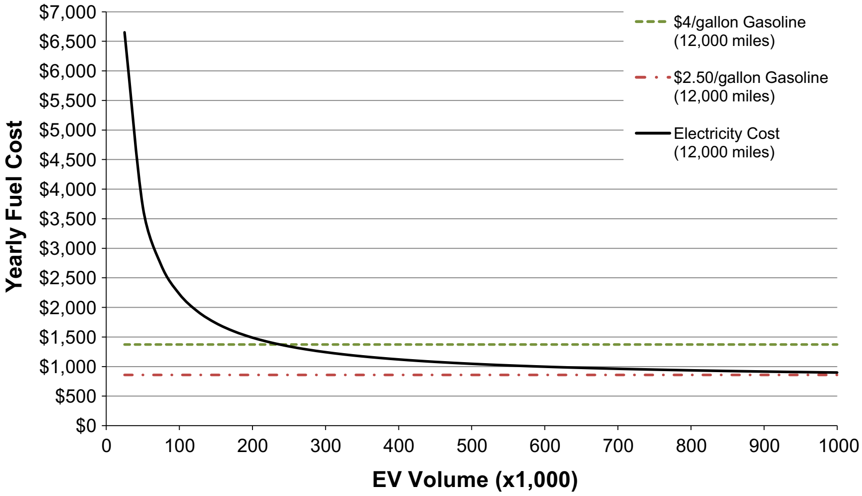

Fig. 7. Total yearly fuel cost comparison.

charging LCOE rates cannot compete on a per gallon basis with gasoline, a portion of the significant savings realized from relatively low residential electricity rates and thus home recharging costs can be spent on more expensive dynamic charging rates to make the overall annual fuel budget competitive. For example, for the 138 kWh consumption scenario at a volume of 500,000 EVs, each EV driver would charge 11,655 miles at home at a cost of about $732 and dynamically charge 345 miles at a cost of about $316. The total annual electricity cost to each EV driver would be about $1048. While dynamic charging costs would constitute 30% of an EVs annual fuel cost in this example, the EV driver would actually save around $323 compared to annual gasoline costs of $1371 at $4 per gallon. This analysis assumes that the dynamic charging system is only used on occasion. In reality, usage will vary in both frequency and quantity of energy consumed.

The disadvantage of assuming uniform usage (average usage) of the dynamic system over all EVs ignores the fact that usage will vary widely and that the heaviest users of the system will be discouraged from using the system if prices are set based on uniform usage LCOE calculations. For instance, if dynamic charging rates are set based on a 20-year LCOE price of $1.22 per kWh assuming uniform usage of 138 kWh per EV for 1,000,000 EVs, a commuter driving between San Francisco and Sacramento 3 times a week per year and only charging dynamically would incur a cost of $2855. Instead of encouraging usage of the system, such high recharging costs would likely act to dissuade drivers from regularly using the system. To adequately assess potential dynamic charging rates, dynamic charging electricity prices should be tiered by usage to incorporate both occasional (weekend) and frequent (weekday) users. The extent to which electricity prices should be tiered in order to incentivize use of dynamic charging is outside the scope of this research and depends largely on the intended goals of the infrastructure.

4. Conclusions

This research evaluated the potential for dynamic charging infrastructure to address range and recharge issues of modern EVs by considering travel to regional destinations in California. A 200-mile electric vehicle with a real range of 160 miles plus 40 miles reserve was assumed to be used by consumers in concert with static and dynamic charging as a strict substitute for gasoline vehicle travel. Different combinations of wireless charging power (dynamic charging levels from 20 kW to 120 kW) and vehicle range (vehicle ranges between 100 miles and 300 miles) were evaluated. Results from the analysis indicated that most statewide travel between popular destinations could be accomplished with a 200-mile EV and a 40 kW, 626-mile dynamic wireless charging system at a cost of about $2.5 billion if static charging is used when traveling between Northern and Southern California regions or to the upper extents of California near the Oregon-California border. The analysis clearly showed that dynamic infrastructure capital costs could be lowered to below $500 million by increasing wireless charging power levels to 200 kW; however, reduction of roadway infrastructure costs through increasing power comes at significant cost to the consumer since additional charging pads are needed on the vehicle to accommodate the increased power transfer. Further research is needed to address consumer budget concerns regarding the cost of on-vehicle charging pads for high power wireless charging.

The analysis further indicated that capital investment required to deploy 40 kW wireless charging infrastructure in California could be recouped under relatively low vehicle volumes and at very low dynamic energy consumption rates within a 20-year period. The $2.5 billion capital cost of a 40 kW dynamic system plus yearly energy costs could be recouped at an average cost to each vehicle of $512 per year at a volume of 300,000 vehicles or $168 per year at a volume of 1,000,000 vehicles. If all 24 million registered automobiles in California used the dynamic system, the yearly cost to each vehicle would drop drastically to $10 per year to charge 27 kWh and to $27 per year to charge 138 kWh. Since these costs are averages, some drivers would pay more or less depending on usage and pricing structure. If it is a goal of policymakers to encourage the frequent use of dynamic charging, it is important to consider a tiered price structure to avoid disincentivizing drivers who may use the system more than the average driver (such as long distance commuters).

Finally, cost comparisons of dynamic charging, increased battery capacity, and gasoline refueling were presented. Dynamic charging, coupled with strategic static charging, was shown to be more cost effective over a 10-year period than gasoline refueling at $2.50 or $4.00 per gallon. At very low battery prices of $100 per kWh, the research showed that dynamic charging can be a more cost effective approach to extending range than increasing battery capacity.

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