SYSTEMATIC DESIGN OF WIRELESS CHARGING TRANSPORTATION NETWORK

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ABSTRACT

Many cities around the world encourage the transition to battery-powered vehicles to minimize the emissions of greenhouse gases. The standard plug-in electric vehicles have a limited amount of power stored in the battery resulting in frequent stops to refill the power. Wireless charging is an innovation of transmitting power through electromagnetic induction to portable electrical devices for energy renewal.

Online Electric Vehicle (OLEV) is a new technology that allows the vehicle to be charged while it is in motion, thus removing the need to stop at a charging station. Developed by the Korea Advanced Institute of Science and Technology (KAIST), OLEV picks up electricity from power transmitters buried underground.

This paper investigating bus routes to determine the optimum study area for planning out the costs of deploying a pilot service network by comparing the cost of initial investment for the three types of wireless charging: Stationary Wireless Charging (SWC), Quasi-Dynamic Wireless Charging (QWC), and Dynamic Wireless Charging (DWC), using OLEV technology for a bus service transit in the borough of Manhattan (MN) in New York City (NYC).

1. INTRODUCTION

In recent years, an expanding need to develop alternative solutions to traditional energy sources from fossil fuels becomes an imperative needed for sustainable cities. Thus, electric buses reduce fossil fuels uses and, therefore, provide a better living environment. Since transit is significant fuel consumption, the development of electric vehicles (EVs), especially electrical buses provided by effective wireless charging technologies, has become even a priority. Studies have shown the benefits and advantages of pure electric vehicles (EVs) compared to internal combustion (IC)-based cars or hybrid EVs in terms of their environmental effects (Jang et al., 2016). Nevertheless, these benefits may be offset by the limited amounts of energy stored in their batteries.

To make EVs even worse, charging with the fastest charger requires at least 30 minutes (Ulrich, 2012). To fill this gap, the use of Remote Charging Technology, also known as wireless charging (Costanzo et al., 2014), (Garnica et al., 2013), has been testing and implemented. Wireless charging is an innovation of transmitting power through electromagnetic induction to portable electrical devices to ensure optimized energy renewal.

In public transportation systems operation, exist three different types of wireless charging systems, to be specific, (a) Stationary Wireless Charging (SWC), the charging only happens when the vehicle is parked or idle, (b) Quasi-Dynamic Wireless Charging (QWC), when a vehicle is moving slowly or in stop-and-go mode the power is transferred, and (c) Dynamic Wireless Charging (DWC), the charging can be provided even when the vehicle is moving (Ulrich, 2012).

This paper compares the cost of initial investment for the three types of wireless charging (SWC, QWC, and DWC) using OLEV technology for a bus service transit in the borough of Manhattan (MN) (Figure 4), in New York City (NYC), the most populous city in the United States (U.S. Census Bureau 2010).

2. LITERATURE REVIEW

The public bus system helps to reduce traffic congestion and exhaust emissions (Song, 2013). Due to vehicle technology limitations, diesel-powered buses still dominate today's bus fleet. Various regulations related to the problem of battery size, cost, and life and onboard batteries have restricted the popularity of electric buses (Liu and Song, 2017).
Wireless charging technology is changing the form of energy transfer and utilization. Since its initial concept suggested by (Bolger et al., 1978), significant technological achievements have been made in developing wireless charging.

The development of wireless charging technology is surveyed (Esser, 1995; Wang et al., 2005; and Covic et al., 2007). To eliminate cables and dangerous sparking, wireless charging has been actively investigated in transit applications, such as charging for electric vehicles (Jang et al., 2016). Other focuses the charging strategy interacting with the power grid (Paul and Yamada, 2014), on e-buses were based on charging infrastructure comparison (Chen et al., 2018; Bi et al., 2015), and the Battery Management Systems (Ding et al., 2015; Hu et al., 2013; Liu and Song, 2017). (Ke et al., 2016) proposed a model for simulating the operation and battery charging schedule of plug-in e-buses and determined the minimum construction cost of an all plug-in electric bus transportation system.

The OLEV system is the first successfully commercialized EV wireless charging system (Jang et al., 2015; Lee et al., 2010; Shin et al., 2013).

Developed by the Korea Advanced Institute of Science and Technology (KAIST), OLEV picks up electricity from power transmitters buried underground. OLEV technology (KAIST, 2009) has its sights set on economizing and sustaining industrial and commercial electric vehicles' performance, with its current focus being bus transits. This is achieved by reducing the number of batteries required to operate the bus service, reducing the vehicle's cost and weight while always staying in service with its efficient, wireless charging technology.

The OLEV consists of shuttles (similar to conventional EVs) and a charging infrastructure containing a set of energy transmitters that can charge the bus's battery remotely utilizing an ingenious non-contact charging component while the buses are moving over the charging infrastructure.

3. MATERIALS AND METHODS

3.1 Characteristics of EV Types

The OLEV technology currently operates in several bus transits worldwide, including Seoul Grand Park and Gumi City transit lines in South Korea. There are three different categories of wireless charging systems (Figure 1) that OLEV can be used:

a) Stationary wireless charging (SWC),
b) Quasi-dynamic charging (QWC), and
c) Dynamic wireless charging (DWC).

SWC is only parked or idle charging, QWC is when a vehicle moving slowly or in stop-and-go mode, and DWC is supplied even when the vehicle is in motion. Each system's cost and benefit depend on various factors such as route and fleet size, service range, battery prices, and installation cost (Jang et al., 2016; Garnica et al., 2013).

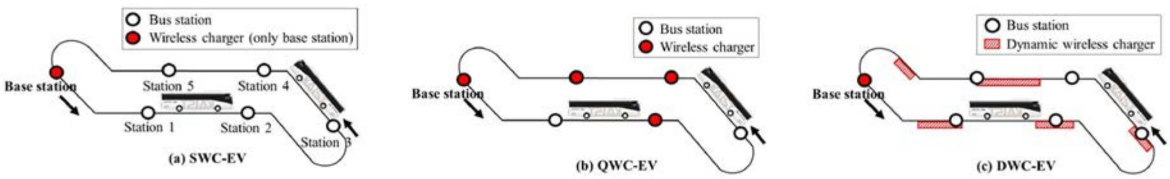


Figure 1. Charging allocation properties for each type of EV (Jang et al., 2016).

Figure 2. shows the OLEV serving as a campus shuttle on the KAIST campus, and the power track installed under the road.

(a) (b)

Figure 2. KAIST OLEV: one of the dynamic wireless charging EVs (DWC-EVs) (Jang et al., 2016). (a) under construction; (b) in operation.

3.2. Dataset Description

Two different datasets were used for the analysis. The first one is the drive-type network data taken from the Open Street Map (OSM) using the OSMnx (Boeing, 2017). The second one consists of General Transit Feed Specification (GTFS), which defines a standard format for public transportation schedules and associated geographic information from the Metropolitan Transportation Authority (MTA, 2020, March 18).

3.3. GTFS Data

The information was collected from the MTA data feeds for the NYC Manhattan Transit Bus transportation services. The downloaded data package contains eight text files: trips, stops, stop_times, shapes, routes, calendar_dates, calendar, and agency.

Open-source Python 2.7.13, an interpreted object-oriented, high-level programming language, was used to visualize GTFS data focusing on MN bus transit into Static Data Feeds (GTFS Schedule Data). Please refer to Correa et al. (2017) for more details on GTFS transit data. Additionally, Matlab programming is used to simulate a battery's state of charge (SoC) throughout a route to determine how well the allocation of charging units fits the model. Figure 3 shows the number of buses from bus lines M1, M2, M3, M4, and M72 arriving at bus stop # 400124 5 AV/E 72 ST, by each hour.

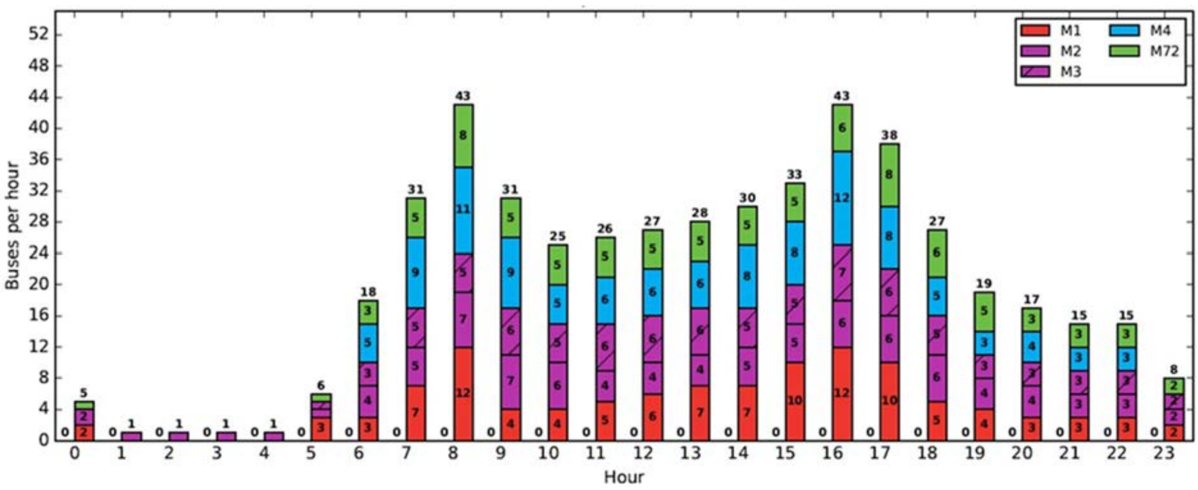


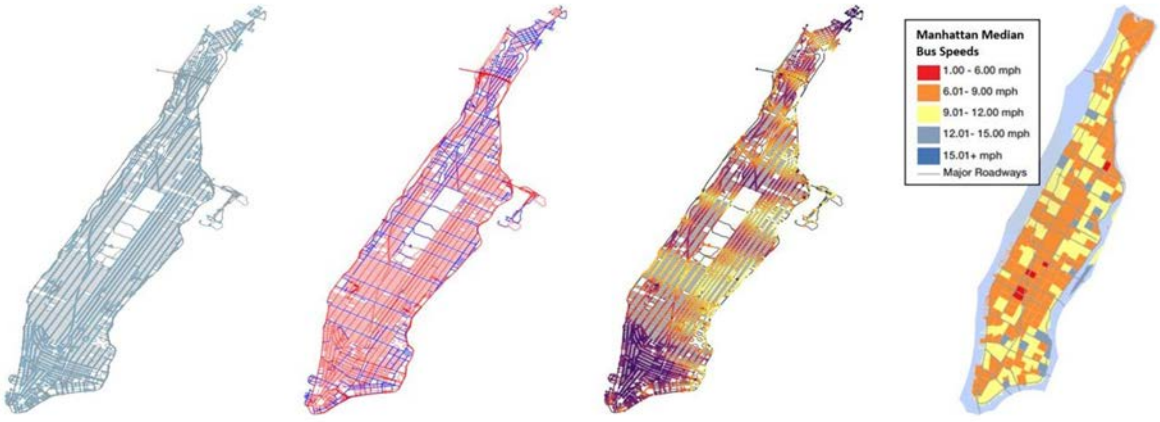
Figure 3. Visualization of GTFZ (Number of arriving buses to bus stop # 400124 at 5 AV/E 72 ST)

3.4 Network Data

Drive-type network data from MN was taken from OSM using the OSMnx (Boeing, 2017) to extract and clear the network. The network contains nodes for road intersections and joints, as shown in Figure 4. OSMnx downloads street network data that performs topological correction and simplification automatically to calculate accurate edges and nodes. The selected network types are "drive" to get drivable public streets and excluding service roads. (Figure 4a).

OSMnx analyzes networks and calculates network statistics, including spatial metrics based on geographic area or weighted by distance.

OSMnx allows classifying one-way and bidirectional streets (Figure 4b). For oneway streets, directed edges are added from the origin node to the destination node. For two-way streets, reciprocal directed edges are counted in both directions between nodes. This ensures that intersections are not considered dead ends. OSMnx also allows identifying the busiest nodes through the network, as is shown in Figure 4c.



(a) (b) (c) (d)

Figure 4. Study area: Manhattan Borough in New York City. Network Data

Visualization, (a) Network contains nodes for road intersections and joints.; (b) Network provides the single way in red and double way in blue; ((c) M22 bus) Network busiest nodes visualized from low (dark-violet) to high (light yellow); (d) Median bus Speeds of Manhattan.

4. DATA ANALYTICS: TOOLS AND METHODS

The quantity of charging on each power track required for a DWC system is a function of vehicle speed and the elapsed time spent on that power track. In the conventional station allocation problem, the vehicle speed is not related to the allocation.

Therefore, for optimum results, the system implementation should be in places where bus speeds are very low (bus stops, streets historically known for slow traffic). The median speed data shown in Figure 4d is established on GPS bus data time, which indicates the location of individual buses over time on their routes. Data was collected between 4 p.m. and 6 p.m. every typical weekday in 2017 (NYCDOT, 2018).

Based on the network and median bus speed information, we select three MN bus routes located within the low busiest node's area in MN in Figure 4c (dark-violet colored) as the best option for actual potential implementation because it will produce less disruption in the city than the other zones such as midtown.

In this project, information was collected from the Metropolitan Transportation Authority (MTA) data feeds for the NYC Manhattan Transit Bus transportation services. Initially, only three Manhattan bus routes: M8, M9, M22 (colored in green), were examined as the first analysis in the energy logistics (battery and charging infrastructure) cost for each system Figure 5).

(a) (b) (c)

Figure 5. Selected Routes. (a) M8 bus; (b) M9 bus; (c) M22 bus

After data processing, we tested the accuracy of the data obtained from GTFZ feeds, comparing bus stops of each selected route to the real bus stops in the city, using google street view, as is shown in Figure 6. This method allows us to eliminate potential bias in the data collected.

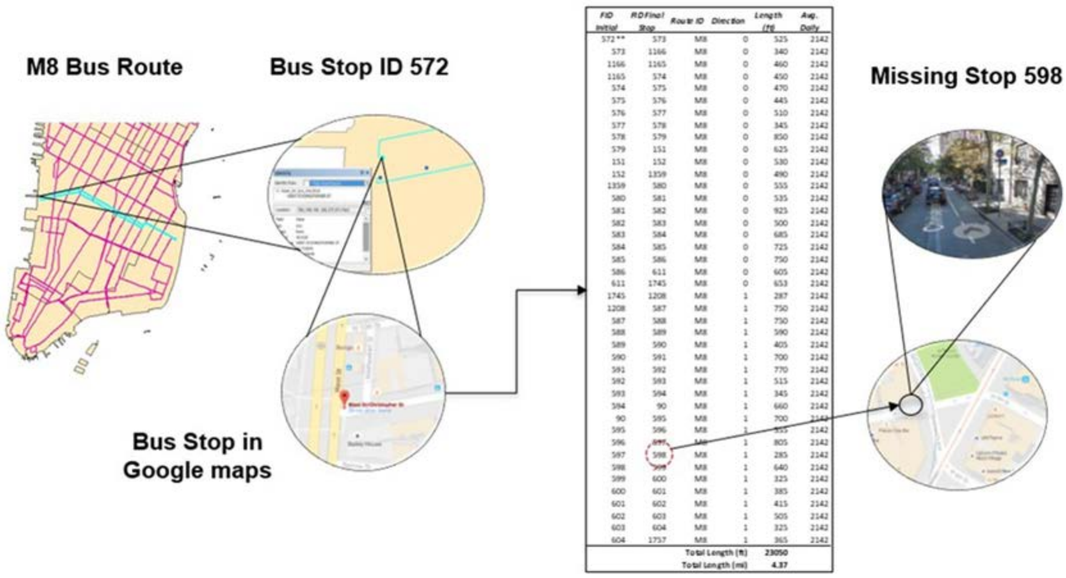


Figure 6. Comparison with real site data

5. COST ANALYSIS

For an EV-based transit system, the initial investment cost is fundamentally composed of two main components: the cost of the charging infrastructure and the cost of a fleet of vehicles.

The cost is divided into the batteries' costs, the vehicle units, and the other charging components. The energy logistics cost accounts for the majority of the total cost of an EV-based transit system.

Therefore, understanding the cost structure of energy logistics is critical for deciding on investments in EV-based transit systems.

In (Jang et al., 2016), there is a qualitative cost-benefit analysis for each wireless system, depending on the battery price and infrastructure cost, as seen in Figure 7. However, investment in the OLEV cannot only be made based on such analysis. Therefore, reports from current OLEV and EV bus transit operations, MTA data feeds, and tools from GIS software were utilized to develop a method for comparing the energy logistics costs for these different types of charging systems on a chosen Manhattan bus route.

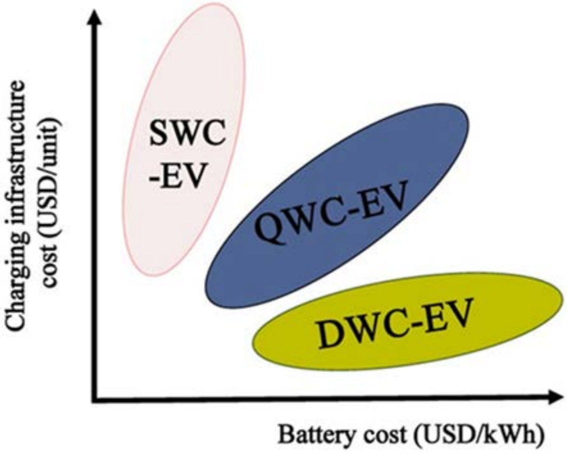


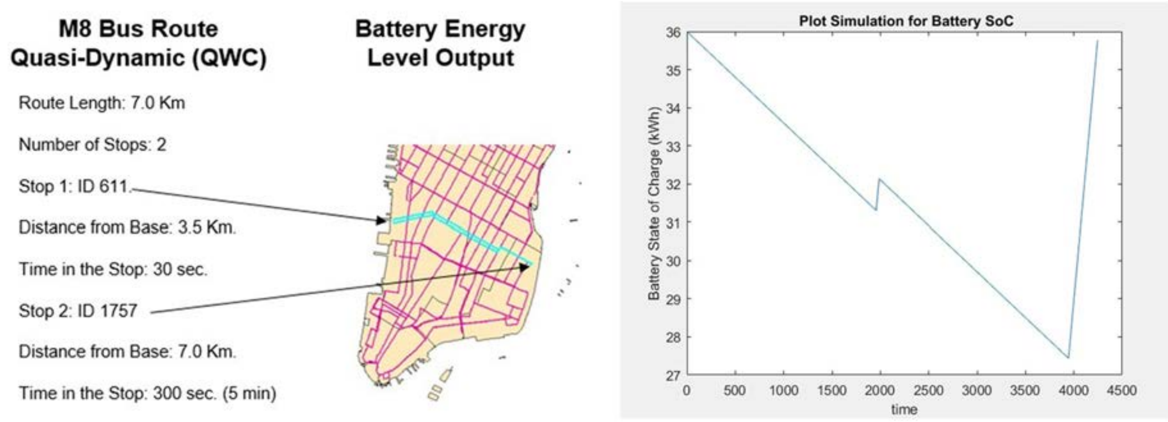
Figure 7. Qualitative analysis of the economic benefits of different EV charging systems (KAIST, 2009)

Allocation of chargers for each system is that SWC should be installed only at the station (base) where the vehicles rest between services; QWC - identify where to install the wireless chargers at minimum cost based on energy consumption and depletion between stops in a route; DWC - as the charging can be done while the vehicle is in motion, the vehicle speed should be considered determining the allocation of chargers along the route.

$$\text{SWC \& QWC: min } [(No.\ Buses) * (Cost\ of\ KWh) * (Service\ Batery\ Size)\ ] + [(Cost\ of\ Charger) * (No.\ Chargers)] \quad (1)$$

$$\text{DWC: min } [(No.\ buses) * (Cost\ of\ KWh) * (Service\ Batery\ Size)\ ] + [(Power\ track\ cost\ per\ meter) * (Power\ track\ lenght) + (Cost\ of\ Charger) * (No.\ Power\ track\ units)] \quad (2)$$

Once we determine the charging infrastructure's location and length, we can use equations (1) and (2) to optimize the minimum energy logistics cost for SWC, QWC, and DWC systems. The cost of battery per energy unit, charging unit, and power track per unit length can be found (KAIST, 2009).



(a) (b)

Figure 8. Simulation for Battery. (a) M8 bus details; (b) Battery energy level

Battery simulation for the M8 bus route Figure 8a is shown in Figure 8b. The energy level is within the upper and lower limits. We assume that the energy capacity of the battery is linearly proportional to the cost of the battery. This assumption is realistic, as an EV battery pack contains multiple battery cells, so the capacity is defined by the number of cells included in the battery pack. This method of linear cost calculation is also widely used in the industry.

6. RESULTS AND DISCUSSION

As shown in Table 1 and Figure 9, the data analysis conducted in this study evaluates the commercial fleet size with the cost structure for each system. Axis x and y represent the number of vehicles and the total investment cost, respectively, for the M8 bus route. The entire cost of the system is proportional to the battery's full size (cost of SWC increases linearly).

Beneath this assumption, the charger is installed only at the station base and is fixed just as if the number of Electric Vehicles grows. Thus, the energy logistics cost is linearly proportional to the fleet. In practice, more charging capacity would need to be added to the base station for the SWC system to avoid delays as busses wait to be charged, producing some non-linear discrepancies in the model.

For the DWC case, the increment rate of cost is less significant than that for the case of SWC. Therefore, if the smaller batteries are more economical, it produces a growing number of EVs that increase optimization.

Stationary (SWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	Base Station	Base Station	Base Station
E needed for service	140	140	140
Battery size (kWh)	233	233	233
No. of Evs	1.0	1.0	1.0
Battery cost per kWh	600	600	600
No. of chargers	1.0	1.0	1.0
Cost per charger	50,000	50,000	50,000
Length of Power Track			
No. of Power Tracks			
Power Track Cost (per m)			
	$ 190,000	**$ 190,000**	**$ 190,000**

Quasi-Dynamic (QWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	BS, 611, 1757	BS, 1720, 1769	BS, 1754, 1713
E needed for service	60	120	80
Battery size (kWh)	100	200	133
No. of Evs	1.0	1.0	1.0
Battery cost per kWh	600	600	600
No. of chargers	3.0	3.0	3.0
Cost per charger	50,000	50,000	50,000
Length of Power Track			
No. of Power Tracks			
Power Track Cost (per m)			
	$ 210,000	**$ 270,000**	**$ 230,000**

Dynamic (DWC)

Route:	M8 (42 stops)	M9 (64 stops)	M22 (44 stops)
Total Dist. in km	7.0	15.7	8.9
FID Stop Station	BS, 611, 1757	BS, 1720, 1769	BS, 1754, 1713
E needed for service (2/3 of bat. size)	24	80	54
Battery size (kWh)	40	133	90
No. of Evs	1.0	2.0	2.0
Battery cost per kWh	600	600	600
No. of chargers	5.0	3.0	3.0
Cost per charger	50,000	50,000	50,000
Length of Power Track	500		
No. of Power Tracks	*4		
Power Track Cost (per m)	600		
	$ 574,000	**$ 310,000**	**$ 258,000**

eff high 0.8 **eff low** 0.2

* x m at West/Christopher, y m at 9th/Broadway, z m at 8th/Mercer (4th charger @ Base Station).

Note: Prices and equations for logistics cost was taken from: (Jang et al., 2016)

Table 1. Cost Analysis of Wireless Network

The cost lines for SWC-QWC and QWC-DWC cross when the number of vehicles is three and seven, respectively, that means if less than three cars, SWC is the most economical; if the number of cars is between three and seven, QWC is competitive. If the number of vehicles is more significant than seven, DWC is the most efficient and economical. The lines with lower costs SWC for fleet <3, QWC for 3 < fleet < 7, and DWC for fleet > 7, regardless of the charging type, should be considered the lower bound for the wireless charging EV.

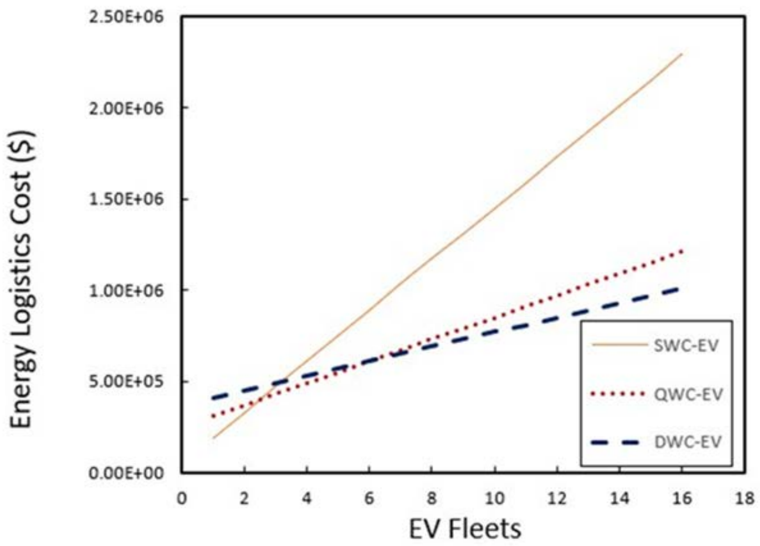


Figure 9. M8 Route Fleet-Scale Plot Analysis.

7. CONCLUSIONS AND FUTURE WORK

Wireless charging technology offers the possibility of eliminating the last remaining cord connections required to replace portable electronic devices. This technology has significantly improved during the past decades and leads to a vast number of applications.

In this article, we have investigated the implementation of wireless charging on bus routes and developed a cost analysis of initial investment for the three types of wireless charging: Stationary Wireless Charging (SWC), Quasi-Dynamic Wireless Charging (QWC), and Dynamic Wireless Charging (DWC), using OLEV technology. They are followed by a cost analysis of existing bus service transit, applying OLEV technology to deploying a pilot study in Manhattan, NYC.

The integration of wireless charging with existing transportation networks creates new opportunities as well as challenges for the development of sustainable cities. This study has shown the analysis of the potential implementation of wireless power charging to an actual bus route, reducing emissions, and improving traffic operations and planning.

This research would provide new possibilities of using OLEV technology, network, and bus route data to determine the optimum study area for planning out the costs of deploying a new electric bus service network. However, the implementation of power charging in networks is less explored and requires further investigation. Additionally, practical challenges in performing similar analyses of several NYC bus routes based on the route's EV history, ridership, and location can be considered the main directions for future research.

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