EVTC

Electric Vehicle Transportation Center

Optimal Charging Scheduler for Electric Vehicles on the Florida Turnpike

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Final Research Project Report
EVTC Project 13 – Optimal Charging Scheduler for Electric Vehicles on the Florida Turnpike

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The objective of the Optimal Charging Scheduler for Electric Vehicles on the Florida Turnpike was to develop the methodology for analyzing the roadway traffic patterns and expected penetration and timing of electric vehicles (EVs) on the Florida Turnpike. The work resulted in the determining of requirements for electric vehicle supply equipment at turnpike plazas, the options for equipment siting and the economics. The work was conducted by Dr. Zhihua Qu, Principle Investigator and his postdoctoral researcher Dr. Azwirman Gusrialdi (who is first author of resulting publications) in the College of Engineering and Computer Science at the University of Central Florida.

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1.0 Abstract

This project developed a methodology to simulate and analyze roadway traffic patterns and expected penetration and timing of electric vehicles (EVs) with application directed toward the requirements for electric vehicle supply equipment (EVSE) siting and purchasing/leasing at turnpike plazas. The project also developed a wireless-communication-based driver-assistance application that would optimize the location and timing of charging for individual drivers as well as efficiency of the overall charging network. The first steps of the project were to develop the systematic methodology for analyzing expected penetration of electric vehicles (EVs) and their impacts on the overall transportation infrastructure. An analytical model consisting of three components was developed and applied. Furthermore, the stability and instability of the proposed model were also analyzed. The developed model was then applied to the Florida Turnpike network as a test system.

2.0 Background

Future predictions show that the U.S. will have from 3 to 5 million electric vehicles on the nation’s roads in 10 years [1]. In comparison to internal combustion engine vehicles, EVs have a more limited driving range and, for a long distance travels, they need to be charged periodically during the trip. Hence, the combination of the limited driving range, the long charging times, and the customer’s satisfaction level when they wait for their EVs to get charged can have a direct impact on decisions by consumers to adopt the use of EVs in the future.

Numerous factors including installment of new charging infrastructure play an important role in addressing the above challenges. The focus of this project was to develop a methodology that can be applied to the EV charging schedule problem with the goal to optimally utilize the existing charging network or infrastructure by applying information and communication technologies.

In particular, the scenario that was modeled assumes a bidirectional highway where there are a number of service stations equipped with EV chargers. The chargers are located at highway service stations where the EV drivers can choose to charge their vehicles. The charging time constraints are the battery charging time which depends upon the charger technology size, waiting times of other EVs at the service stations and the state of charge of the EV battery. The project goal is to apply appropriate scheduling and coordination strategies so that utilization of the charging stations on the highway are optimized with respect to time and use.

Hence, the project objective was to develop both a scheduling algorithm of directing EV flows into service stations and a distributed decision making algorithm to facilitate individual EV drivers to make better charging decisions. In this regard, a systematic methodology was developed for analyzing expected penetrations of electric vehicles and their impacts on the overall transportation infrastructure. The analytical model consisted of three components:

- A dynamic model which, for a highway with a total of N nodes (entrances and exits), admits either instantaneous or average traffic flow passing through entrances/exits;
- A queuing model on the number of EVs waiting at a given service station for charging and their waiting time;
- A network level model that prescribes the decision making process of individual drivers as well as any coordination among services stations and individual drivers using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

Using the model, a network-level protocol was synthesized to optimize the performance (minimum waiting/charging time) of the overall system. In particular, a distributed scheduling algorithm was used for the overall charging network and a cooperative decision making algorithm for individual drivers to make their decisions. Furthermore, the stability of the proposed distributed scheduling algorithm was also systematically analyzed.

Using the above described methodology, the Florida Turnpike network was then used as a test system for the project. Two meetings were held between the research team and Florida Turnpike engineers and real-world data were collected and compiled from Regional Integrated Transportation Information System (RITIS) database in collaboration with the EVTC "Assessing the SunGuide® and STEWARD Databases" project [2]. Case studies via computer simulations were then conducted using 24-hour Florida Turnpike roadway traffic data and the currently installed electric vehicle charging equipment at the turnpike plazas. The charging equipment utilization and electric vehicle waiting time are compared for different EV penetration rates and charging strategies in order to demonstrate the proposed strategy results in a uniform utilization of the charging equipment at the service stations.

The project results were presented as three project reports that have been completed and are posted on the EVTC website. These results were originally published in the Institute of Electrical and Electronics Engineers (IEEE) journals and conferences. The citations for these three reports are:

1. Azwirman Gusrialdi, Zhihua Qu, and Marwan A. Simaan, "Scheduling and Cooperative Control of Electric Vehicles' Charging at Highway Service Stations," *in Proceedings of the 53rd IEEE Conference on Decision and Control*, Los Angeles, California, USA, pp. 6465-6471, December 15-17, 2014.
2. Azwirman Gusrialdi, Zhihua Qu and Marwan A. Simaan, "Distributed Scheduling and Cooperative Control for Charging of Electric Vehicles at Highway Service

Stations," *IEEE Transactions on Intelligent Transportation Systems*, to appear 2017. DOI: 10.1109/TITS.2017.2661958.

3. Azwirman Gusrialdi and Zhihua Qu, "Analysis of Cooperative Systems with Time Delay: Application to Transportation Systems," *IEEE Multi-Conference on Systems and Control*, Buenos Aires, Argentina, September 19-22, 2016.

A summary of the project research presented in these three papers follow.

3.0 Research Results

The following papers describe the use and development of two real-time control algorithms: 1) a distributed scheduling algorithm, and 2) a cooperative decision making algorithm for individual EV.

Paper 1 -- Scheduling and Cooperative Control of Electric Vehicles' Charging at Highway Service Stations

As a first step, a dynamical model describing the average flow of EVs passing through the entrances/exists and entering the service stations along the highway is developed. Moreover, queueing theory (Figure 1) is further used to predict the average number of EVs waiting at a specific service station for a given average number of EVs entering the service station and the capacity (i.e., number of chargers and the charging time) of the service station. In contrast to the existing spatial and temporal model described in literature [3], the model presented by this work is simple and flexible which in turn facilitates the analysis and design of the distributed scheduling algorithm. Finally, a simple model of the electricity consumption of an EV is derived which is used to predict the EV's battery State-of-Charge (SOC) when approaching the service station.

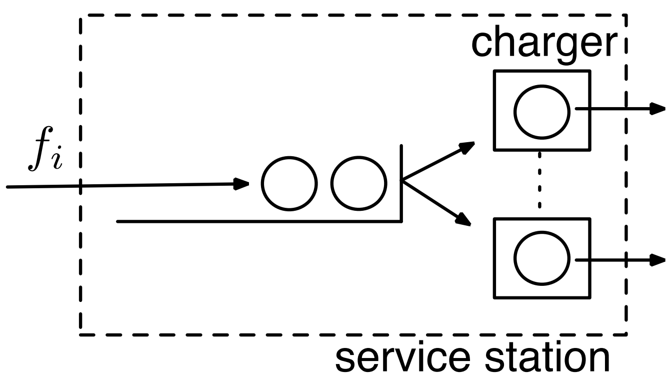


Figure 1. Illustration of queue at a service station.

Using the developed model, a network-level protocol was synthesized to optimize the performance (minimize the total waiting/charging time) of the overall system. In particular, a distributed scheduling algorithm was designed for the overall charging network and a cooperative control algorithm was developed for individual drivers to make their charge or not charge decisions. A distributed scheduling algorithm is highly desirable due to its scalability (which reduces the computational and communication costs) with respect to the numbers of the EVs and charging network since it only requires local knowledge about the system. Moreover, it is also more robust to information intermittency in both communication and transportation networks. For example, when a communication link between the service stations is broken, the information can still be transmitted using an alternative communication path which allows the entire system to remain functional. The distributed scheduling algorithm is based on the consensus algorithm which relies solely on information of local traffic flows and the number of queues at the neighboring service stations.

First, it is shown that to minimize the total waiting time for the EVs to get charged is equivalent to equal allocation of the total charging demands across the network. This means that the utilization of each service station is equal (that is, the ratio between the number of EVs queueing and the capacity of the service station). Hence, the distributed scheduling algorithm which decides number of EVs that should enter each station is designed such that a consensus on the service station's utilization is achieved. In this paper, the two distributed scheduling algorithms were developed and used. These two algorithms are dependent on whether or not the total vehicle charging demands is larger or smaller than the total capacity of the service stations. In the second paper discussed below, an improved scheduling algorithm was developed which can handle both cases in a unified manner. The distributed scheduling algorithm forces the service stations to equally utilize their capacity and, thus, the chargers at each station can be used close to their limit capacity. Next, given the optimized number of EVs that should enter each service station a cooperative decision making algorithm is developed by taking advantage of local vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. Specifically, this algorithm is designed for each EV to determine whether or not to pass a specific service station by taking into account its own battery charge constraints while meeting the desired flow level from the scheduling algorithm. Instead of communicating the current SOC, each EV exchanges the value of the required energy which provides a better way to preserve the driver's private information.

Finally, the proposed algorithm was evaluated via several simulations. These simulations were performed for a network of four service stations and constant average traffic flow. The results from the simulation (Figure 2) showed that the proposed scheduling algorithm results in an equal utilization for all service stations.

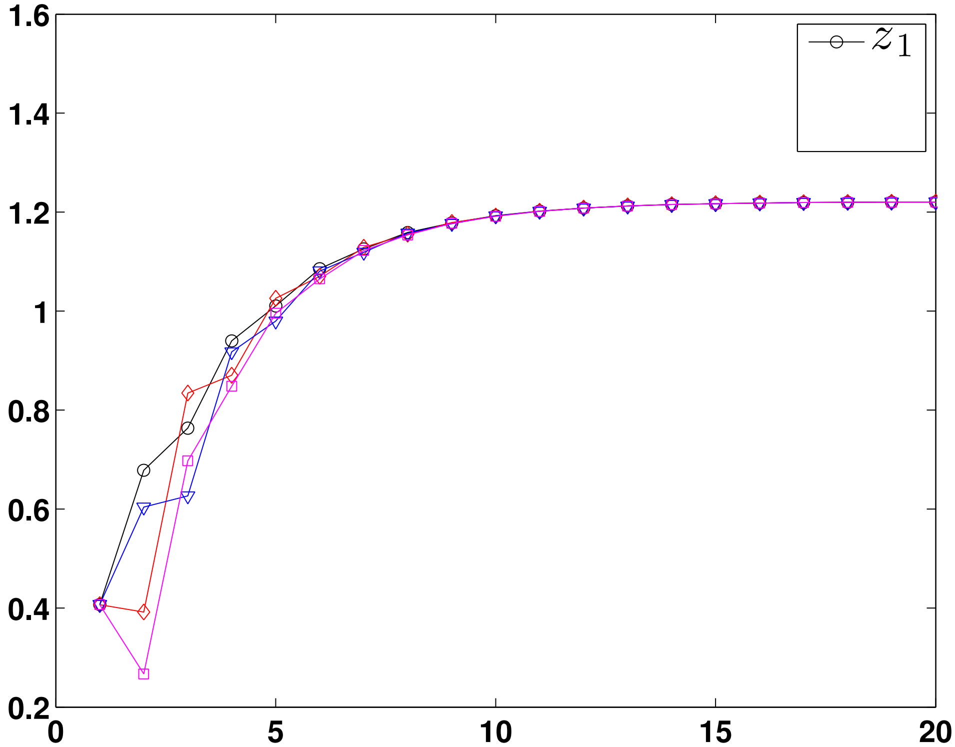
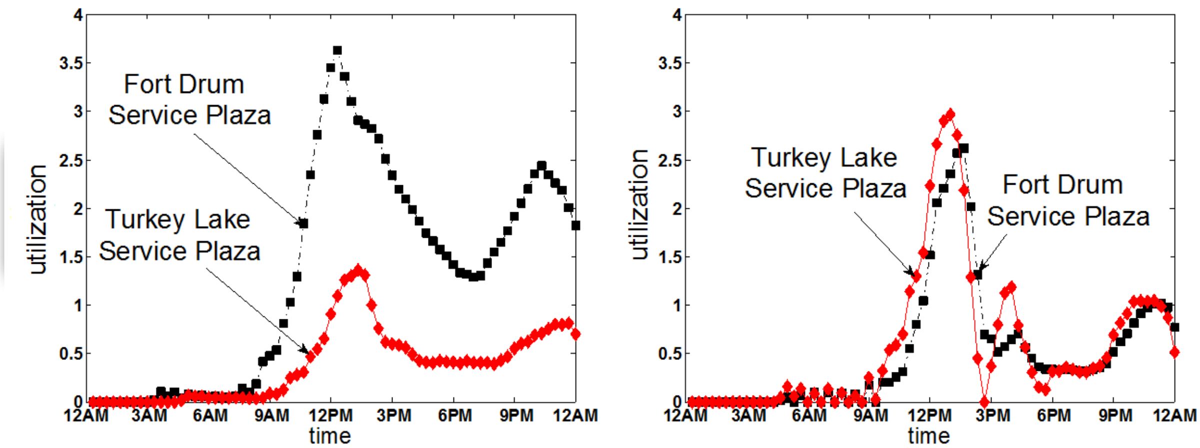


Figure 2. Utilization of each service station (z_i) versus time-step using the proposed algorithm.

Paper 2 – Distributed Scheduling and Cooperative Control for Charging of Electric Vehicles at Highway Service Stations

As stated above, this paper develops an improved scheduling algorithm which can handle the two distributed scheduling algorithms that depend on whether the total charging demands is larger or smaller than the total capacity of the service stations. This algorithm is then tested by applying it to a real data case of the Florida Turnpike network that includes 24-hour Florida Turnpike roadway traffic data and the currently installed electric vehicle charging equipment data at the turnpike plazas. In order to evaluate the effectiveness of the proposed scheduling algorithm, the algorithm is compared with an alternative strategy called as State-of-Charge (SOC) based random strategy which employs the information on the EV's battery's SOC when approaching the service station. In this strategy, a SOC threshold value to 30% is assigned for charging.

When an EV approaches a service station, the algorithm will check whether the EV's SOC is below the threshold. If the SOC is below, then the driver will recharge at the approaching station. Otherwise, the EVs randomly decide whether to enter the approaching station or to pass the station given that the current SOC allows the EVs to reach the next station. The simulation results (Figure 3) show that in the case of SOC-based random strategy, there is a large difference of utilization between the service stations since no information of the current queue length of the neighboring station is used for deciding whether to charge at a specific service station. On the other hand, the proposed algorithm allocates the EVs along the highway such that the service stations are uniformly utilized by using the information on the real time queue length at the neighboring stations. Consistent results are also observed for simulations with different parameters such as the number of service stations and number of chargers at each station.



(a) SoC based random strategy (b) Proposed strategy

Figure 3. Simulation results on Florida turnpike with two service stations.

Paper 3 -- Analysis of Cooperative Systems with Time Delay: Application to Transportation Systems – In papers 1 and 2, a distributed scheduling algorithm was developed which resulted in all of the service stations being uniformly utilized and as a result the total waiting time for the EVs to get charged is minimized. Even though the stability analysis of the proposed algorithm (in the sense of the boundedness of the number of queues at the service stations) was presented, the result was not clear on how the distance between the service stations influence the number of queues over time. This paper systematically studies how the delay (i.e., the distance between the service stations) affects the boundedness, unboundedness and oscillation of the number of queues at each service station over time when applying the proposed distributed scheduling algorithm.

Based on dynamical system theory, a dynamical model was developed and analyzed which can be used to predict the behavior of the number of queues at each service station depending on the delay and also the communication topology between the service stations. The results found that the delayed negative local feedback is one of the sources for the undesired oscillations. The simulation results for a network of two service stations with equal capacity also demonstrated via simulation (on a network of two service stations with equal capacity) that the service stations are uniformly utilized and the trajectories (i.e., the number of queues at each station over the time) may have sustained oscillations for a long travel distance between the service stations. Finally, based on the analysis, a simple method to eliminate such oscillations was presented which utilized the non-delayed information received via the communication network.

4.0 Impacts/Benefits

1. The proposed dynamical model of the average traffic flow and the average queue length can be used to predict the length of queue at the service stations over the time for any charging scheduling strategy.
2. The proposed distributed scheduling algorithm together with the cooperative decision making algorithm for individual EV can be adopted by a highway authority to optimize the overall charging network by minimizing the total waiting time for the EVs to get charged.
3. The proposed algorithm and its analysis provide a guideline for the installment of required information and communication technologies for future smart transportation system so that its performance can be optimized. Moreover, it can also be used to study the infrastructure installment problem; for example to decide how many chargers need to be installed and where to install them so that the total waiting for the EVs to get charged remains to be reasonable.

5.0 Conclusions

This report summarizes the project's results on development of a wireless-communication-based driver-assistance application that would optimize the location and timing of charging for individual drivers as well as efficiency of the overall charging network. First, a dynamical model for analyzing expected penetration of electric vehicles (EVs) and their impacts on the overall transportation infrastructure was developed. Using the developed model, a network-level protocol was synthesized to optimize the performance (minimize the total waiting/charging time) of the overall system. In particular, a distributed scheduling algorithm was designed for the overall charging network resulting in an equal utilization of all the service stations and a cooperative decision making algorithm was developed for individual drivers to make their charge or not charge decisions. Furthermore, the stability and instability of the proposed model were analyzed. The developed model was then applied to the Florida Turnpike network as a test system. The results can be used to improve the performance of the EVs' charging in the future smart transportation systems.

6.0 References

1. Block, D & Brooker, P; "Prediction of Electric Vehicle Penetration"; EVTC Report Number: FSEC-CR-2069-17, May 2017.
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