Utility Maximization Framework for Opportunistic Wireless Electric Vehicle Charging

MD Zadid Khan*
Ph.D. Student
Glenn Department of Civil Engineering, Clemson University
351 Fluor Daniel, Clemson, SC 29634
Tel: (864) 359-7276, Fax: (864) 656-2670
Email: mdzadik@clemson.edu

Mashrur Chowdhury, Ph.D., P.E., F. ASCE
Eugene Douglas Mays Endowed Professor of Transportation and
Professor of Civil Engineering and Professor of Automotive Engineering
Glenn Department of Civil Engineering, Clemson University
216 Lowry Hall, Clemson, South Carolina 29634
Tel: (864) 656-3313, Fax: (864) 656-2670
Email: mac@clemson.edu

Sakib Mahmud Khan, Ph.D. Student
Glenn Department of Civil Engineering, Clemson University
351 Fluor Daniel, Clemson, SC 29634
Tel: (864) 569-1082, Fax: (864) 656-2670
Email: sakibk@g.clemson.edu

Ilya Safro, Ph.D.
School of Computing, Clemson University
228 McAdams Hall, Clemson, SC 29634
Tel: (864) 656-0637
Email: isafro@clemson.edu

Hayato Ushijima-Mwesigwa, Ph.D. Student
School of Computing, Clemson University
229 McAdams Hall, Clemson, SC 29634
Tel: (818) 428-9055
Email: hushiji@clemson.edu

*Corresponding author

Abstract: 236 + Text: 5432 + References: 737 + 4 tables/figures: 1000 = 7405 words
Submission date: August 1, 2017
ABSTRACT
The advancements in Electric Vehicle (EV) wireless charging technology have initiated substantial research on the optimal deployment of Wireless Charging Units (WCU) for dynamic charging or Charging While Driving (CWD) applications. This study presents a novel framework, named as the Simulation-based Utility Maximization of Wireless Charging (SUM-WC), which aims to maximize the utility of WCUs for EV charging through the optimal WCU deployment using the concept of opportunistic CWD at signalized intersections. At first, a calibrated traffic micro-simulation network of the area of interest is required for this framework. The calibrated traffic network is used to create the utility function and control delay function for each selected lane at the selected intersections of the road network. The lanes are selected based on their potential to charge EVs. An optimization problem is formulated using the utility and control delay functions, where the objective is to maximize the utility of WCUs, and the decision variables are location and length of WCUs and traffic signal timing. The constraints of the optimization formulation are budget, locations, minimum green signal times and acceptable Level of Service (LOS). A global solution is achieved for this optimization problem using the Genetic Algorithm. The optimized utility is compared with other deployment schemes, such as deployment following betweenness centrality and placement at lane with the highest traffic volume. SUM-WC framework achieves at least 1.5 times more utility per hour than these other deployment schemes.

Keywords: Resource Allocation, Opportunistic Wireless Charging, Transportation Planning, Charging While Driving, Traffic Signal
INTRODUCTION
The US transportation sector is characterized by the dominance of fossil fuel powered vehicles. Vehicles relying on fossil fuels are not sustainable due to their non-compliance with the US environmental, economic and energy goals (1). Electric Vehicles (EV) are the fastest growing alternative fuel vehicles in the market today. However, EVs have technical and economic limitations related to the electricity storage (i.e., battery) technology such as low energy density, large battery size, limited lifetime, long charging times, and high cost. With these limitations, EV users are faced with a difficulty known as range anxiety. EV users are constantly worrying about having enough charge in battery to complete the trips, and constantly looking for charging stations nearby when battery is running out of charge (2). To overcome this, EVs equipped with wireless charging capabilities (i.e., pick-up coils in the bottom) can use electromagnetic induction for wireless charging when they are driven over Wireless Charging Units (WCUs) placed on the road, which is called dynamic charging or Charging While Driving (CWD). It can solve the issue of limited range by increasing the range of EVs in transit (3). WCUs placed on roads take up no extra space, so less urban space is required for EV charging. Recent developments in wireless charging technology by automobile companies and research institutes indicate that CWD infrastructure can be deployed for widespread use within next ten to twenty years (3)-(6). However, a proper infrastructure planning with effective resource utilization is required to deploy this technology. Optimal placement of WCUs on the roads is a major factor in widespread adoption of CWD for EVs (2).

One possible solution is to place WCUs at signalized intersections in urban areas to utilize the frequent stops of vehicles at traffic signals for recharging. In urban areas, the amount of time that a vehicle spends at signalized intersections each day is significant in terms of EV wireless recharging. This intersection stop time could be utilized for EV’s recharging. Utilizing the stop-and-go situation at signalized intersections for wireless recharging is more appealing than charging stations at parking lots.

In this paper, we present a SUM-WC framework, which includes a simulation-based optimization strategy to help identify the optimal placement of WCUs for a signalized roadway network in any area type and size (e.g., city, county or state). The objective of this research is to find the optimal placement and sizing of WCUs at specific intersections within a certain budget, so that the utility is maximized while the intersection continues to operate at an acceptable Level of Service (LOS). LOS is a qualitative measure used to relate the quality of traffic service using levels A through F, with A being the best and F being the worst (7). For signalized intersections, LOS is used to assign traffic quality levels based on the control delay, which is defined as the difference between the travel time that would occur in the absence of traffic signal, and the travel time that results because of the traffic signals. Control delay has three components, namely, deceleration delay, stop delay and acceleration delay. Control delay is always calculated for a lane group, which consists of all the lanes that are directing traffic flow in the same direction (7).

RELATED WORKS
CWD for EVs has been a topic of major interest in recent years. Many studies have been conducted on the prospects of wireless power transfer for EV, efficient wireless charging systems, and dynamic charging scheme testing (8)-(10). One of the significant works focuses on optimal system design of the online electric vehicle (OLEV) that utilizes wireless charging technology (11). In that study, a particle swarm optimization method is used to find a minimum cost solution for WCU installation considering the battery size, total number of power
transmitters (WCUs) and their optimal placement as decision variables. The model is calibrated to the actual OLEV system (11). The OLEV and its WCUs were developed and deployed in Korea Advanced Institute of Science and Technology (12, 13). Other notable institutions who have successfully implemented WCU system for EVs and performed field testing include Siemens, Volvo, Highways England, Auckland University, HaloIPT (Qualcomm), Oak Ridge National laboratory (ORNL), MIT (WiTricity) and Delphi. However, there is still a long way to go for a full commercial CWD implementation, since it requires making significant changes to the current transportation infrastructure.

In (14), a wireless charging for EVs at signalized intersections is investigated. The authors propose adaptive control strategies of traffic signals for charging of EVs at intersections that would meet EV’s energy demand while the control delay at intersections is minimized. This study does not focus on selecting the optimal locations for WCU installation to maximize charging. Earlier studies (15, 16) do not consider signalized intersections or effect of traffic signals on EV charging in the analysis. One of the problems with non-simulation based mathematical models is that they often do not accurately capture the real-life traffic scenarios. Most of the existing optimization models are computationally hard as they typically contain non-linear and non-convex components with integer variables. As a result, they are more applicable for small networks. In (17), authors introduce an integer programming model that is built upon taking into account different realistic scenarios of routes. The authors compare the computational results for the proposed model with faster heuristics and demonstrate that their approach provides significantly better results for fixed budget models. Using standard optimization solvers with parallelization, they succeed to provide fast and high-quality solutions for much larger networks.

Many studies focus on WCU infrastructural issues. In (18), a method for analyzing the traffic and electrical performance of wireless CWD systems for EVs is presented. This study is useful for a preliminary design of the infrastructure and the specific EV Supply Equipment. A thorough analysis of the costs associated with the implementation of a dynamic WPT infrastructure and a business model for the development of a new EV infrastructure are presented in (19).

METHOD FOR DEVELOPING SUM-WC FRAMEWORK
The analysis starts with the assumption that signalized intersections in urban areas are the most suitable locations to place WCU. Traffic simulation is performed to validate this assumption. In this section, we introduce the SUM-WC framework by describing all the components and the method of developing the workflow.

SUM-WC Framework Development
Steps to construct the SUM-WC framework are explained below.

- **Download map of the area of interest from the OpenStreetMap (OSM) and generate a network file with all the traffic information from the OSM file.**

- **Using available data, data collected from field and Institute of Transportation Engineers (ITE) Trip Generation Manual, create routing (Origin-Destination pairs) for all vehicles in the road network for a specific timeframe. Assume a value of penetration level for EVs based on study in (20). Combine network file with the generated routing data and make adjustments to traffic simulation parameters to calibrate the model with real data.**
- Run the traffic simulation network once with no WCU to get an average control delay for all lane groups.
- Identify the set of lanes approaching traffic signals. Select lanes from the lane group that have an LOS C.
- Run traffic simulation with WCU placed at each of the selected lanes with low-mid-high values for WCU length and green signal times of each phase (assuming fixed-time signal operations). Three values are chosen for each variable for nine combinations. This is done so that the whole solution space can be covered.
- Extract total energy transferred to all EVs (Utility) and average control delay of all selected lanes for each simulation run.
- Using WCU length and green signal times as inputs and utility as output, develop an interpolant for utility of each selected lane.
- Using green signal time as input and average control delay as output, develop an interpolant for control delay of each selected lane.
- Using the utility and control delay interpolants of each lane, run the optimization model and get optimized WCU locations, lengths and green signal times for the whole network.
- Evaluate the effectiveness of the optimization framework by comparing the framework’s utility with other deployment schemes based on WCU placement heuristics.

**Framework Tool Selection**
The traffic simulation is performed in Simulation of Urban Mobility software (SUMO) (21). SUMO is used to convert the OSM file (map) directly to a .net file, which is the road network file for SUMO. SUMO also has its own EV and WCU modules. In order to create a calibrated micro simulation model for an urban area, short term traffic volumes (turning volumes) need to be collected at all the intersections. Furthermore, the ITE Trip Generation Manual can be used to estimate the entering and exiting traffic from different entities such as businesses and residential areas. Finally, travel time information needs to be collected for some major roads. The traffic simulation parameters such as driver imperfection and speed distribution can be adjusted to match the travel times and turning volumes at intersections. After the calibrated model has been developed, the traffic simulation control and optimization are performed using MATLAB. SUMO TraCI (Traffic Control Interface) is used to interface from MATLAB with SUMO. The genetic algorithm is used to solve the optimization problem. The Matlab Genetic Algorithm (GA) function is used. Our optimization model is a Mixed-Integer Non-Linear Program (MINLP) for which a global solution is required. The Matlab GA function has the capability to solve MINLP and find a global solution from the solution space. Details about the model can be found in (22).

**Assumptions about Traffic Signal**
The focus of this study is to maximize the utility of WCUs through opportunistic EV charging at signalized intersections. Our assumption is that all traffic signals in the study area are two-phase pre-timed signals.

**Optimization Problem Formulation**
The optimization formulation is based on utility of WCUs. Here, the decision variables are length of WCUs at each signalized intersections and green signal times of each phase of those
intersections. The objective function is the total utility in a one-hour simulation run. The constraints are the budget, locations, minimum green signal times and LOS.

For pre-timed signal control, if yellow time and all red time for each phase are fixed, then the sum of the green signal times of the two phases are also fixed, since it is assumed that the cycle length remains constant. However, there is a minimum limit to the green signal time for each state, defined by the Signal Design Manual of that state, such as the manual in (23). Green signal times also have to be integer numbers. Therefore, there is a range of green signal times for each lane approach at each intersection. Considering these constraints, the optimization problem is formulated as shown below.

Maximize \( \sum_{i \in I} u_i(l_i, g_{i1}) x_i \)

Subject to,
\[ \sum_{i \in I} l_i x_i d \leq b \]
\[ ACD_i(g_{i1}) \leq c, \quad \forall i \in I \]
\[ g_{i1} + g_{2i} = g_i, \quad \forall i \in I \]
\[ g_{\text{min}} \leq g_{i1}, g_{2i}, \quad \forall i \in I \]
\[ x_i \in \{0, 1\}, \quad \forall i \in I \]
\[ l_i, l_{i1}, g_{i1}, g_{2i} \text{ are integers} \]

Where,
\( I \) = Set of all selected lanes approaching a traffic signal
\( i \) = A lane approaching a traffic signal
\( u_i \) = WCU Utility function at lane \( i \) (Wh)
\( l_i \) = Length of WCU at lane \( i \) (m)
\( l_{\text{unit}} \) = Length of unit WCU (m)
\( x_i \) = Binary Variable for WCU installation at lane \( i \), 1 if installed at lane \( i \), 0 otherwise
\( g_{i1} \) = Green signal time of phase corresponding to lane \( i \) (s)
\( g_{2i} \) = Green signal time of opposite phase to lane \( i \) (s)
\( g_{\text{min}} \) = Minimum green signal time (s)
\( g_c \) = Total green signal time at intersection for base case (s)
\( c \) = Control delay limit corresponding to target LOS (s/veh)
\( d \) = Price of WCU per length ($/m)
\( b \) = Budget ($)
\( ACD_i \) = Average control delay of lane \( i \) (s/veh)

The objective function has two components. The first one, WCU utility of each lane \( (u_i) \), is a function of the installed WCU length \( (l_i) \) and green signal time of each phase of the
intersection \((g_{ij})\). The second variable, \(x_i\), represents the decision of WCU installation at a lane. Therefore, the objective function is actually the sum of the total utility from WCU installation in the road network (in Wh).

There are six constraints of the formulation. The solution to the optimization problem must obey all these constraints. For clarification, the constraints are described below in sequence.

- The total cost of the installation should be less than or equal to the budget.
- The average control delay for all the selected lanes should be less than the target LOS limit. In this case, target LOS is C and ACD limit is 35 s/veh.
- The sum of green signal times of all phases at all the intersections should remain constant.
- The green signal times should be greater than or equal to the minimum green signal time allowed.
- The location variable is binary, if WCU is installed at lane \(i\), then \(x_i\) is equal to 1, otherwise it is 0.
- Number of WCU units and green signal times are always integers.

**Control Delay Calculation and Lane Selection**

Initially, we set the running time of the simulation to a fixed value (usually an hour) with no WCU installed at any location in the network. The average control delay for each lane is then calculated by using the simulation output. There are many techniques to calculate control delay of an intersection lane group, as mentioned in Highway Capacity Manual (HCM) 2010 (7). Among these techniques, the queue-count technique is chosen for the control delay calculation.

The queue-count technique is developed for calculating control delay using traffic data collected from the field. For a specific lane group, the data required from the field is the total number of vehicles, number of stopped vehicles, number of vehicles in queue, approach speed and cycle length. The stop delay can be calculated from field data, but the acceleration and deceleration delay are very difficult to measure without sophisticated tracking equipment. This technique has been shown to yield a reasonable estimate of control delay by application of appropriate adjustment factors (24, 25). In this study, the technique is applied to a simulation environment, where the data collection from field is mimicked in simulation. Detectors are used in simulation to collect the input data for the technique. The technique is illustrated in the following.

Given the following: Total Vehicles \((V_{tot})\), Total vehicles in queue \((V_q)\), Stopped Vehicles \((V_{stop})\), Number of cycles surveyed \((N_c)\), Approach Speed \((S)\), Number of Lanes \((N)\), Time Interval \((I_s)\), the following equations describe the queue-count technique.

From Chart: Acceleration deceleration correction factor, \(CF\) (From \((7)\), using \(V_{qplpc}\) and \(S)\)

Equations:

- Time-in-queue per vehicle, \(d_{vq} = I_s / V_q\)
- Fraction of stopped vehicles, \(FVS = V_{stop} / V_{tot}\)
- Number of stopped vehicles /lane/cycle, \(V_{qplpc} = V_{stop} / (N_c*\ N)\)
- Acceleration deceleration correction delay, \(d_{ad} = FVS*CF\)
- Control delay, \(d = d_{vq}+d_{ad}\)

The control delay is calculated for each lane group. This is an average for all the lanes in the lane group, so the same control delay is used for individual lanes. From \((7)\), the LOS of the lane group is determined using the control delay.

In \((7)\), LOS C is described as the stable flow (acceptable control delay) regime, while LOS D is described as regime approaching unstable flow. The intersection lanes that have LOS
worse than C are omitted from the analysis, since they are already performing at an unacceptable LOS. On the other hand, the lanes that have LOS better than C are not suitable for WCU installation, as the control delay is not sufficient to charge the EVs properly while stopped. So, only the lanes that have LOS of C (20-35 s/veh control delay) are shortlisted for potential WCU placement. This step reduces the computational burden of the framework by reducing the number of required traffic simulation runs.

**Traffic Simulation**

After the lanes are shortlisted, we run the simulation to evaluate the utility of WCU for each selected lane as a function of WCU length and green signal time. Also, it is required to evaluate the control delay of each selected lane as a function of green signal time.

There is a large range for green signal times and WCU lengths, so performing an exhaustive simulation for each green signal time and each length of WCU at each selected lane is not feasible. Rather, simulation is performed for a limited number of points, and these points are used for linear interpolation to get the value of utility and control delay for intermediate values of WCU lengths and green signal times. Three values of WCU lengths and three values of green signal times are chosen for simulation, such that they cover the whole range of values. These values are termed as low, mid and high values. As a result, nine simulation runs are performed for each lane, corresponding to three values of green signal times and WCU lengths. Then, these nine points are used in 2D interpolation to get the values of utility for all intermediate points. On the other hand, the control delay does not vary with WCU length; it only varies with green signal times. Therefore, linear interpolation is performed to get the values of control delay for all intermediate green signal times.

Some approximations are made in order to reduce the computational runtime of the framework. Firstly, only the minimum number of points to span the solution space are taken, which is three for any variable. As there are two independent variables, the number of required simulation runs is the product of the number of evaluation points for two variables. Taking three values for each variable keeps the number of simulation to a minimum value of nine, while still spanning the whole solution space. Secondly, it is assumed that the utility function and control delay function are linearly dependent on their respective variables. Each lane at each intersection will have a different characteristic, and finding the accurate relationship of utility and control delay for each lane is a non-trivial task. For simplicity, linear interpolation is used for both utility and control delay.

**CWD Scheme Comparison**

The utility and control delay interpolants of all lanes are carried forward to the optimization step, where the solution is obtained for the entire road network. This solution is then validated by performing one more simulation with the optimized solution. The utility is compared with two other heuristic placement based deployment schemes, betweenness centrality and installation at lane with highest traffic volume, to show the effectiveness of the SUM-WC framework.

**CASE STUDY RESULTS**

This section presents an evaluation of the SUM-WC framework for a sample road network. The Clemson city network from South Carolina is used for this analysis. We run the traffic simulation using this network for one hour. In this case study, the traffic simulation model is not a calibrated model, the routing is not representative of the actual scenario. Instead, the routing is generated
randomly from different locations. Developing a calibrated traffic simulation model for a city is not a trivial task, and it is considered as a separate research topic. Because many studies have been done previously on how to create a calibrated traffic simulation model (26, 27), the focus of our research is not to develop calibrated traffic simulation models. Instead, we focus on developing a ubiquitous framework which can be used with any traffic simulation model, and a sample traffic simulation network is used to illustrate the functionality of the framework. The key characteristics of this road network and a visual representation of the network is shown in Figure 1. The text box in the figure contains all the information regarding the traffic simulation. The red circles indicate location of traffic signals.

FIGURE 1 Clemson City Road Network

**Opportunistic Wireless Charging at Signalized Intersections**
To prove the hypothesis that signalized intersections are the best locations for WCU installations, simulation is run on a sample four-way signalized intersection. It is observed that when the WCUs are placed away from the intersection, the utility suffers due to the lack of opportunity for charging while stopped. So, distance from intersection is a major contributor in the overall utility of the WCUs. So, only signalized intersections are considered for WCU placement in this research. Moreover, some additional simulations are performed to investigate the effect of signal timings and WCU lengths on the utility of the WCU. We observe that these variables have a major impact on the utility; reducing green signal time increases the utility, but it degrades the LOS of the intersection. On the other hand, increasing the length of WCU increases the utility. Simulations show approximately fivefold advantage for one-hour timeframe, if WCUs are placed at intersections, considering regular traffic. This finding is illustrated using Figure 2 (a), where the first two locations are at intersections, and the last two locations are away from intersections.

**EV and WCU Parameters**
The EV and WCU modules in SUMO are developed in (28). For each simulation step, the model calculates the energy consumption of the EV, and the energy transferred to EV from WCU if applicable. The parameters used for an EV passenger car in the network are shown in Table 1.
These values are default values for a passenger EV in SUMO. The values obtained for the WCU are also shown in Table 1.

TABLE 1 EV and WCU SPECIFICATIONS

| Specification | Properties                  | Value        |
|---------------|-----------------------------|--------------|
| EV            | Air Drag Coefficient        | 0.3          |
|               | Front Surface Area          | 0.8 m$^2$    |
|               | Internal Moment of Inertia  | 0.01 kgm$^2$ |
|               | Maximum Battery Capacity    | 54 KW        |
|               | Propulsion Efficiency       | 0.9          |
|               | Radial Drag Coefficient     | 0.2          |
|               | Recuperation Efficiency     | 0.9          |
|               | Roll Drag Coefficient       | 0.01         |
|               | Vehicle Mass                | 1700 Kg      |
|               | Initial Battery Capacity    | 27 KW (50%)  |
| WCU           | Length of smallest WCU      | 6m           |
|               | Budget Constraint           | 30m (30/6 = 5 units) |
|               | Charging Delay              | 0s           |
|               | Efficiency                  | 85%          |
|               | Power of each wireless charging unit | 7.2KW    |

Lane Selection
As per the framework, an initial simulation is performed for one hour with no WCU installed at any location in the network. This step is performed in order to identify the candidate lanes for WCU installation. The data we use consists of 116 lanes at 20 signalized intersections in the network. After that, the average control delay for each lane is calculated by using the queue-count technique. The delay for all lanes are shown in Figure 2 (b). The enclosed region corresponds to LOS C, so this is our area of interest for the remaining steps of the framework.

In Figure 2 (b), we observe that there are 42 lanes with LOS C. Only these lanes are carried forward in the remaining steps of the SUM-WC framework.
FIGURE 2 Summary Findings using SUM-WC

(a) Sensitivity of wireless charging to location of WCU

(b) Control Delay of All Lanes at Signalized Intersections

(c) Utility Response Surface for Lane

(d) Control Delay Lane A

(e) Optimization Result Visualization in SUMO

(f) Comparison of Utility for different paradigms
Traffic Simulation Results
After the selection of lanes, a traffic simulation is performed, where the WCU is placed at all selected lanes individually for each simulation run. For each lane, nine simulation runs are performed in order to evaluate the utility and delay functions. For WCU length, the minimum length of WCU is one unit (6m), and the maximum length is five units (30m), i.e.- the average value is three units (18m). On the other hand, the green signal times for all signals are bounded by the cycle times of that signal. Therefore, the sum of two green signal time periods remains constant. The minimum green signal time for any phase at a major 4-way intersection is 15 seconds; this is the value of \( g_{\text{min}} \) in the framework. This \( g_{\text{min}} \) comes from the SCOT signal design manual (23). Using this as a bounding value, the low-mid-high green signal times of both phases for all signals are calculated. The lowest green signal time for the green phase of a lane corresponds to the highest green signal time in the opposite green phase of that lane.

Showing the simulation results for all 42 selected lanes would be redundant. Instead, a sample lane at a sample intersection is chosen, and the simulation results are shown for that lane only. Each lane has its own unique id, the id of the selected lane is `473901199_0`. For simplicity, the lane is named lane A. Figure 1 demonstrates the location of lane A in the network. The results for Utility from the simulation is given in Table 2 for WCU installed at lane A. From the analysis for lane A, for 15, 28 and 42 sec green time, the control delay was found to be 42, 29 and 11 sec. respectively. This lane had a base control delay of 29 s/veh.

| Green signal time (s) | Length (m) | 6 | 18 | 30 |
|-----------------------|------------|---|----|----|
| 15                    |            | 964 | 3091 | 4228 |
| 28                    |            | 446 | 1297 | 1532 |
| 42                    |            | 394 | 940  | 1229 |

After getting the boundary values for all lanes, 2D linear interpolation is performed to get the values of utility at all WCU lengths and green signal times in the solution space. Furthermore, interpolation is performed to get the values of control delays for all green signal times. A resulting response surface of utility for lane A is shown in Figure 2 (c) and the resulting curve of control delay for lane A is shown in Figure 2 (d). In Figure 2 (c), it is observed that the maximum utility is achieved for minimum green signal time and maximum length, which is 4228 Wh. The minimum utility is 394 Wh for maximum green signal time and minimum length.

In Figure 2 (d), it is observed that the maximum control delay occurs for minimum green signal time, which is 42 s/veh. Note that this is LOS D, which is unacceptable. The minimum delay is 11 s/veh for maximum green signal time, which corresponds to LOS B.

Optimization Solution
After the utility and control delay functions have been created, it is desired to maximize the utility by placing the WCUs such that the utility is maximized while the LOS remains LOS C or better for all intersections. The optimization problem has already been formulated earlier in the previous section. Genetic algorithm is used to perform the optimization. We choose genetic algorithm because it provides fast implementation, it is scalable and performs well for discontinuous objective functions (29). The optimization problem does not involve any traffic
simulation, since all the traffic simulation have already been done beforehand. A single objective formulation reduces the complexity of the problem and gives accurate results quicker. The decision variables are selected lanes, lengths of WCU at that lane and the green signal time corresponding to the lane. The optimized output is the maximum utility achievable with all constraints satisfied.

Two lanes (Lane A and Lane B) have been selected for WCU installation. The budget constraint allowed only 30m (five units) of installation, so 18m is installed at Lane A and 12m is installed at Lane B. The green signal times for the approach phases of the lanes are 22 s and 17 s, respectively. The total utility achieved (total energy charged) is 2992 Wh. The average control delay at the selected lanes are 35 s/veh and 34 s/veh, respectively. Therefore, the control delays are below 35 s/veh, which is the limiting value for LOS C. The performance of the lanes has degraded, but the lane group LOS has remained C, which was the objective of this research.

After obtaining the results, we run the simulation model with WCUs installed at the selected lanes in order to validate the results. It is seen that the utility value and the control delay values are very close to the results from the SUM-WC framework. Therefore, the interpolants provide a good approximation for the utility and control delay of each lane. Figure 2 (e) provides a visual representation of where the WCUs are installed on road network for utility maximization.

**Comparison with Other CWD Deployment Frameworks**
The SUM-WC framework is compared with two other WCU placement strategies in order to validate the effectiveness of the proposed framework. At first, it is compared with the betweenness centrality model (30) for allocating the WCUs in the road network. The betweenness centrality model is a widely-used concept in network science that measures edge significance using the normalized number of shortest paths that pass through this edge. The betweenness centrality of an edge \( v \) is given by the expression:

\[
g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}
\]

Where,

- \( \sigma_{st} \) = Total number of shortest paths from node \( s \) to node \( t \)
- \( \sigma_{st}(v) \) = Total number of shortest paths from node \( s \) to node \( t \) that pass through node \( v \)

We assume that drivers typically chose either one of the shortest or almost shortest paths to plan their routes, which makes this heuristic an acceptable candidate for the comparison purposes. Based on betweenness centrality, two edges are chosen with the highest betweenness centrality value. Each edge has two lanes, so four lanes are shortlisted. In order to make a one-to-one comparison, the total WCU is divided into two sub-units of 18m and 12m. Then, using the four lanes and two sub-units, the deployment which yields the maximum utility is found using multiple traffic simulation. The maximum utility achieved is 1943 Wh, compared to 2992 Wh from SUM-WC framework. The betweenness centrality model gives a lower utility because a lane with high betweenness centrality may not be a lane at a signalized intersection, which limits its potential for opportunistic charging. It may serve higher number of EVs compared to SUM-WC framework, but the total energy charged is lower than that of SUM-WC. Therefore, the
SUM-WC framework performs better at maximizing utility than the betweenness centrality model.

The framework is also compared with another simple deployment paradigm, installation at two lanes with the highest traffic volumes. The lanes with the highest traffic volumes are found by placing detectors on all lanes in the simulation. Extracting the vehicle counts for each lane and looking for the highest volume. This paradigm has very low computational requirements, as it is based on simple assumptions. However, it also provides relatively low utility (1465 Wh) compared to the SUM-WC framework and betweenness centrality model. It has the same problem of limited opportunistic charging as the betweenness centrality model. The comparison of all allocation paradigms is shown in Figure 2 (f). The gain in utility using SUM-WC framework is almost 1.5 compared to betweenness centrality and almost 2 compared to placement at lanes with highest volumes.

CONTRIBUTION OF THIS RESEARCH
In this study, a novel ubiquitous framework (SUM-WC) is developed. It can use a calibrated traffic micro-simulation network of any area and identifies (a) the placement and sizing of WCUs, and (b) the traffic signal timings, which maximize the utility of the deployment within a given budget. We demonstrate that the utility is maximized since WCUs installed at different locations transfer the maximum amount of charging to EVs in a certain timeframe. The optimization problem is formulated using the traffic micro-simulation model and a global optimization method is developed to solve the formulated model. To the best of our knowledge, this is the first study that combines opportunistic wireless charging at intersections and selection of optimal intersection lanes to place the WCUs, such that the utility of WCU deployment is maximized within a given budget. The traffic micro-simulation based approach to utility maximization is also a new concept for CWD application. Previous works have focused on EV energy management and routing strategies based on location of charging facilities. However, the concepts of our focus were excluded from previous work. Our framework also has an advantage of scalability; it can be used for large-scale networks with thousands of signalized intersections. The pre-processing before the optimization step significantly reduces computational burden, by reducing the number of required traffic simulation runs and the initial population size of the genetic algorithm. Our framework also performs LOS measurement of signalized intersections that ensures that non-EVs do not suffer from delay due to the EV charging scheme.

CONCLUSIONS AND FUTURE WORKS
The SUM-WC framework successfully maximizes the utility of the WCU deployment in a large network through optimal placement and traffic signal timing parameters. The concept of opportunistic in-motion charging is applied here, which yields a higher utility compared to other techniques such as- betweenness centrality method. EVs need to stop or slow down to receive the wireless power, which is why the opportunistic charging at signalized intersections yields a higher utility than many other deployment schemes in an urban area. Moreover, the optimization model ensures that all intersections perform at acceptable LOS, so that the non-EV users do not suffer from delay due to this deployment.

Opportunistic CWD for EV is a fast-growing field, and this research will provide the building blocks for further research work. This study can be extended to investigate the effects of actuated and adaptive signals on opportunistic wireless charging at signalized intersections. Connected Vehicle Technology can be incorporated in all EVs, which will allow the EVs to
interact with roadside infrastructure such as traffic signals and charging stations for data sharing. A smart real-time charge scheduling method can be developed for EVs, which will consider routing based on location of EV charging stations and WCUs on the road network. In addition, V2I communication with traffic signals can further increase the utility for WCUs for EVs. EVs can ask for more stop time at signalized intersections, which will allow them to charge based on the urgency of their energy needs.

ACKNOWLEDGEMENTS
This research is supported by the National Science Foundation under Award #1647361. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
REFERENCES
1. Available online at: http://www.prnewswire.com/news-releases/alternative-fuel-and-
hybrid-vehicle-afhv-market-to-reach-614-billion-by-2022-globally-allied-market-
research-597605631.html
2. Egbue, Ona, and Suzanna Long. "Barriers to widespread adoption of electric vehicles: An
analysis of consumer attitudes and perceptions." Energy policy 48 (2012): 717-729
3. Vilathgamuwa, D. M., and J. P. K. Sampath. "Wireless Power Transfer (WPT) for
Electric Vehicles (EVs)—Present and Future Trends." Plug in electric vehicles in smart
grids. Springer Singapore, 2015. 33-60
4. Cirimele, Vincenzo, Fabio Freschi, and Paolo Guglielmi. "Wireless power transfer
structure design for electric vehicle in charge while driving." Electrical Machines
(ICEM), 2014 International Conference on. IEEE, 2014
5. Lukic, Srdjan, and Zeljko Pantic. "Cutting the cord: Static and dynamic inductive
wireless charging of electric vehicles." IEEE Electrification Magazine 1.1 (2013): 57-64
6. Fuller, Micah. "Wireless charging in California: Range, recharging, and vehicle
electrification." Transportation Research Part C: Emerging Technologies 67 (2016): 343-
356.
7. Manual, Highway Capacity. "HCM2010." Transportation Research Board, National
Research Council, Washington, DC (2010)
8. Zicheng Bi, Tianze Kan, Chunting Chris Mi, Yiming Zhang, Zhengming Zhao, and
Gregory A Keoleian. A review of wireless power transfer for electric vehicles: Prospects
to enhance sustainable mobility. Applied Energy, 179:413–425, 2016
9. Siqi Li and Chunting Chris Mi. Wireless power transfer for electric vehicle applications.
IEEE journal of emerging and selected topics in power electronics, 3(1):4–17, 2015
10. Chun Qiu, KT Chau, Chunhua Liu, and CC Chan. Overview of wireless power transfer
for electric vehicle charging. In Electric Vehicle Symposium and Exhibition (EVS27),
2013 World, pages 1–9. IEEE, 2013.
11. Young Dae Ko and Young Jae Jang. The optimal system design of the online electric
vehicle utilizing wireless power transmission technology. IEEE Transactions on
Intelligent Transportation Systems, 14(3):1255–1265, 2013
12. Young Jae Jang, Young Dae Ko, and Seungmin Jeong. Optimal design of the wireless
charging electric vehicle. In Electric Vehicle Conference (IEVC), 2012 IEEE
International, pages 1–5. IEEE, 2012
13. Young Jae Jang, Young Dae Ko, and Seungmin Jeong. Creating innovation with systems
integration, road and vehicle integrated electric transportation system. In Systems
Conference (SysCon), 2012 IEEE International, pages 1–4. IEEE, 2012
14. Mohrehkesh, Shahram, and Tamer Nadeem. "Toward a wireless charging for battery
electric vehicles at traffic intersections." Intelligent Transportation Systems (ITSC), 2011
14th International IEEE Conference on. IEEE, 2011
15. Riemann, Raffaela, David ZW Wang, and Fritz Busch. "Optimal location of wireless
charging facilities for electric vehicles: flow-capturing location model with stochastic
user equilibrium." Transportation Research Part C: Emerging Technologies 58 (2015): 1-
12
16. Chen, Zhibin, Fang He, and Yafeng Yin. "Optimal deployment of charging lanes for
electric vehicles in transportation networks." Transportation Research Part B:
Methodological 91 (2016): 344-365
17. Hayato Ushijima-Mwesigwa, MD Zadid Khan, Mashrur A Chowdhury, Ilya Safro
"Optimal Installation for Electric Vehicle Wireless Charging Lanes", submitted, preprint at arXiv:1704.01022, 2018.
18. Deflorio, Francesco, et al. "Modeling and Analysis of Wireless “Charge While Driving” Operations for Fully Electric Vehicles." Transportation Research Procedia 5 (2015): 161-174.
19. Jasprit S Gill, Parth Bhavsar, Mashrur Chowdhury, Jennifer Johnson, Joachim Taiber, and Ryan Fries. Infrastructure cost issues related to inductively coupled power transfer for electric vehicles. Procedia Computer Science, 32:545–552, 2014.
20. “Fuels Institute Tomorrow’s Vehicles Report”, available online at https://www.fuelsinstitute.org/ResearchArticles/TomorrowsVehicles.pdf
21. Behrisch, Michael, et al. "SUMO—simulation of urban mobility: an overview." Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind, 2011.
22. Available online at https://www.mathworks.com/help/gads/ga.html
23. “SCDOT Traffic Signal Design Guidelines”, available online at http://www.scdot.org/doing/technicalPDFs/publicationsManuals/trafficEngineering/2009_Signal_Design_Guidelines.pdf.
24. Reilly, W. R., and C. C. Gardner. Technique for Measuring Delay at Intersections. In Transportation Research Record 644, Transportation Research Board, National Research Council, Washington, D.C., 1977, pp. 1–7.
25. Powell, J. L. Field Measurement of Signalized Intersection Delay for 1997 Update of the Highway Capacity Manual. In Transportation Research Record 1646, Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 79–86.
26. Dowling, Richard, et al. "Guidelines for calibration of microsimulation models: framework and applications." Transportation Research Record: Journal of the Transportation Research Board 1876 (2004): 1-9.
27. Hollander, Yaron, and Ronghui Liu. "The principles of calibrating traffic microsimulation models." Transportation 35.3 (2008): 347-362.
28. Kurczveil, Tamás, Pablo Álvarez López, and Eckehard Schnieder. "Implementation of an Energy Model and a Charging Infrastructure in SUMO." Simulation of Urban MObility User Conference. Springer Berlin Heidelberg, 2013.
29. Gen, Mitsuo, and Runwei Cheng. Genetic algorithms and engineering optimization. Vol. 7. John Wiley & Sons, 2000.
30. Brandes, Ulrik. "A faster algorithm for betweenness centrality." Journal of mathematical sociology 25.2 (2001): 163-177.