taking **charge**:
Optimizing Urban Charging Infrastructure for Shared Electric Vehicles

by
Praveen Subramani

Bachelor of Science in Electrical Science & Engineering
Minor in Urban Studies & Planning
Massachusetts Institute of Technology, 2010

Submitted to the Program in Media Arts and Sciences
School of Architecture and Planning
In Partial Fulfillment of the Requirements for the Degree of

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Signature of Author
Program in Media Arts & Sciences
MIT Media Lab
August 2012

Certified by
Kent Larson
Principal Research Scientist
Director, Changing Places Group, MIT Media Lab
Thesis Advisor

Accepted by
Patricia Maes
Associate Professor of Media Arts & Sciences
Associate Academic Head, Program in Media Arts and Sciences

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ABSTRACT

This thesis analyses the opportunities and constraints of deploying charging infrastructure for shared electric vehicles in urban environments. Existing electric vehicle charging infrastructure for privately owned vehicles is examined and critiqued. A prototype of smartCharge, an integrated locking, charging, and ambient information system for shared electric vehicles is presented. Design methodology, fabrication of mechanical and electrical systems, and testing of the smartCharge system is documented. Urban implementation case studies for such a universal charging and locking station illustrate the potential of optimized infrastructure for shared vehicles to transform urban streetscapes and improve mobility.

An analysis of leveraging existing building electrical infrastructure for vehicle charging is conducted, including phasing strategies for deploying rapid charging. Technological constraints to rapid charging such as battery chemistry, pack design, and power input are presented and evaluated. A strategy for buffering rapid electric vehicle charging with commercial uninterruptible power supply (UPS) systems is described. Two recent buildings on the MIT campus are used as case studies to demonstrate the overhead transformational capacity that exists in many modern, multi-purpose buildings. Connectivity between electrified transport, the electrical grid, and renewable energy sources is explored. A vision for personal urban mobility enabled by fleets of shared electric vehicles powered by clean, renewable energy and intelligent charging infrastructure is proposed.

Thesis Supervisor: Kent L. Larson
Title: Principal Research Scientist, MIT Media Lab

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Thesis Advisor: ______________________
Kent L. Larson
Principal Research Scientist
MIT Media Lab

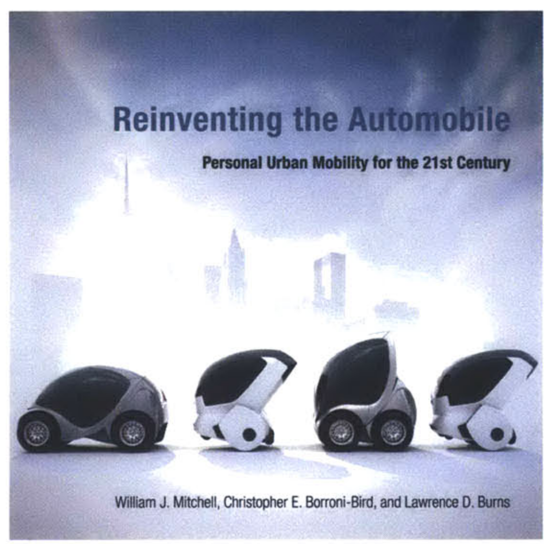
Thesis Reader: ______________________
Joseph A. Paradiso
Associate Professor of Media Arts & Sciences
MIT Media Lab

Thesis Reader: ______________________
Dennis M. Frenchman
Leventhal Professor of Urban Design & Planning
MIT Department of Urban Studies & Planning

Dedication

This thesis and the entirety of my graduate research at MIT are dedicated to the memory of Professor William J. Mitchell.

Bill was an incredible urban visionary, an unparalleled educator and academic, and a personal inspiration to countless students. Less than a month prior to his untimely death in June 2010, Bill accepted Nicholas Pennycooke and myself as his last two students into the Smart Cities group at the MIT Media Lab. Though our time with Bill as graduate students was limited, he left us a vast collection of books and writings detailing his vision for the future of cities, mobility, and architecture. In particular, his 2010 book, *Reinventing the Automobile: Personal Urban Mobility for the 21st Century*, served as inspiration and guidance for many of our projects, especially during the full-scale development of the CityCar.



Bill touched generations of students with his charm, intellect, and mentorship. He had a unique talent for recognizing the long-term significance of new technologies, particularly with regards to how they could influence urban life and city form. Urbanist, architect, technologist, visionary, mentor, father, husband, and teacher – Bill's descriptors were numerous, but he always had a passion for creating places and things that surprised and delighted.

His loyal cadre of students, affectionately termed 'Students of Bill,' continue to work tirelessly in his absence throughout academia and industry to realize and expand on his visions for the future of cities and human civilization. While Bill is missed deeply each day, his work lives on through this research and countless other projects that blossomed from his wisdom and creativity.

"It's important to get the technology and the policy right, but in the end, the way you break a logjam is by engaging people's imagination, people's desire, by creating things that they never thought of before."

-- William J. Mitchell
1944 – 2010

Acknowledgements

Thank you to Bill Mitchell, for his boundless wisdom, unparalleled charm, and his enduring urban vision that we have strived to realize each day in his absence.

Thank you to my advisor Kent Larson, for taking us in after Bill's passing and giving us the flexibility to continue our projects and pursue our passions. I deeply appreciate your guidance, leadership, and our many conversations over the past two years. The opportunities and responsibilities you gave us as graduate students were truly unique, and I thank you sincerely for the trust and respect you have given us.

To my colleagues in the Smart Cities and Changing Places group, in particular the Hiriko CityCar team: Ryan Chin, William Lark, Nick Pennycooke, and Raul-David "Retro" Poblano. I could not have imagined a better team to work with on our challenging projects, and I am deeply grateful for the opportunity to collaborate with and learn from each of you. Thank you all for your advice, wisdom, and friendship over the past several years.

Thank you to my thesis readers, Joe Paradiso and Dennis Frenchman. I have learned much from both of you in classes and in working on this thesis.

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Thank you to the Changing Places group undergraduate researchers (UROPs) – Sean Cockey, Guangyan Gao, and Jean Martin – who participated heavily in the prototyping of the smartCharge system. The realization of the functional prototype would not have been possible without your hard work.

Thank you to my many Media Lab colleagues, especially: Pol Pia Conesa and Susanne Seitinger for their help with the Philips Color Kinetics systems; Tom Lutz, Nadya Peek, and other Media Lab shop gurus who were always willing to lend a hand during the prototyping process; Leo Bonanni for welcoming me into the Media Lab family as an undergraduate researcher in 2007.

Thank you to my many friends from MIT, my hometown of San Diego, and around the world who have shared in late nights of hard work, fascinating conversations, and many good times.

Thank you to the Media Lab consortium of sponsors, from whom I have learned much over the past two years. In particular, I would like to thank the Denokinn group for funding much of this research and the related development of the Hiriko CityCar.

Finally, and most importantly, thank you to my parents Suresh Subramani and Feroza Ardeshir. Nothing in my life, particularly the incredible educational opportunities I have had, would have been possible without your enduring support and guidance. Thank you.

Table of Contents

List of Figures

{I} Introduction

For the first time in human history, the United Nations reported in 2007 that the world's urban population had surpassed its rural population. Today, more than half of the world's seven billion people live in cities or dense urban areas, with many urban theorists and sociologists predicting this figure to increase consistently throughout the 21st century. For example, a study from the Imperial College Urban Energy Systems Project reported that 90% of population growth in the next century will be in urban areas and that transportation and building operations typically account for at least 60% of urban energy use. [1] Much of this inefficient energy use, along with the perennial problems of urban pollution and congestion, is caused by the prevalence of private vehicles in cities. Compounding these issues, a private vehicle spends the majority of its life parked, waiting idly for its owner to return and consuming valuable urban real estate in the interim. This low vehicle utilization rate has resulted in cities that are saturated with parking lots and large portions of urban land dedicated to providing parking for empty vehicles.

To address the global issues of urban pollution and congestion, a number of vehicle sharing systems have emerged in cities throughout the world since 2006. Many American vehicle-sharing systems are managed by private entities, such as the Cambridge-based Zipcar, which operates on a reservation and two-way rental model. With such a system, while an individual vehicle is shared amongst all members of the vehicle-sharing service, it requires an advance reservation and requires the user to return the vehicle to the same location after the rental period. Reservations are enforced with high penalties for late returns, and users rental accounts are linked to credit cards to protect the assets of the fleet operators. Particularly noteworthy are the bicycle sharing programs that exist in many European and North American cities such as Paris, Boston, and Barcelona, which allow commuters to pick up a bicycle from any number of stations within a city, ride it to their destination, and drop the bike off at another station. This one-way rental model allows for flexibility in commuting because users can pick up and drop off at different stations. Thus, the vehicle utilization rate is greatly improved because a shared vehicle is available to any commuter. In addition, shared vehicle systems reduce the total number of vehicles in a city, which can greatly alleviate urban congestion and air pollution. [2]

With shared electric vehicles fleets, a potentially emerging market in dense urban areas, the task of charging becomes significantly more complicated. Since users of these systems do not personally own the vehicles, they have less of an incentive to plug in the car to charge after each use, since they will not be making their next trip in the same vehicle. There are also issues with cable management and potential hazards with tripping and entanglement, as cars often need to be connected to chargers for several hours during charging (Figure 1). Furthermore, a higher turnover rate in users results in multiple drivers of a single vehicle throughout a day, which increases the number of people who must assume responsibility for plugging the car in after each use or when the battery is at low capacity. Finally, this increased utilization of electric vehicles results in electric power demand profiles that could potentially strain electric grids in locations with aging infrastructure or limited sourcing capacity.

Figure 1: The ZenCar program of shared electric vehicles in Brussels, Belgium employs standard charging cables for charging their fleet. As demonstrated in this image, the charging cables can cause tripping and entanglement hazards, and there is no mechanism to prevent severing or vandalism of the charging cord.

Along with the inclusion of lightweight electric vehicles such as electric bikes and scooters in shared mobility systems, there is an additional need for locking vehicles when they are parked at charging stations since the vehicles are not massive enough to prevent theft, even if equipped with a keyed ignition system. Thus, there is an opportunity for the charging process to be unified with the docking process in a single intuitive connector. Currently with nonelectric vehicles, users return their vehicles to a station that typically incorporates a locking mechanism, which communicates to the kiosk and a central information system that the vehicle has been returned. In the case of electric vehicles, this locking system also provides an opportunity to make a charging and data connection to the vehicle's battery management system. Once the vehicle is returned to the rental station, it can begin automatically recharging through a simple and intuitive connector. The station can then use ambient information such as diffused LED lighting to provide instant, visual feedback to users on the state-of-charge of vehicles, availability state (i.e. reserved or unreserved), and maintenance information for fleet operators.

The integrated docking, charging, and ambient information station presented in this thesis has several advantages over traditional mechanisms for charging electric vehicles. While many designs and standards for electric vehicle chargers exist today, most of them simply replicate the aesthetics of a gas pump. For example, many chargers feature a central unit, which is typically mounted to a wall or a pedestal, and a sizable handle with an electromechanical interlock that can be connected to a car and joined to the station with a thick, insulated cable. These cables can cause numerous hazards such as tripping or entanglement and are subject to significant wear and tear when exposed to outdoor environments and repeated use by many customers throughout the day. An integrated docking and charging system for lightweight vehicles improves the urban design quality of electric vehicle rental stations, allows for quicker turnover in vehicle rentals, and ensures that vehicles are put back to charge after each use. By incorporating the locking and charging into a single structure, the added process of requiring a user to plug in the vehicle after use will streamline the pickup and dropoff processes, and eliminate the scenario in which users forget to plug in their vehicles after use. Meanwhile, the integrated ambient information systems allow users to obtain real-time information about the vehicles without having to interact with a kiosk or mobile device. For example, a user in a hilly city may wish to pick up a fully charged, shared electric bicycle for an uphill trip. Meanwhile, another customer with a less strenuous commute might be fine with taking a pedal-assist vehicle that is only partially charged, perhaps at a discounted price. With the addition of an ambient information system to the docking station design, the user would be able to quickly glance at the station from afar and immediately determine which vehicles are charged and available. When connected with distributed information systems that are accessible through the Internet and mobile devices, the station becomes an intelligent element in a networked system of urban infrastructure that can greatly enhance the efficiency and utilization rate of shared vehicle systems.

The primary application of this docking, charging, and ambient information system is to electric vehicle sharing stations. Electric vehicle sharing programs have only begun emerging recently, so infrastructural designs for charging stations are still immature. Most stations simply employ a cabled or battery swapping scenario, which is not ideal for a number of reasons described above. The prototype presented in this thesis could potentially be designed for manufacturing and robustness, and eventually commercialized for broad applications to shared systems of electric bikes, scooters, and new lightweight electric vehicle classes.

In addition to the design and user interface concerns associated with fleet vehicle charging, the subject of scaling electric vehicle charging infrastructure to cities – particularly infrastructure that supports rapid charging – is explored. This thesis explores the tradeoffs between charge time and power draw from a systems engineering perspective, while acknowledging the transportation-driven necessity for a rapid charging solution. Though a number of technical and economic challenges have slowed the widespread deployment of rapid chargers, a mitigation strategy for overloading the electric grid with charging vehicles is presented. This strategy is based on the use of a DC battery buffer that can be placed between the grid and vehicles. This buffering strategy was designed and the necessary technical equipment and conversion elements are specified as part of this research, but have yet to be tested.

{II} Related Work & Prior Art

Shared vehicles systems are by no means a new concept. Community bicycle sharing programs trace their roots to northern Europe, where shared community bicycles have been available for public use through informal programs in cities like Amsterdam and Copenhagen since the 1960s. Many of these early programs suffered from severe theft and vandalism, as the bicycles were often rented on the honor system and there were no systems for automation of rental and locking processes. Various strategies such as coin deposit systems, requiring personal identification, and the use of customized parts and paint colors for shared bikes were employed through the last quarter of the 20th century with limited success. The rise of information technology such as electronic payment systems and networked kiosks with secure, electronically actuated locking systems contributed to the development of the first IT-based bike sharing programs in the early 21st century. Velo'v in Lyon, France was deployed in May 2005 and is commonly cited as the first modern bike sharing system, incorporating modern IT infrastructure to streamline the rental and return processes while reducing vandalism and theft. The Velo'v pilot gave rise to Paris' world-renowned Vélib' bike sharing program in 2007, which in turn kicked off a global proliferation of IT-based urban bike sharing programs. As of May 2011, there were nearly 150 bike sharing programs worldwide, with Europe leading in the prevalence of systems. [3] In the United States, Boston, MA deployed its Hubway bike-sharing program in 2011 and New York City will launch its Citibike bike share program in July 2012. [4]

Today, many cities and urban dwellers view vehicle-sharing programs as an increasingly viable alternative to owning private vehicles and a strong complement to public transportation that addresses the first mile/last mile issue with transit. In addition to bicycle sharing programs, IT-based car sharing programs have also witnessed prolific growth in the first two decades of the 21st century. Companies such as Zipcar and car2go have demonstrated the commercial viability of car sharing systems in the US and Europe. Zipcar, the world's largest car sharing network, is based in Cambridge, MA and has major operations in fifteen North American and European cities. As of May 2012, the company reported over 709,000 members and 2012 first quarter revenue of $59 million. [5] Zipcar's well-publicized success has inspired the creation of dozens of similarly structured vehicle sharing services around the globe.

While car sharing programs are certainly a major step in the right direction and contribute to reduction of private vehicle ownership, most of the vehicles used in car sharing systems today are traditional gas-powered vehicles and are not optimized for vehicle sharing. However, electric vehicles are gradually making their way into vehicle sharing programs. car2go, a subsidiary of Daimler North America, piloted the first North American all-electric car sharing program in San Diego, CA in November 2011. The San Diego system employs 300 smart "fortwo" two-passenger electric drive vehicles. [6] ZipCar is also currently experimenting with a small number of commercially available shared electric vehicles, with a handful of EVs available to members in cities such as Cambridge, San Francisco, and Chicago. [7]

2.1 – Mobility on Demand

The Changing Places and Smart Cities groups at the MIT Media Lab have been pioneering the development of electric vehicles and mobility systems that are optimized for shared urban use. The cohesive vision for this urban transportation system is known as Mobility-on-Demand (MoD). In order to enable non-incremental gains in reduction of urban pollution and congestion, MoD outlines a plan for a shared vehicle ecosystem based on lightweight electric vehicles that were designed and prototyped at the MIT Media Lab. Unlike Zipcar which functions on a two-way rental model, MoD operates like bike sharing programs, which allow users to pick up and return vehicles at different stations. This allows users to use MoD as a viable commuting solution, because they do not need to rent a vehicle for an entire day to use it for a brief trip to or from the workplace. In addition, the vehicle rental is truly "on demand," allowing users to pick up any available vehicle at a charging station without an advance reservation. Another important distinguishing feature of MoD is the multi-vehicle ecosystem that forms its backbone. Rather than employing traditional gas engines and large, four or five passenger vehicles that are ill suited for urban trips, MoD is based on a fleet of compact electric vehicles that are optimized for urban driving. These vehicles are powered by all electric drivetrains, have no onsite emissions, and incorporate a variety of features and engineering design to make them lightweight, compact, and maneuverable in dense cities. They are also optimized specifically for vehicle sharing programs, reflected by features such as highly energy dense batteries, modular architecture, and low-maintenance design. [8]

As of 2012, three vehicles have been fully developed in the MoD ecosystem (an electric bicycle, scooter, and car), and a fourth vehicle is currently under development. With MoD, users can take the minimum footprint vehicle required for their trip type. For example, a trip to pick up a child from school on a pleasant day could involve taking a shared electric bicycle for a five-mile journey to the school. A shared electric car could be selected for the return trip to accommodate the extra passenger and any necessary cargo such as backpacks and sports equipment. The current MoD vehicle ecosystem is now presented in detail.

2.2 – GreenWheel

The GreenWheel is an electric bicycle wheel that contains all its complexity in the wheel unit itself. It features an in-wheel electric motor, motor controller, and planetary gearbox, which are surrounded by circumferentially placed Lithium iron phosphate batteries. This wheel can be retrofit onto any existing bicycle frame to turn it into an electric bicycle. Thus no modifications to the frame are necessary and since the vehicle operates on either pedal-assist or a wireless throttle, no wiring between the wheel and the handlebars is necessary (Figure 2).

Figure 2: The GreenWheel prototype, designed by the MIT Media Lab Smart Cities group.

2.3 – RoboScooter

The RoboScooter is a lightweight, folding electric scooter (Figure 3). The vehicle weighs approximately 40 kg so it can potentially be folded by the user and carried onto public transportation systems such as buses and subways. The RoboScooter is based on "robot-wheel" technology, incorporating in-wheel motors, suspension, and braking into the wheel unit itself. This frees up space in the body of the vehicle and is enabled by the fully electric drivetrain. Steering is managed through a fork-steering system with the handlebars.

Figure 3: The RoboScooter prototype, designed by the MIT Media Lab Smart Cities group and manufactured in conjunction with lab sponsor SYM Sanyang Industry Co. The left image shows the scooter in the unfolded, driving mode while the right image shows the scooter in its folded, parking mode.

2.4 – CityCar

The CityCar is a folding, two-passenger electric car. The CityCar folds up to reduce its footprint by approximately 40%, thereby providing significant space savings compared to a standard vehicle. In fact, three folded CityCars can fit in the area occupied by one traditional sedan. It incorporates robot-wheel technology, including in-wheel drive motors, steering, suspension, and braking. The CityCar is a front ingress/egress vehicle and its folded length is comparable to the width of a traditional automobile. Thus users can park the car "nose-in," and step directly onto the curb without the hazard of opening a side door into oncoming traffic or blocking bike lanes. The vehicle is also fully drive-by-wire, meaning that there is no mechanical connection between the driving interface and the steering systems. Rather, the driving interface sends electronic signals to the driving and steering motors, allowing for significant reduction in component weight and mechanical complexity of the drive train. The electronic driving control paired with the robot-wheel architecture enables the vehicle to be highly maneuverable, as it can spin on its own axis in an “o-turn.” The CityCar is constructed largely from lightweight, recyclable materials such as aluminum and structural glass. In 2010, a Spanish sponsor of the MIT Media Lab licensed the CityCar concept and provided directed research grants to take the vehicle from half-scale prototype and concept design to a full-scale, functional car. The first full-scale prototype of the CityCar was debuted in January 2012 after a two-year design effort involving a team of MIT Media Lab researchers and a consortium of Spanish companies, brought together by the Hiriko consortium (Figure 4). The development of the Lithium ion battery systems and high voltage electronic architecture for the full-scale CityCar encompassed the first year of my Master’s research, which ultimately laid the groundwork for the infrastructural research presented in this thesis.

Figure 4: The first full-scale prototype of the Hiriko CityCar, designed by MIT Media Lab researchers in conjunction with the Hiriko consortium.

2.5 – Persuasive Electric Vehicle (PEV)

The PEV is the latest addition to the MIT Media Lab's MoD fleet, and is a unique type of single-passenger vehicle designed to address numerous societal issues such as congestion, pollution, obesity, and energy inefficiency. The PEV is a pedal assist, three-wheel electric vehicle that is designed to operate in bicycle lanes. The PEV can function as a fully electric vehicle, a fully human-powered vehicle, or a variable power-assist vehicle. Today, people find endless excuses not to use bicycles for transportation, and the PEV seeks to mitigate these problems. It is designed to be accessible by the young, the elderly, businesspeople in suits and skirts, and the average commuter. It also can provide shelter from the elements through a modular or removable enclosure screen. The PEV is paired with a mobile interface that offers incentives to encourage human power exercise. Initial concept designs and a structural model for the PEV have been completed, so the next phase of research will involve developing the concept designs into a full-scale, functional prototype. An initial concept rendering of the PEV is shown in Figure 5.

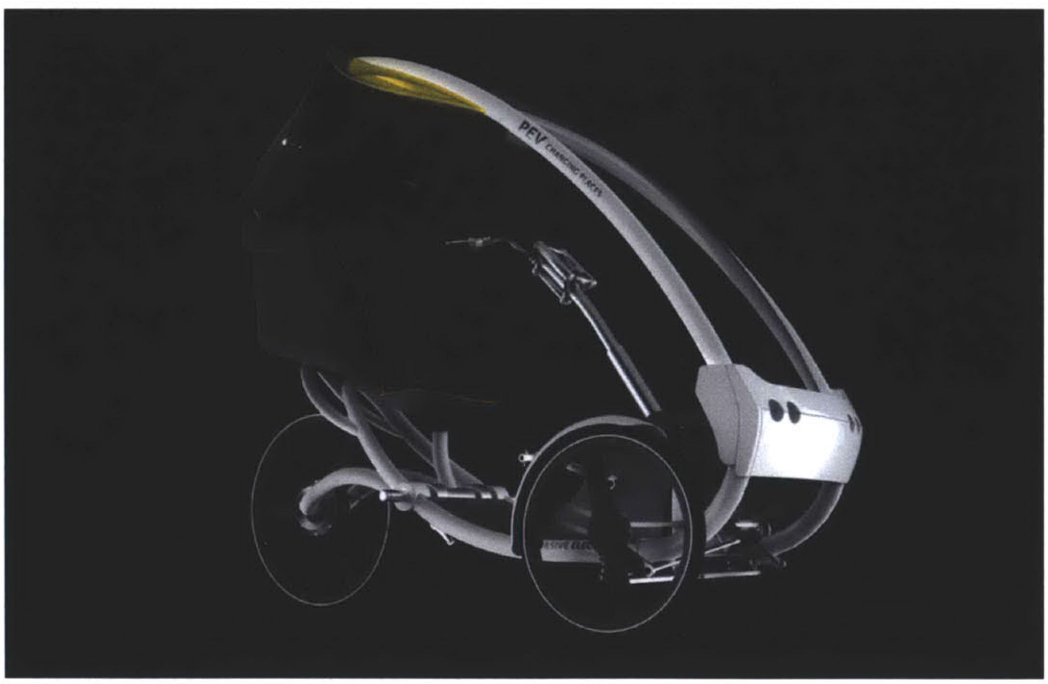


Figure 5: Concept rendering of the Persuasive Electric Vehicle (PEV). The PEV is designed to democratize access to bike lanes by providing a pedal-assist, hybrid human/electric-powered vehicle that can be used by all demographics and promote exercise.

When coupled with the necessary rental infrastructure and IT network, these vehicles and other lightweight EVs designed for urban sharing systems enable a new model of mobility ecosystem that is flexible, efficient, and clean. With the integration of electric vehicles into sharing programs, the existing challenges of parking, locking (for bikes and scooters that can be stolen), and registering vehicle return is further complicated by the need for electric charging infrastructure. Unlike traditional vehicles that store their onboard energy with highly energy-dense gasoline, electric vehicles need to be charged on a regular basis due to the comparably low energy density of current battery technology. Thus, parking areas for shared electric vehicles will need to be coupled with charging stations that are connected to the electric grid.

2.6 – Existing Vehicle Sharing Service Stations

A number of systems for docking and locking shared vehicles such as scooters and bikes exist in the commercial and research space. However, few of these systems are tailored for electric vehicle recharging and those that are typically require a separate charge plug or cable to be inserted manually after docking. Ambient information systems are also growing more common throughout cities and the transportation space, particularly in parking garages and on street with smart parking meters. This section presents a sample of relevant technologies in the commercial space that this thesis builds on.

Automated shared bicycle rental systems are now ubiquitous in many European and North American cities. These systems, such as Vélib' in Paris and Hubway in Boston, incorporate a variety of docking and locking strategies for affixing vehicles to the station. The Boston Hubway program uses infrastructure operated by Alta Bike Share that employs a front docking mechanism. The user pushes the front wheel of the bicycle into the alignment guides and the front of the bicycle frame locks to the station with a latch that is released by an RFID key fob for annual members or a temporary access code that is provided to the user after a one-time credit card payment (Figure 6) [9].

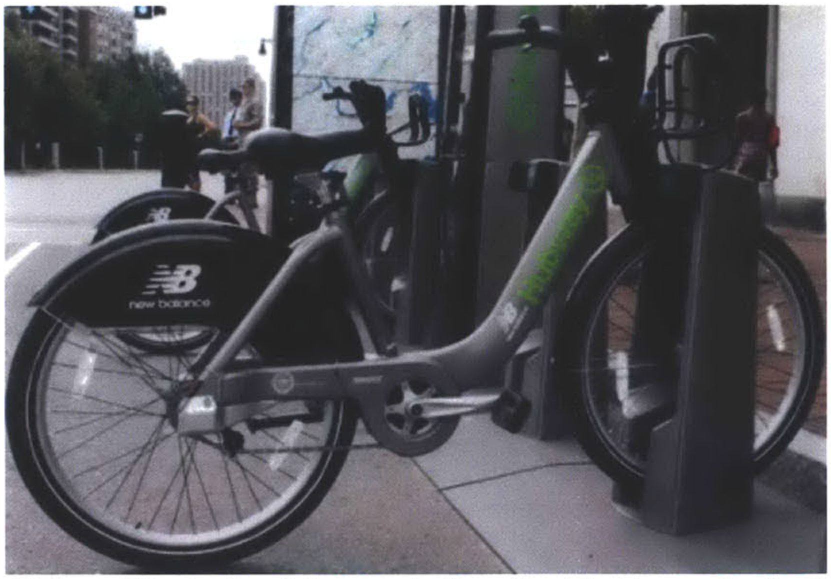


Figure 6: A Boston Hubway bike sharing station, employing a front docking mechanism in which users push the front wheel into an alignment dock while the front of the frame locks to the station.

A precedent for electric bike sharing stations is demonstrated at the University of Tennessee, Knoxville, where the USA's first automated e-bike sharing system was introduced in September 2011 (Figure 7). These stations mechanically dock electric bicycles with user-removable batteries that can be swapped out for charged batteries from a central battery charging and vending system. [10] This system employs battery swapping rather than real-time charging of vehicles, which requires extra time and effort on the part of the user and could result in battery theft or vandalism. Furthermore, battery swapping requires a surplus of batteries within a system (i.e. 1.5 or 2 times as many batteries as bikes), which drives the cost of the system up because Lithium batteries and their management systems are the primary non-commoditized components of electric vehicles and are still very expensive. Battery swapping also necessitates the inclusion of extra infrastructure to vend and recharge the batteries, adding to the cost, complexity, and size of the station. Battery swapping has also been explored for automotive applications by companies such as Better Place, which are creating robotic battery swapping stations. However, the incredibly high cost and complexity of these stations, the need for a surplus of batteries, and the severe limitations that a swappable battery imposes on vehicle design have greatly impeded the progress and commercial viability of these technologies.

Figure 7: An electric bicycle sharing station at University of Tennessee, Knoxville. The central unit is a battery recharger and vending machine that is connected to electrical infrastructure via a central conduit, visible on the brick wall. This station utilizes battery swapping rather than an integrated charging and docking system.

An additional set of precedent installations worth mentioning are the electric motorbike charging stations that have recently been deployed in the cities of Paris and Barcelona. For example, Barcelona has recently deployed fifteen electric motorcycle and scooter charging stations for public use throughout the city. These stations, designed by a company called Mobecpoint, offer EV charging through a wired, conductive solution that employs a typical charging cable and plug (Figure 8) [11]. Since these systems are not designed for shared vehicles, they do not employ a locking or docking mechanism that is suited for fleet vehicle applications. Rather, users have the option of locking their vehicle with a separate chain to the post, or simply relying on the keyed ignition system to prevent theft.


Figure 8: Electric Motorcycle Charging Stations in Barcelona, designed by Mobecpoint. These stations employ a standard charge plug and do not incorporate a docking or locking mechanism.

2.7 – Transportation-Related Ambient Lighting Systems

The ubiquity of wireless networking and solid-state lighting technologies has spurred the exploration of urban lighting systems that convey context-sensitive information about real-time events and object states in the city by urban theorists and designers alike. In his 2005 book *Placing Words*, William J. Mitchell presciently described the emergence of independently addressable lighting systems that form "time-based expressive medium[s]" in modern cities:

> *"Some of the most dramatic recent developments have been in lighting. Here, increasingly tiny and efficient solid-state devices – particularly LEDs, light-emitting diodes – are challenging the bulky glass spheres and tubes that we have known for so long. LEDs can vary their intensities and colors. They can readily be embedded in strips of tape, or arrayed on surfaces. These arrays can be dense or sparse, and on opaque, transparent, or optically variable substrates to provide a huge variety of effects. Lighting is becoming a function of surfaces rather than of discrete fixtures, and the difference between lighting and information display systems is rapidly vanishing."* [12]

Building on this technology, a number of transportation-related technologies incorporating ambient lighting systems have emerged. For example, precedents for the use of ambient information in parking systems are demonstrated in many covered parking garages that use colored LED lighting to indicate space availability and networked, digital signage to offer real-time information on the number of available spots. These systems typically employ ultrasonic or passive infrared sensors to detect a vehicle in a parking spot, and display a red light to mark the spot as occupied and a green light to denote a spot's availability (Figure 9) [13]. These systems streamline traffic flow within covered parking garages and reduce the amount of time that drivers spend looking for parking by providing simple and intuitive ambient lighting cues to drivers.

LED-driven, digital signage has also been introduced to public transportation networks over the past decade, such as dynamic information displays that provide information on the arrival of the next bus or subway train. These systems function as important tools to commuters, giving them real time information on transit timings and allowing them to alter their mobility behavior based on wait times or service delays due to maintenance, congestion, or emergencies (Figure 10) [14]. While these systems fall under the category of urban information lighting systems, they are not explicitly ambient because they simply use LEDs to spell out textual and numerical information.

Ambient lighting does play a role in most public transportation systems, but it is typically in the realms of blue-light emergency intercoms that only employ static, constant-color lighting.

Figure 9: LED-based ambient information systems in parking garages provide real-time feedback to users about which parking spots are available. Green LEDs indicate available spots while red indicates occupied.

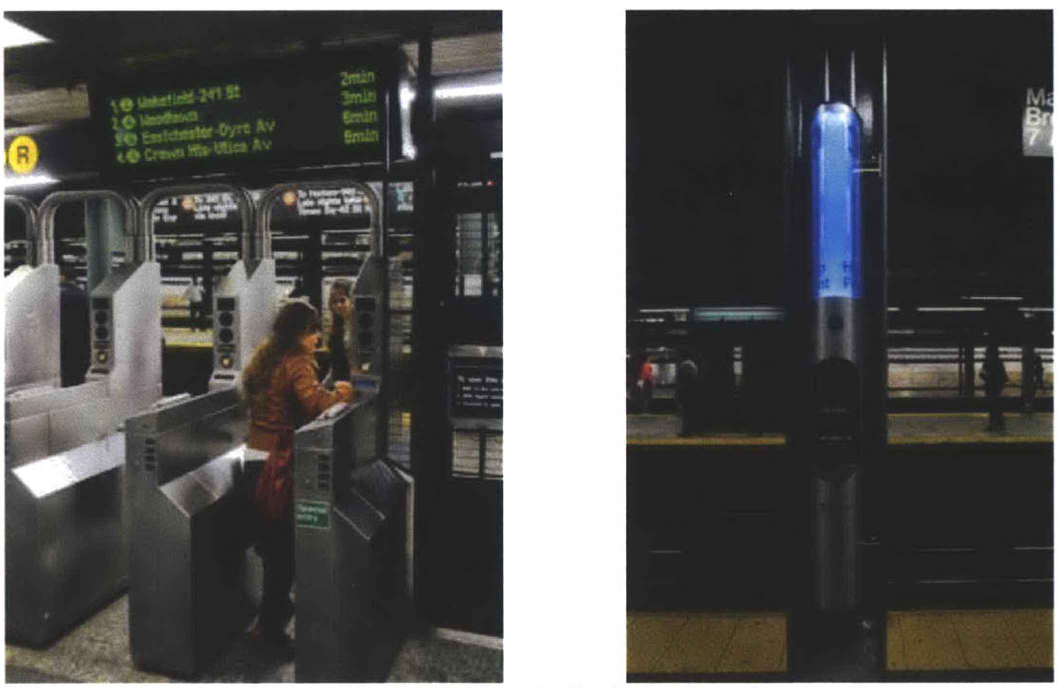


Figure 10: Interventions based on solid-state lighting technologies have improved commuter experience in public transportation systems by employing real-time urban information and ambient lighting. On the left, a train arrival information sign in a New York City MTA subway station. These train arrival signs provide real-time information on the status of incoming public transit vehicles and allow users to dynamically adjust their mobility choices based on this information. On the right, an NYC MTA "blue-light" help point intercom that is illuminated by a soft blue light. These intercoms allow commuters to easily report emergencies and incidents or simply request help from an MTA employee.

2.8 – Traditional Electric Vehicle Charging Infrastructure

It is also worth commenting on the current design of most traditional electric vehicle charging stations. Most charging stations mimic a gas pump aesthetic, employing a wall-mounted or pedestal-stand control electronics box which is connected to the charge plug via a long cable. A wide assortment of charging plugs and standards exist today for electric vehicle. In this thesis, the SAEJ1772 connector was studied as a precedent for commercial charging station design because it is the most common standard in North American and was ratified by the Society of Automotive Engineers (SAE) for widespread use in the US and Europe. The SAEJ1772 standard is akin to consumer electronics standards, such as USB, in which the connectors and communication protocol are specified but manufacturers can create a range of devices with different formfactors and functionality. A range of charging station designs by Schneider Electric that are compatible with the SAEJ1772 standard is shown below (Figure 11) [15].

Figure 11: A range of commercial Level II electric vehicle chargers manufactured by Schneider Electric that are compatible with the SAEJ1772 standard. From left to right: (1) residential wall-mounted charging station, (2) commercial wall-mounted charging station, (3) commercial pedestal-mounted charging station, (4) commercial pedestal-mounted, dual-unit charging station.

There are a number of reasons for the replication of the gas pump aesthetic in the design of commercial electric vehicle chargers. One important reason is the familiarity of the system, as early adopters of electric vehicles would likely already be familiar with the form and functionality of a gas pump. Thus there is a lower technological barrier-to-entry for this technology by replicating the style of this well-known device. Furthermore, the long-cable design provides some key advantages in terms of flexibility. As charging station manufacturers design their hardware to work with multiple vehicle types, this flexibility is important, as the station must interface to vehicles ranging in size from compact city cars to large electric vans or trucks. In addition, the long cable allows for a variety of parking configurations and positions of vehicles. However, the long cables employed by these charging stations also have significant drawbacks. Principally, they are a major hazard when placed in urban environments. Tripping, entanglement, and possible severing of cables are very real concerns when considering outdoor urban applications. The cable design also lacks elegance and would likely not be welcomed in certain jurisdictions with tight restraints on urban design aesthetics. The long cable also provides an easy opportunity for vandalism, as there is no structural or secure element contained within it. Thus, these charging cables can be easily severed, resulting in uncharged vehicles, nonfunctional charging stations, and potentially safety hazards with exposed metal contacts that are connected to high voltages.

A brief study of the pros and cons of employing a traditional rubber-coated cable for charging vs. a stiffer but less flexible coating, such as stainless steel, is presented in **Table 1** below:

Table 1: Pro & Con Evaluation of Conductive Cord Housing

	Rubber-coated Cord	**Stainless-steel, Retractable Cord**
Pros	• Flexibility • Greater leeway for vehicle positioning	• Secure, more theft-resistant • Reduced tripping hazard • Can also be used for locking vehicle • Greater durability
Cons	• Tripping Hazard • Entanglement Hazard • Easy to Vandalize & Sever • Poor Urban Design of "cable droop"	• Limited flexibility • Higher material cost

{III} The smartCharge System

The principal design goal of the smartCharge system is to improve the aesthetics and functionality of public charging infrastructure for shared electric vehicles. As the constraints and use patterns for shared vehicles in public settings are quite different from charging electric vehicles in a private ownership model, the charging infrastructure has different functional requirements. Convenience and rapid rental/return processes were strong considerations, as users of shared vehicle systems are often commuters who are seeking to reduce total commuting time and streamline their travel experiences. Furthermore, since users do not own the vehicles, there is a decreased sense of responsibility, which can potentially lead to poor treatment of the vehicles such as neglect for their maintenance and charging needs. In the words of an old American adage regarding rented cars: "it's a rental, don't be gentle." smartCharge makes the vehicle rental and return processes simple one-step tasks that take less than five seconds each. A stainless steel, retractable cord further allows the station to function as a better urban design element, with reduced hazard of tripping and entanglement (Figure 12).

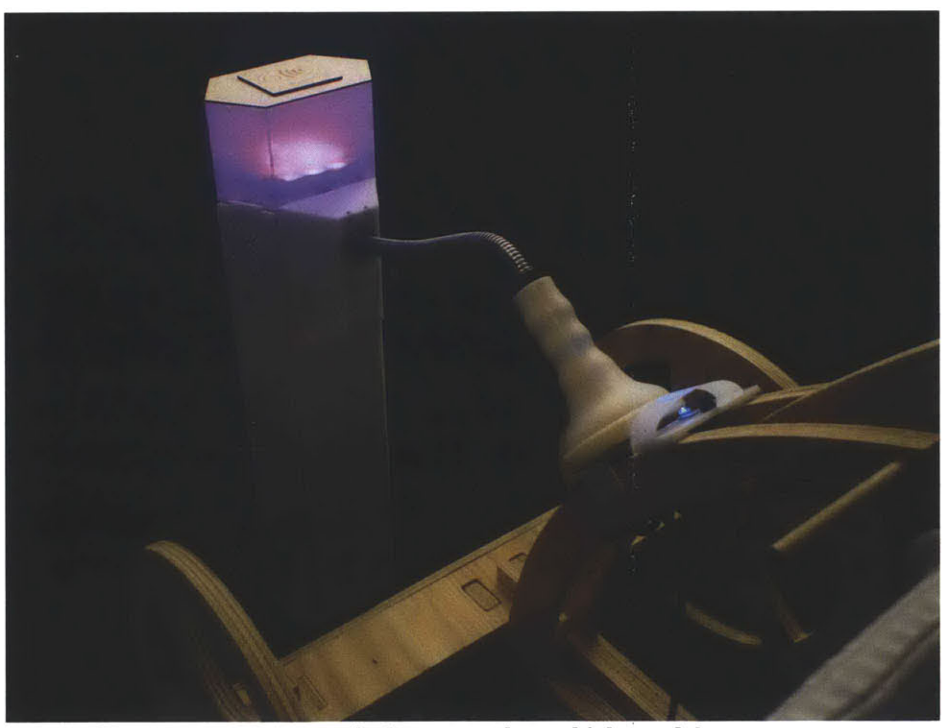


Figure 12: The smartCharge prototype attached to a wooden vehicle model.

3.1 – Rental Process

During the design phases of smartCharge, a primary concern was to streamline the dropoff and pickup processes for renting shared electric vehicles. Cues from existing vehicle sharing programs and electric vehicle charging stations were examined and optimized for simplicity. Bike sharing programs provide an optimal case study for this rental process, as they are currently the most common type of vehicle sharing systems in the world today. Using smartCharge, the rental process is as simple as tapping an RFID (radio-frequency identification) access card onto the top of the station (Figure 13). This platform could be easily extended to support NFC-enabled mobile devices, as access systems are moving increasingly towards mobile devices such as smartphones and tablets. RFID was selected due to the stability of the technology and the fact that serial-compatible RFID readers are inexpensive and widely available for commercial prototyping purposes.

Upon detection of a valid card, smartCharge stops the vehicle charging process by opening a high power mechanical relay, akin to the contactors that are present in high voltage charging systems. The system then changes the color of its ambient lighting system, alerting the user that the access card was valid and that the vehicle can be taken. Finally, the electromagnetic lock disengages, detaching the vehicle from the charging station and allowing it to be taken by the user. It is important to note that no charging current is flowing upon disengagement of the electromagnet, so there is no risk of electrical shock. The system is constantly performing a safety function loop to check for accidental disengagement, such that if the connector is somehow removed without a valid access card, charging will be immediately terminated. The entire rental process takes less than a second, but can be controlled with an operator-specified delay to increase the time delay between deactivating charging and releasing the connector. This time delay can provide a small safety window to ensure that any transients in the current flow are eliminated. In the prototype testing, a three second time delay was used for this purpose.

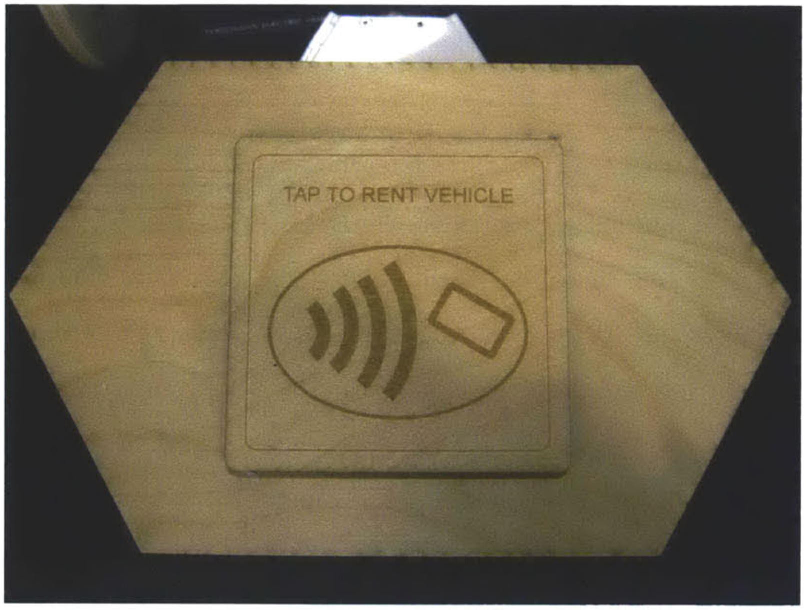


Figure 13: The top of the smartCharge prototype, featuring a laser-etched graphic that invites the user to tap an access card on the station.

3.2 – Return Process

Returning the vehicle is a similarly simple process, involving only a single step on the part of the user. The user can bring the vehicle to the station, and touch the connector to the vehicle charging port. The electromagnet immediately engages, locking the vehicle to the station. After a specified time delay for safety, the smartCharge ambient light cap changes color to indicate to the user that the vehicle has been properly returned and locked. The vehicle transmits information on its state-of-charge to the station, and smartCharge automatically starts charging the vehicle without any extra effort from the user. Since the vehicle transmits information to the charging station about its battery type and state-of-charge, smartCharge can dynamically determine whether to charge the vehicle. For example, if the battery is returned at 95% capacity, it is better for most battery chemistries to wait for additional discharge before recharging.

3.3 – Electromagnetic Locking

smartCharge locks and charges the attached vehicle with a single connector. Of primary importance is the integrated locking and charging functionality provided by the smartCharge system. Upon connection of the plug, smartCharge automatically locks the vehicle to the charging station with an electromagnet. For smaller electric vehicles such as bicycles and scooters, the locking functionality prevents the vehicle from being stolen during charging. For larger vehicles such as the CityCar or traditional electric cars, the mass of the vehicle is enough to prevent outright theft of the car. However, the locking functionality still serves to secure the plug to the vehicle during charging, preventing vandalism, disruption of the charging process, and risk of electrical shock.

The electromagnetic lock used in the smartCharge prototype is designed for home security and automation applications. This technology is akin to the electromagnetic locking systems used in RFID access-controlled doors in commercial and institutional environments. The electromagnetic lock consists of two pieces: (1) a primary electromagnet that is activated with 24V of DC power, and (2) a paired plate that securely latches to the primary coil when it is energized. Because the paired plate contains a tuned coil, the electromagnet will not latch to any metallic surface, but only the paired plate. Thus there is no risk of picking up extraneous metallic objects when the coil is energized. The electromagnet used in the prototype secures the vehicle with 250 pounds of holding force. In commercial applications, this holding force would need to be increased to 1000 – 2000 pounds to prevent vehicle theft, though the 250-lb magnet was sufficient in the prototype for proving the concept. Electromagnets of higher force are commercially available, though they can vary in size and formfactor. Integrating a commercial electromagnet with a holding force of 1000 pounds or greater would require at least a 30% increase in the size of the electromagnet.

When the station is vacant, the electromagnet is un-energized and no power is flowing through the connector. Thus it is safe to touch without risk of electrical shock or short-circuiting the system. Upon connection to the vehicle by the user, the smartCharge system conducts a handshake between the vehicle and the charging station. The first step of this handshake is to engage the electromagnetic lock, securely connecting the vehicle to the station. Once the vehicle is locked in place, the vehicle sends information on its battery state-of-charge, maintenance needs, and other service info.

The electromagnet is controlled with relays that are controlled by 5V logic sent from a central microcontroller board. The relay, an electrically operated logic-controlled switch, closes to provide current through the electromagnet and activate it, thereby locking the vehicle. Similarly, to deactivate the electromagnet and unlock the vehicle, the relay opens the circuit, leaving the electromagnet un-energized. Commercially available logic-controlled relay boards are common and can be used in the mass production of this type of system.

3.4 – DC Charging Interface

To optimize the smartCharge system for shared electric vehicles, we designed a custom DC charging interface. DC power transfer was employed because batteries store DC power for electric vehicles, so transferring AC power to the vehicle requires an extra conversion process onboard the vehicle which results in excess space and decreased efficiency.

The smartCharge prototype employs a DC charging system. The connector is capable of delivering up to 36A of DC power, as all of the wiring, PCB traces, and connection pins are rated for at least this amperage level. The integrated power supply delivers 24V of DC power because it was designed to interface with prototype electric vehicles in a laboratory environment. Thus the smartCharge prototype is capable of delivering 864W of DC power to the vehicle. However, this power supply could easily be replaced with a larger supply to be sufficient for Level II electric vehicle charging.

One of the user interface aspects of the smartCharge system addresses the complexity associated with inserting traditional charging plugs into a vehicle charge port. Because of the fixed location of multiple conductors, these handles require insertion from a highly specific angle. To mitigate this issue and reduce the complexity of charging the vehicle, the smartCharge system is designed with a rotationally symmetric connector. The connector interface was designed around the cylindrical electromagnetic plates, which measured approximately 1.86" in diameter. Thus both the male and female connector interface elements were constructed as annular shapes with sufficient space to place the locking electromagnet in the center. The connector features four conductive elements: power, ground, data positive, and data negative (Figure 14). These four conductive elements were chosen with the intent of allowing the smartCharge connector to serve as a universal charging element. Like a USB plug, which can transfer power and data to a variety of electronics devices, so too can smartCharge interface with existing EV charging plugs to provide a universally accessible formfactor for fleet operators.

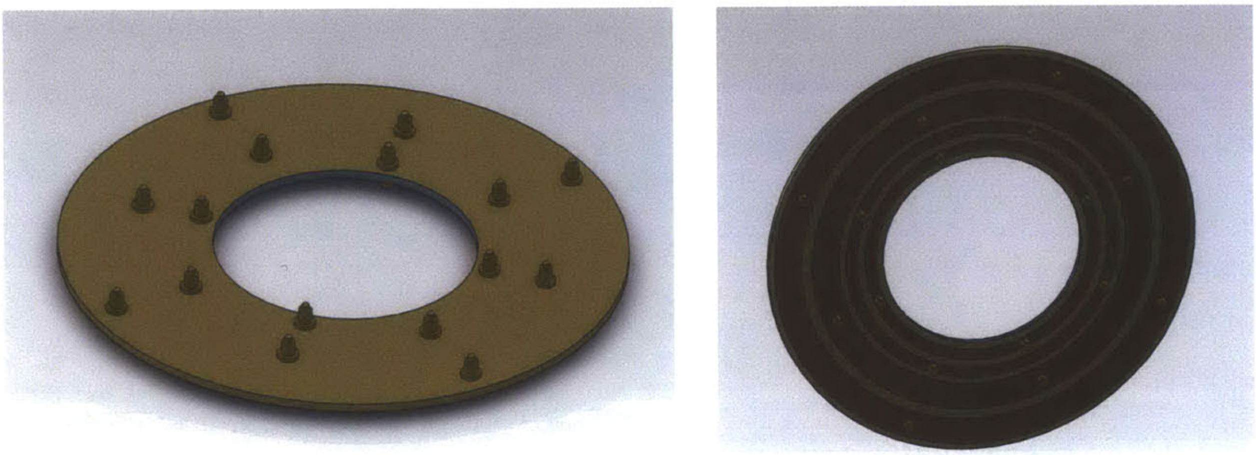


Figure 14: CAD models of the male-connector interface. The left image shows the top view while the right image depicts the bottom. The four conductors are each soldered to four spring-loaded pins, for a total of sixteen pins. Four pins were employed so that the connector would maintain rotational symmetry and to improve the current-carrying capacity of the connector.

The male side of the DC charging interface is based on a custom printed circuit board (PCB) that uses spring-loaded pins to transfer power and data. The spring-loaded pins were selected to provide a small amount of mechanical tolerance at the connection interface. The width of the traces was determined based on the current carrying capacity that was required for each conductor. For example, the inner two rings are thinner because they are only used for data transfer. However, the outer rings are used for power transfer so were sized adequately to carry sufficient current for Level II electric vehicle charging.

Four copper traces were etched from a copper sheet on a Modela milling machine and coated with solder to improve their conductivity (Figure 15). Spring-loaded pins were then mounted on the opposite side of the board from the copper traces, connecting to each trace and providing a rotationally symmetric conductive baseboard for the system. Wires were soldered to each of the traces to connect the male interface to the internal electronics of the charging station.

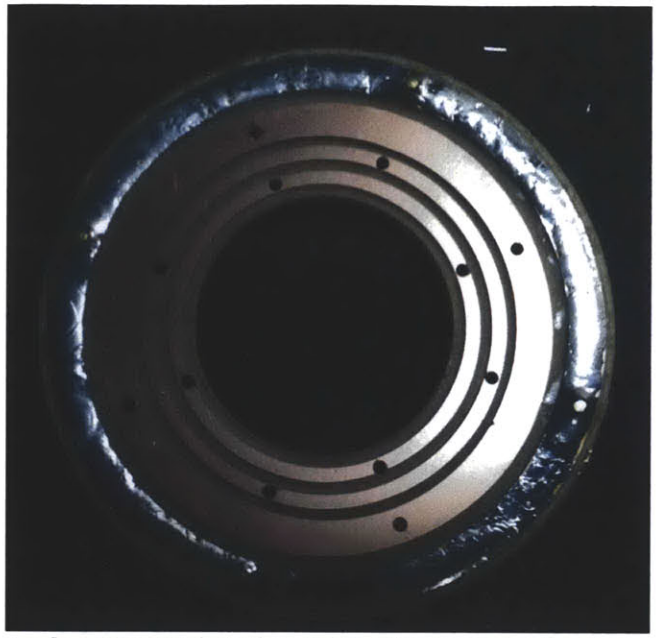


Figure 15: Assembly of the male connector interface PCB. The outer ring has been "tinned," coated in a thick layer of solder to increase its conductivity and the four spring loaded pins for the outer conductor have been attached. The remaining three traces are unassembled in this image.

The mating female connector that is mounted on the vehicle was constructed in a similar pattern. Instead of fabricating a custom PCB for the female connector, rings of ultra-conductive copper were cut on a waterjet cutter and separated with wooden spacers that were fabricated on a laser cutter (Figure 16 and Figure 17). Upon connection, the spring-loaded pins in the male connector make mechanical and electrical contact with the copper rings in the female connector. Wires were mounted to the female-side copper rings with silver-based conductive epoxy. This epoxy provided both the mechanical adhesion and electrical conductivity that were necessary for this interface. Though copper was used for the initial smartCharge female connector prototype, exposed copper planes are not suitable for commercial connectors in outdoor environments due to copper's tendency to oxidize. Conductive epoxy is similarly unsuitable for commercial applications. This is discussed further in Chapter IV, detailing evaluation and future work.

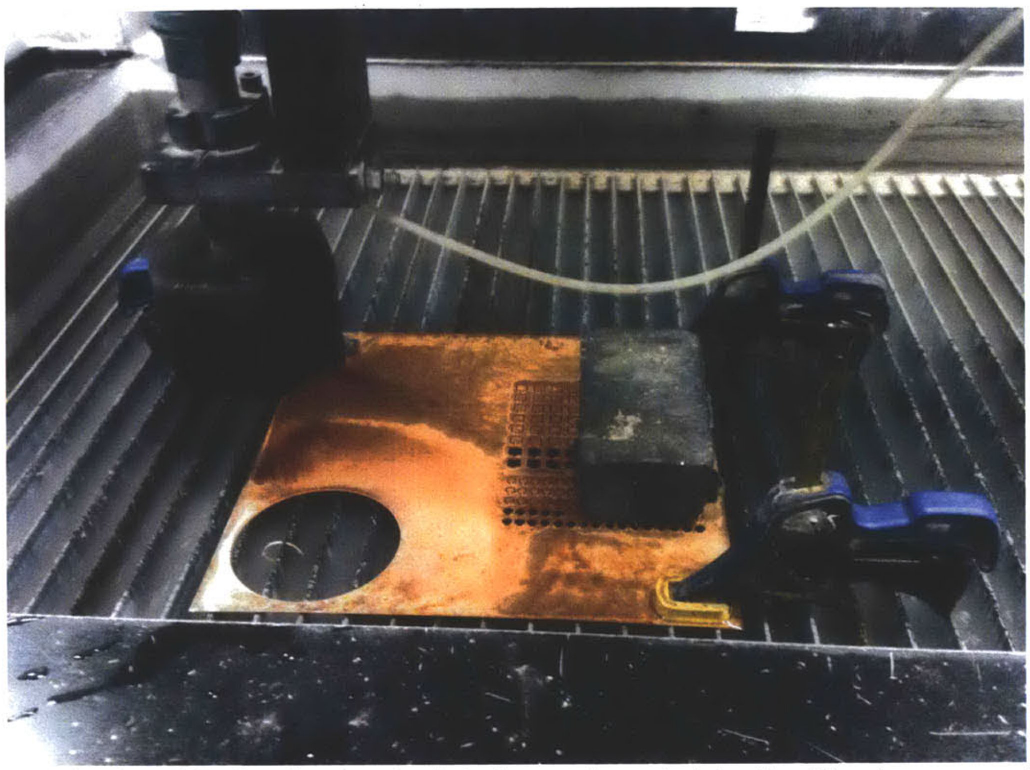


Figure 16: Fabrication of the female connector interface on the waterjet cutter. The rings were cut from a 1' x 1' sheet of ultra-conductive copper.

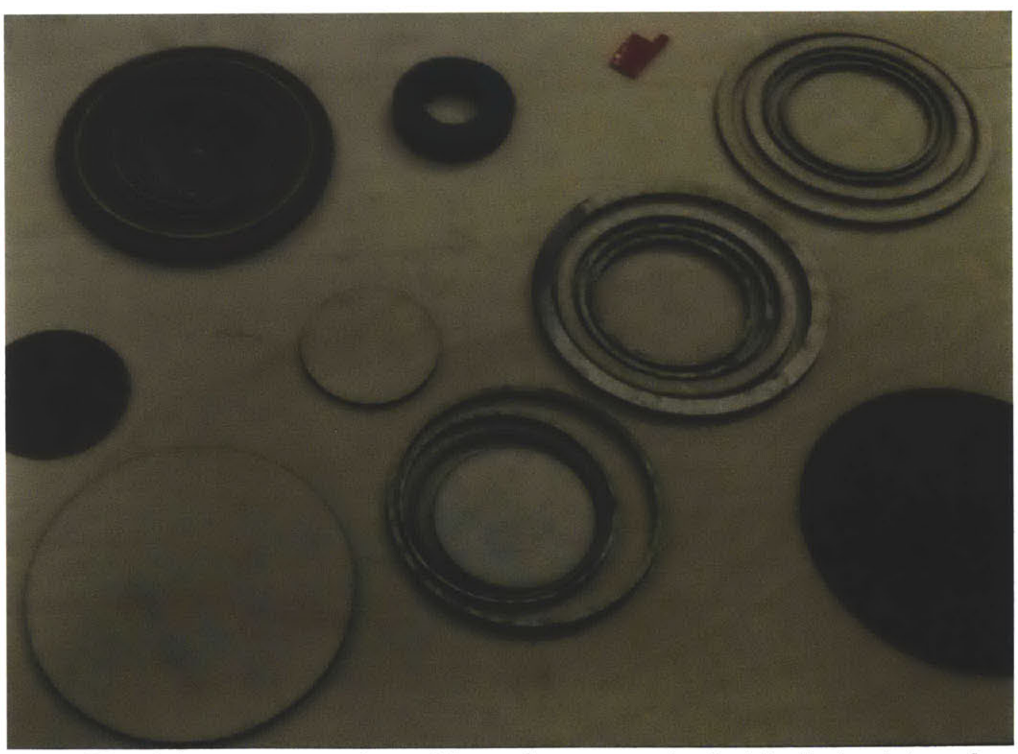


Figure 17: Assembly of the cut copper rings with wooden spacers to electrically insulate and mechanically separate the four conductive rings. The spacers were cut from 1/8" thick plywood on a laser cutter.

3.5 – Handle and Enclosure Design

Once the concentric connector design was established and the PCB was fabricated, the primary constraints for the electrical connection interface were fully specified. In addition, the mechanical interface was largely defined by the constraint that the electromagnetic locking system requires full planar connect to securely lock. The next stage of the design process involved fabricating the enclosures to fit around the electromechanical charging and locking hardware to provide a convenient and comfortable formfactor for the user. To maintain the aesthetics and design standard of the rotationally symmetric connector, it was determined that the handle enclosures should also be rotationally symmetric. The enclosure design was separated into two parts, male and female, each designed in the SolidWorks CAD software suite and fabricated from ABS plastic with 3D printing. The male enclosure attaches to the charging station and is held by the user while the female connector is attached to the vehicle and remains static. 3D printing was selected as the fabrication process based on the complex, nontraditional shape of the enclosures. The Dimension ABS printer at the MIT Media Lab was employed for fabricating both parts (Figure 18).

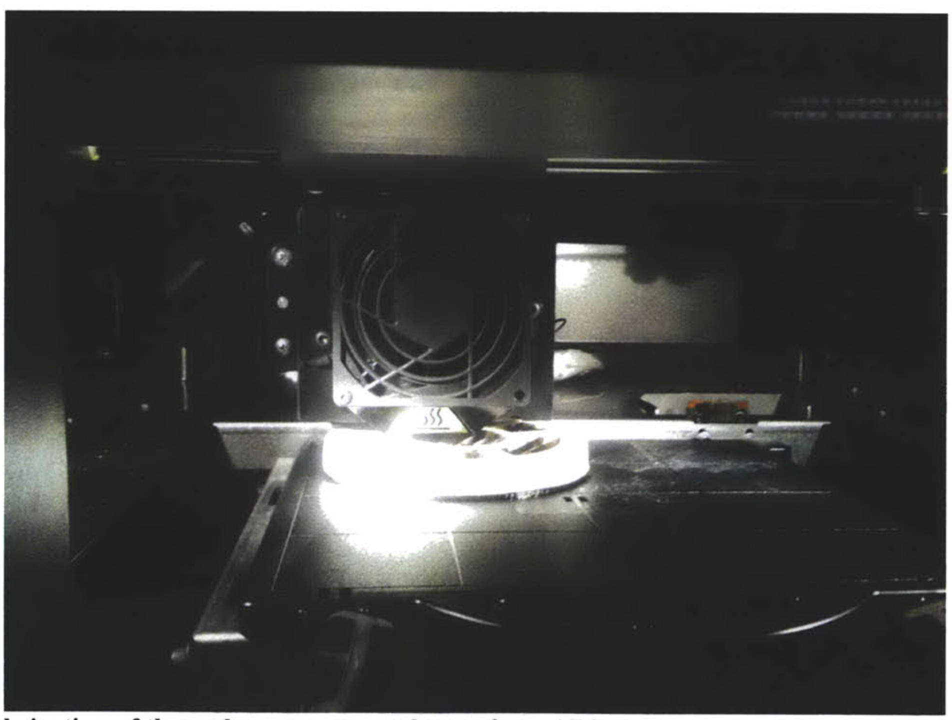


Figure 18: Fabrication of the male connector enclosure from ABS plastic in the MIT Media Lab's Dimension 3D printer.

The male connector was designed first, with the primary design goals of enclosing and securing the necessary hardware for the electromechanical charging and locking interface and providing a comfortable formfactor for the user to hold. It was determined through analysis of existing charging infrastructure that traditional charging station handles are largely replicative of gas pumps. This leads to consistently uninspired design in charging infrastructure that imposes blight upon urban environments and detracts from ergonomic functionality. Inspiration for smartCharge's male connector enclosure design was instead drawn from user-centrically designed devices incorporating ergonomic handles such as modern kitchen equipment.

As the planar surfaces of the electromagnets on each side of the connector required planar alignment, a well was created with a holding shelf for the locking coil of the electromagnet. Space for the PCB was then modeled around the magnet well, providing sufficient material thickness to allow for sturdiness of the part. A gently contoured external surface was modeled for the grip portion of the handle. Wire runs from the back of the connector PCB and the electromagnet were critical for maintaining electrical functionality and cable management. Four wires connect to the PCB while two connect to the electromagnet, for a total of six wires. Since material volume is directly correlated to the part price for 3D printing, the part was hollowed out as much as possible to reduce the volume of print material (ABS) while maintaining the structural integrity of the component. In addition, hollowing out the core of the handle resulted in reduced overall mass of the handle, requiring less effort on the part of the user to connect. The cost of 3D printing is currently prohibitive for manufacturing purposes, but this part could be fabricated with injection-molded plastic in two identical halves and joined at a small seam with screws or plastic welding for mass production. For this prototype, a ribbed structure was employed internal to the handle to cut down on material use while providing adequate support. The resulting assembly was an ergonomically functional handle with attachment wells for the PCB and electromagnet, and an internal wire run system to connect the electrodes through the cord (Figure 19).

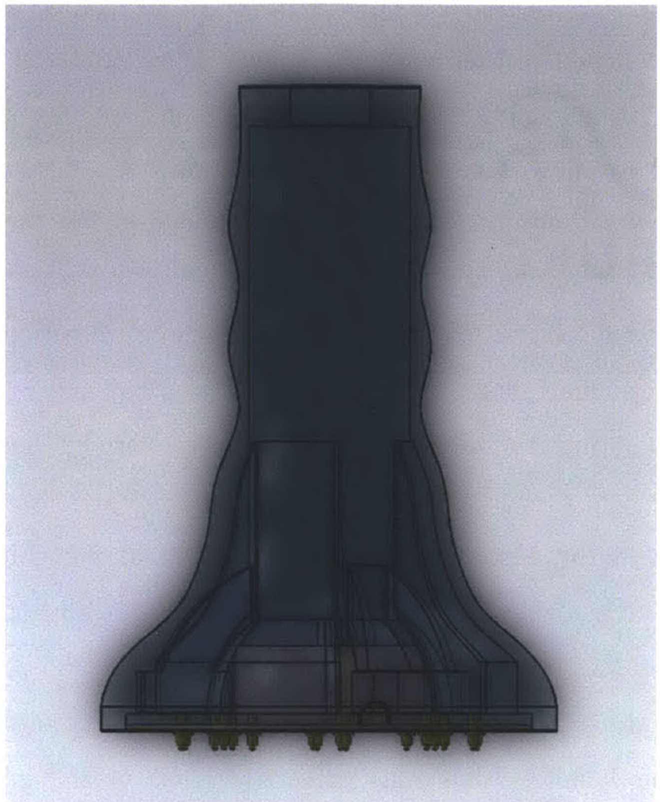


Figure 19: Front view of the CAD Model of the male connector assembly. The electromagnet is seated in a support well and attached from back with a mounting screw. The male PCB with spring-loaded pins is designed in an annular shape to fit around the electromagnet and provide a flat surface that is flush with the magnet.

Once the male connector enclosure was fabricated, measurements were taken with calipers to determine the level of error introduced by the 3D printing fabrication process. The electromagnet fit as designed into the well and the PCB socketed nicely into its holding tray around the electromagnet. The handle was qualitatively evaluated for ergonomics and was generally quite comfortable to use and aesthetically pleasing.

The design of the female enclosure consisted of a similar process. As there was no PCB for the female side, the waterjet copper rings were mounted with epoxy to a wooden backboard, which was lasercut to the proper dimensions. Wooden spacers were placed between each of the four electrodes to prevent electrical shorting and maintain their concentric alignment. Small notches were cut in the backboard using a laser cutter for wire runs from each of the copper plate electrodes. The female connector enclosure housed this assembly as well as the paired plate for the electromagnet. In addition, a permanent magnet was placed behind the electromagnetically activated plate to provide alignment assistance. This permanent magnet employed for connector alignment is similar to the technology employed by Apple's "MagSafe" chargers for laptop computers. The permanent magnet does not provide sufficient strength to hold the connector in place without the users assistance, nor does it lock the handle to the vehicle. Rather, it simply provides a small amount of "snap-in" force that gently assists the user in aligning the handle.

The female enclosure houses these three elements and they are secured with a mounting screw that is inserted from the front of the electromagnetic plate. The female connector also assists with alignment of the male connector, and provides external walls to prevent sheer force on the electromagnetic lock. Since the holding force of the electromagnet is rated for lateral force, it was important to account for sheer force in the mechanical design of the enclosure. Furthermore, these walls function to mechanically isolate the active electrical connections during charging, protecting users from electrical shock and keeping out dirt and moisture. Finally, the edges of the connector were filleted for aesthetic purposes (Figure 20).

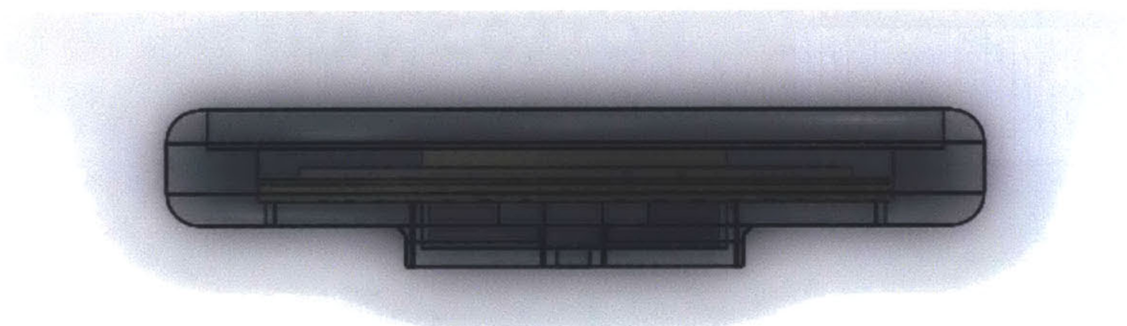


Figure 20: Front View of the CAD Model for the female connector enclosure. The enclosure houses the connector electrodes and their backboard, the electromagnetic plate, and a permanent magnet to assist with alignment. The walls of the connector are sized to allow for precise mating of the male connector and to prevent sheer force from disrupting the holding force of the electromagnet while the vehicle is locked.

The following series of images show the labeled CAD model of the full male/female connector interface from various angles, and the fabricated and assembled parts that create the full smartCharge connector assembly (Figure 21 – Figure 27).

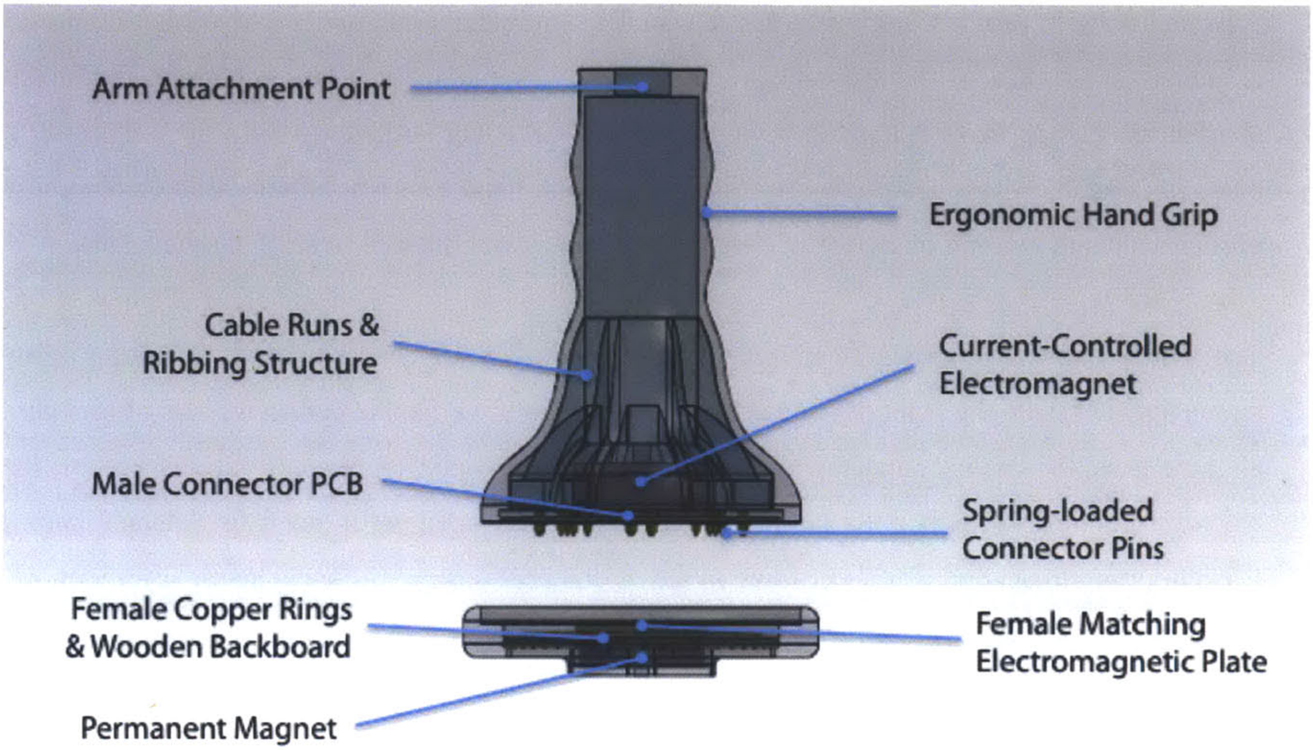


Figure 21: CAD Model of the complete male/female connector interface, including both male and female enclosures, the electromagnets, and the electrical interface. The wires are not shown to reduce clutter.

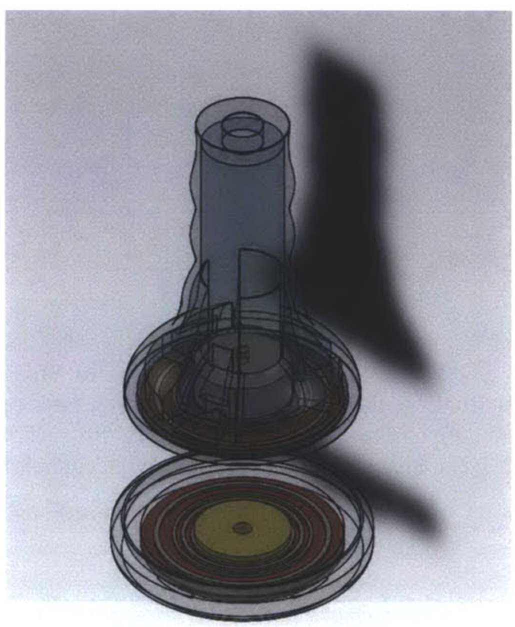


Figure 22: Isometric view of the male-female connector assembly. From this view, the top of the female connector can be seen in better detail. The matching female electromagnetically current-activated plate sits in the center, with a mounting hole in its center. It is surrounded by the four copper plates that make contact with the spring-loaded pins on the male connector. The copper planes are electromechanically isolated from one another with wooden spacers.

Figure 23: The fabricated and assembled male connector, held by a user. The female connector assembly is visible in the background, attached to a wooden model of a lightweight electric vehicle.

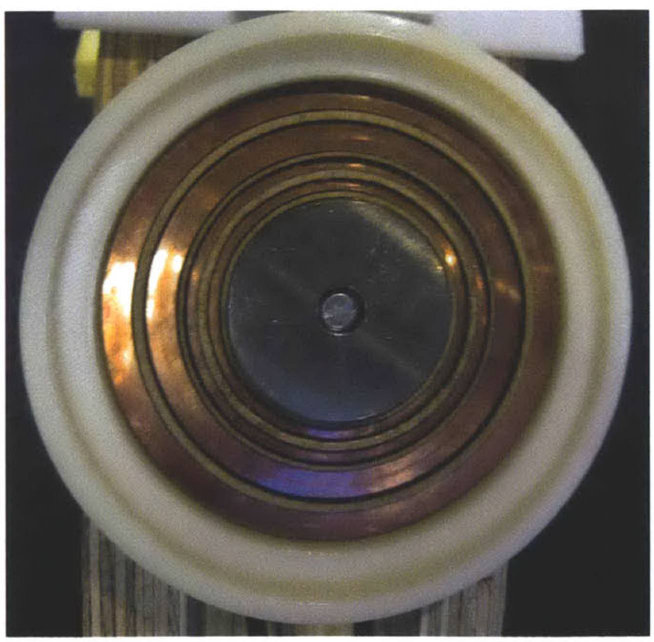


Figure 24: A close-up view of the fabricated female connector assembly. The 3D printed enclosure, fabricated from ABS, sits around the electromechanical interface, which consists of the copper rings, spacers, and the female electromagnet. The entire assemble is held together with a central mounting screw, which connects directly to the vehicle body for stability.

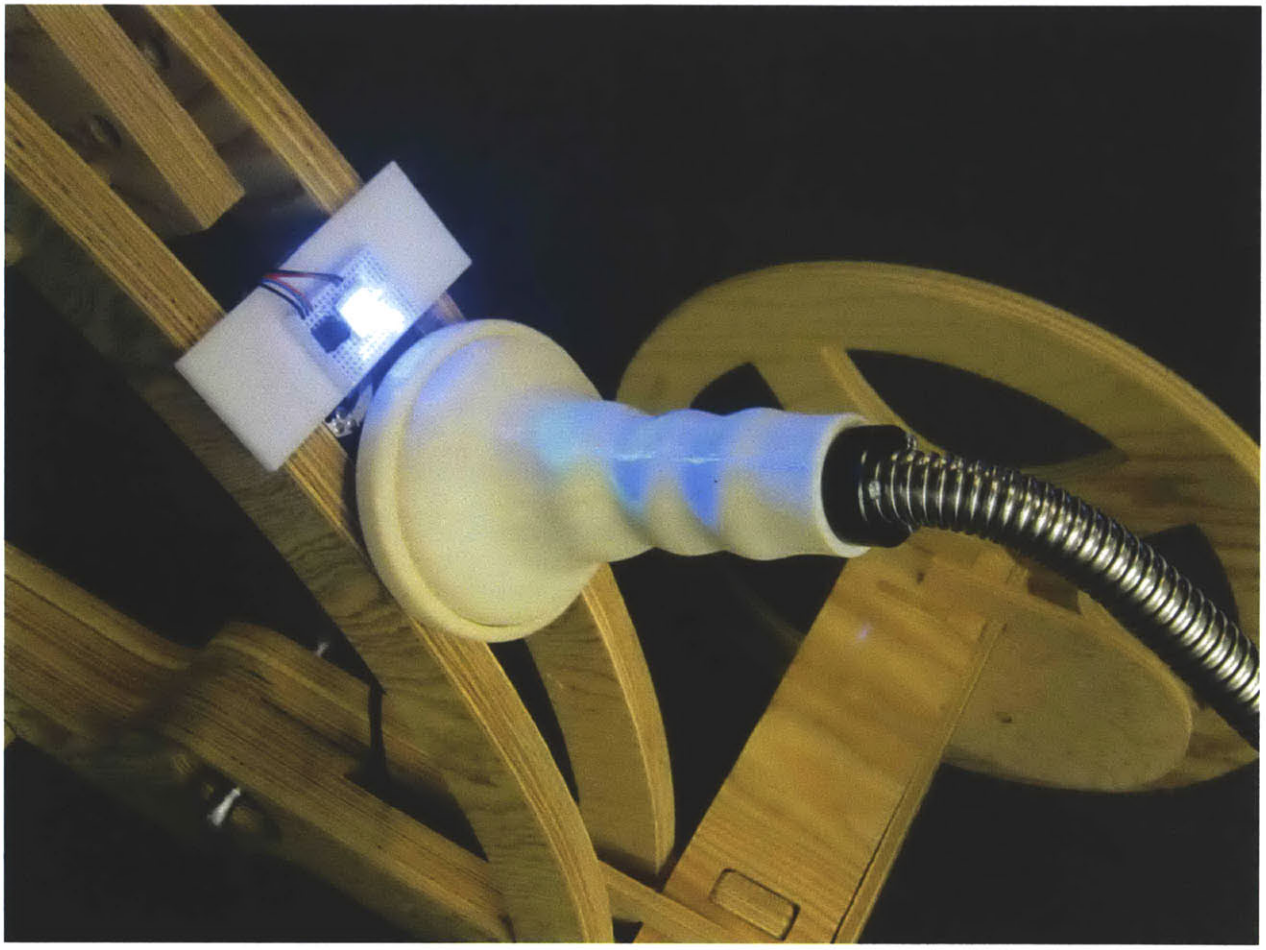


Figure 25: The full connector assembly in the locked position. When the vehicle is docked, the electromagnet securely attaches it to the station, so the handle is held in with force preventing theft of the vehicle and vandalism of the charging process. The vehicle is charging in this configuration, as indicated by the pulsing LED light.

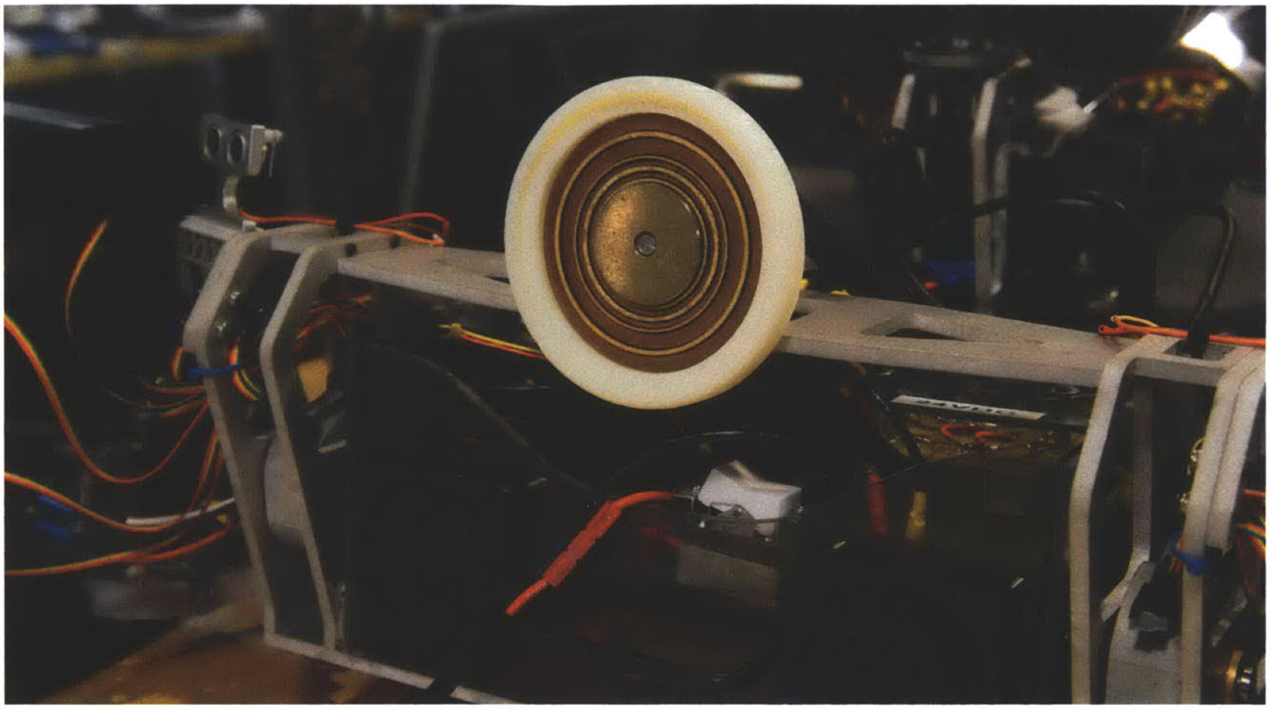


Figure 26: The smartCharge connector mounted on the CityCar half-scale prototype 2.0, demonstrating its compatibility with multiple vehicle types.

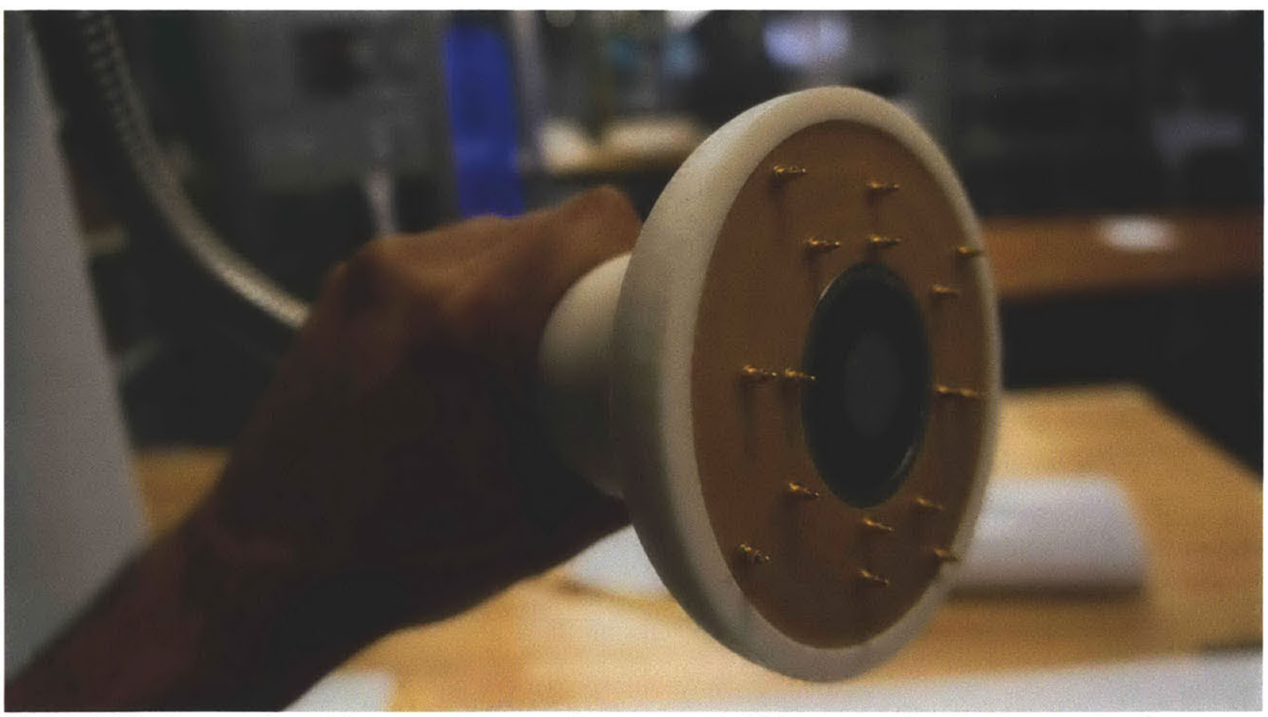


Figure 27: A closeup view of the smartCharge male connector held by a user, showing the rotational symmetry and the placement of the locking electromagnet and conductive power and data pins.

3.6 – Ambient Lighting System

smartCharge contains two ambient lighting elements, both of which are based on Philips Color Kinetics lighting systems. The Color Kinetics systems consist of strings of independently addressable LEDs that can be assigned any RGB value. These strings of lights are accompanied by power supply units and a host controller that communicates with a master controller, such as a computer or microcontroller, via Ethernet. Each power supply/host controller unit is capable of powering two strands of lights, which can range in length from 0 to 100 lights. smartCharge incorporates one Color Kinetics power supply/host controller and two independent LED strands for its ambient lighting systems.

The first lighting element is a simple charge meter that consists of five LEDs mounted to the back of the smartCharge station (Figure 28). When a vehicle is docked to the station, it constantly transmits its battery state-of-charge as an integer between 0 and 100. smartCharge rounds this integer to the nearest 20% interval and illuminates the appropriate number of lights. For example, a vehicle with 65% state-of-charge would result in three out of five lights illuminated while a vehicle with 95% state-of-charge would display five out of five lights illuminated. This system could easily be extended to higher granularity, though it was determined in the design process that five LEDs – translating into 20% granularity – would provide a good balance between resolution and clutter. This visual charge meter permits users to quickly glance at the station, and see which vehicles have the most charge. Users who are embarking on short trips would require less range and could potentially rent vehicles with 20% - 50% state-of-charge. It is worth noting that percentage of charge will correspond to different driving ranges, depending on the vehicle type and its battery capacity. Thus, it would be helpful for new users of a shared electric vehicle fleet to have driving ranges for relevant vehicles posted on the smartCharge enclosure. For example, a CityCar with a 120km range on full charge would provide approximately 60km of range when only half charged, which could be indicated visually on the station itself. However, a bicycle may only provide 15km of range on a half charge. New business models based on the variable price of electricity and rental rates depending on time of day and vehicle state-of-charge are also possible with this type of system.

Figure 28: The smartCharge system connected to a vehicle with approximately 80% state-of-charge. The charge meter is mounted to the back of the post and consists of five LEDs mounted in a custom 3D-printed housing, fabricated from ABS. In this prototype, the charge meter displays the vehicle state-of-charge in 20% increments.

The more sophisticated lighting element is smartCharge's custom-programmable ambient light cap. This light cap consists of nine Color Kinetics LED lights that are held in a square pattern with a custom housing, and shielded with a diffuser enclosure. These nine lights are programmed to act in unison, providing a bright visual signal that can relay information about the docked vehicle's state and maintenance needs. The enclosure for the light cap was fabricated by laser cutting transparent acrylic into six sheets, milling the edges to 120° angles to maintain the cap's hexagonal shape, and sandblasting the sheets to increase the opacity and diffuse the light. Originally, opaque acrylic was tested but it absorbed too much light to provide sufficient visual brightness. Sandblasting the transparent acrylic was a more time consuming process, but it allowed for precise tuning of the opacity to the desired level. The six sheets were then fitted together and epoxied to maintain their shape. A wooden sheet was placed on the top of the cap to prevent light from emitting vertically from the system and contributing to light pollution. The resulting enclosure acts as an aesthetically pleasing ambient lighting cap that gently diffuses the internal light. This diffuser enclosure also houses the RFID reader that allows users to rent vehicle from smartCharge.

This prototype of smartCharge is programmed to demonstrate several lighting cues, though the cap is easily programmed to show any RGB color. As such, this lighting cap can be custom programmed by cities or fleet operators to match their urban lighting standards. For example, some cities may find colored lighting in residential neighborhoods to be disruptive, so they can vary the color and intensity of the lights accordingly. Others may devise ways to harness the light caps for vehicle-related information display as well as public information, such as flashing the lights during public emergencies.

In the initial prototype, smartCharge's ambient lighting cap is programmed to display five lighting cues. The first three correspond to the state-of-charge of the vehicle. When the docked vehicle has less than 20% state-of-charge, smartCharge's post cap displays red. When the vehicle battery is between 20% and 60% state-of-charge, the light cap displays yellow. When the docked vehicle is above 60% state-of-charge, the cap is illuminated in green (Figure 29). While this programmed set of cues provides somewhat redundant functionality – since the charge meter gives more detailed information on the state-of-charge – the lighting cap is more prominent. Thus if users are looking to rent a vehicle for a certain length of trip, they can quickly glance at the variety of available vehicles and have instant visual information on the charging state that can potentially be visible from longer distances.

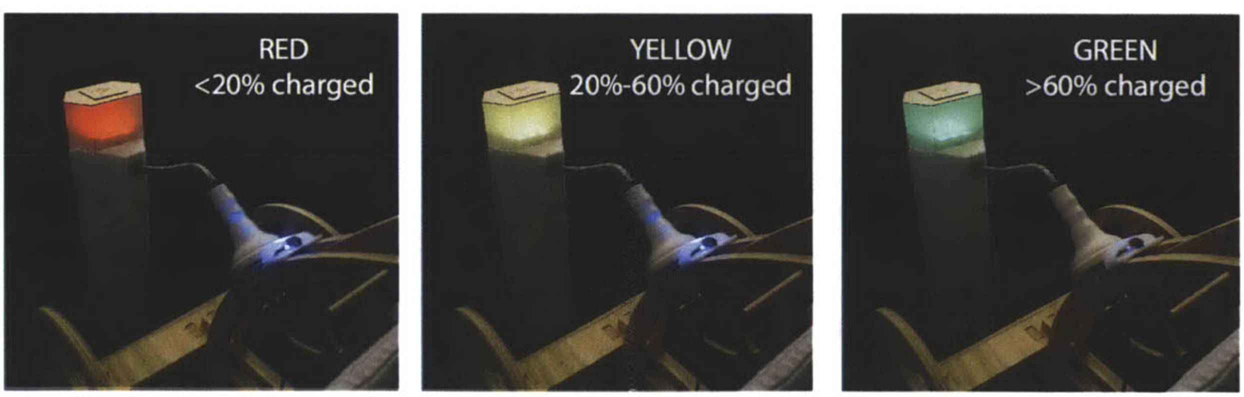


Figure 29: The ambient light cap changes color to reflect the state-of-charge of the vehicle. This allows users a quick and intuitive visual cue about which vehicles are best suited for their trip duration.

The other two preprogrammed cues correspond to a vacant spot, designated by a blue light, and a maintenance alert, denoted with flashing purple (Figure 30). The blue light indicates to users that the station is available for returning a vehicle to that charging station. The flashing purple maintenance cue is activated when a maintenance signal is sent from the vehicle. When maintenance mode is enabled, the vehicle cannot be rented even with a valid RFID access card, and the station flashes the maintenance cue until deactivated by a fleet operator. This mode could easily be extended to provide additional information about the nature of the maintenance needs, such as using varying colors and intensities of light for different maintenance issues.

Figure 30: smartCharge in vacant spot mode and maintenance mode, designated by solid blue and flashing purple respectively.

Ultimately, the ambient lighting cap is designed to be a flexible and customizable lighting element. These five sample cues were built into the initial prototype to demonstrate the functionality of the cap, which can be programmed with varying light color, intensity, and flashing patterns. For example, shared vehicle systems that operate on a hybrid reservation/on-demand model could use smartCharge's ambient light cap to indicate which vehicles have been reserved and which are available for immediate pickup.

3.7 - Microcontroller Architecture

The smartCharge communication, charging, locking, and lighting systems are orchestrated entirely by microcontrollers. While designing the system with microcontrollers instead of a host PC resulted in several tradeoffs, this decision was made because the cost of placing a computer in every charging station makes them unrealistic for practical applications. The Arduino prototyping language and Arduino Uno prototyping boards (based on ATmega 328 microcontrollers) were employed in the smartCharge system (Figure 31). [16] One Arduino, the master board, is responsible for managing the unlocking and locking process, controlling the charging cycles, and sending commands to the other boards. A second Arduino, the light slave board, is attached to an Arduino Ethernet shield and communicates with the Philips Color Kinetics lighting system. This separate microcontroller was required because the lighting system requires a constant Ethernet signal to stay active, which interfered with the unlock/lock functions on the master Arduino board. The third microcontroller in the system is the vehicle controller, which is responsible for sending information about the vehicle type, its state-of-charge, maintenance needs, and any other necessary information to the smartCharge station. The Arduino code for all microcontroller boards can be found in **Appendix 1**.

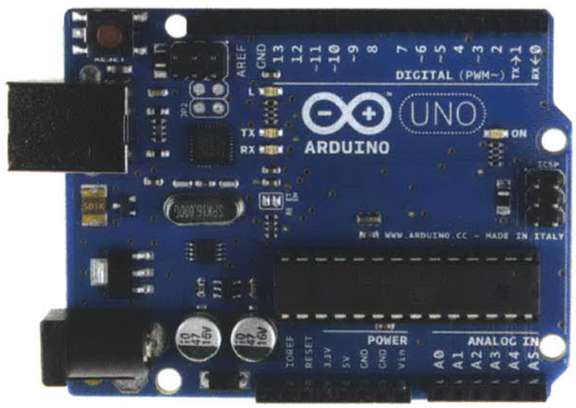


Figure 31: Arduino Uno microcontroller prototyping board, incorporating the ATmega328 microcontroller, 14 digital input/output pins, 6 analog inputs, and a USB connection for programming.

3.8 – Communication Protocol

The safety and reliability of the charging process relies on a communication protocol and handshaking process that occurs between the vehicle and the smartCharge station. Of critical importance is the fact that live power is flowing into the connector only when the vehicle is docked. If for any reason the connector is disengaged, either through an approved process such as vehicle rental or unapproved processes such as theft or vandalism, the system immediately deactivates the charge pins. This prevents electrical shock and interference from the user during the charging process.

For the initial smartCharge prototype, all inter-microcontroller communication employs the I^2C communication protocol. This includes the handshake between the vehicle and the station as well as the internal communication within the smartCharge system. I^2C is a two-wire, serial communication protocol that enables low-speed communication among electronics peripherals. The protocol operates through a master/slave relationship and is a multi-master bus, providing arbitration and collision detection for competing signals. [17] I^2C communication on Arduino boards is enabled natively through the Wire libraries, which allow for simple communication between a master board and multiple slave boards. In the smartCharge system, a central host microcontroller acts as the master while two slave boards control the ambient lighting system and the vehicle information, respectively (Figure 32).

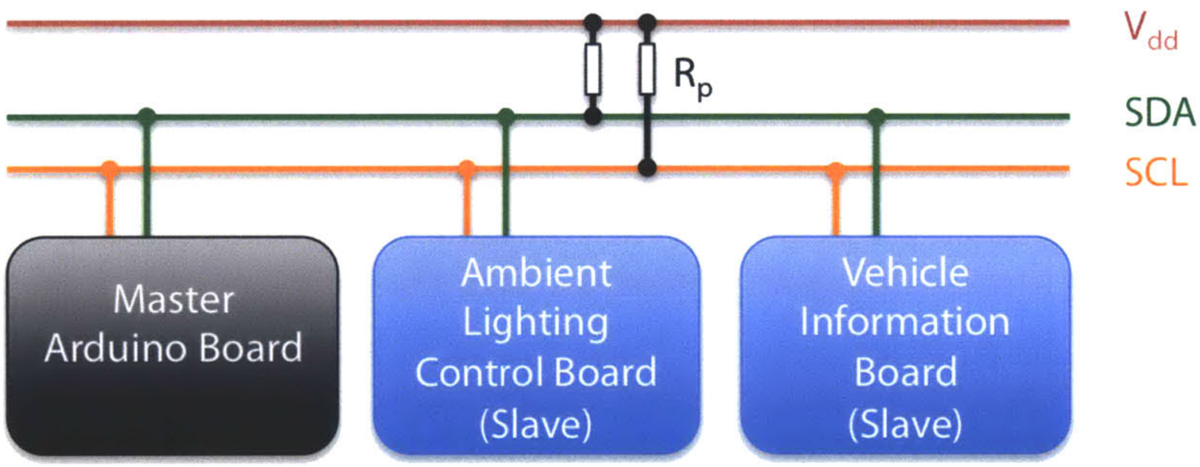


Figure 32: Schematic of the smartCharge I^2C bus. The master board is responsible for the main system functionality such as locking, managing the charge handshake, activating the charge relays, etc. The ambient lighting control board is a slave device that connects to the Philips Color Kinetics lighting system via Ethernet. The vehicle information board is part of a vehicle's internal microcontroller architecture, which provides information on the state-of-charge, vehicle type, and maintenance needs to the charging station. These three microcontroller boards communicate with the I2C protocol, using one line for data (SDA) and the other for clock (SCL).

Using the I^2C protocol also allows for the integration of numerous devices on the same two-wire bus. Thus, the same communication system can be extended to offer additional functionality such as NFC support, or new types of vehicles.

3.9 – Retractable Cord and Pulley System

Traditional electric vehicle charging stations typically feature lengthy cables of up to 20 feet. These cables are sized to allow users to park in a variety of configurations and to accommodate various vehicles, ranging from compact cars to large trucks and sport utility vehicles. These long cables are acceptable for indoor contexts such as commercial and private garages, but they are ill suited for the outdoor streetscape environments in which many vehicle sharing stations are found. Long cables introduce a number of hazards into the electric vehicle charging process. They create tripping and entanglement hazards, are an easy target for vandalism, and are subject to significant wear and tear in urban environments. Furthermore, these cables are very unsightly and negatively impact urban design in public areas and main straights. With the ubiquity of the "NIMBY" (Not-In-My-BackYard) mentality, it is difficult to imagine the installation of traditional EV charging stations being well received by neighboring residents and business owners.

To address these issues, smartCharge integrates a retractable cord that is shielded with reinforced stainless steel tubing. The use of stainless steel provides for increased longevity of the cord, resistance to harsh environmental conditions, and acts as a theft deterrent. Since smartCharge is also responsible for locking the vehicle, a sturdy and reliable material was necessary for the cabling as a traditional rubber-coated charging cable can easily be severed. The retractable cord allows users to extend the length of the cable to attach to their vehicle to connect to smartCharge. When the vehicle is locked, the cable will remain in the extended state because the connector is secured to the vehicle with the holding force of the electromagnet. Upon unlocking the vehicle, the cord retracts into the system to mitigate "cable droop."

The retractable cord system in smartCharge is a linear system that functions with a spring, mass, and pulley (Figure 33). For the prototype, a hollow aluminum cylinder was attached to a custom support structure with a pulley system. The stainless steel tubing houses the six wires that connect to the male handle (four for the connector and two for the electromagnet), and the steel tubing was attached to the 3D printed male handle enclosure with a shaft collar. The other end of the steel tubing is attached to a stainless steel extension spring, which is in turn attached to the aluminum cylinder. When the user pulls on the handle, the pulley system allows for a smooth extension of the cable. When the handle is released, the force of the spring pulls the handle back into the station. While this functionality is suitable for a prototype, the extension length provided by this linear extension spring was only about ten inches because of the limited space inside the enclosure. For a commercial version, a rotary retraction system with a torsion spring, akin to the technology employed by tape measures and vacuum retractable cord systems, would allow for more range. However, limiting the amount of range to 1 – 2 feet could be ideal, because it would assist in keeping vehicles organized at the charging station.

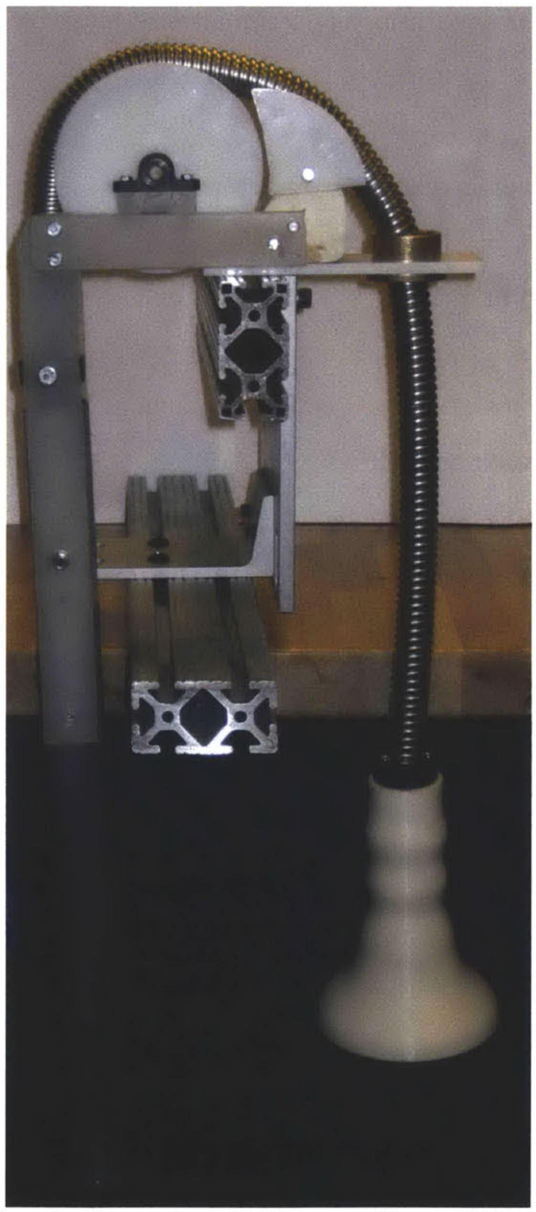


Figure 33: The retractable cord and pulley system inside smartCharge. This system was then integrated into the enclosure to ensure that the retractable system was securely attached to the body of the charging station.

3.10 – RFID Reader

To authenticate a valid user and permit vehicle rental, smartCharge employs an RFID reader that controls the electromagnetic locking system and the charging process. The reader is a commercially available Parallax RFID Card Reader that connects to the Arduino-based microcontroller via serial communication. This system reads passive RFID tags at a frequency of 125 kHz. Passive RFID tags are the technology employed in most electronic ID cards and passports because they do not require a built in battery or power supply to operate. Rather, they simply contain an RF antenna and transmit a signal only upon receiving an RF signal from a nearby reader. This allows the tag to be compactly embedded into ID cards and key fobs.

The RFID reader in smartCharge reads tags and parses their ten-character identification strings. It then checks the tag identification string against a list of authorized tags. This list can be dynamically updated by a central server to allow for new members or block users who have not returned vehicles or otherwise misuse the system. A users identification string can be linked to a centrally managed mobility profile, which could be extended to include access for public transit systems and other authentication procedures.

3.11 – Power Supply

The initial prototype of smartCharge operates on a DC power supply. Since this prototype was designed to interface with other prototypes of electric vehicles, most of which operate on battery packs with 24V or 12V, a 24V DC power supply is built into the system. This power supply takes standard 115V AC input and provides regulated 24V DC output. In practical electric vehicle charging applications, this power supply would need to be scaled up to a higher power system and could transmit either AC or DC power, depending on the type of charging. Inside the smartCharge prototype, various voltages are required for powering the microcontrollers, switching relays, and other electronic components. To address this, a voltage conversion board was designed and built to provide regulated 12V and 5V DC power in addition to the "high voltage" 24V bus (Figure 34).

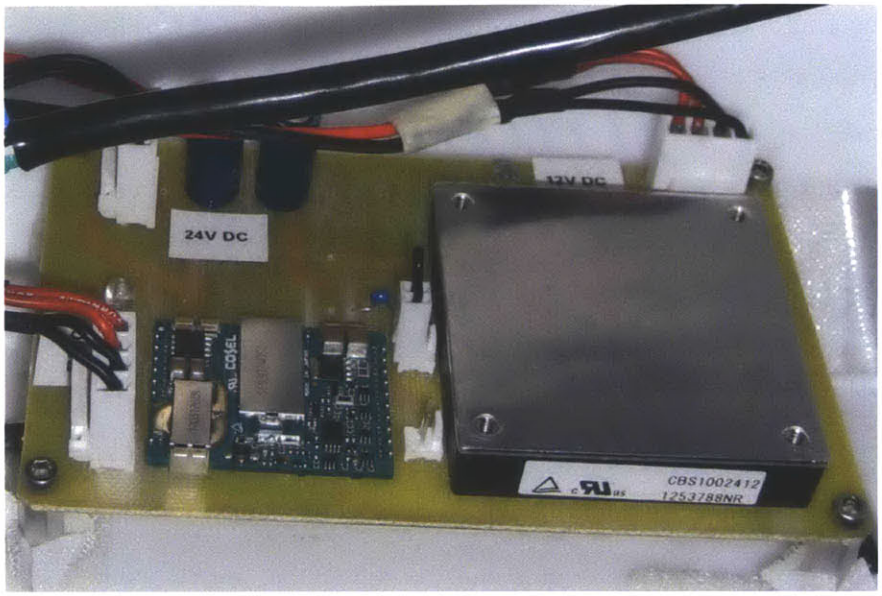


Figure 34: The custom voltage conversion board inside smartCharge, which provides regulated 12V and 5V rails for internal use from the master 24V power supply.

The DC-to-DC converters were chosen based on current sourcing capacity. A 30W 5V converter and a 50W 12V converter were selected, and a custom PCB with the supporting filtering electronics and input protection was fabricated.

3.12 – Enclosure Fabrication

The smartCharge enclosure was designed around the constraints and volume of the necessary electronics and mechanical equipment. In addition, its height was an important design concern. In sizing the height of the station, lightweight electric vehicles such as e-bikes and electric scooters were measured to estimate the distance between the battery pack and the ground. The prototype station height was designed to match the height of the PEV. The structural post measures 30 inches in height and the ambient lighting cap is an additional 5 inches, for a total of 35 inches or just under three feet. This size can be easily increased with the addition of a height-boosting pedestal of the same footprint.

The prototype enclosure was first fabricated out of plywood to assess the structural design, and a second version made from acrylic was then created for improved structural stability and integrity. The enclosure was designed with the DS SolidWorks parametric CAD software suite and fabricated using a laser cutter. Since a laser cutter makes only two-dimensional cuts, the enclosure was designed as an assembly of 2D panels that fit together with a notching system. The acrylic panels were cut individually on the laser cutter, edges were milled for the hexagonal shape, and the pieces were bonded together with acrylic solvent cement. This solvent cement functions by chemically "melting" the pieces together, providing high bond strength no visible seams.

The enclosure contains three shelves that function as component bays for the internal electronic and mechanical components of smartCharge (Figure 35). The enclosure also contains attachment points for the ambient lighting systems and the retractable cord system, each of which function as separate assemblies within the final enclosure.

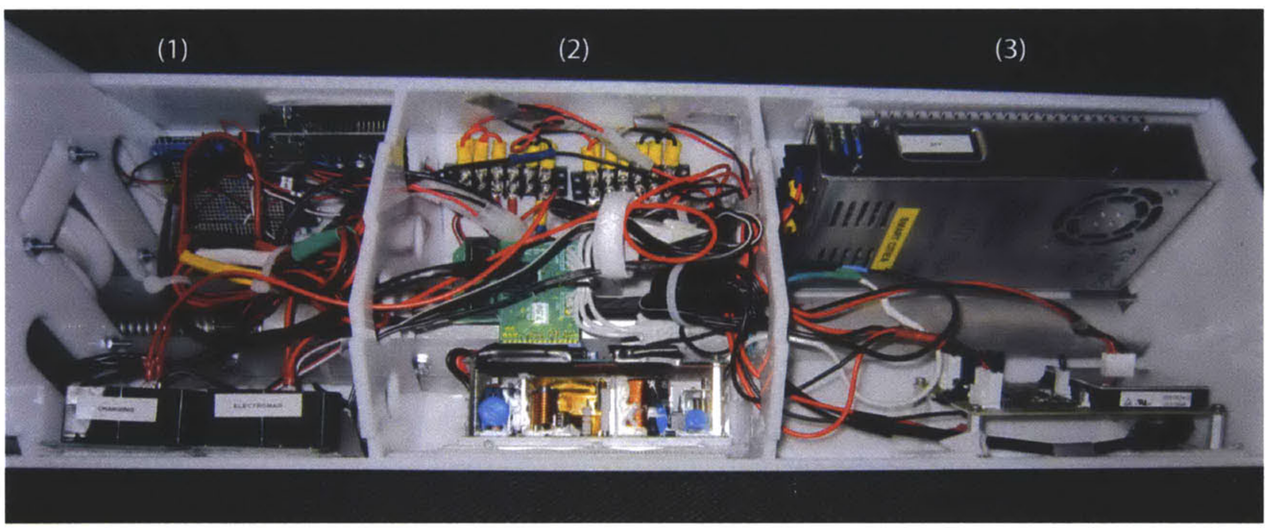


Figure 35: A side-view of the internal, embedded electronics systems that drive smartCharge. Component bays from left to right: (1) charging and electromagnet control relays, master microcontroller board and lighting control slave board (2) Color Kinetics lighting control unit and power supply, low voltage bus bars (3) 24V power supply, voltage regulation board, and power distribution system

{IV} Evaluation & Future Work

The smartCharge prototype was developed to completion and debuted for testing and evaluation at the Media Lab sponsor meeting in April 2012. During the sponsor meeting, three "lab explorations," structured as open houses windows were held. The open houses gave over 50 users the opportunity to interact with and provide feedback on the smartCharge prototype. The feedback was overwhelmingly positive, and users found the system generally quite intuitive and user-friendly. In particular, the simplicity of the system coupled with the short time required for rental and return was seen as a highly distinguishing feature, as many of the users had suffered through the process of renting a shared vehicle from a traditional station.

4.1 – Prototype Functionality Testing

Most of the core features of the prototype functioned as designed, including the locking functionality, the charging, the data communication protocol, and the ambient lighting system. The prototype successfully locked a vehicle to the station and transferred regulated DC power once the proper handshake was made. While the electromagnet used in the prototype was only capable of 250 lbs of holding force, a stronger electromagnet could be employed for practical applications in outdoor environments. The prototype was demonstrated successfully with multiple functional modes including:

(1) invalid card mode (flash red, vehicle remains locked)
(2) valid card mode (flash white, stop charging, unlock vehicle)
(3) maintenance mode (flash purple, prevent vehicle from being rented)

Feedback on the lighting system and the pre-programmed lighting cues was quite positive. The vast majority of users were able to quickly identify the functionality of the charge meter, and caught on easily to the red, yellow, green progression of the ambient lighting cap. In indoor applications, the lighting cap was highly visible from distances of up to 100 feet, though outdoor testing was not conducted. The fact that the ambient lighting cap can be custom programmed allows for the system to be extended to various urban contexts, and more detailed user testing could be conducted to determine the optimal set of lighting cues to associate with various states.

One extension that could greatly benefit the system would be to improve the granularity of the maintenance function. Currently, the maintenance function is a binary cue that only indicates if the vehicle requires maintenance or not. However, this could easily be extended into an error code system, which could be sent to the fleet operator and reflected in the color of the light cap. For example, a vehicle error could correspond to a certain flashing color while a station error could correspond to a different color. Even higher granularity could be provided, such as indicating to maintenance workers which module or component of the vehicle requires maintenance through the ambient lighting cap. This is of course a delicate tradeoff between providing granular information through the lighting system and overloading the observer with too much visual information. Incorporating too many colors and flashing patterns could grow visually garish, contribute to light pollution, and impair functionality.

Some glitches with the retractable cord system were observed in the prototype, which can be attributed mainly to the fact that it was based on a vertical spring system, which limited the range of extension. In a commercial version of the system, the retractable cord could be designed with a rotary system similar to the technology employed by vacuum cleaners with retractable cords. Users reported that the aesthetic of the station would be improved if the cord fully retracted into the system, leaving no apparent slack until being pulled. Selection of stainless steel tubing for the cord was generally quite functional, as it provided adequate housing for the wires and the strength and durability needed for outdoor applications. Some users commented that merely the presence of steel tubing would be a visual deterrent to potential thieves and vandals, as opposed to a simple rubber-coated cord.

An additional observation during informal user testing was that upon unlocking with a valid card, the male handle would be released from the vehicle and simple fall due to the effects of gravity. While the retractable system was strong to prevent it from hitting the ground, it still provided a bit of a surprise for users who were not expecting the handle to disengage and fall. A number of design strategies could address this issue. For example, a stronger retractable cord could be implemented such that the force of retraction is greater than the downward force of gravity, which would result in the plug being pulled into the station upon disengagement. An alternative strategy would be to increase the strength of the permanent magnet that was incorporated into the female connector for alignment. Due to the weight of the handle, this permanent magnet was not sufficiently strong to hold the plug in on its own, and merely provided alignment guidance. However, with a stronger magnet, the handle could stay in on its own after unlocking but could still be easily removed by the force provided by a user's hand. A third solution would be to shift the orientation of the female charge port on the vehicle, such that the plug would stay in due to the downward force of gravity alone.

Some users reported that the size of the handle was slightly larger than they would expect for a charging plug. While the handle was indeed fairly sizable at its base (4.5" inches in diameter), its contoured handgrip was regarded as quite comfortable for most users. In addition, a larger base allows for more contact surface area, enabling the charging plug to carry more current and incorporate a stronger electromagnet, thus providing additional holding force. Nonetheless, the size of the base could be reduced by narrowing the traces of the PCB surrounding the electromagnet and reducing the volume of the enclosure casing. The enclosure for the male connector was built as a one-off prototype, but mass production would involve a different fabrication process such as injection molding and could be of a different shape and style.

The entire resistance of the connector interface – from power supply to load – was measured with a Fluke 115 True RMS Multimeter, yielding a result of approximately 0.2 Ω. DC current was tested up to 15A with no noticeable heating or degradation of the connector interface or internal components.

4.2 – Scaling to Outdoor Urban Applications

Users with experience in the automotive and electric vehicle standards noted the fact that there are existing standards for Level II vehicle charging, which have been ratified by the Society of Automotive Engineers (SAE). The introduction of a new type of connector and charging protocol could therefore require a lengthy UL approval process and would involve a different interface than those that currently exist on many vehicles. While this observation is correct, it still remains true that no charging infrastructure optimized for shared vehicles yet exists. smartCharge is designed for a specific type and use case of vehicles that are operated and maintained by a central fleet operator. When purchasing a fleet of electric vehicles – which could include bikes, scooters, cars, and other vehicle types – the fleet operator can make an active decision to integrate a particular type of charging infrastructure. Indeed, many shared vehicle systems already deploy custom infrastructure to improve security, durability, and maintainability. In the case of smartCharge, this universal charging and locking element can be integrated into any vehicle type. Its simple, "open-source" communication protocol and charging standard allows it to function as an interface for existing standards. Like a USB plug, the smartCharge system contains positive and negative contacts for power and data. Other applications for the system can be easily extended from this common hardware and communication framework.

To make the smartCharge system viable for real-world applications, design for manufacturing and improved robustness of the components and assembly will be necessary. The initial prototype was designed as a proof-of-concept and is not suitable for the abuses of outdoor use and repeated vehicle rentals. However, with proper material selection and manufacturing processes, the concept should be fully translatable to a commercial product. For example, the exposed copper plates that are used for the mating female connector are unsuitable for practical applications. While copper is highly conductive, it rapidly oxidizes in the presence of air, and the quality of the connection will degrade as this oxide layer builds up. A possible solution to this would involve coating the copper conductive plates with tin or silver, which are less susceptible to oxidation galvanic corrosion. Other conductive materials could be used in lieu of copper. Furthermore, the wood spacers that are used to isolate the conductive rings are unsuitable for commercial applications for a high current connector. Wood was employed in this prototype because the wooden rings were quickly and easily fabricated on the laser cutter. However, wood is hydroscopic, is subject to compression and rotting, and can be potentially flammable. For a commercial version, a dielectric structural plastic such as acetal or rubber could be employed. Finally, some of the prototyping techniques such as the use of conductive epoxy for attaching wires to the copper planets instead of hard bolting or riveting, are also unsuitable for practical commercial applications. However, the materials and prototyping methods employed were effective for a functional laboratory prototype and were chosen based on availability of prototyping tools and speed of assembly. As with any infrastructural element, extensive reliability testing of a commercial version of smartCharge should be conducted to ensure that the components of such a system are durable and suited for repeated use cycling.

{V} Urban Implementation

smartCharge is designed to work with any lightweight electric vehicle. For Mobility-on-Demand vehicle sharing stations, having a diversity of vehicles at each station is critical to allow users to take the size of vehicle that is appropriate for their trip type. For example, for a three-mile trip to a grocery store on a sunny day, a user may elect to take an electric bicycle to her destination. On the return journey, she can select a compact electric vehicle with some cargo space for groceries. This type of flexibility allows users to take the most efficient vehicle that is required for their trip. It also allows users to incorporate healthier and zero-emission modes into their commuting trips, such as walking and cycling when possible, and taking compact electric vehicles for trips that require storage space, shelter from climate, or are simply of longer distance. Today, urban commuters simply find too many excuses not to walk or cycle.

smartCharge can form the backbone of a truly flexible, multimodal Mobility-on-Demand charging station for cities. Instead of having separate charging stations and parking spots for bikes, scooters, and cars, a system based on a universal charging station like smartCharge allows for flexibility in station design and vehicle distribution. For example, central commuting hubs near public transit stations may feature a wide array of vehicle types, while stations in the periphery of cities may feature more cars and long-range vehicles. With one-way rental systems, there is a very real concern of not having an available parking space at the drop-off station. With electric vehicles, this is further complicated because a user looking to drop off a vehicle must find both an available parking spot *and* the appropriate type of charging infrastructure for the vehicle. Stations that have flexible infrastructure that can charge a variety of vehicle types are thus much better suited for shared vehicle systems that offer one-way rentals.

The following scenarios present case studies of parking positions and vehicle distributions for shared vehicle charging stations. Standard lane dimensions are based on guidelines for the city of Boston, MA. [18] These studies illustrate how a flexible charging infrastructure element such as smartCharge can form the basis of Mobility-on-Demand stations.

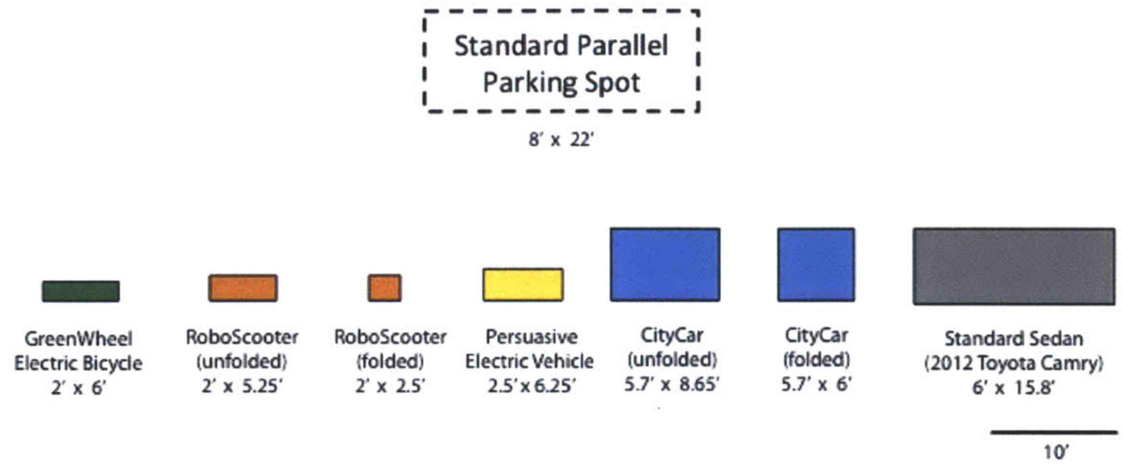


Figure 36: Vehicle parking areas compared to a standard parallel parking spot in the city of Boston, MA.

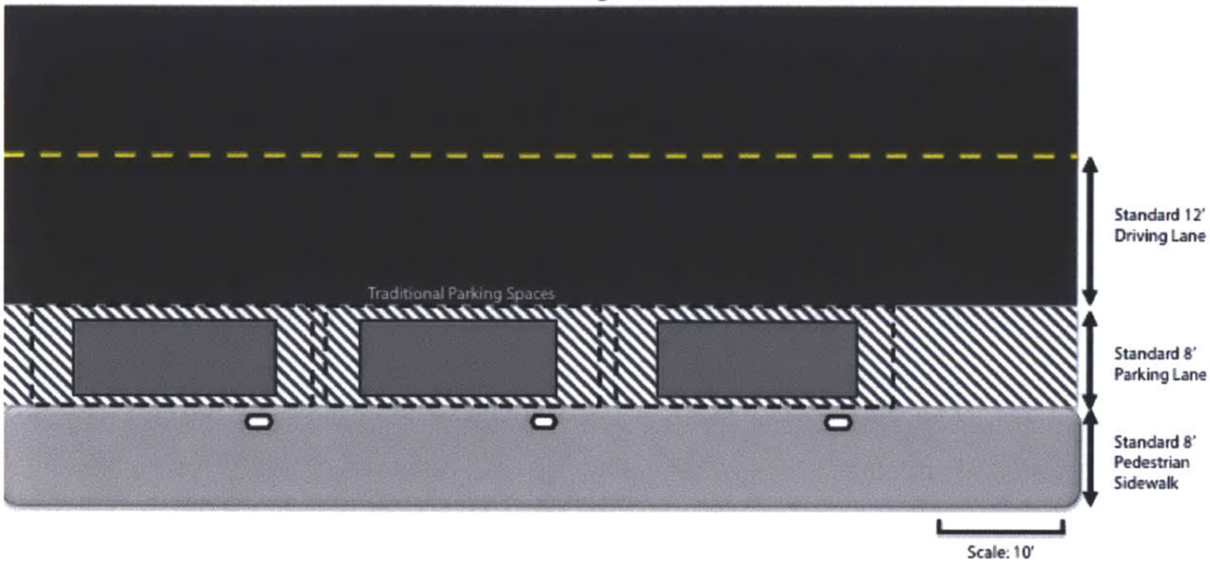
Figure 36 above shows the parking areas of various Mobility-on-Demand fleet vehicles compared to a traditional sedan. Because of the compact size of these vehicles compared to the area of a traditional parallel parking spot, highly effective and versatile Mobility-on-Demand stations with multiple vehicle types can be created in the area of only three parking spots. These stations will rely on a universal and functional piece of charging infrastructure, such as smartCharge.

Scenario 1 depicts a standard 28-foot half right-of-way. A half right-of-way is defined as the size of the right-of-way between the traffic directional median line (depicted in dashed yellow) to the end of the sidewalk. This standard street typology accommodates a 12-foot standard driving lane, an 8-foot parking lane, and an 8-foot pedestrian sidewalk. Through the inclusion of smaller vehicle types and flexible infrastructure, these three parking stations can be turned into a variety of multi-modal Mobility-on-Demand stations. By incorporating only two-wheeler parking and removing the traditional parallel parking, a bicycle lane can be accommodated into this streetscape typology, along with parking and charging infrastructure for up to nine two-wheelers.

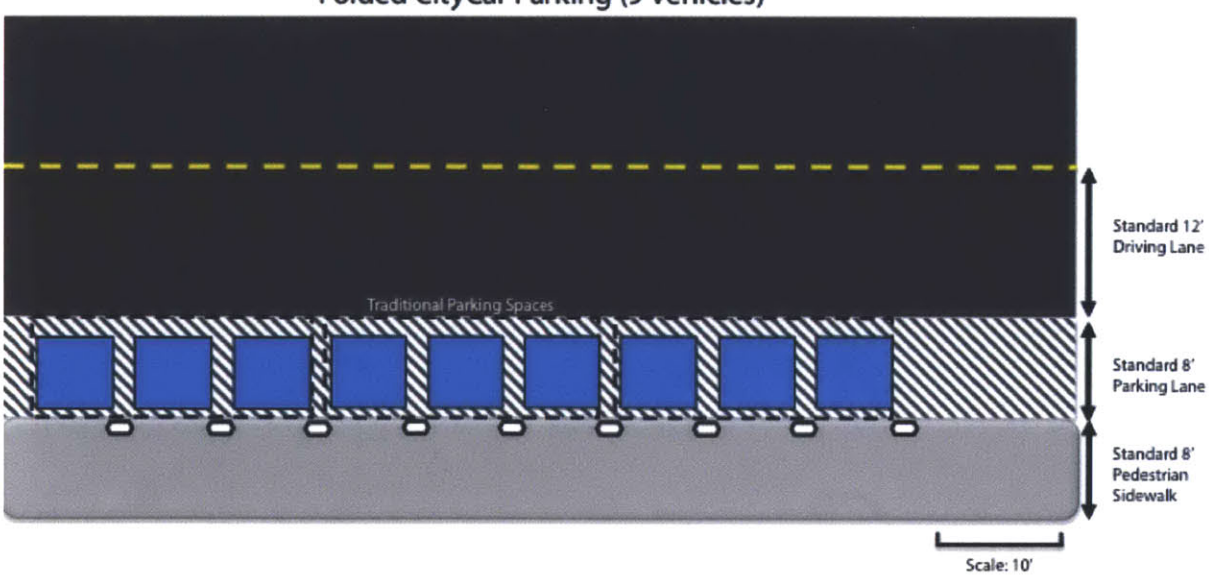
Scenario 2 depicts a larger, 34-foot half right-of-way that already incorporates a bike plane. By replacing the traditional parallel parking spots with Mobility-on-Demand vehicles and infrastructure, extra pedestrian space on the sidewalk can be easily created.

5.1 – Urban Implementation Scenario 1

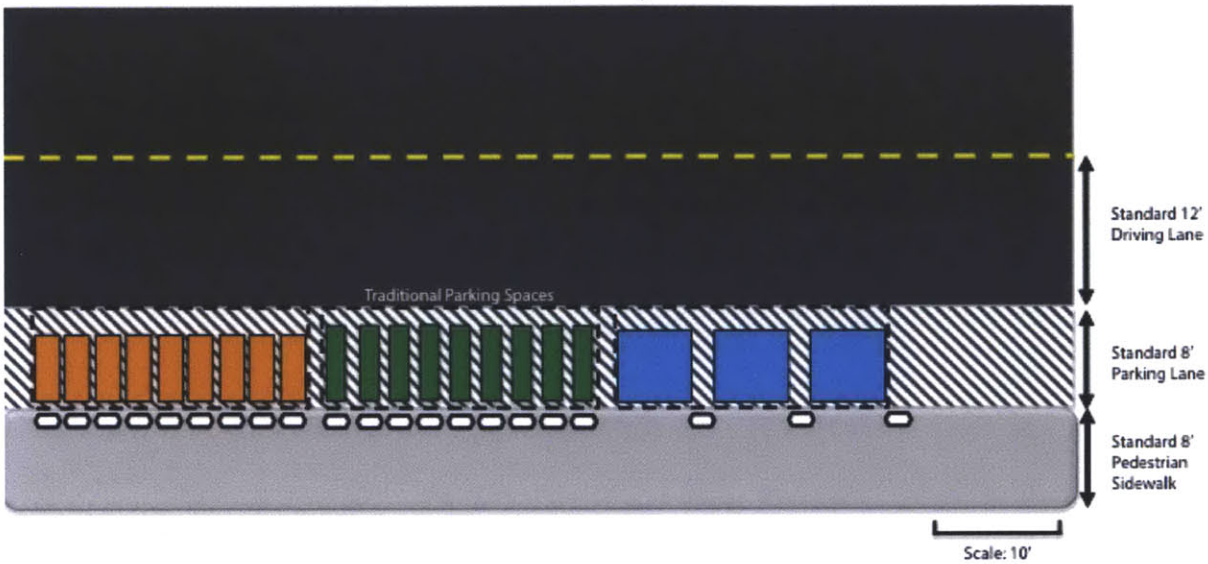
Scenario 1a: 28' Right-of-Way
Traditional Car Parking (3 vehicles)



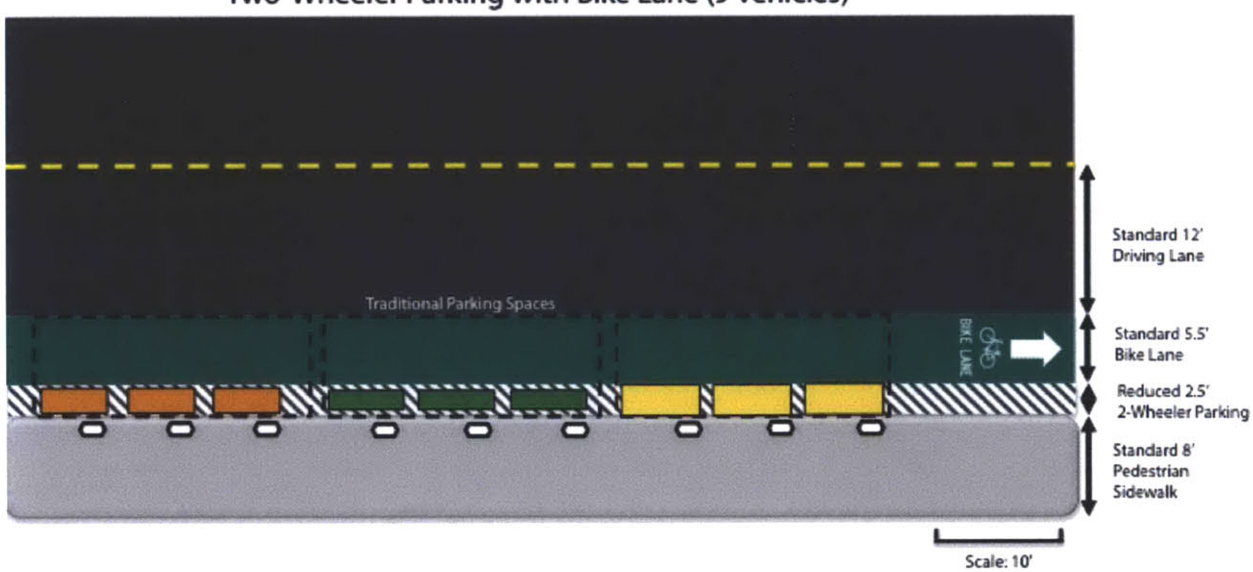
Scenario 1b: 28' Right-of-Way
Folded CityCar Parking (9 vehicles)



Scenario 1c: 28' Right-of-Way
GreenWheels, RoboScooters, & CityCars (21 vehicles)

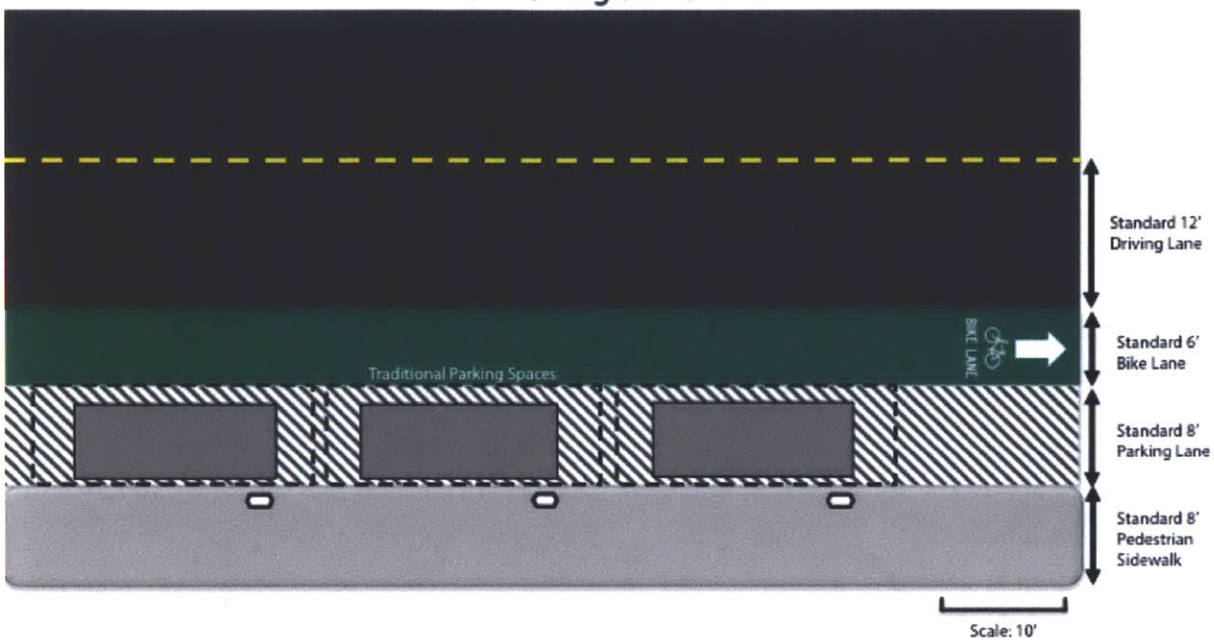


Scenario 1d: 28' Right-of-Way
Two-Wheeler Parking with Bike Lane (9 vehicles)

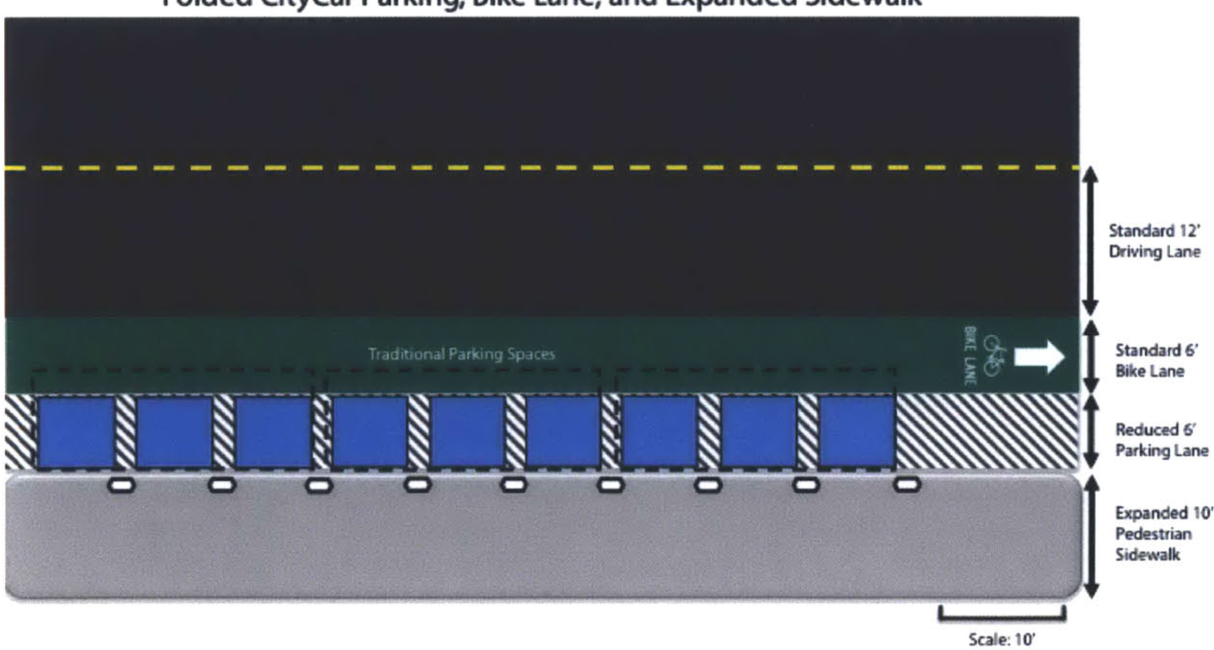


5.2 – Urban Implementation Scenario 2

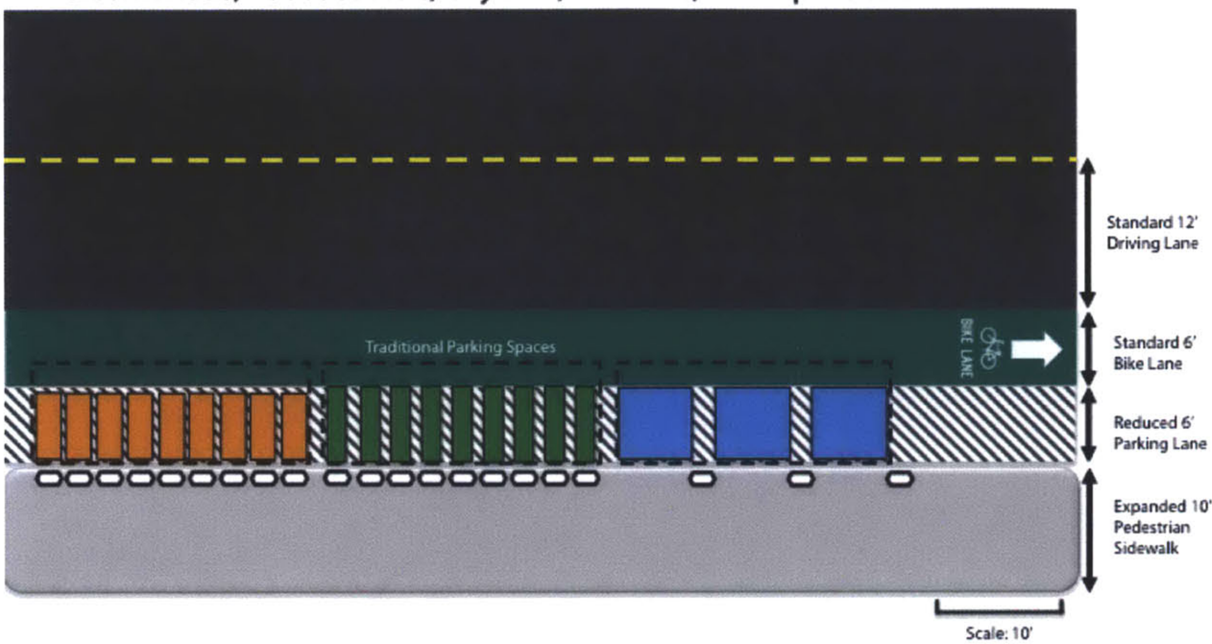
Scenario 2a: 34' Right-of-Way
Traditional Car Parking & Bike Lane



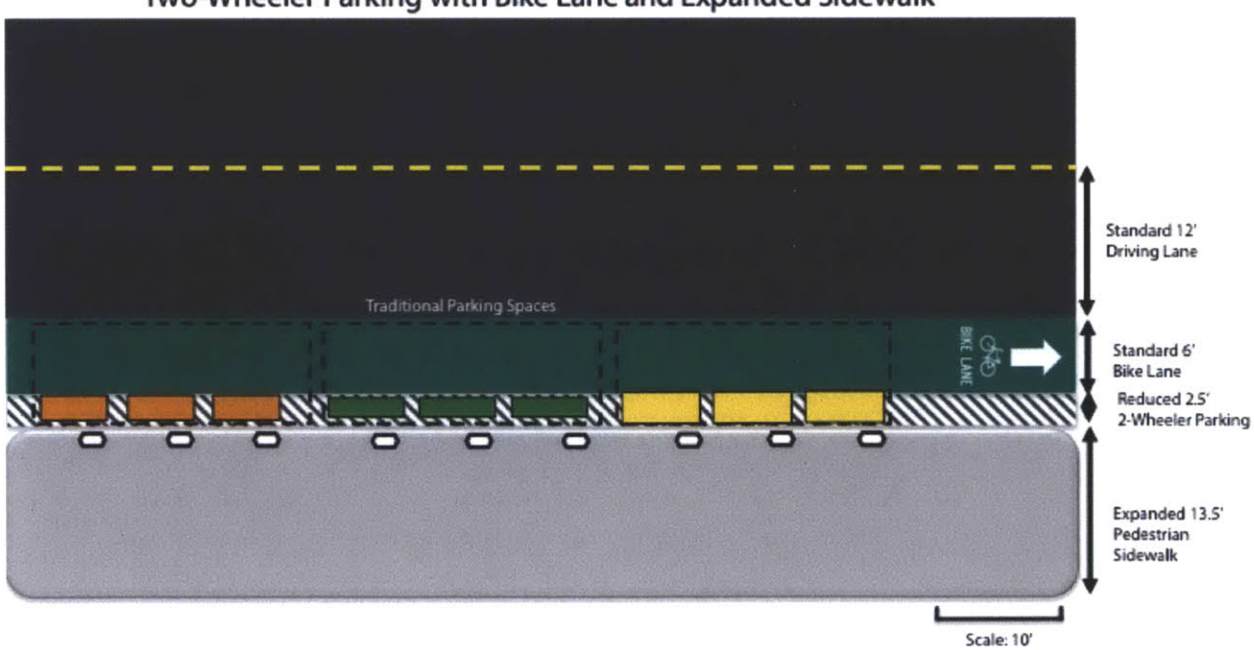
Scenario 2b: 34' Right-of-Way
Folded CityCar Parking, Bike Lane, and Expanded Sidewalk



Scenario 2c: 34' Right-of-Way
GreenWheels, RoboScooters, CityCars , Bike Lane, and Expanded Sidewalk



Scenario 2d: 34' Right-of-Way
Two-Wheeler Parking with Bike Lane and Expanded Sidewalk



{VI} Deploying Charging Infrastructure & Rapid Charging In Cities

Along with the design and interface concerns of deploying electric vehicle charging infrastructure to city streetscapes comes the related issue of supplying sufficient power to charge these vehicles. Unlike nonelectric vehicle-rental kiosks, which only require a small amount of power for the rental interface so can be stand-alone solar powered, electric vehicle sharing stations require significant levels of power. This issue is further compounded by the fact that the utilization rate for shared vehicles is typically much higher than that of private vehicles, so the vehicles need to be recharged quickly and frequently. For example, Zipcar founder Robin Chase estimates that each of their "well-used" shared vehicles enables fifteen to twenty users to eschew private vehicles, and can provide functional service for between thirty and fifty people. [19]

Since most urban trips are short in duration and distance, the driving ranges of compact vehicles such as the CityCar – which provides 100km to 120km of range on a full charge – are more than adequate for urban driving patterns. However, for a heavily utilized electric vehicle sharing system, it is reasonable to expect one to two full recharges per vehicle per day. Furthermore, it is unrealistic to expect users to spend significant time periods waiting for a vehicle to be sufficiently charged for rental use. In order for Mobility-on-Demand electric vehicle sharing services to be viable in the commercial urban transportation market, the waiting time for vehicles must be comparably low to other modes of transport such as taxis, bus, and subway.

In the United States, electric vehicle chargers are currently grouped into three broad categories based on the power consumption of each category, presented in **Table 2** [20]. Level I and Level II commercial electric vehicle chargers transfer AC power, typically in the 115V – 240V range, from the electric grid to the vehicle. The power is then rectified to DC with an onboard charger that connects to the battery management system (BMS) of the vehicle to charge the vehicle's battery pack. Alternatively, Level III chargers manage the AC to DC conversion in the offboard charger and transfer direct DC power to the vehicle, which is then responsible for distributing charge power to the battery pack.

Table 2: Electric Vehicle Charging Levels

Charging Level	Power Level	Form of Power Transfer to Vehicle	Approx. Charge Time for 20 kW-hr Passenger Vehicle	Approx. Charger Retail Price
Level I	< 2kW (household outlet)	AC	10 hours	$1000
Level II	2 kW – 19 kW	AC	1 – 10 hours (though most commonly 3-6 hours)	$3000 - $5000
Level III	20 kW – 90 kW	DC	10 minutes – 1 hour	$20,000+

6.1 – Lithium Battery Technologies for Rapid Charging

As rapid charging involves the transfer of large amounts of current into battery cells, most cells that are not designed to handle these large currents will undergo serious overheating and possibly ignite due to their nontrivial internal resistances. Resistive power loss is dissipated as heat and is linearly related to the internal resistance of the battery cell but quadratically related to the current, as given in **Equation 1** [21]:

$$P_{diss} = I^2 R \qquad \textbf{Equation 1}$$

This is further complicated by the fact that most commercial rechargeable energy storage systems (RESS) for electric vehicles are actually created by grouping hundreds of thousands of smaller battery cells in series and parallel combinations (Figure 37). The series wiring of cells results in an additive increase in apparent resistance for the charge current, which contributes to the dissipation of additional heat and raises significantly thermal management issues as the charge current is increased. Furthermore, as these cells are packed tighter together, thermal dissipation and potentially harm batteries and lead to uneven wear in certain parts of the pack. As such, the goal of many modern automotive battery cooling systems is to reduce the thermal load on the cells as well as to evenly regulate the temperature across the pack, such that the thermal loading profiles are roughly consistent for all cells.

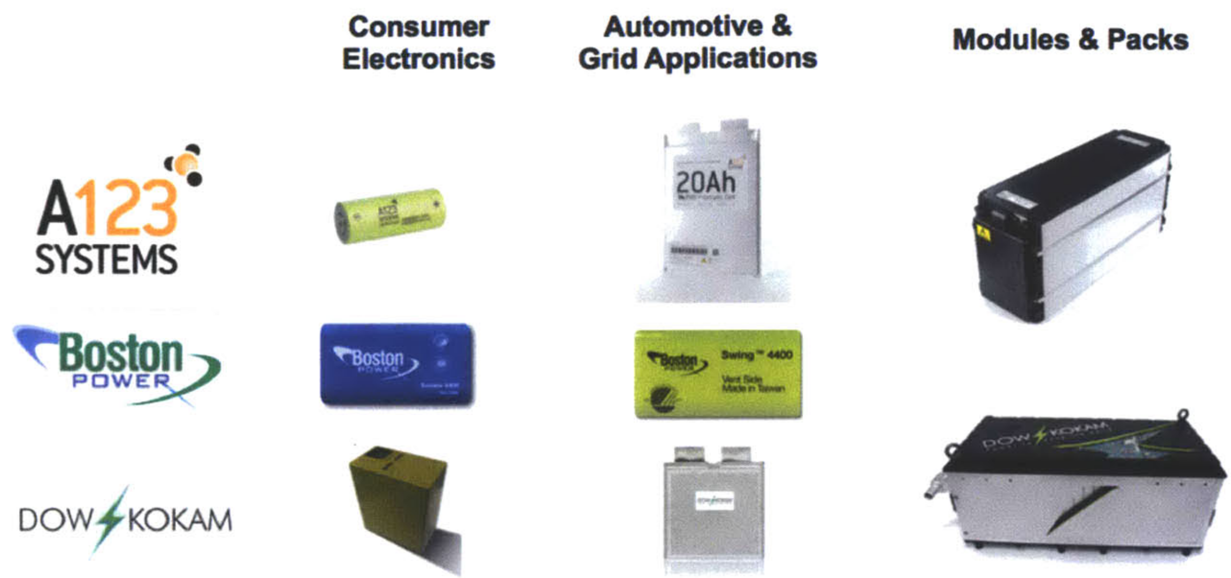


Figure 37: A range of battery products from leading battery manufacturers. Automotive grade cells are often developed in pouch or prismatic form, which offers a better formfactor for series wiring than traditional cylindrical cells. The modules and packs section above are then created by stringing multiple cells together in appropriate series and parallel combinations to achieve the desired nominal pack voltage and capacity. The full vehicle rechargeable energy storage system (RESS) is often created with a number of these modules in conjunction with a battery management system, thermal management, and a high-voltage front end.

Fortunately, with recent developments in Lithium ion (Li-ion) battery technologies and charging systems, Level III (rapid) charging is growing increasingly viable for use in commercial electric vehicles. The production of Lithium iron phosphate ($LiFePO_4$) batteries with low internal resistance has enabled experimental rapid charging (up to 4C rates) of commercially available cells from 0% to 95% state-of-charge (SOC) for over 1500 cycles. [22] To date, commercial rapid Level III electric vehicle charging units consist of a high power AC to DC rectification system with a high current DC output, and can require over 30 kW of power to operate. As electric vehicles grow more prevalent, large-scale deployment of rapid chargers will be necessary to alleviate range anxiety, allow for long distance trips, increase the utilization rate of shared-use fleet vehicles, and quickly charge depleted vehicles in emergency situations. [23]

Scaling battery-based energy storage from cells to modules to complete vehicle traction RESS packs is a major bottleneck of the global Li-ion battery industry. Many prominent battery firms have experienced great difficulty in maintaining product reliability as they increase production volumes, and relatively low manufacturing yield has been one of the single greatest deterrents to the success of this industry. Automakers face an equally challenging proposition from a validation and integration standpoint, as RESS packs are by no means commodity components. Rather, energy storage systems must be custom-built for each vehicle architecture, and are often severely limited by the volumetric constraints of automotive chassis that have been converted from traditional ICE vehicles. Packaging the battery modules safely requires mounting them carefully to minimize vibration, thermal loading, and exposure to moisture and particulate matter. Until improved modularity is achieved in the Li-ion scaling business, electric vehicle manufacturers will be required to invest large amounts of financial and human capital in the development of custom battery packs for each vehicle platform (Figure 38).

Figure 38: A team of engineers working on the testing and integration of commercially purchased Li-ion modules, which were then scaled into a fully functional automotive RESS for the CityCar prototype through extensive mechanical, electrical, and thermal engineering.

6.2 – Infrastructural Requirements for Rapid Charging

Beyond the availability of battery cells that support rapid charging, the infrastructural power requirements demanded by rapid charging can also be prohibitive for deploying and scaling and the technology. A typical commercial Level III electric vehicle rapid charger takes three-phase input at 200V – 480V AC, and rectifies this power to output 350V – 500V DC, with accompanying feedback and control circuitry to regulate the charging current and voltage appropriately. The charging time for Li-ion batteries is predominantly limited by the amount of current the charger can supply and more importantly, the corresponding amount of current that the batteries can accept. Thermal constraints are of chief concern, as discussed earlier, as excessive dissipated heat can quickly damage Li-ion batteries and cause safety issues.

For a fixed capacity vehicle energy storage element E_{pack} (i.e. a 10 kWh vehicle battery pack), the required instantaneous charging power P_{charge} is given by **Equation 2,** where α is the relative charging efficiency, typically 90% - 95%:

$$P_{charge} = \frac{E_{pack}}{\alpha \cdot t} \qquad \textbf{Equation 2}$$

Due to the inverse relationship between charging power and time, the amount of power required to sustain charge times below ten minutes is prohibitively high, even for a relatively small 10 kWh battery pack (Figure 39). Even a 15-minute charge requires about 40 kW of charging power, so rapid charging multiple vehicles simultaneously requires an enormous power supply. As many passenger electric vehicles incorporate packs of 20 kWh and more, the electric power requirements for large-scale rapid charging pose a serious problem for the existing electric grid.

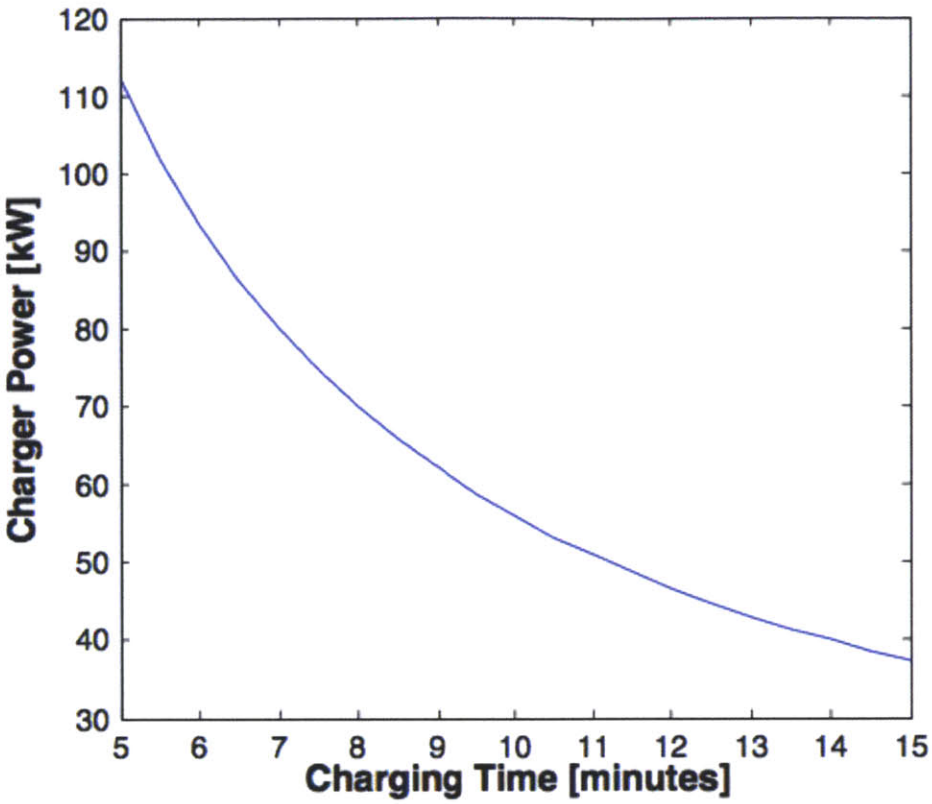


Figure 39: Instantaneous charging power vs. charging time for a 10 kWh electric vehicle traction battery pack, assuming a 200V DC charger providing constant current only for a 94% refill. As charge time decreases, the amount of power required increases nonlinearly. Thus pushing charge times below 10 minutes requires enormous amounts of power, and is likely unfeasible given the capacity of present-day electric grid infrastructure.

The following graphical matrix depicts vehicle charge times by power source for a variety of electric vehicle pack sizes (Figure 40). The vehicles highlighted in green were designed at the MIT Media Lab. The top axis shows a variety of American power sources, ranging from a low power 1.8 kW household AC outlet to an extremely high power 830 kW industrial loading connection for industrial applications such as heavy machinery and factories. This matrix uses charge times assuming 100% efficiency (α = 1), so the actual charge times would be longer depending on efficiency.

Vehicle Charge Times by Power Source

Vehicle		Pack Size (kWh)	Level I 120V, 15 A: 1.8 KW (~ 2 x)	Level II 220V, 50 A: 11 KW (~ 11 x)	Level III 220V, 200 A: 44 KW (~ 44 x)	480V, 400 A: 330 KW* (~ 330 x)	480V, 1000 A: 830 KW* (~ 830 x)
GreenWheel (20 mi pedal assist)		0.2	7 min	1 min	< 1 min	< 1 min	< 1 min
RoboScooter (20 mi)		0.5	17 min	3 min	< 1 min	< 1 min	< 1 min
Motorcycle (50 mi)		5	3 hours	27 min	7 min	< 1 min	< 1 min
CityCar (60 mi)		15	8 hours	2 hours	20 min	3 min	1 min
Sedan (100 mi)		30	17 hours	3 hours	41 min	6 min	3 min
Taxi (180 mi)		60	34 hours	6 hours	2 hours	11 min	5 min
Public Shuttle Bus		150	84 hours	14 hours	3 hours	27 min	11 min

** 3-phase power: Power = sqrt(3)*Current*Voltage*

Note: All Charge Times are Ideal Calculations Assuming 100% Efficiency

Figure 40: Graphical matrix depicting vehicle charge times by power source for a variety of electric vehicle pack sizes, highlighting the high infrastructural demands of rapid charging.

6.3 – Grid-to-Vehicle Energy Buffering with Uninterruptible Power Supplies

As demonstrated in the previous section, the power and infrastructural requirements of rapid chargers are very demanding on electric networks. Installing these high power rapid charging systems on large scale can require costly major upgrades to building electrical infrastructure, including larger transformers to manage increased throughput of electrical substations. Furthermore, many urban electric grids are already strained to capacity and the addition of several rapid charging electric vehicles to the standard load can be prohibitively burdensome on the grid's ability to supply reliable power to cities. As a potential mitigation measure for this, we propose the use of an uninterruptible power supply (UPS) – a battery-storage element that is typically used for providing short-term backup power to critical applications during power outages – as a buffer between the grid and electric vehicles and as a storage element for intermittent sources of power generation, such as solar and wind. In addition, the "second life" of automotive Li-ion batteries for use in grid energy storage applications can be tested to determine the feasibility of using partially depleted Li-ion cells from vehicles in UPS systems after they have lost some fraction of their initial state-of-health.

A standard UPS system consists of three power stages: (1) input: AC to DC rectification, (2) DC energy storage in sealed lead-acid (SLA) batteries and (3) output: DC to AC inversion. The typical behavior of a UPS is to charge gradually from the electric grid to store energy in its SLA battery bank, and discharge the stored energy through the output inverter to provide backup AC power in the event of power failure. [24] UPS systems are ubiquitous in power critical applications such as data farms, hospitals, IT equipment rooms, and are becoming increasingly common in developing nations where power outages are frequent.

The DC battery bank contained within the UPS provides an opportunity for interfacing electric vehicles to the grid via an energy buffer. For a variety of historical and technical reasons, AC power is used for electrical transmission and distribution throughout the world. However, energy consumption and storage often requires DC power, necessitating costly and sizeable devices for rectification and inversion that dissipate significant energy conversion losses as heat. As rapid charging of electric vehicle demands large amounts of power that could overtax the power sourcing capacity of urban electric grids, particularly at peak hours, there is an opportunity to employ a DC battery buffer to provide direct DC power to vehicles with minimal conversion losses and impact to the peak loading of the grid. This energy buffer would lessen the direct load on the electrical grid during peak EV charging times and gradually charge itself from the grid in off-peak hours. [25]

Incorporating a DC energy storage element into building and urban power systems also provides a valuable role for connectivity with renewable power. Intermittent power generation sources such as solar and wind can now be incorporated directly into buildings and urban infrastructure, but often the power is not generated when it is needed and the production capacity of major power plants cannot be quickly scaled down to effectively harness alternative energy sources. The UPS battery bank could therefore function to store energy from these intermittent sources and can improve efficiency in the case of DC power generation technologies such as photovoltaic modules, since no DC to AC inversion stage would be required. [26] In the long term, it may even be feasible to incorporate small-scale, localized DC microgrids into building infrastructure to minimize conversion losses associated with intermittent power generation, some of which can be produced and consumed directly in urban areas without requiring an interface with an extensive transmission or distribution grid (Figure 41).

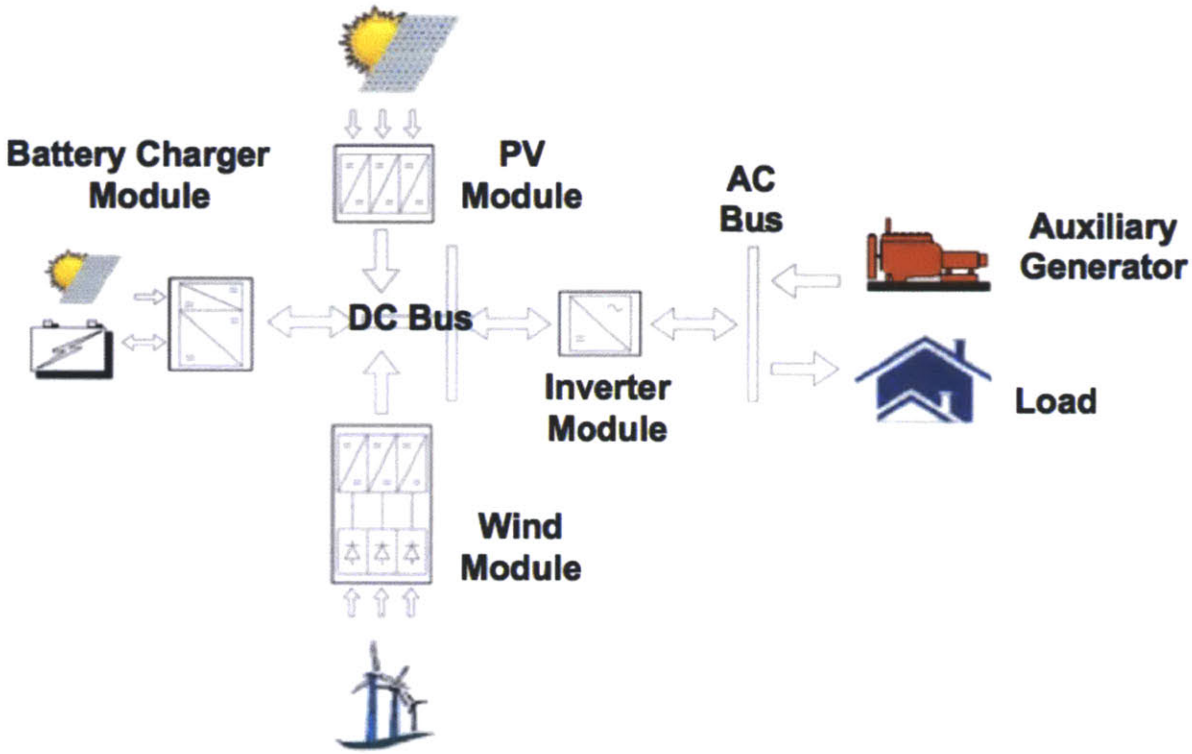


Figure 41: Depiction of a local DC microgrid that can connect to DC storage elements and renewable power sources to minimize conversion and transmission losses associated with locally generated intermittent power sources. (Modified image, original courtesy of Ingeteam)

6.4 – Repurposing Vehicle Traction Batteries for Stationary Grid Storage in a UPS

The volume and mass of current commercial UPS systems are very large due to the poor gravimetric and volumetric energy density of lead-acid batteries (about 40 Wh/kg and 100 Wh/L compared to 150 Wh/kg and 230 Wh/L for average Li-ion cells). [27] As automotive applications of Li-ion batteries in the traction pack are particularly abusive due to hostile thermal conditions, rigorous current profiles, and extreme vibration, there is likely significant value in repurposing partially depleted Li-ion batteries for grid storage applications after they have lost some of their ability to store charge (known as state-of-health) and are no longer ideal for vehicular use to meet a minimum range specification (Figure 42). [28]

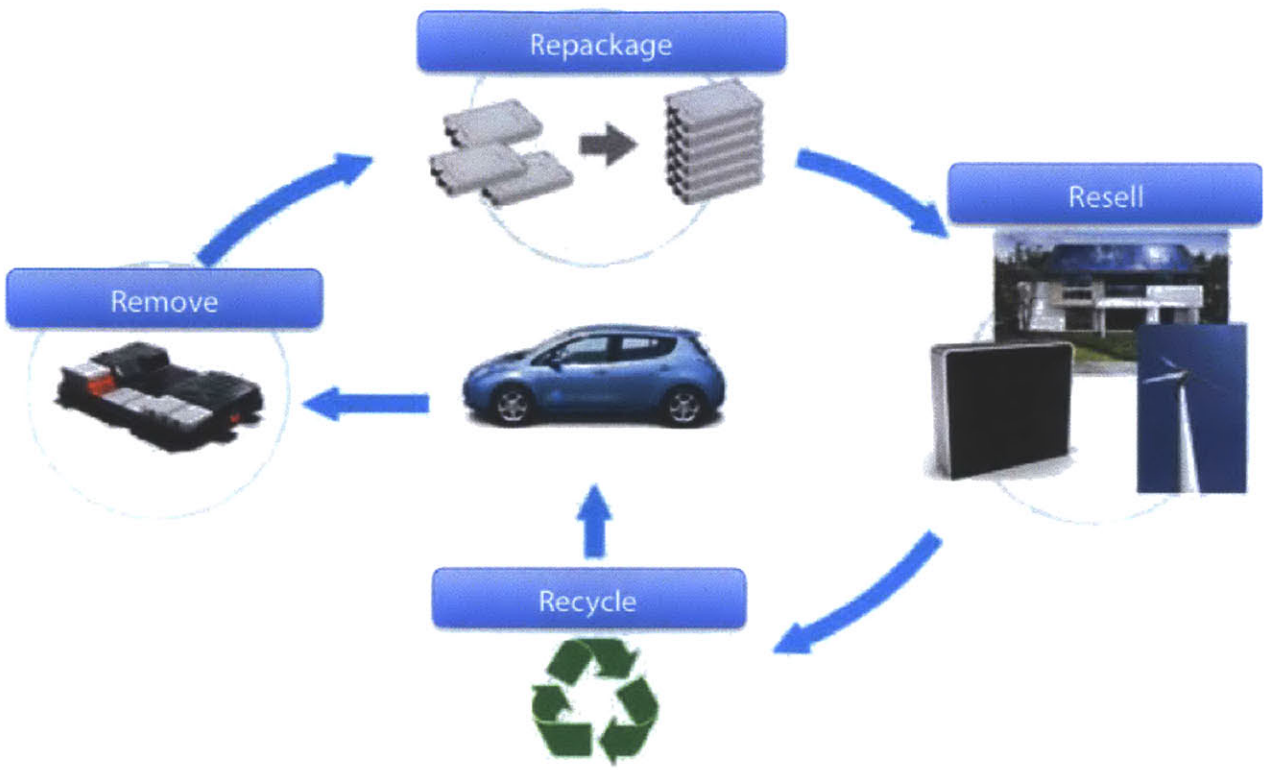


Figure 42: A visual depiction of a model for second-life applications of partially cycled automotive traction batteries. After refabricating the cells for other applications such as grid storage and consumer electronics, the cells can eventually be recycled for raw material components.

This "second life" for vehicular batteries may contribute to reduced footprint for battery-based grid storage units and make the high market prices of Li-ion batteries more palatable to automotive manufacturers, as the batteries will have resale value beyond raw material recyclability. Of particular interest are the implications of this reuse strategy on rapid charging stations for shared vehicle fleets that allow for standardization of traction battery geometries suitable for repurposed UPS applications. In shared use fleet scenarios, a fleet operator or battery leaser can specify both the grid storage charging infrastructure and fleet vehicle batteries for interchangeability. American battery manufacturers, such as A123 Systems, have recently started releasing "lead-acid replacement modules," a combination of Li-ion cells, a battery management system, and protection circuit module (PCM). These replacement modules act as drop-in replacements for the traditional lead-acid batteries used as UPS systems, car starter batteries, and grid storage. However, they offer the improved benefit of higher energy density, improved cycle life, and lower mass. [29]

6.5 – Schneider Electric Symmetra PX Case Study

To investigate the feasibility of using an SLA-based UPS as a buffer between the electric grid and vehicles, we studied a 250 kW Symmetra PX UPS manufactured by 'APC by Schneider Electric.' This particular UPS can be loaded with SLA modules for an energy storage capacity of up to 80 kWh of battery storage. By replacing the SLA batteries with repurposed Li-ion modules, the UPS energy storage capacity can be nearly doubled. As Level III rapid charging requires a DC output and the UPS is designed to provide standard AC output, power from the internal DC battery bus voltage of the UPS needs to be drawn in a nontraditional way. There are two principal strategies for using the UPS internal battery bank as a DC energy source for electric vehicle rapid charging:

(1) DC output through a medium-voltage motor controller, which can carefully regulate the supply current
(2) DC output through a current-controlled buck/boost converter (Figure 43)

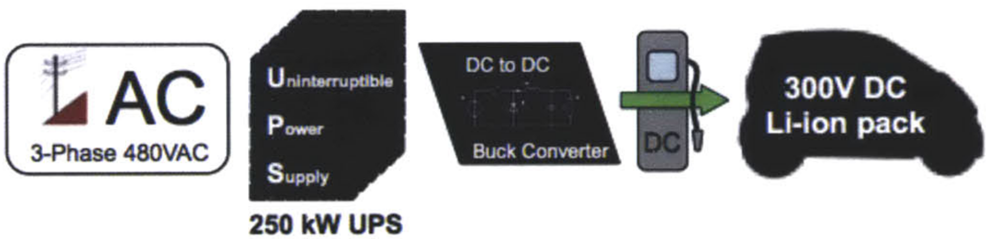


Figure 43: Power path for a UPS-buffered DC rapid charging prototype system. DC output from the UPS can be obtained using a buck converter, a medium-voltage motor controller, or a diode-coupled system.

Ultimately, further work is required to evaluate if the creative combination of new and existing UPS systems with repurposed vehicle traction batteries and strategic planning & policy can leverage existing electrical infrastructure to charge future urban EV fleets while minimizing major investment in supplemental power generation and distribution infrastructure. A dual-phase research strategy using the Symmetra PX as a research platform for further investigating the UPS buffering strategy is now presented.

Since Li-ion batteries require a very specific charging profile to maintain their cycle life – typically a constant current (CC) stage followed by a constant voltage (CV) stage for the final 10% - 20% of SOC – the DC output system from the UPS requires feedback circuitry to regulate the charging parameters and a communication protocol to interface with the pack's battery management system (BMS). Phase I of the research experiments can consist of designing and constructing the custom DC-DC output system with current regulation and feedback to interface safely and reliably to a vehicle battery pack. Power curves (charging power vs. charge time) for packs of increasing capacity can be measured, with the goal of determining the actual tradeoffs between the output power and the charge time for a typical building-sized UPS. Furthermore, battery cycling experiments that vary the input power and output loads can be performed to accurately characterize the charging time of the SLA modules and determine the ideal charging rate for using the UPS as a grid-to-vehicle energy buffer.

After the initial cycling tests using the UPS as a buffer for grid-to-vehicle rapid charging, the repurposing of partially depleted vehicle batteries for energy storage in the UPS can be tested in Phase II of the research experiments. Life cycle analysis of the repurposed batteries can provide deeper understanding of the feasibility of second life of vehicle traction batteries. As the UPS is currently designed for lead acid cells and the repurposed vehicle batteries will be of Li-ion chemistry, nontrivial modifications to the UPS power electronics circuitry for charging and discharging the batteries will be required to enable the switch. However, a handful of battery manufacturers are beginning to commercially produce lead-acid replacement modules with Li-ion cells, which contain power electronics and logic to adapt an SLA charging profile for Li-ion. This type of module would allow for a more rapid modification of the UPS system to accommodate the repurposed cells, which would allow for increased energy storage capacity of the UPS system and possibly faster charge times.

6.6 – Clean, Distributed Energy Networks for Powering Electric Mobility

The relative efficiency of electric vehicles depends heavily on the source of the electricity used to power the vehicles. A form of life cycle assessment known as "wells-to-wheels" analysis is used to compare the relative efficiencies of different modes based on raw fuel input to mileage output. In wells-to-wheels analyses, both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are consistently more efficient and output less pollution than vehicles powered by internal combustion engines, regardless of the form of energy generation. For example, a 2007 study by the Natural Resources Defense Council and the Electric Power Research Institute highlighted the fact that a traditional gasoline vehicle outputs approximately

450 grams of CO_2 per mile, while a PHEV powered by coal-generated electricity (one of the most polluting forms of modern electricity generation) is responsible for only 325 grams of CO_2 per mile. This figure drops to as low as 150 grams of CO_2 per mile if the electricity used in PHEVs is generated with a clean, renewable energy source such as wind and solar. [30] Raw energy consumption for PHEVs and BEVs, measured in megajoules per kilometer is also consistently less than internal combustion engine, gasoline-powered vehicles. This is largely attributable to the low efficiency of automobile internal combustion engines (typically about 14% - 26%), which is far worse than electricity generating plants, even accounting for transmission, distribution, and conversion losses. [31] For a pure BEV coupled with renewable energy sources, the reductions in energy consumption and emissions are even more significant, and a future in which vehicles are responsible for little to no greenhouse gas emission is fully realizable.

The true non-incremental gains of electric mobility are realized by combining shared vehicles systems with lightweight, compact vehicle design and clean energy generation. Along with the vision for a localized DC ecosystem presented earlier, there is an opportunity to leverage distributed energy generation within cities to improve resilience. Today, electricity is generated at a number of large, centralized nodes such as utility power plants. The accompanying transmission and distribution infrastructure required to transmit this electricity to the bulk of electrical loads in cities is incredibly costly and contributes to reduced inefficiency. A localized and distributed energy generation subsystem, also known as a microgrid, could potentially complement the larger centralized electrical networks to provide improved efficiency and reliability of electric power in cities. This vision for small-scale, localized generation is already playing out across the world. For example, in 2010, Colorado became the first American state to mandate that 30% of utility-scale electricity come from renewable sources and that 3% come from distributed generation. [32]

The backbone of this vision for energy generation and distribution can be divided into two segments: a local DC bus coupled with grid storage, and a traditional AC bus that is connected to existing transmission networks. Grid storage can take the form of battery storage, such as second-life EV batteries or utility-scale liquid metal batteries, or harness the vehicles themselves.

The grid storage acts as a buffer for rapid charging of electric vehicle and provides a reservoir for intermittent energy sources such as wind and solar. This energy storage also provides resiliency and could mitigate the need for backup generation sources such as highly polluting gas generators that are often found in power-critical applications such as hospitals and data centers. These two backbones can then be linked with a high efficiency hybrid AC/DC converter to allow for energy flow when necessary, but the goal would be to minimize the bulk high-voltage AC/DC conversions to maximize efficiency.

Small-scale energy generation sources such as rooftop solar and microturbines can combine with the much more powerful utility-scale installations of solar farms and wind farms to feed into the DC backbone. When energy demand is well matched to the supply, the energy can be routed directly from the source to the load, providing direct DC power for charging of electric vehicles and the operation of in-building DC devices such as LED lighting, computers, TVs, and consumer electronics. When surplus energy is available, energy can be captured in battery storage units, which are coupled directly to the DC bus. If the generation and storage capacities are sufficiently sized, this storage element could potentially power homes and vehicles even when generation sources are at low output capacity.

Traditional AC loads such as manufacturing plants, factories, and the existing AC ecosystem can be powered by incrementally cleaner forms of energy generation such as biomass plants. These sources can connect into the existing AC bus where the loads operate largely at AC. Thus, AC loads are powered by AC generation sources and DC loads are powered by DC generation sources, coupled with battery storage for resiliency. Conversion losses are minimized in normal applications, though either system can supply energy to the other in the event of emergencies or equipment failure through the hybrid converters. The resulting energy network is a powerful, hybrid AC/DC model that merges the efficiency of renewable power with the security of battery storage and the reliability of non-intermittent sources (Figure 44).

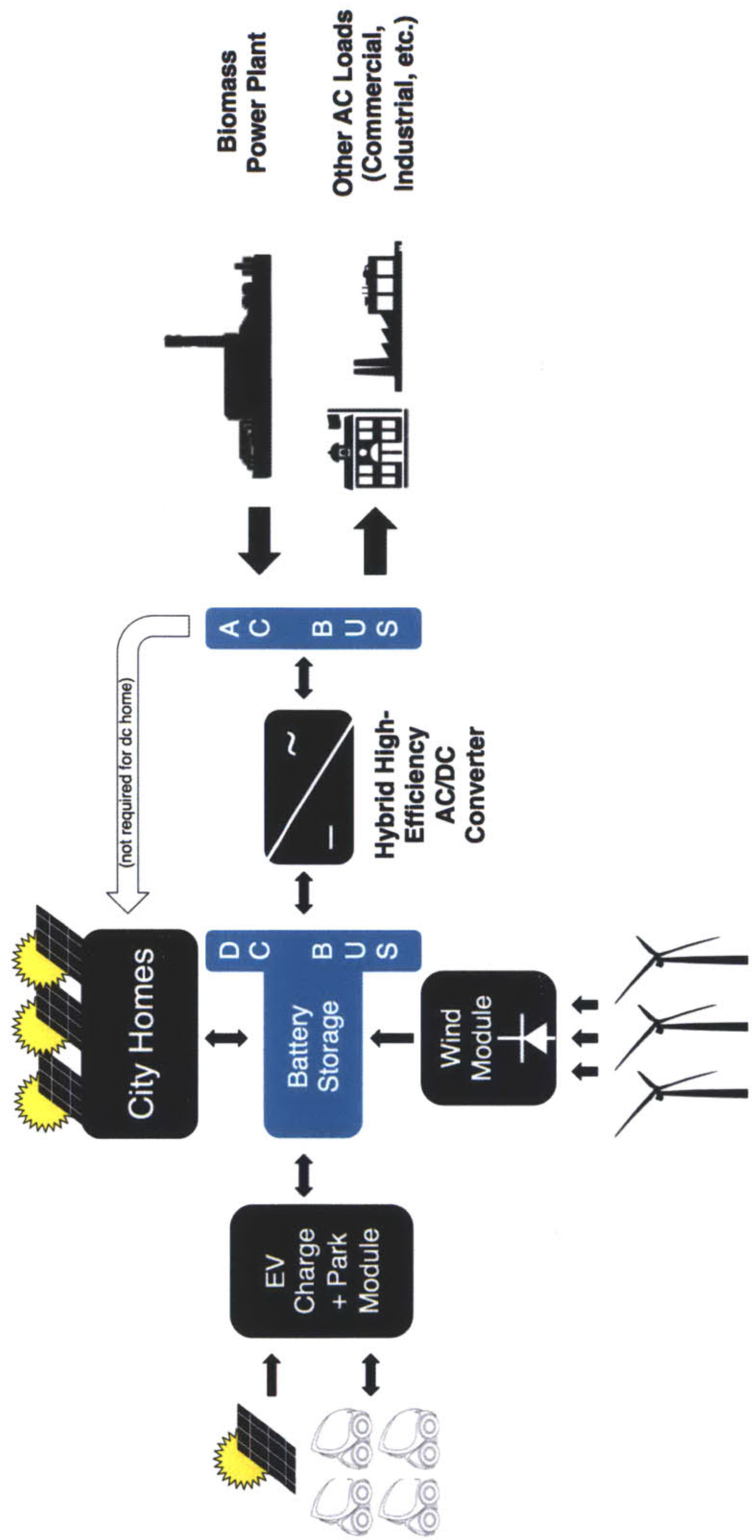


Figure 44: A graphic depiction of the proposed hybrid AC/DC ecosystem that incorporates renewable power generation, energy storage, and traditional AC loads. Electric vehicles and DC loads can charge directly from the DC bus for improved efficiency, and housing units can eventually be designed to operate entirely on DC power. Meanwhile, the traditional AC bus provides reliability through non-intermittent power sources and supplies AC power to traditional AC loads such as factories and manufacturing plants.

{VII} MIT Campus Building Case Studies

Given the daunting infrastructural and power generation requirements demanded by rapid charging, it has been a slowly adopted technology that has been limited to small-scale installations. However, there are a variety of key opportunities for scaling rapid charging infrastructure to urban scale scenarios. The feasibility of a nascent technology can be divided into five evaluation criteria, as presented below:

1) **Technology**: Can the battery packs and chargers be built?
2) **Infrastructure**: Can the grid supply the power?
3) **Profitability**: Is it cost-effective? Can viable business models be created around rapid charging?
4) **Demand**: Will customers need it and actually use it?
5) **Scalability**: What are the limitations on charging a car? A bus? A fleet? How many rapid charging stations can be constructed in a fixed area, and how many are necessary?

This section explores the themes of technology, infrastructure, and scalability as they relate to rapid charging, using two buildings on the MIT campus as case studies. Of particular importance is the concept of leveraging existing building infrastructure and transformational capacity to supply power to electric vehicles.

7.1 – Substations & Power Transformation

The basic role of a substation is to take an input voltage, often from a power transmission grid, and transform it to a different (typically lower) voltage for use in distribution or delivery. In the urban power grids of centuries past, electrical substations typically took the form of independent, stand-alone buildings that appeared throughout cities. However, as buildings have grown larger, their power requirements have grown immensely. As such, many large buildings today such as office buildings and university facilities generally incorporate their own electrical substations at ground or basement level. These substations house the transformers, switch boxes, fusing, and control systems that are necessary for distributing power safely throughout a building.

In many newer buildings, the transformational capacity of these substations is significantly oversized. In other words, the transformers in the electrical substation are capable of transforming and delivering much more power than the buildings are actually using. This transformer and substation capacity oversizing exists for a number of reasons. Firstly, if transformers are run at 100% duty cycle, their usable life depreciates significantly so they are often operated at lower duty cycles to reduce dissipated heat and extend equipment lifetime. Secondly, many buildings contain multiple transformers such that there is a backup option for power if other transformers are malfunctioning or require maintenance. Finally, electrical substations within buildings are often oversized because the exact power requirements of buildings are not known upon their construction, so extra capacity is often built to avoid the hefty cost of infrastructural retrofitting. Nonetheless, the amount of overhead capacity built into some modern buildings is so large that there is great potential to utilize some of this surplus for charging electric vehicles.

7.2 – Leveraging Existing Building Infrastructure

Due to the excess transformational capacity provided by many modern buildings, there is a potential to leverage this existing infrastructure to charge electric vehicles (Figure 45). It should be noted that the electricity required to charge these vehicles would not be "free," in the sense that it would require additional production of energy downstream. However, interfacing electric vehicle charging to existing substations with overhead capacity could greatly reduce the financial and material cost of constructing the dozens of charging stations that would be necessary for a shared electric mobility system. Furthermore, this strategy allows the vehicle batteries to potentially act as add-on power storage elements to the building. If traditional AC transformers are eschewed in favor of high-efficiency, direct DC to DC power transfer, vehicle-to-grid technology becomes much more feasible.

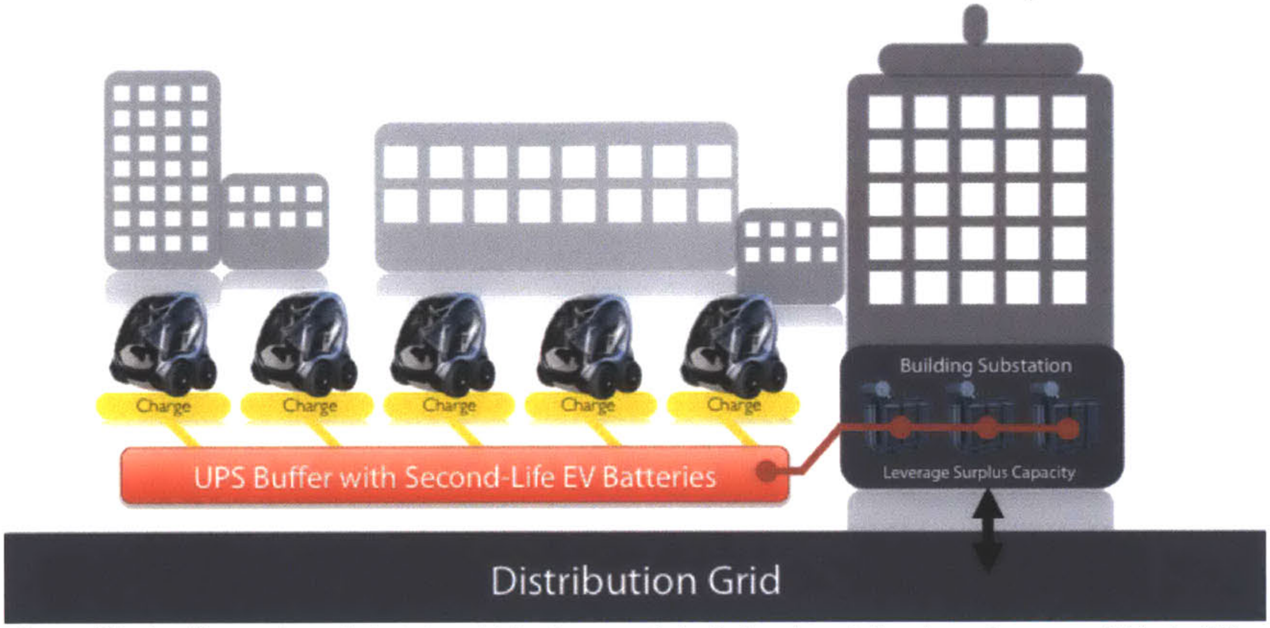


Figure 45: An illustration of electric vehicle chargers interfacing to existing transformers within building substations. Lightweight, urban electric vehicles are particularly suited to this type of connection, as their use in fleet systems will require distributed charging stations throughout the city.

To demonstrate the potential for electric vehicles to charge from existing building power infrastructure, two recently constructed buildings on MIT's campus were examined. It should be noted that these buildings should not be interpreted to represent average urban structures. Rather, these are laboratory-grade facilities constructed in the past 10 years that were built with the intent of future growth and longevity throughout the diverse uses demanded by an academic plant. However, they do provide some insight into how much surplus transformational infrastructure might be available in recently constructed buildings. These buildings also highlight the potential for electric infrastructure in institutional facilities such as universities, hospitals, museums, and government buildings to play an important role in creating a backbone for electric vehicle charging networks.

7.3 – Power Generation and Distribution on MIT's Campus

The campus of the Massachusetts Institute of Technology features a cogeneration power plant with a maximum capacity of 20.4 MW. Any additional energy demands, which range from 0 to 20 MW depending on the season and the campus electricity demand, are purchased from the local Cambridge grid utility provider, NSTAR. Electricity is distributed throughout campus through a local distribution network containing 13.8 kV and 2.4 kV lines, with the lower voltages typically servicing older buildings.

7.4 – MIT Stata Center Case Study

The Stata Center at the Massachusetts Institute of Technology was designed by Gehry Partners architectural firm and opened in 2004. The building contains 430,000 gross square feet of indoor space plus an additional 290,000 square foot underground parking garage. The building uses are widely mixed, ranging from flexible research facilities and classrooms to fitness and childcare centers, each with their own energy demands. [33] Typical power consumption for the Stata Center ranges from 1.2 MW – 1.5 MW, accounting for over 5% of the cogeneration plant's capacity. Electrical power is fed to the Stata Center's two electrical substations, located at basement level, at the high distribution voltage of 13.8 kV. This voltage is then converted to 480V AC by large transformers which service electrical panels for building distribution, as well as a number of smaller transformers that convert the voltage down to typical industrial and household voltage specifications (Figure 46). These lower voltages are then distributed throughout the building, ranging from 480V AC for systems such as elevators and HVAC to 115V AC for standard electrical outlets.

The physical scale of the electrical substations is of particular importance. While the input 13.8 kV lines have only about an eight to ten inch diameter, the transformers, switches, and safety equipment necessary to convert this input power into usable electricity for the building are quite large. Two entire basement level rooms, one in each tower, are devoted to these electrical substations and the cabinets housing the transformers are an order of magnitude larger than the size of humans (Figure 47). Thus it is clear that placing this type of transformational infrastructure at street level or in public spaces would be very detrimental to urban environments.

While the equipment can be hidden or obstructed to some degree, transformers require proper cooling and ventilating and must be accessible for maintenance and inspection on a regular basis. Furthermore, this type of electrical equipment emits a characteristic 60 Hertz hum, which is undesirable and unpleasant in public spaces.

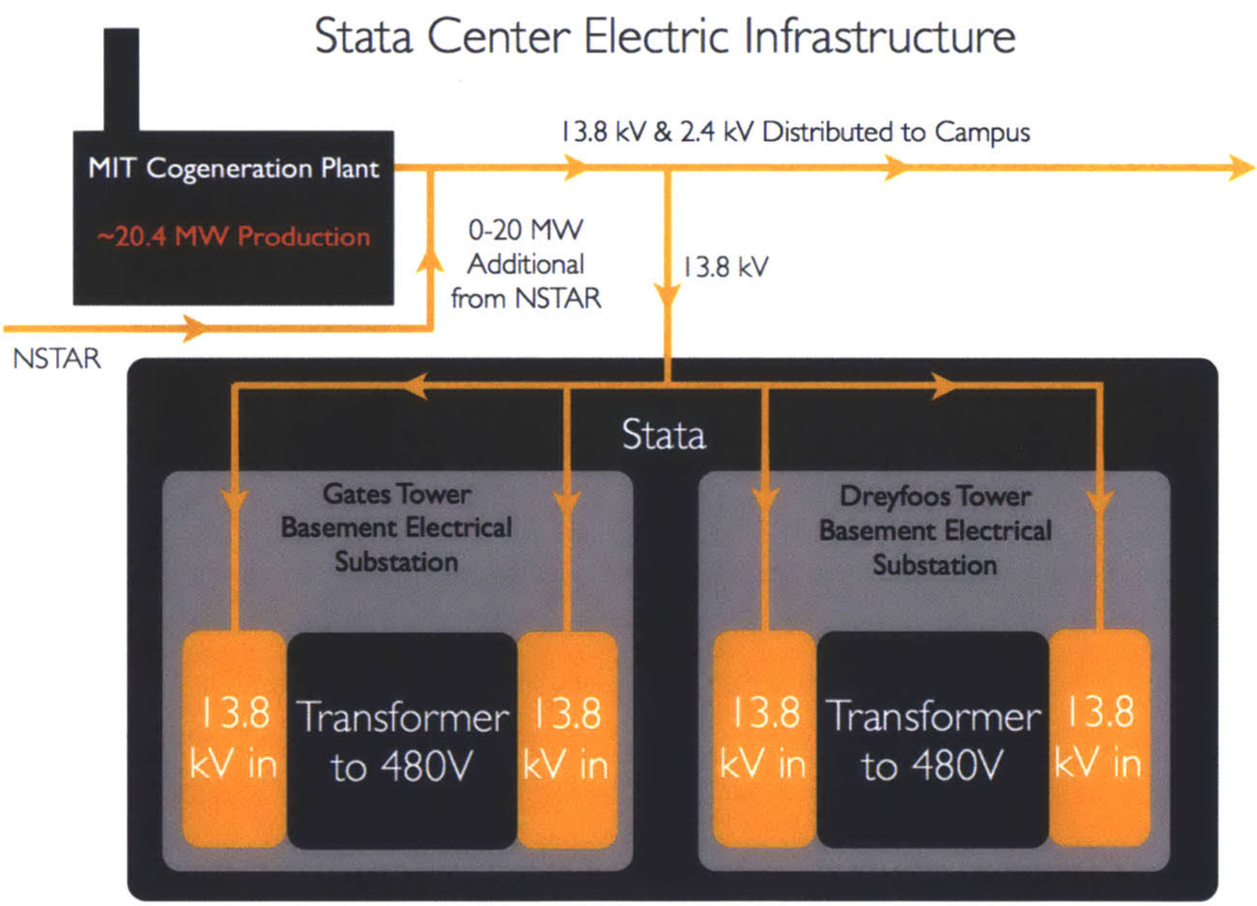
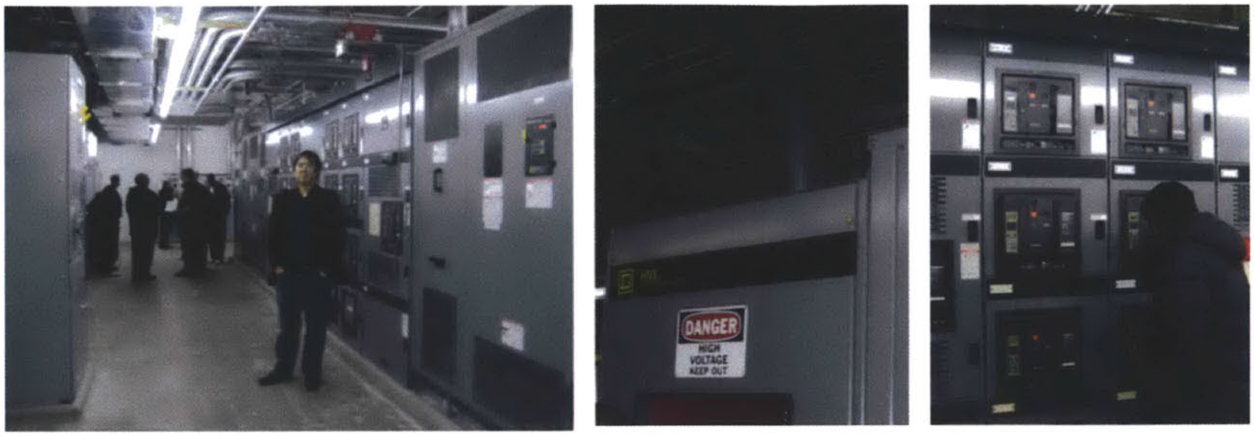


Figure 46: Stata Center Electric Infrastructure. The building is fed with 13.8 kV input which is directed to two substations. Each substation is capable of independently powering the building in the event of the other's failure.



Individual Tower Substation (Gates Tower) **13.8 kV Input Line** **480V Output Monitor Panels**

Figure 47: Human-scale references for a variety of electrical systems contained in the Stata Center electrical substations

Both of the Stata Center's substations contain two mega-transformers, each of which is capable of sourcing 3200 Amperes of three-phase power at 480V. Each transformer's maximum rated capacity is given by:

Single Transformer Power = 3200 A x 480V x √(3) = **2.66 MW**

Thus the entire building transformational capacity (two substations with two transformers is given by:

Total Power = 4 x 2.66 MW = **10.6 MW power capacity**

Given that the building's peak power consumption is approximately 1.5 MW, this represents a 9.1 MW surplus in transformational capacity. In other words, less than 15% of the building's transformational capacity is being utilized, leaving over 85% unused. As discussed earlier, it is not optimal to run transformers at full duty cycle because it reduces their longevity. In addition, part of this overhead capacity is necessary for emergencies and maintenance scenarios. However, even if just 11% of this surplus 9.1 MW transformational capacity were allocated for electric vehicle charging, a full megawatt of capacity would be available. Keeping in mind that an average Level II charger might draw up to 10 kW including efficiency losses, this would provide capacity for 100 electric vehicle charging stations from a single building alone. If rapid, Level III chargers were employed, using a high-end reference specification of 50 kW, this still provides transformational capacity for 20 rapid chargers. In practice, some balance of Level II and Level III chargers would probably be optimal to provide a combination of all-day charging for private vehicle owners and lightly utilized vehicles, while Level III charging can be available for the most heavily used fleet vehicles or by private EV owners who need a quick recharge for their commute home. In addition, the rapid chargers could be positioned closest to entry and exit points to the parking structure, or nearest to the pedestrian inflow points (Figure 48).

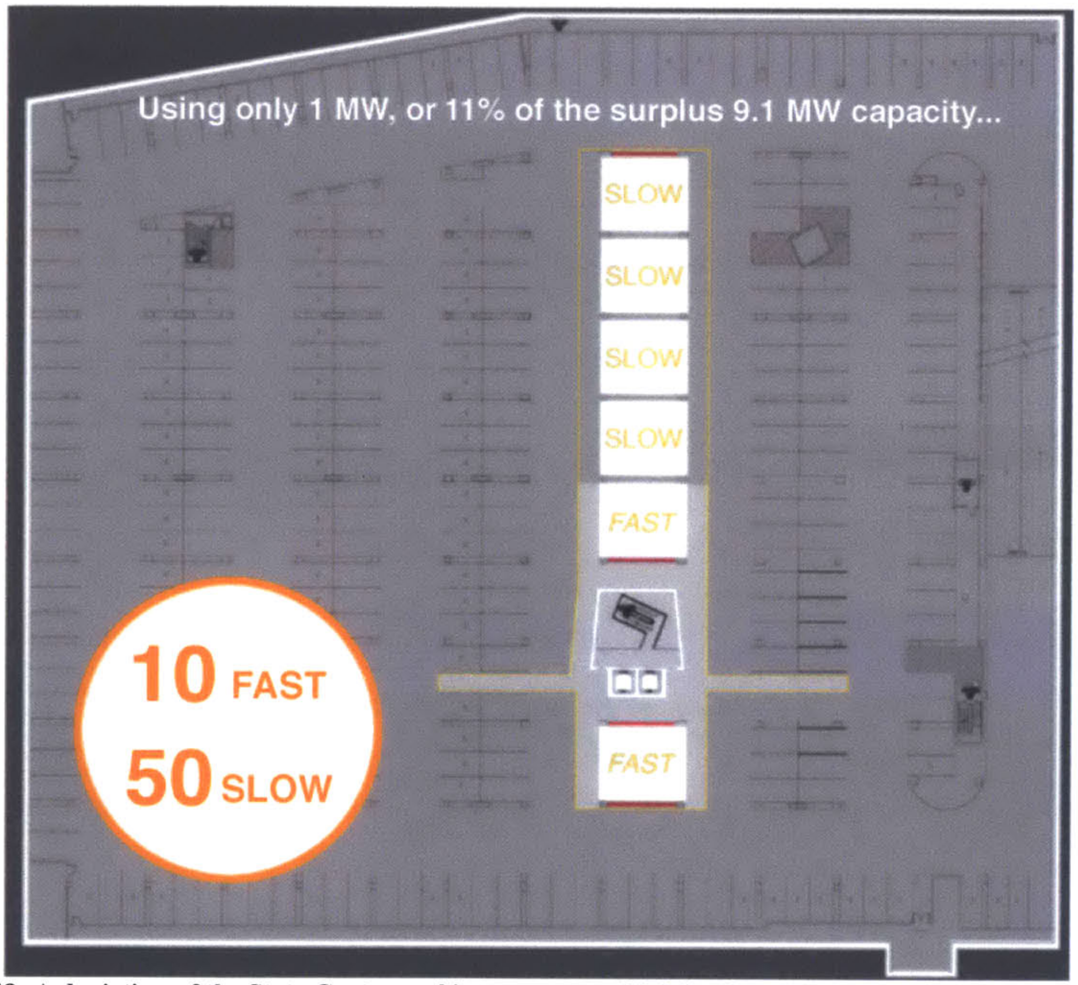


Figure 48: A depiction of the Stata Center parking garage enabled for electric vehicles, balanced between fast charging (Level III at 50 kW) and slow charging (Level II at 10 kW). Using 1 MW, which is only 11% of the building's surplus transformational capacity, 10 Level III and 50 Level II chargers can be installed without necessitating the installation of any new transformers.

This case study demonstrates that, at least in some modern buildings, there is an incredible amount of surplus transformational capacity that can be harnessed for charging electric vehicles. This finding is further supported by the fact that many large commercial and office buildings in dense cities contain their own substations. While these substations are probably not as oversized as the Stata Center's, even if each one could provide the transformational capacity for 5-10 electric vehicle chargers, the cost of deploying electric charging infrastructure for fleet systems would be greatly reduced. In addition, these businesses would benefit from new mobility options for their employees and customers, which could potentially function to increase land value and improve land use.

7.5 – MIT Media Lab Case Study

The Media Lab facility at the Massachusetts Institute of Technology was designed by Fumihiko Maki and Associates and opened for use in 2009. This mixed-use facility encompasses 163,000 gross square feet of lab space, machine shop facilities, performance space, classroom facilities, and more. The building was constructed at a cost of $90 million and features a true exterior that is largely glass, providing natural light from its south-facing side towards the Charles River and the city of Boston. [34]

Electrical infrastructure within the Media Lab is designed in a similar fashion to that of the Stata Center. The campus distribution network reaches a basement-level substation within the building and the 13.8 kV distribution line is converted to 480V AC for use within the building and transformation to lower voltages (Figure 49). The primary difference between the Media Lab's substation and the Stata Center's electrical feed architecture is that the Media Lab contains only a single substation, while the Stata Center contains separate substations for each of its two towers. However, it should be noted that the new Media Lab building is connected to an older Media Lab facility, which also contains its own electrical substation. This secondary substation is not included in these calculations.

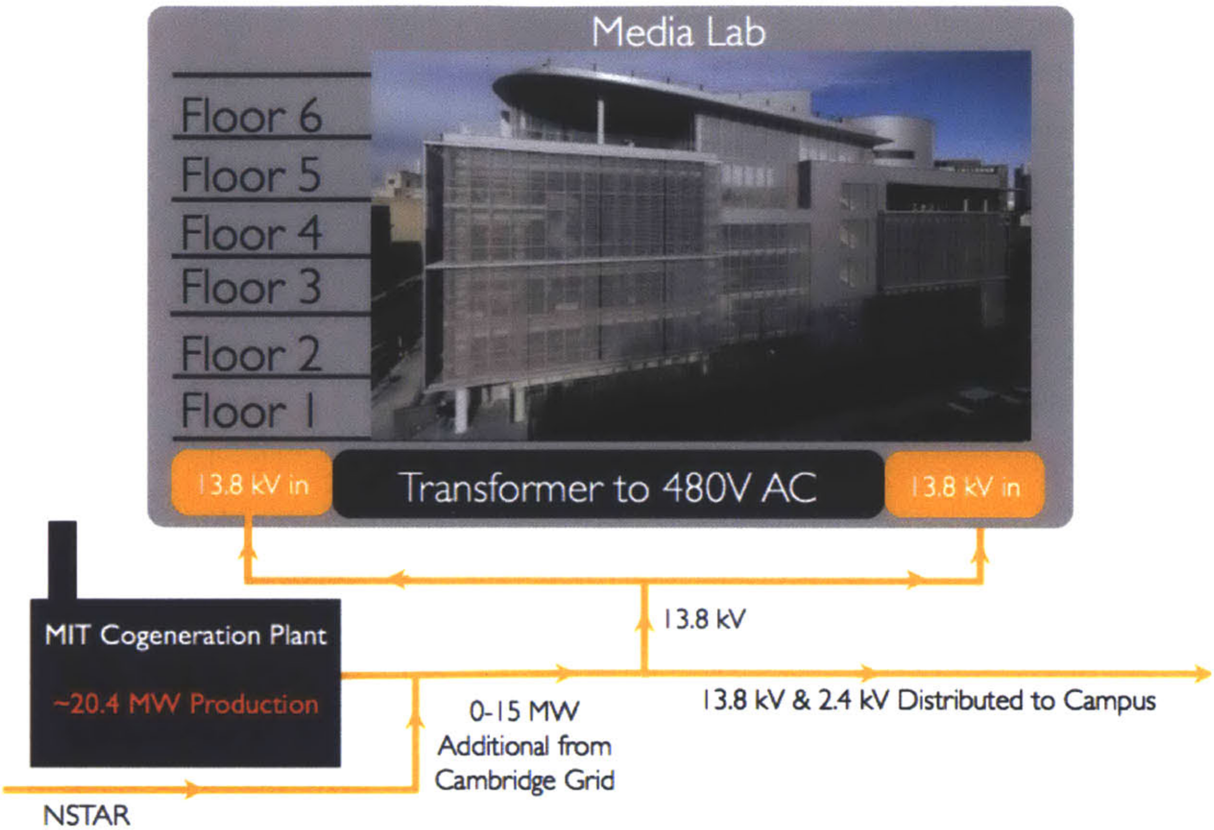


Figure 49: Electrical distribution diagram for the MIT Media Lab facility. Like the Stata Center, this building is fed with 13.8 kV from MIT's distribution network, which is then converted to 480V by the major transformers in the building's substation.

The Media Lab building contains two mega-transformers, each of which is capable of sourcing 3200 Amperes of three-phase power at 480V. Each transformer's rated capacity is given by:

Single Transformer Power = 3200 A x 480V x √(3) = **2.66 MW**

Thus the entire building transformational capacity (two substations with two transformers is given by:

Total Power = 2 x 2.66 MW = **5.3 MW power capacity**

Given that the building's peak power consumption is approximately 500 kW, this represents a 4.8 MW surplus in transformational capacity. Thus, less than 10% of this building's transformational capacity is actually in use from current building operations, HVAC systems, lighting, and other power loads. Unlike the Stata Center, the Media Lab does not feature a parking garage, so visitors to the building typically park in other MIT parking lots, street parking on the adjacent streets, or utilize other modes of transportation such as walking, cycling, and the nearby MBTA Red Line Station at Kendall Square. Since an urban streetscape can accommodate fewer parked vehicles than the parking garage, there is even less of a load requirement for electric vehicle charging.

So if even 5% of the Media Lab's surplus capacity were dedicated to electric vehicle charging, this would provide 240 kW of transformational capacity for vehicle use. This could, for example, provide a combination of two 50 kW Level III chargers and fourteen Level II chargers running full time. Given the proximity of other major buildings in this area that likely have substantial overhead capacity, it is unlikely that the Media Lab would even need to be able to host this many vehicles.

7.6 – Distributing Charging Infrastructure Across Buildings

These case studies illustrate how groupings of buildings in urban environments, particularly those that have large overhead capacity such as institutional structures and major commercial centers such as malls and office buildings, can act as energy hosts for charging electric vehicles. While the supplementary power for charging vehicles will need to be produced at some point upstream through an energy generation process, existing transformational infrastructure can be used to reduce the installation cost and equipment footprint of charging stations. In cities of the 21st century, buildings can be designed with street-level transformer access panels to facilitate the installation of street-level charging infrastructure. Multiple buildings can play a role in providing charging power to any mobility corridor, and mobility hubs can be created with a methodology that incorporates overhead capacity as a factor. Figure 50 illustrates how Vassar Street, an arterial connector that runs along the northern border of MIT's main campus could be serviced by multiple abutting buildings to provide street-level electric vehicle charging. This strategy would reduce the infrastructural demands on any particular building and would distribute the responsibility amongst multiple buildings. Furthermore, efficiency gains can be realized by reducing the length of cabling and conduit that would need to be run from a single building to provide power to the entire corridor.

A set of sample criteria for conducting a site-suitability analysis for electric vehicle mobility hubs could include:

- Availability of surplus electric transformational capacity
- Proximity to important commercial and residential locations that can benefit from increased real-estate value
- Traffic circulation patterns on the street and adjacent road networks
- Population density
- Availability of street parking
- Proximity to existing public transportation networks and nodes

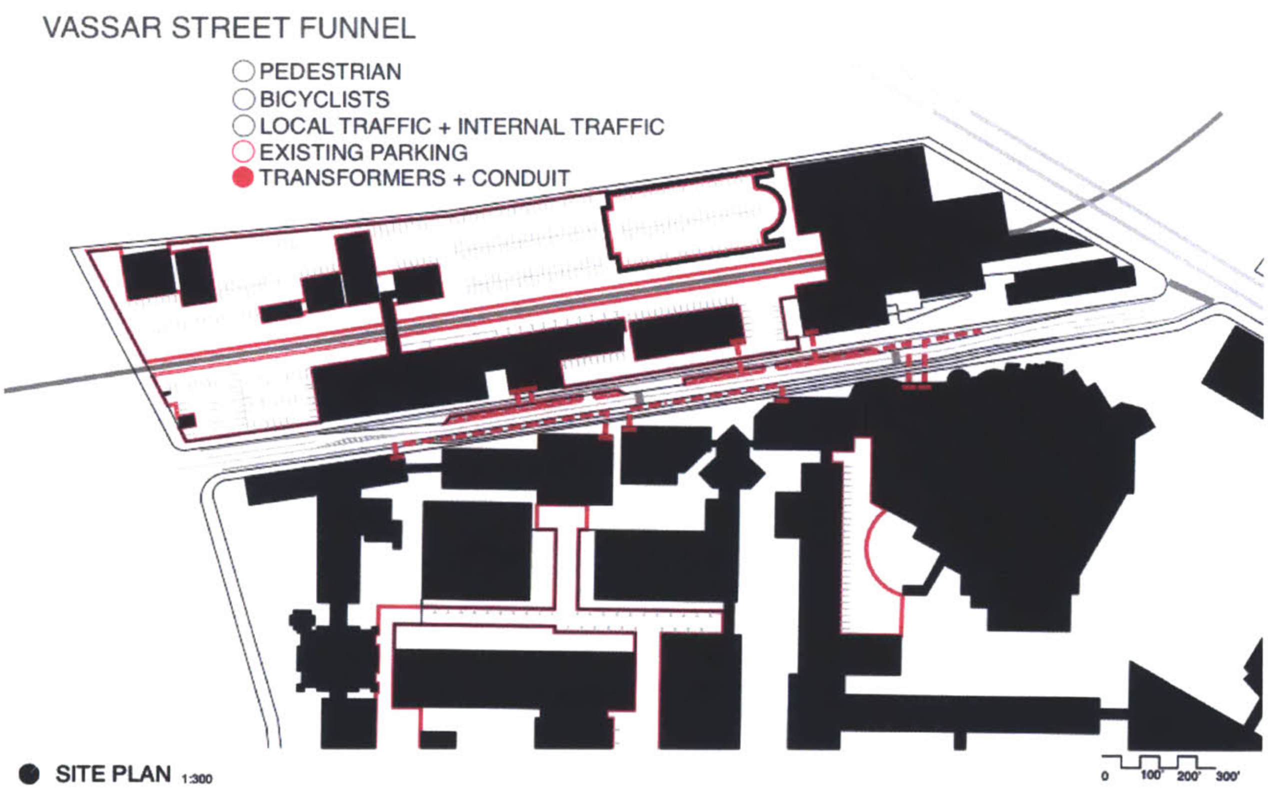


Figure 50: The Vassar Street corridor runs along the northern boundary of MIT's main campus. This image illustrates how transformers and electric infrastructure from multiple buildings can be tapped to provide power for multiple street-level and garage charging stations.

{VIII} Conclusion

The global challenges of pollution, congestion, and climate change will not be adequately addressed by flaccid governmental policy that provides weak incentives for the adoption of new technologies. Rather, technologically viable solutions to these daunting challenges must become compelling enough from a cost and user interface standpoint to spur widespread adoption. Today, shared vehicle systems offer an increasingly viable mode of metropolitan transportation for millions of urban residents worldwide. As these systems grow to incorporate a range of electric vehicles, it will be essential to analyze the system-scale challenges associated with deploying urban charging infrastructure, supplying clean energy, and managing fleets of shared electric vehicles. While electric infrastructure is often thought of as unpleasant and complex, improved product design and integration of digital connectivity can gradually change this perception and usher in an era of intelligent infrastructural development in industrialized nations.

In order for shared urban transportation systems to be perceived as functional and convenient by users who have grown accustomed to private vehicles over the course of decades, they must provide outstanding convenience, intuitive user design, and personalized mobility options. Fortunately, improvements in technology and shared mobility system service models have already initiated this shift. Indeed, declining preference for private automobile ownership among younger generations has already been documented and is expected to continue throughout the 21st century, as the myriad of negative externalities associated with private ICE-powered cars grows more visible. For example, the New York Times reported in March 2012 that between 1998 and 2008, the percentage of drivers' license ownership among potential drivers below the age of 20 dropped from 64.4% to 46.3%. Furthermore, drivers between the ages of 21 and 30 drove 12% fewer miles in 2009 than in 1995. In today's global marketplace of sleek consumer electronics and ubiquitous connectivity, devices such as smartphones and tablets have become the new prominent status symbols of the 21st century. Meanwhile, millions of people who have experienced the frustration of sitting in traffic, breathing smog-filled air, and paying outrageous sums for car ownership and maintenance have relegated the value of private automobile ownership to the back seat of the bus. [35]

The opportunities for the electrification of shared mobility systems in dense urban environments are numerous. Though shared vehicles are often perceived as threats to the automotive industry, which has long relied on the private ownership model, it has grown increasingly apparent that this defunct model of urban transportation must change. This is particularly true in developing and highly populated nations such as India and China, in which the vehicle ownership rates are relatively low, but urban pollution and congestion are rampant. The automotive OEMs that embrace their futures as mobility companies, rather than purely automakers, will have a number of opportunities for new products and services that will enable new business models for urban mobility. By targeting cities and shared vehicle fleet operators – from Paris' JCDecaux to Berlin's Deutsche Bahn to Cambridge's Zipcar – and focusing on the development of seamless mobility services, a myriad of new customers and business opportunities emerge. Perhaps even more promising are prospects in the developing world, in which infrastructural networks are nascent, so planners and policymakers have an opportunity to learn from the mistakes of post-industrial nations.

smartCharge functions as one linked physical and digital element of the Mobility-on-Demand ecosystem of vehicles, infrastructure, fleet management, and new business models for shared electric mobility. By addressing some of the specific flaws of traditional charging infrastructure when used in the context of shared vehicles, smartCharge provides an optimized platform for charging and locking vehicles in cities while providing contextual information through its ambient lighting display. The smartCharge system allows users to rent and return shared vehicles in a matter of seconds, without having to endure a multiple-step process for docking and charging their vehicles. Furthermore, it provides an agile platform for charging a variety of fleet electric vehicles and is capable of accommodating new vehicle types as they emerge, reducing the need for costly retrofitting of infrastructure. This type of integrated infrastructural element can help improve public spaces such as urban streetscapes, and contribute to the reclamation of land that is currently allocated for car parking. A networked system of smartCharge stations that tie together information on fleet status, vehicle states-of-charge, and maintenance issues would provide a powerful infrastructural backbone for the Mobility-on-Demand system. Incorporating intuitive interfaces and seamless user experience will be critical for lowering the barrier to entry for potential adopters of shared electric mobility. smartCharge exemplifies this user-centric design philosophy, and strikes a balance between intuitive product design and technical functionality.

Arguably even more critical are the phasing and design strategies for deploying electric vehicle charging stations in cities presented in this thesis. Managing the generation and demand for clean, renewable energy is vital for securing the impressive gains that can be realized by fully electric mobility. Similarly, leveraging existing building infrastructure will be important for mitigating the cost of new infrastructure installation and distributing the load of charging EVs across multiple facilities. The inclusion of mobility hubs near existing business and residences will improve connectivity for their occupants and can create new economic opportunities for the surrounding areas.

This thesis focused on the technology and infrastructure design and deployment strategies that will be necessary to realize non-incremental reductions in urban pollution and congestion through shared electric mobility. While the high price of automotive traction batteries is still cost-prohibitive for many consumers and automotive manufacturers, electric vehicles will grow increasingly practical as battery manufacturing yield improves and economies of scale gradually lower their cost per kilowatt-hour. In order to extract the maximum energy-saving and emissions-reducing improvements from these vehicles, forward-thinking nations must commit to powering their cities with a diverse portfolio of renewable and conventional energy sources. The incorporation of grid energy storage elements such as battery banks can perform the dual function of buffering rapid vehicle charging while providing a storage element for intermittent, renewable power sources such as solar and wind. While reliable and cost-effective solutions are nascent in today's market, the future is bright for energy storage. As of 2012, dozens of startups and established corporations are working fervently to develop low cost energy storage solutions based on technologies such as Lithium-ion batteries, compressed air, biofuels, fuel cells, supercapacitors, and even liquid metal batteries. In the words of Donald Sadoway, Professor of Materials Science & Engineering at MIT and a pioneer in low-cost, battery-based energy storage: "*if we had [the proper] battery, we would have this beautiful situation in which you could draw electrons from the sun even when the sun isn't shining. And that's really compelling. That gets people out of bed in the morning.*" [36]

Thesis Committee

Kent L. Larson
Principal Research Scientist
Director, Changing Places Group, MIT Media Lab

Kent Larson directs the MIT Media Lab's Changing Places group and is a founding director of the City Science Initiative in MIT's School of Architecture and Planning. His current research is focused on four related areas: responsive urban housing, new urban vehicles, ubiquitous technologies, and living lab experiments. Larson practiced architecture for 15 years in New York City, with work published in *Architectural Record, Progressive Architecture, Global Architecture, The New York Times, A+U,* and *Architectural Digest.* His book, *Louis I. Kahn: Unbuilt Masterworks* was selected as one of the Ten Best Books in Architecture, 2000 by *The New York Times Review of Books.* Related work was selected by *Time* magazine as a "Best Design of the Year" project.

Joseph A. Paradiso
Associate Professor of Media Arts & Sciences
Director, Responsive Environments Group, MIT Media Lab

Joseph Paradiso directs the Responsive Environments group, which explores how sensor networks augment and mediate human experience, interaction, and perception. In addition, he co-directs the Things That Think Consortium, a group of industry sponsors and Media Lab researchers who explore the extreme fringe of embedded computation, communication, and sensing. After two years developing precision drift chambers at the Lab for High Energy Physics at ETH in Zurich, he joined the Draper Laboratory, where his research encompassed spacecraft control systems, image processing algorithms, underwater sonar, and precision alignment sensors for large high-energy physics detectors. He joined the Media Lab in 1994, where his current research interests include embedded sensing systems and sensor networks, wearable and body sensor networks, energy harvesting and power management for embedded sensors, ubiquitous and pervasive computing, localization systems, passive and RFID sensor architectures, human-computer interfaces, and interactive media. His honors include the 2000 *Discover* Magazine Award for Technological Innovation, and he has authored 200 articles and technical reports on topics ranging from computer music to power scavenging. After receiving a BS in electrical engineering and physics summa cum laude from Tufts University, Paradiso became a K.T. Compton fellow at the Lab for Nuclear Science at MIT, receiving his PhD in physics there for research conducted at CERN in Geneva.

Dennis M. Frenchman

Leventhal Professor of Urban Design & Planning
Director, City Design & Development (CDD), MIT Department of Urban Studies & Planning

Dennis Frenchman is the Leventhal Professor of Urban Design and Planning at MIT. He currently directs the MIT Center for Advanced Urbanism and is also on the faculty of the Center for Real Estate. He is a founding principal of ICON architecture in Boston, an international architecture, urban design and planning firm. He has taught and practiced extensively in Asia, Europe, and South America and served as External Advisor on urban livability to the President of the World Bank. In the US, he has served on the boards of the Association of Collegiate Schools of Architecture and the National Architectural Accrediting Board.

Dennis Frenchman's practice and research focuses on the transformation of cities. He is an expert on the application of media technology to city design and has designed large-scale technology driven developments including *Seoul Digital Media City,* in Korea, *International Media Avenue,* Beijing, China; the *Digital Mile,* in Zaragoza, Spain, and *Media City:UK.* He has a particular interest in the redevelopment of industrial sites and has prepared plans for the renewal of textile mill towns, canals, rail corridors, steels mills, coal and oil fields, shipyards and ports, including many of national historical significance. Among these, his plans for *Lowell National Historical Park* and the *New York Urban Cultural Park System* have become standards for urban cultural development in the US. He has played a major role in the renewal of downtown commercial centers and neighborhoods. Projects include the *West Broadway Comprehensive Renewal Program*, a national model for the revitalization of severely distressed public housing. His work in these areas has been widely published and has been citied three times as the most outstanding in the United States by the American Planning Association. He holds a Master of Architecture in Advanced Studies and a Master of City Planning Degree from MIT.

Appendix I: Arduino Microcontroller Code

Appendix 1.1: Master Board Control Program

```
/*
smartCharge Master Control System
Praveen Subramani and Sean Cockey
praveens@mit.edu
scockey@mit.edu
MIT Media Lab
*/

//Import Servo Library for controlling relay board
#include <Servo.h>

//Import I2C Communication Library
#include <Wire.h>

//create new Servo object for control of the relay board
Servo lockRelay;
Servo chargeRelay;
int relay1 = 2000;
int relay2 = 1000;
int open_relays = 1500;

//safety delays for starting and stopping charging
int unlockChargeDelay = 1000;
int lockChargeDelay = 5000;


int  val = 0;
char code[16]; //an array in which to store the code from the RFID reader
char check[16];//an array in which to store the varification code from the RFID reader
char toCheck[16];//a dummy array for implementing the check() function
int bytesread = 0; //number of bytes read from the RFID reader

int maintenance = 0; //equals 1 if the car needs maintenance, 0 otherwise--a dummy
variable for demonstration purposes.

//initializes tags
char validTag1[16];
char validTag2[16];
char maintenanceTag[16];

//initializes light colors
byte r = 0;
byte g = 255;
byte b = 0;
//initializes light color memory variables (for resetting lights to a previous state)
byte memR = 0;
byte memG = 0;
byte memB = 0;

byte charge = 0;  //percent charge divided by 20 (each light is 20%)
byte chargeMemory = 0;  //gives previous charge
byte docked = 0;  //equals 0 if the car is not docked and 1 if it is
byte dockedMemory = 0; //equals 0 if the car was not docked in the last loop and 1 if
it was
```

```
void setup()
{
  //attach the relay board to PWM pin 10
      lockRelay.attach(10);
      chargeRelay.attach(9);

      //LOCK THE SYSTEM
      lockRelay.writeMicroseconds(relay1);

      //turn off charging
      chargeRelay.writeMicroseconds(open_relays);

      Serial.begin(2400); // RFID reader SOUT pin connected to Serial RX pin at
2400bps
      pinMode(2,OUTPUT);   // Set digital pin 2 as OUTPUT to connect it to the RFID
/ENABLE pin
      digitalWrite(2, LOW);                  // Activate the RFID reader

      strcpy(validTag1,"0000C3ACFC");  //designate which tag will unlock the car
      strcpy(maintenanceTag, "03008ED956"); //designate the maintenance tag

      //Initialize Communication
      Wire.begin();
      transmit();
}

void loop()
{
  chargeMemory = charge;  //store the previous state of charge in memory
  readCharge();  //read the new state of charge and docking---if the car was "removed"
without unlocking it, this will give a false reading for charge, so the dock()
function fixes this
  transmit();// send the charge to the lights
  dock();  //lock in a new vehicle and fix any false readings from readCharge()
  chargeVehicle();  //start or continue charging the vehicle as appropriate
  resetCode();  //reset the RFID code to prevent false positives
  checkReader();  //check if a valid tag has been swiped and if so, unlock the car for
unlockTime seconds and allow it to be removed.  If the car is not unlocked after
unlockTime seconds, relock the system.
  transmit(); //update the indicator lights
  flushReader(); //flushes extraneous data from the RFID reader to prevent false
positives
  ifMaintenanceNeeded(); //a temporary way to flash the lights in maintenance mode
}


void readCharge() //read the new state of charge and docking---if the car was
"removed" without unlocking it, this will give a false reading for charge, so the
dock() function fixes this
{
  Wire.requestFrom(2, 1);
  if (Wire.available()==1)
  {
    charge = Wire.read();
    Serial.println(charge);
    docked = 1;  //if a signal comes though, the car is obviously docked
    chargeMemory = charge;

    setTopLights();
  }
  else if (dockedMemory == 1)
  {
    charge = chargeMemory;
    Serial.println(charge);
```

```
  }
  else
  {
    charge = 0;
    docked = 0;  //if no signal comes though, the car may or may not be docked, so the
dock() function fixes any mistakes here
  }
}

void takeVehicle() //allows the user to take the vehicle after it has been unlocked
{
  Wire.requestFrom(2, 1);
  if (Wire.available()==1)
  {
    charge = Wire.read();
    Serial.println(charge);
    docked = 1;  //if a signal comes though, the car is obviously docked
    chargeMemory = charge;
  }
  else
  {
    charge = 0;
    docked = 0;  //if no signal comes through, the car has been taken
  }
}

void chargeVehicle()
{
  if (charge > 4.7)
  {
    chargeRelay.writeMicroseconds(open_relays);
  }
  else if (docked == 1)
  {
    chargeRelay.writeMicroseconds(relay1);
  }
}

void resetCode() //reset tag and tag check to all zeroes to prevent false positives
{
  for(int i = 0; i < 10; i++)
  {
    code[i] = '0';
    check[i] = '0';
  }
  //Serial.println("Code reset to: ");
  //Serial.println(code);
  //Serial.println(check);
}

void checkReader()
{
  if (docked == 0)  //don't allow it to unlock if a car is not docked.
  {
    return;
  }
  if(Serial.available() > 0)
  {          // if data available from reader
    if((val = Serial.read()) == 10)
    {   // check for header
      bytesread = 0;

      digitalWrite(2, HIGH); // deactivate the RFID reader for a moment so it will not
flood
```

```
      while(bytesread<10) {               // read 10 digit code
        if( Serial.available() > 0) {
          val = Serial.read();
          if((val == 10)||(val == 13)) { // if header or stop bytes before the 10
digit reading
            break;                        // stop reading
          }
          code[bytesread] = val;          // add the digit
          bytesread++;                    // ready to read next digit
        }
      }
      if(bytesread == 10)
      {
        // if 10 digit read is complete

        //successful tag read:
        Serial.print("TAG code is: ");   // possibly a good TAG
        Serial.println(code);            // print the TAG code

        if(checkValidTag(code))
        {
          //unlock for 10 seconds if car does not need maintenance
          if (maintenance == 0)
          {
            Serial.println("Valid Tag detected. Unlocking system.");
            unlock(5);
          }
          else
          {
            Serial.println("Maintenance needed.  The system cannot be unlocked");
          }
          resetCode();
          digitalWrite(2, HIGH); // deactivate the RFID reader for a moment so it will
not flood
          if (maintenance == 0)
          {
            delay(1000);//lock the user our for 1 second to prevent multiple
inadvertant unlocks
          }
        }
        else
        {
          if (checkMaintenanceTag(code))
          {
            maintenanceMode();
            digitalWrite(2, HIGH); // deactivate the RFID reader for a moment so it
will not flood
            delay(1000);//lock the user our for 1 second to prevent multiple
inadvertant tag reads
          }
          else
          {
            Serial.println("Invalid tag. System remains locked.");
          }
        }


      }
      bytesread = 0;
      digitalWrite(2, HIGH);                 // deactivate the RFID reader for a
moment so it will not flood
           delay(500);                     // wait for a bit
           digitalWrite(2, LOW);               // Activate the RFID reader
```

```
    }
  }
}

//Function for unlocking the electromagnetic
void unlock(int unlockSeconds)
{
  //stop charging
  setLights("white");
  delay(2000);
  chargeRelay.writeMicroseconds(open_relays);
  delay (unlockChargeDelay); //dealy between stopping charge and unlocking vehicle for
safety
  //OPEN THE RELAYS, CUTTING POWER TO THE ELECTROMAG LOCK
  lockRelay.writeMicroseconds(open_relays);

  setLights("green");  //indicate that the car can be taken;

  //reset read RFID code to zeroes to prevent a false positive after an unlock
  resetCode();

  int counter = 0;
  do  //allow the car to be removed during the period unlockTime seconds after the
system is unlocked
  {
    takeVehicle();
    if (docked == 0)  //car has been taken, so reset system
    {
      setLights("blue");
      dockedMemory = 0;
     break;
    }
    else
    {
      counter++;
      delay(10);
    }
   } while(counter < unlockSeconds*100);
    if (docked == 1) //car has not been taken, so relock system
    {
      lock();
      setTopLights();
    }
}

//function for checking if the swiped RFID tag is the one that should unlock the car
boolean checkValidTag(char checkCode[10])
{
  //Serial.print("Check valid tag is being run with code: ");
  //Serial.println(checkCode);

  if(strcmp(checkCode, validTag1) == 0 )
  {
    return true;
  }
  else
  {
    return false;
  }
}

//function for checking if the swiped RFID tag is the one that should initiate
maintenance mode
boolean checkMaintenanceTag(char checkCode[10])
```

```
{
  //Serial.print("Check valid tag is being run with code: ");
  //Serial.println(checkCode);

  if(strcmp(checkCode, maintenanceTag) == 0 )
  {
    return true;
  }
  else
  {
    return false;
  }
}

//function for displaying the maintenance lights
void maintenanceMode()
{
  if (maintenance == 0) //enter maintenance mode when maintenance card is swiped and
the car was not in maintenance mode before
  {
    Serial.println("Maintenance needed.");
    maintenance = 1;
    setLights("purple");
  }
  else //exit maintenance mode when maintenance card is swiped and the car was in
maintenance mode before.
  {
    Serial.println("Maintenance finished");
    maintenance = 0;
    setTopLights();
  }
}

//checks the state of charge and sets color of the top light cap accordingly
void setTopLights()
{
  //if car is not docked, set lights to blue
  if(docked == 0)
  {
   setLights("blue");
  }
  else if(docked == 1)
  {
      if(charge < 1)
      {
        setLights("red");
       }
      else if(charge > 1 && charge < 3)
      {
        setLights("yellow");
      }
      else if (charge > 3)
        setLights("green");
  }
  else
  {
    maintenance = 1;
  }

}

void lock()  //locks the system and sets the lights accordingly
{
  //setLights("red");
```

```
  setTopLights();

  //CLOSE THE RELAY, RE-ENERGIZING THE ELECTROMAGNET
  lockRelay.writeMicroseconds(relay1);
  delay(lockChargeDelay);//lock the user out to prevent false unlock
  dockedMemory = 1;
}

void dock()//lock in a new vehicle and fix any false readings from readCharge()
{
  if (docked == 1 && dockedMemory ==0)
  {
    setLights("white");
    delay (500);
    setTopLights();
    lock();
  }
  else
  {
    charge = chargeMemory;
  }
}


void flushReader()//flushes extraneous data from the RFID reader to prevent false
positives
{
  //digitalWrite(2, LOW); //reactivate the RFID reader
  for (int i = 0; i<50; i++)  //flush the Serial buffer
   {
    Serial.read();
   }
  //digitalWrite(2, HIGH); //power cycle the RFID reader
  //delay(10);
  //digitalWrite(2, LOW);
  resetCode();
  //delay(100);
  Serial.println("Flush");
}


void setLights(char* color) //function for changing the color of the lights
{
  if (strcmp(color, "green")==0)
  {
    r = 0;
    g = 255;
    b = 0;
  }
  else if (strcmp(color, "red")==0)
  {
    r = 255;
    g = 0;
    b = 0;
  }
  else if (strcmp(color, "blue")==0)
  {
    r = 0;
    g = 0;
    b = 255;
  }
  else if (strcmp(color, "yellow")==0)
  {
    r = 255;
```

```
    g = 255;
    b = 0;
  }
  else if (strcmp(color, "purple")==0)
  {
    r = 255;
    g = 0;
    b = 255;
  }
  else if (strcmp(color, "orange")==0)
  {
    r = 255;
    g = 100;
    b = 0;
  }
  else if (strcmp(color, "white")==0)
  {
    r = 255;
    g = 255;
    b = 255;
  }
  else  //if any other input, turn lights off
  {
    r = 0;
    g = 0;
    b = 0;
  }
  transmit();
}

void transmit() //updates the indicator lights
{
  //Serial.println("transmit");
  Wire.beginTransmission(1);
  Wire.write(r);
  Wire.write(g);
  Wire.write(b);
  Wire.write(charge);
  Wire.endTransmission();
  //Serial.println(charge);
}

void ifMaintenanceNeeded()
{
  if (maintenance == 1)
  {
    delay (500);
    checkReader();
    if (maintenance == 1)
    {
      setLights ("black");
      delay (500);
      setLights("purple");
    }
  }
  else
  {
    setTopLights();
  }
}
```

Appendix 1.2: Color Kinetics Control Board Program (Slave I)

```
/*
smartCharge Lighting Slave Control System
Praveen Subramani and Sean Cockey
praveens@mit.edu
scockey@mit.edu
MIT Media Lab
*/

 #include <Wire.h>

#include <SPI.h>
#include <KiNET.h>
#include <Ethernet.h>

byte mac[] = {0x90, 0xA2, 0xDA, 0x00, 0x79, 0x95};
byte myip[]= { 10, 32, 0, 2};
byte gateway[] = {10, 1, 1, 1};
byte subnet[] = {255, 255, 255, 0};


// Set up Lights
uint8_t LIGHT_IP[] = {10, 32, 0, 93};                  // the IP of the lights. this
is written on the inside of the control box on a little sticker
const int NUM_LIGHTS1 = 15;
const int NUM_LIGHTS2 = 5;  // most of the light strands have 50 lights
uint8_t data1[NUM_LIGHTS1 * 3];
uint8_t data2[NUM_LIGHTS2 * 3];

void setup()
{
        Wire.begin(1);
        Wire.onReceive(changeLights);
         KiNET.begin(mac,myip,gateway,subnet);
        Serial.begin(9600);
}

void loop() {
 delay(100);
}


void setLights1(int r, int g, int b) {   //sets top lights (line 1)
       for(int i = 0; i < 6; i++) {
              data1[i*3 + 0] = 0;
              data1[i*3 + 1] = 0;
              data1[i*3 + 2] = 0;
       }
        for(int j = 6; j < 15; j++) {
              data1[j*3 + 0] = r;
              data1[j*3 + 1] = g;
              data1[j*3 + 2] = b;
       }

       KiNET.send(LIGHT_IP,data1,NUM_LIGHTS1*3,1);
}

void setLights2(int r, int g, int b, int c) {  //sets pannel lights (line 2) always
green, displays charge
        for (int j = 0; j < c; j++){
                data2[j*3 + 0] = 0;
```

```
            data2[j*3 + 1] = 255;
            data2[j*3 + 2] = 0;
        }

        for(int i = c; i < NUM_LIGHTS2; i++) {
            data2[i*3 + 0] = 0;
            data2[i*3 + 1] = 0;
            data2[i*3 + 2] = 0;
        }

        KiNET.send(LIGHT_IP,data2,NUM_LIGHTS2*3,2);
}

void changeLights(int numBytes)
{
  int r = Wire.read();
  int g = Wire.read();
  int b = Wire.read();
  int c = Wire.read();
  setLights1(r, g, b);
  setLights2(r, g, b, c);
  Serial.println(c);
}
```

Appendix 1.3: Vehicle Charge-State Control Board Program (Slave II)

```
/*
smartCharge Lighting Slave Control System
Praveen Subramani and Sean Cockey
praveens@mit.edu
scockey@mit.edu
MIT Media Lab
*/

#include <Wire.h>

#include <SPI.h>
byte charge = 0;

void setup()
{
        Wire.begin(2);
        Wire.onRequest(sendState);
        Serial.begin(9600);
        pinMode(A0, INPUT);
        pinMode(13, OUTPUT);
}

void loop() {
 int c = analogRead(A0);
 c = map(c, 0, 1023, 0, 100);
 charge = c/20;
 Serial.println(charge);
 delay(100);
}


void sendState(){
  Wire.write(charge);
  Serial.println("send");

  digitalWrite(13, HIGH); //set LED on
  delay(10);
  digitalWrite(13, LOW);
}
```

References

[1] "Urban Energy Systems Project" Imperial College London, n.d. Web. <http://www3.imperial.ac.uk/urbanenergysystems>.

[2] "Velib Website." Velib Paris, n.d. Web. <http://en.velib.paris.fr/>.

[3] Shaheen, Susan, and Stacey Guzman. "Worldwide Bikesharing." *ACCESS: the Magazine of UCTC*, Fall 2011. Web. <http://uctc.net/access/39/access39_bikesharing.shtml>.

[4] Sood, Suemedha. "Travelwise: Bike Sharing around the World." *BBC Travel*, 09 Sept. 2011. Web. <http://www.bbc.com/travel/blog/20110909-travelwise-bike-sharing-around-the-world>.

[5] "Zipcar Reports First Quarter Results." Zipcar, Inc., 25 Apr. 2012. Web. <http://ir.zipcar.com/releasedetail.cfm?releaseid=667131>.

[6] "car2go Launches North America's First All-electric Carsharing Network in San Diego." *Green Car Congress*, 18 Nov. 2011. Web. <http://www.greencarcongress.com/2011/11/car2go-20111118.html>.

[7] "Zipcar Charges Up Car Sharing in Chicago with Electric Vehicle Pilot Program." Zipcar, Inc., 22 Mar. 2012. Web. <http://ir.zipcar.com/releasedetail.cfm?releaseid=658849>.

[8] Mitchell, William J., Chris Borroni-Bird, and Lawrence D. Burns. *Reinventing the Automobile: Personal Urban Mobility for the 21st Century*. Cambridge, MA: MIT Press, 2010. Print.

[9] "Hubway: Your Bike Sharing System in Boston." Hubway, n.d. Web. <http://thehubway.com/>.

[10] Holmes, Whitney. "UT Launches Nation's First Fully Automated E-bike Sharing System" *Tennessee Today* (The University of Tennessee Knoxville), 6 Sept. 2011. Web. <http://www.utk.edu/tntoday/2011/09/06/nations-first-automated-ebike-system>.

[11] Scholtus, Petz. "Plug In! First Electric Motorcycle Charging Stations in Barcelona." *TreeHugger*, 31 Mar. 2011. Web. <http://www.treehugger.com/cars/plug-in-first-electric-motorcycle-charging-stations-in-barcelona.html>.

[12] Mitchell, William J. "Elegy for a G4," *Placing Words: Symbols, Space, and the City*. Cambridge, MA: MIT, 2005. Print.

[13] Lynn, Cristina. "Parking Guidance Systems." Parking Consultants International, 16 Aug. 2009. Web. <http://www.slideshare.net/ParkingConsultants/car-parking-guidance-systems-1868308>.

[14] "New Technology Helps Keep Customers Informed." New York City MTA, n.d. Web. <http://www.mta.info/news/stories/?story=109>.

[15] "EVlink Charging Solutions for Electric Vehicles." Schneider Electric, n.d. Web. <http://www2.schneider-electric.com/corporate/en/products-services/products-services-intermediate.page?f=NNM1:EVlink+charging+solutions+for+electric+vehicles&p_function_id=20030>.

[16] "Arduino Uno Board Specifications." Arduino, n.d. Web. <http://arduino.cc/en/Main/ArduinoBoardUno>.

[17] "I2C-Bus: What's That?" I2C Bus, n.d. Web. <http://www.i2c-bus.org/>.

[18] D'Amato, Andrea. *Streetscape Guidelines for Boston's Major Roads*. Rep. Boston Transportation Department, July 1999. Web. <http://www.cityofboston.gov/transportation/accessboston/pdfs/streetscape_guidelines.pdf>.

[19] Chase, Robin. "Carsharing: It Is the Future of Car Mobility, without Question." MIT Professional Education Program. MIT Media Lab, Cambridge, MA. July 2011. Lecture.

[20] "Charging Standards." Coulomb ChargePoint, n.d. Web. <http://www.chargepoint.net/faq-standards.php>.

[21] Hua, A.C.-C., and B.Z.-W. Syue. "Charge and Discharge Characteristics of Lead-acid Battery and LiFePO4 Battery." *Power Electronics Conference (IPEC), 2010 International* (2010): 1478-483. *IEEE Xplore*. IEEE. Web. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5544506&isnumber=5542000>.

[22] Rodgers, Lennon; et al. "Rapidly Charging Battery Systems." *MIT Electric Vehicle Team Report* (2010): n. pag. Print.

[23] Op. cit. [7]

[24] Rasmussen, Neil. *The Different Types of UPS Systems*. Technical report. no. 1. American Power Conversion (APC), May 2004. Web. <www.apcmedia.com/salestools/SADE-5TNM3Y_R5_EN.pdf>.

[25] Ton, My, Brian Fortenbery, and William Tschudi. *DC Power for Improved Data Center Efficiency*. Report. Lawrence Berkeley National Laboratory on Behalf of California Energy Commission, Mar. 2008. Web. <http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReport.pdf>.

[26] Vasallo, M.J., J.M. Andujar, C. Garcia, and J.J. Brey. "A Methodology for Sizing Backup Fuel- Cell/Battery Hybrid Power Systems." *Industrial Electronics, IEEE Transactions on* 57.6 (2010): 1964-975. *IEEE Xplore*. IEEE, June 2010. Web. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4895326&isnumber=5463268>.

[27] Reddy, Thomas B., and David Linden. *Linden's Handbook of Batteries*. New York: McGraw-Hill, 2011. Print.

[28] "Aiming to Initiate Second-life Business for Electric Car Batteries." Sumimoto Corporation, n.d. Web. <http://www.sumitomocorp.co.jp/english/business_overview/finance/outline22a.html>.

[29] "ALM Lead Acid Replacement Batteries." *A123 Systems*, n.d. Web. <http://www.a123systems.com/products-modules-lead-acid.htm>.

[30] *The Electrification of the Transportation System: Issues and Opportunities*. Report. Cambridge, MA: MIT Energy Initiative, April 2010. Web. <http://web.mit.edu/mitei/research/reports/transport-electrification.html>.

[31] "Fuel Economy: Where the Energy Goes." US Department of Energy, n.d. Web. <http://www.fueleconomy.gov/feg/atv.shtml>.

[32] Galbraith, Kate. "Colorado Increases Renewables Requirements." *Green: A Blog About Energy and the Environment*. The New York Times, 22 Mar. 2010. Web. <http://green.blogs.nytimes.com/2010/03/22/colorado-to-boost-renewables-requirements/>.

[33] "Ray and Maria Stata Center." MIT Facilities, n.d. Web. <http://web.mit.edu/facilities/construction/completed/stata.html>.

[34] "Media Lab and SA+P Extension." MIT Facilities, n.d. Web. <http://web.mit.edu/facilities/construction/completed/medialabext.html>.

[35] Chozick, Amy. "As Young Lose Interest in Cars, G.M. Turns to MTV for Help."*Media & Advertising*. The New York Times, 22 Mar. 2012. Web. <http://www.nytimes.com/2012/03/23/business/media/to-draw-reluctant-young-buyers-gm-turns-to-mtv.html>.

[36] Fletcher, Seth. *Bottled Lightning: Superbatteries, Electric Cars, and the New Lithium Economy*. New York: Hill and Wang, 2011. Print.