A systematic review of dynamic wireless charging infrastructure location problem for electric vehicles

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Abstract

Wireless Power Transfer (WPT) technology has been seen as an efficient alternative for electric vehicles (EV) charging while maintaining seamless traffic flow. This paper presents a review of the evolution of WPT technology over the years and issues related to its infrastructure allocation in terms of real-world integration. The first part of the paper provides an overview of all the major progress and achievements made by different research organizations in the area of WPT technology for EV charging. These technologies are ranked based on two indices namely technological readiness level (TRL) and system readiness level (SRL). The optimal location of wireless charging facilities comes with more design and operational issues than conventional static charging facilities. However they are similar in terms of the infrastructure modelling approach to locate these charging facilities, as the overall goal is to maximize the network flow and minimize the overall system cost. The second part of the paper assesses different modelling techniques used to optimize the location of static and dynamic wireless charging (DWC) facilities. The economic feasibility of the technology is an important consideration for successful system integration as well as the overall performance of the system. As such, this paper also provides a synopsis of different socio-economic studies related to the DWC infrastructure allocation problem. Finally, future research directions in this field are discussed based on the knowledge gaps identified from the existing literature.

Keywords: wireless power transfer; dynamic wireless charging; traffic flow; technology readiness level; system readiness level; infrastructure allocation problem

1. Introduction

An electrified road is a transportation infrastructure that can deliver power to charge electric vehicles (EVs) efficiently irrespective of a vehicle's motion using a specific conductive or wireless charging system. A wirelessly charged EV is the one in which charging is done through WPT technology, without any physical contact with the vehicle. WPT technology has evolved since the late 1980's when a pilot test of inductive power transfer (IPT) charging system was first carried out by California Partners for Advanced Transit and Highways (PATH) (Covic et al, 2013; Chen et al, 2015). The first attempt to develop a commercial IPT system, operating at high frequency was carried out in mid 1990's at University of Auckland, New Zealand (US patent 5 293 308A) and was developed in Daifuku monorail systems for vehicle assembly plants and clean factory automation by John T. Boys and Andrew W. Green (Boys et al, 2000). In 1998, a first commercial IPT system was successfully tested for EV movement at Rotorua Thermal Park in New Zealand (Covic et al, 2000), and this was followed by commercial bus charging developments in association with Conductix-Wampfler in Europe and USA (Boys et al, 2015). Subsequently, various researchers investigated the different pickup topologies for battery charging using loosely coupled IPT for EV charging (Stielau et al, 1999; Boys et al, 2000; Stielau et al, 2000). In 2005, a 2kW prototype IPT system with a grid to battery efficiency of over 85% was developed for private vehicles at University of Auckland. The first commercialized dynamic IPT EV system known as On-Line Electric Vehicle (OLEV) was developed by Korean Advanced Institute of Science and Technology (KAIST) (Huh et al, 2011).

One of the important design factors for wireless EV charging system is the variation in IPT pad size and misalignment. Various studies have been dedicated to the optimal design of primary IPT pads and power transfer efficiencies (Budhia et al, 2010; Budhia et al, 2013;

Nagendra et al, 2014; Lin et al, 2015) to maximize the energy received by EVs. **Figure 1** shows a basic IPT charging system for an EV.

System planning, charging infrastructure facility, operations scheduling as well as the initial investment cost are important considerations, the importance of which varies based on use (category of use). WC has been divided into the following three categories (Covic G.A, 2016; Jang et al, 2016; Zaheer et al, 2017).

- Stationary: Charging while EV is stationary for a longer period
- Quasi-Dynamic/Semi-Dynamic: Charging while EV move at very low speed e.g. at taxi rand and close to traffic signals.
- Dynamic: Charging while EV is in full motion

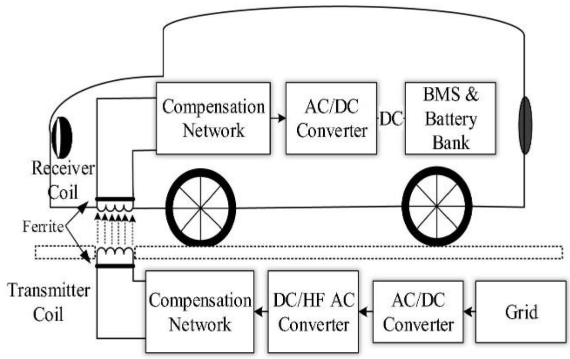

Figure 1. Basic block diagram of IPT charging system for EVs (Panchal et al, 2018)

Stationary wireless charging (SWC) provides power wirelessly to an EV when the vehicle stands still, while Quasi-dynamic or Semi-Dynamic charging mainly are designed to charge an EV when the vehicle is moving at very low speed e.g. at a taxi rank, signalized intersection approach or at a bus stop to drop-off and pick up passengers. In the case of DWC, an EV receives power while in-motion. In comparison to static charging (SC) or plug-in charging, WC makes the charging process more reliable, safe and environment friendly (Brecher & Arthur, 2014).

There have been a number of excellent reviews over the past five on WPT technology for EV charging, however these are often technology based and focussed on the electro-magnetic or power electronics aspects. Covic and Boys (2013) summarizes the challenges to create low-cost inductively coupled EVs operating under stringent conditions in terms of pad size and efficiency, whereas Fisher et al (2014) discusses the organizational involvement in WC system and suggests the necessity of safety standards for WPT implementation. An overview of existing WPT infrastructure and recommendations on support system for fault diagnostics, power control and maintenance of WPT system is given by Brecher and Arthur (2014). Gill and Tailber (2014) focus their study on recent advancements in WPT for EV charging in regards topower electronics. Chen et al (2015) organize their study based on various aspects of E-Road infrastructure, design structure, maintenance and performance issues. Bi et al (2016) study the technology and sustainability performance of WPT system and suggest the use of EVs as a mobile energy storage device due to bi-directional power transfer as proposed by Thrimawithana and Madawala (2009). Foote and Onar (2017) focus their study on Power electronics of high power WPT (HPWPT) system and recommend the cohesive usage of a frequency range for HPWPT and passenger battery electric vehicles (BEVs). Ahmad et al (2018) provide the characteristics and standards of different WC system, whereas Jang et al (2018) focus their study on operational and system aspects. Panchal et al (2018) provide an overview of different electro-magnetic components used in WPT system and a comparative assessment of wireless vehicle-to-grid and plug-in vehicle-to-grid architecture. Machura and Li (2019) also present technological components of WPT and recommend application of high temperature superconductors (HTS) for WPT.

As stated above, none of the above review papers have addressed the charging infrastructure modelling issues for WPT system integration. This paper therefore aims to fill in this research gap by presenting a comprehensive review of the existing research on WPT technology for EV charging in the following areas.

- An overview of the research and development in WPT technology for EV charging.

- Challenges in the modelling optimal location of charging infrastructure for SC and DWC of EVs.
- An economic analysis of dynamic wireless charging system uptake for EV charging.

The paper is organized into six sections. The following section presents the review technique adopted in this study. Section 3 provides a summary of the various technological developments for wireless charging of EVs. Sections 4 and 5 cover the infrastructure modelling aspects of different charging techniques and economic analyses of wireless charging, respectively. Section 6 delivers discusses and recommends future research areas for WC modelling.

2. Review Technique

A systematic review approach was followed to collect literature relevant to the study objectives. A combination of keywords and phrases were used to search the literature using databases including Google Scholar, Science Direct, Web of Science, Transportation Research Board and IEEE. Keyword searches were supplemented with reference search from the library and from google search, which include articles, short communications and editorials. The search was started with two compulsory keywords that were *("Dynamic wireless charging") AND ("Electric vehicle")*. Other supplementary keywords such as *("Infrastructure location") OR ("Route Optimization") OR ("Dynamic charging lane")* were included in the search to get relevant articles of interest for this review. The relevant research papers were shortlisted based on the following screening criteria.

Step 1: Search database was limited to Google Scholar, Science direct, TRID online library, Web of Science and IEEE explore Library.

Step 2: Preliminary screening was conducted based on title and abstract

Step 3: Scanning the whole document for relevance w.r.t. the review objectives

Step 4: Final screening was conducted by removing literature with insufficient data and measured technique

Google Scholar yields the largest number of articles, for which we used all the supplementary keywords along with compulsory keywords to curb down the search result. A total of 1,400 articles were recovered with duplication of the file in multiple search engines. **Figure 2** presents a general statistics of these search results.

A total of 103 articles were finally selected from the pool of papers for the literature review using the screening strategy shown in **Figure 3**. Among the selected articles, 65% are based on modelling approaches related to SC and DWC, 23% are based on the evolution of WPT technology for EV charging and the remaining 12% are focused on economic aspects of WPT infrastructure, respectively.

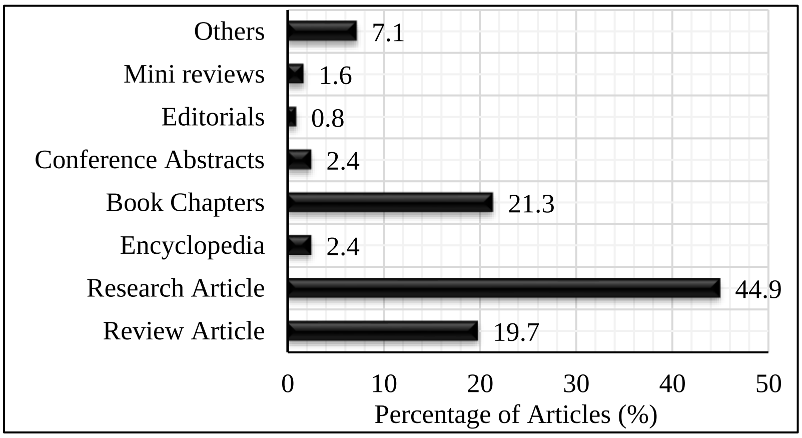

Figure 2. Summary of Search results

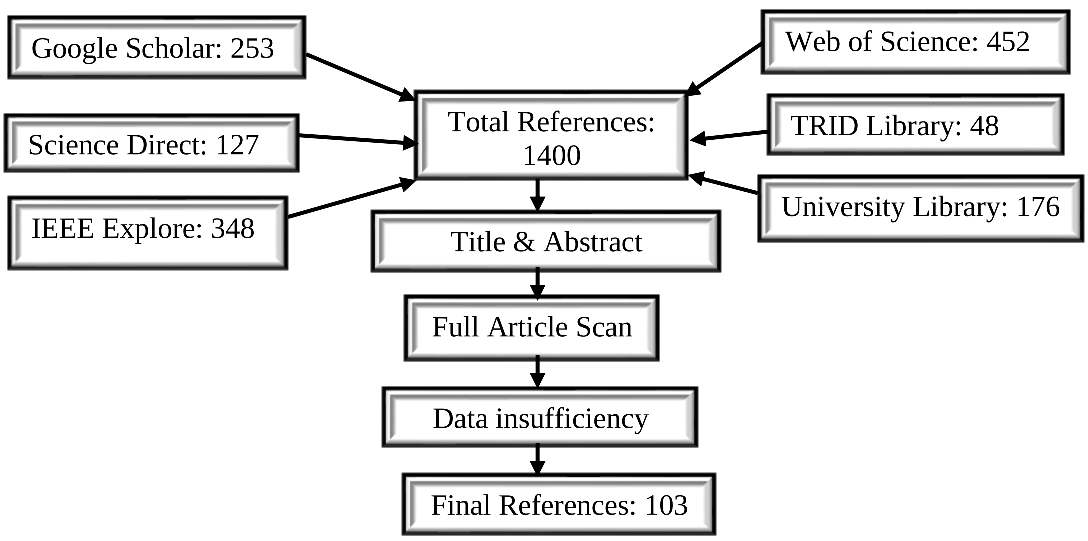

Figure 3. Selection strategy for literature review articles

3. Research and Development related to Wireless Charging infrastructure

Since the inception of WPT technology in the late 1980s, a number of major developments have been observed in the last two decades. We categorize all wireless EV charging solutions proposed in literature based on a system tool developed by National Aeronautics and Space Administration (NASA), known as Technology Readiness Level (TRL) and System Readiness Level (SRL), developed by Sauser et al. (2006). TRL level indicates the technological advancement in nine different levels, where level 1 represents the "basic principle developed for any technology" and level 9 represents the "tested and proven technology in an operational environment". On the other hand, SRL gives a maximum score of 5 for the highest level of integration of a developed technology with an existing technologies. **Table 1** presents an overview of the SRL ranking system.

Several organizations or research groups have been working on the development of wireless charging models for EVs, however, prototypes are still underdeveloped and not yet suitable for large scale deployment. **Table 2** presents a summary of research activities conducted by different organizations on the development of WPT technology for EV charging along with information on vehicle type, application type (static versus dynamic), major achievement highlights, setbacks/ future scope, TRL and SRL scores.

Table 1. System Readiness Level Definitions (Sauser et al., 2006).

SRL	Name	Definition
5	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	*Production & Development*	Achieve operational capability that satisfies mission needs.
3	*System Development & Demonstration*	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	*Concept Refinement*	Refine initial concept. Develop system/technology development strategy

Table 2. Research activities in wireless charging technology for EVs

Organization/ Research project	Labs/ Consortium	Vehicle Type	Application Type	Major Highlights	Setbacks/ Future Scope	TRL	SRL	Official Site
PATH	Lab	Car	SWC	The first working prototype of wireless charging EV with an air gap of 2 to 3inch	Technical infeasibility and low energy transfer efficiency	TRL4	SRL1	https://path.berkeley.edu/
WiTricity	Lab	Car	SWC	DRIVE 11 WC system is capable of delivering 11kw power at energy transfer efficiency up to 94%	Designed for stationary WC of EVs at parking lot	TRL7	SRL3	https://witricity.com/
KAIST-OLEV	Lab	Bus	DWC	The first commercial DWC system with an energy efficiency up to 80%	Operating in a fixed route with low velocity	TRL8	SRL4	https://olev.kaist.ac.kr/en/
Bombardier PRIMOVE	Consortium	Bus	SWC and DWC	Two meters wide, 25cm thick charging pads with capability to charge 200kwh battery capacity EV in few minutes (Brecher and Arthur, 2014)	Existing hardware not suitable for cars, modification needed for an urban scenario	TRL7	SRL3	https://www.bombardier.com/en/home.html
ORNL	Lab	Car	DWC	A WPT system, having 120kw power at an energy transfer efficiency of 97% in a 6inch air gap (Onar et al, 2016)	An advanced wireless charging system is under development and needs further technical improvements	TRL6	SRL3	https://www.ornl.gov/
UNPLUGGED	Consortium	Bus	SWC	Two power charging system at 3.7kw and 50kw, meant for passenger car and commercial vehicle.	Prototypes were not tested rigorously and not validated under an operational environment	TRL7	SRL2	http://unplugged-project.eu/
VICTORIA	Consortium	Bus	DWC	DWC system, capable of charging at 50kw with 2.1m vehicle displacement (Ahmad et al, 2018)	For DWC, operating speed of the bus was 10kmph which was very low	TRL6	SRL2	NA
Qualcomm-Halo	Lab	Car	SWC and DWC	SC capable of delivering up to 11kW at 94% efficiency. Dynamic in-motion EV charging proven to be at up to 20kW above 80% efficiency at highway speed (120km/h)	SWC designed for WC of private vehicles in parking lots. DWC Prototype was tested in a controlled environment	TRL6	SRL3	https://www.youtube.com/watch?v=wNQPikt13Lk
FABRIC	Consortium	Car and Bus	DWC	Max. transferred power 6.5kw, Efficiency 80-90%, Speed 50km/h	Allowable limit of misalignment is 30cm (Italy test site) (Guglielmi, P., 2018)	TRL7	SRL2	https://www.fabric-project.eu/

WaveIPT	Lab	Bus	SWC	Transfer from 50kW up to 250kW power for Bus charging systems	Operational systems available in USA	TRL 8	SRL4	https://waveipt.com/
Momentum Dynamics	Lab	Bus	SWC	SWC system consists of 4 charging pads, each pad provides 50ke power to the battery	The SWC system is tested, DWC system efficiency is yet to be established	TRL7	SRL3	https://www.momentumdynamics.com/
GREEN POWER	Lab	All	SWC and DWC	WC systems (1kW-1000kW) in various applications including EV cars, buses, tram and port equipment	Commercialization of OLEV systems from KAIST, product offerings based on WiTricity's DRIVE 11 design, which deliver 11 kW of power at efficiency and speeds similar or higher to plug-in EV chargers.	TRL8	SRL4	http://www.egreenpower.com/eng/company4.php
IPT Technology	Lab	All	SWC	Transfer efficiency of 92% for up to 300kW power with an air gap of 13cm	Fully tested and operational systems for over 17years in multiple countries	TRL 9	SRL5	https://ipt-technology.com/
ElectReon	Lab	All	SWC and DWC	SWC system charge a fully electric 40-tonne truck and trailer wirelessly at a test facility near Stockholm with 20kW power transmission at 90% efficiency.	Planning to test DWC system in Bus on public roads	TRL8	SRL4	https://www.electreon.com/about

IPT Technology has been categorized under SRL 5 due to its technology maturity and highest level of system integration whereas KAIST-OLEV and WaveIPT have been grouped under SRL 4 due to partial achievement of wireless technology, not covering all the spectrum. The model developed under PATH program is categorized as SRL1 due to concept refinement. The rest of the prototypes are either able to reduce technological risks for system integration, improve affordability or operational capability, hence they are levelled here as SRL 2 or SRL3.

A number of prototypes that are categorized as TRL 6 such as Qualcomm-Halo and WiTricty and others are tested in a controlled environment and have demonstrated their technological readiness. Some other prototypes by FABRIC, PRIMOVE have shown their capability further and are tested in an operational environment and hence categorized as TRL7. Only few prototypes, developed by KAIST-OLEV and Momentum-Dynamics and IPT Technology have been successfully tested and implemented in real-world environment and hence categorized as TRL8. IPT Technology (formerly Conductix-Wampfler) have been delivering solutions for over 17 years into the market successfully across Europe and USA, and are TRL9 systems.

4. Charging infrastructure location problem

In many parts of the world, EV charging infrastructure is considered as one of the most challenging tasks due to large financial investment and its optimal placement for efficient use by EVs. From an EV user's point of view, it is essential to have sufficient charging infrastructure in the vicinity of their daily route. Researchers have been investigating the optimal placement of charging infrastructure for EVs to minimize the infrastructure cost and optimize network traffic flow. The modelling approaches used to evaluate charging infrastructure can be broadly categorized into the following three types.

- **Macroscopic Modelling:** This is used when fast simulations are required and broadly based on aggregate properties like traffic speed, density and flow. The model is largely influenced by fluid dynamics properties.
- **Microscopic Modelling:** This approach heavily relies on individual driver behaviour, resulting from car-following, lane changing and gap acceptance model.
- **Mesoscopic Modelling:** The level of detail that can be achieved using this modelling approach fits in between the two models described earlier and is useful when the scale is too large to analyse microscopically.

Table 3 presents a summary of modelling approaches used for EV charging infrastructure. Microscopic modelling approach is by far the most popular modelling approach followed by macroscopic approach, while mesoscopic approach is rarely used.

Table 3. Summary of modelling approaches used for EV charging infrastructure and their findings

Modelling Approach	Percentage of Research	Observed Findings
Microscopic	69%	• Predominantly fixed route with known journey time • In case of overlapping of routes, the approach becomes obsolete • Absence of Driver Uncertainty, only EV Bus type
Mesoscopic	3%	• Consideration of Small Traffic Network by incorporating Individual Driver Behaviour • Energy modelling in combination with Traffic parameters
Macroscopic	28%	▪ Location of charging infrastructure affect the route choice, thus traffic flow. ▪ Unreasonable assumptions in design framework such as fixed SOC level, fixed Origin-Destination

4.1 SC Infrastructure Problem

For widespread uptake of EVs, a reasonable number of charging stations at convenient locations are essential. Several studies identify the issues pertaining to the charging infrastructure location problem (CILP) by considering various parameters in the modelling approach. The CILP is a two stage problem; first, looking at the optimization of the charging infrastructure cost and second, the optimization of the network flow. Although a great deal of research works have been devoted to this research area, each model is too specific in addressing certain issues and there is an urgent need for a holistic approach to resolve the problems for large scale adoption of EVs. Optimization models used for static CILP can be broadly categorized into six categories as shown in **Figure 4.**

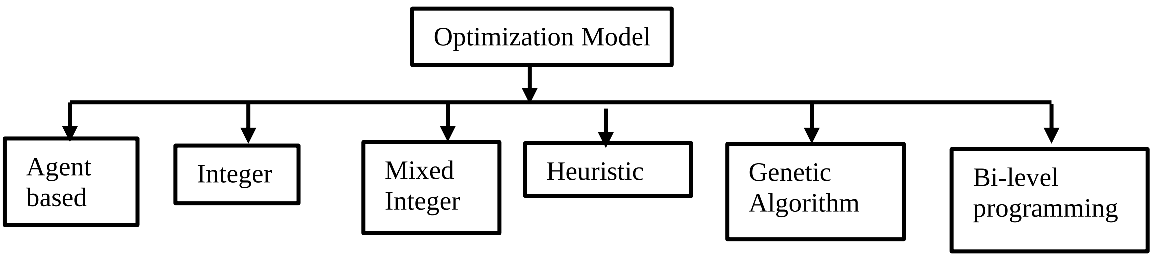

Figure 4. Optimization models used for static CILP

4.1.1 Agent-based modelling (ABM)

These models have been used by many researchers for simulating the actions between individuals and large entities to evaluate their effect on the system. For instance, Acha et al. (2012) proposed an agent-based model to emulate the EV driver's travel pattern for optimal charging. The authors were able to extract key information to forecast maximum utilization charging load, thus solving the spatial and temporal difficulty in mobile load transfer. Using the same modelling analogy, Viswanathan et al. (2016) studied the Singapore city road network based on nanoscopic city-scale simulation method. A novel agent-based simulation model was proposed and optimal location was identified based on the daily energy consumption rate, trip location and trip length. Their study emphasized that large scale EV adoption could be possible for the city without changing the existing driver's behaviour.

The main weakness of this approach is that it excludes social phenomena under which irrational driver behaviour, subjective decision-making process and complex psychology fall. ABM approach looks at constituent units rather than the aggregate level which makes it computationally expensive.

4.1.2 Bi-level programming

He et al. (2018) used a bi-level programming model to optimize the charging station location by considering driving range using route choice user-equilibrium. Their study assumed that energy consumption in EVs is distance-dependent rather than flow-dependent and EVs could reach the destination with only once charging. However, the study did not optimize the charging location based on traffic congestion. The maximum flows on the charging route was also unstable if the path flows were not unique. Xiong et al. (2018) on the other hand suggested a bi-level optimization as well as a heuristic approach to the CILP to minimize the scalability issue for Singapore city. The study was able to capture the strategic charging behaviour by EV drivers.

4.1.3 Genetic Algorithm (GA)

Bazrani et al. (2011) proposed a Mixed-Integer Non-Linear Problem (MINLP) using GA to minimize the total cost including station development and electrification cost for Tehran City. By considering the traffic density and charging station's capacity as constraints, a grid partition method for locating charging station using GA was developed by Ge et al. (2011). But the proposed model was limited to the local road network as the traffic density of the road network was not considered. Hess et al. (2012) proposed a mobility model that considered a change between vehicular mobility and navigation to the nearest charging station on demand. Dong et al. (2014) also applied GA to determine the optimal location for the charging stations. Their study highlighted that there is no change in the activity pattern when drivers switch from gasoline to EV. Using Beijing city data, He et al. (2015) optimized the public charging station locations based on driver's decision parameters such as adjustments, interaction in the transportation network and recharging decision within a budget. Their study found that high accessibility to charging stations encourages drivers to adopt EV for transportation. However, the study did not consider the traffic congestion at the charging stations while standing in the queue. Moreover, Li et al. (2016) proposed a multi-period multipath refuelling location model based on GA to fulfil origin-destination trips by optimizing the charging station location for public EV in South Carolina.

The major issue with this approach is that it does not guarantee an optimal solution for charging station location problem and the solution quality deteriorates with an increase in network size.

4.1.4 Heuristic approach

Xi et al. (2013) carried out a study on private-owned EVs in the central Ohio region. Their study was able to establish the relationship between service rates and the chargers deployed in the network. In the same year, another study was done by Sathaye and

Kelly (2013) to optimize the public charging infrastructure location based on demand uncertainty for the Texas region. Their study indicated that a continuous optimization approach for locating charging stations is computationally less burdensome and can be applied to large scale infrastructure deployment. Nie and Ghamami (2013) also studied the trade-off between battery capacity and charging stations in a long journey for Chicago city. It was found that for a reasonable level of service, fast-charging stations are required to minimize the social cost to achieve battery savings and promote EV adoption. Similarly, Schneider et al. (2014) solved the CILP for limited freight service based on customer time windows and a suitable charging scheme. Li and Huang (2014) developed a multi-path refuelling location model through a heuristic approximation to the mixed integer programming approach. He et al (2016) took a different approach by considering the effect of local constraints from the supply and demand side to optimize the EV charging station location. Their result aimed at providing a better understanding to policymakers on various charging facility location models. However, this approach does not necessarily produce optimal solutions for static CILP due to its complexed data handling capability.

4.1.5 Integer programming

Worley et al. (2012) formulated their CILP as a discrete integer programming optimization problem based on classic vehicle routing problem by gathering demand data with vehicle range and power consumption for light-duty electric trucks of Chicago city. He et al. (2013) also proposed an equilibrium analysis framework for investigating the interactions between route choice, electricity price in a coupled transportation and power network system. A mathematical programming model was superimposed on the framework to optimize the public charging station location. However, their study failed to consider the time-varying demand for travel and electricity and the proposed model was also static. Baouche et al. (2014) optimized the charging station locations for the Lyon metropolitan area focussing on minimizing the trip energy consumption and total location cost subjected to mobility energy demand.

4.1.6 Mixed-integer programming

Jia et al. (2012) proposed a mixed-integer quadratic programming approach to minimize the integrated cost of investment and operation subject to charging demand for optimizing the charging locations. Andrews et al (2013) also suggested the same approach to minimize the total distance travelled by EVs to access selected charging stations for Chicago and Seattle city. The model was limited to EVs, unable to complete the trip with only home charging. A study conducted by Chen et al. (2013) was able to determine the optimal charging location by minimizing the EV user's cost while accessing the station by penalizing the unmet demand. Wang and Lin (2013) adopted the same method to formulate the capacitated multiple recharging station location. The research focused on providing multiple types of charging stations such as slow charging, fast charging and battery swapping stations under cost-effective facility planning for Penghu Island, China. Lam et al. (2014) suggested multiple methods that are non-deterministic polynomial-time complete based on charging station coverage and convenience of drivers to solve the CILP. An optimal location strategy by maximizing the vehicle mile travelled within Beijing city, was later investigated by Shahraki et al. (2015). However economic considerations were not made in their study. Xylia et al. (2017) proposed a solution of CILP for EVs in Stockholm city and found that only 10-15 percent of bus stops require charging infrastructure based on minimum cost or energy consumption.

4.1.7 Other empirical models

Wang et al. (2010) introduced a Multi-objective planning model that accounts for the placement of charging stations by considering charging demand, power grid distribution and charging station characters for Chengdu city, China. Ip et al. (2010) used cluster analysis for Macau city to sole CILP in dense traffic concentrations. Road traffic and demand data were fed into the cluster followed by linear programming techniques to assign charging locations to the demand clusters. Frade et al. (2011) used the maximal covering model to optimize the charging station location for parked vehicles in Lisbon city. Likewise, Hanabusa and Horiguchi (2011) developed an analytical method for planning of charging locations by considering driver's route choice behaviour and spatial distribution of electricity demand. Particle swarm optimization model was used by Liu et al. (2012) to solve CILP by considering EV type, battery characteristics, charging time and charging environment as key influencing factors.

A modified primal-dual interior-point algorithm (MPDIPA) for optimal planning of EV charging stations through a two-step screening method was introduced by Liu et al. (2013). The model was able to reduce network loss and improve the voltage profile. Four years later. Chung and Kwon (2015) suggested a multi-period optimization model using traffic flow data of Korean Expressway. However, factors such as charging demand, waiting time and variable charging time were not considered in their study. Dong et al. (2016) proposed a spatial and temporal planning model based on Origin-Destination analysis on a freeway by considering the uncertainty in battery characteristic and transportation behaviour. Wu and Sioshansi (2017) used a stochastic flow capturing location model for the central Ohio City in a two-stage integer program to optimize the location of a public fast-charging station. The model focused on location optimization rather than charging load balance at the station.

4.2 DWC Infrastructure Location Problem

As the DWC system can provide continuous power to an EV while on the move, it is best-suited for public transport as well as a private vehicle taking longer transit route. Although such a WPT system has the potential to improve the sustainability performance of EVs, large scale deployment of this charging infrastructure still needs a critical evaluation from an economic, environmental and energy perspectives. Several considerations need to be made while analysing the feasibility of such a system such as-

- the placement and serviceability of power tracks for maximizing the traffic network flow
- the cost and quantity of WC infrastructure for a given transit network
- the effect of DWC lanes on existing traffic movement
- the reduction in EV's battery size for DWC as compared to SC

Figure 5 illustrates the overall modelling approach identified in various literature within the field of DWC infrastructure problem.

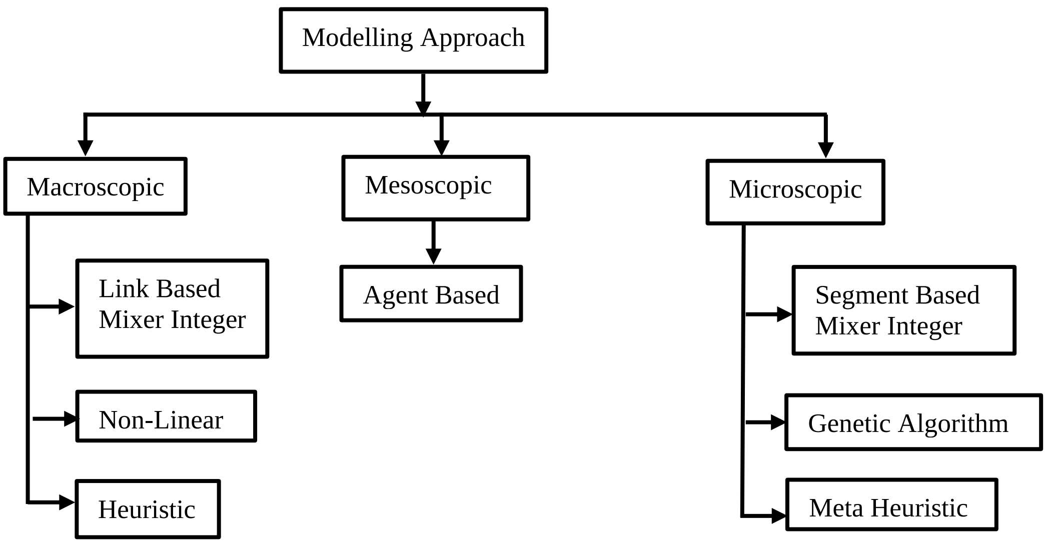

Figure 5. Modelling approaches used for DWC infrastructure location problem

Dynamic route choices are made by EV drivers based on several factors such as traffic congestion, availability of charging facility and charging cost. The amount of charge that an EV receives from the power track is dependent upon the time spent by that EV on the charging lane that in turn directly relates to vehicle speed and energy transfer efficiency. To solve the DWC infrastructure problem, EV user behaviour needs to be studied thoroughly. As has already been discussed in the static infrastructure problem, the optimization of the system cost and the network flow are the two major objectives which need to be fulfilled to solve these CILP.

4.2.1 Macroscopic Modelling

Reimann et al. (2015) investigated the optimal location of WPT infrastructure for EVs and developed a probabilistic model at a given set of locations by analysing the driver's route choice behaviour using stochastic user equilibrium principle. Their study is considered as a benchmark in deviating from conventional deterministic modelling of WC infrastructure for EVs. On the other hand, Mourhim et al. (2016) used particle-swam optimization technique to find minimum total investment cost for the OLEV system with multiple route environment. The proposed model demonstrated the robustness of the solution against the non-linear optimization technique. Another study by Chen et al. (2016) proposed a new user equilibrium model to optimize the WC location by an active set algorithm.

In the same year, Fuller (2016) developed an optimization model to minimize the capital cost of WC infrastructure subjected to battery capacity and vehicle charging level using the location model developed by Wang and Lin (2009) for various cities in California. Interestingly, his study contradicted an earlier finding that intermittent charging in between nodes is possible only by stopping the vehicle. An incapacitated flow-based location model was developed based on exclusive pathways.

In a subsequent study done by Liu and Wang (2017), a tri-level model was proposed for various recharging facilities such as SC, SWC and DWC facilities by minimizing the social cost using Siox-falls network. Two shortest pathfinding problems for WC and SC were developed in their study. Using the Manhattan city road network data, Ushijima-Mwesigwa et al. (2017) proposed an integer programming model to find the optimal location of WC by minimizing the driving range anxiety and maximizing the battery range per charge. The proposed models in their research were able to minimize the infeasible routes by improving various centrality-based heuristics.

4.2.2 Mesoscopic Modelling

This approach is one of the least explored areas in DWC infrastructure modelling. Deflorio et al. (2016) investigated the daily energy demand of EVs on motorways subject to the availability of a WC facility under different level of service and estimated the maximum investment cost. By considering the battery SOC level as a key parameter in simulation modelling, their study highlighted that use of DWC lane at higher speed would be beneficial both for drivers and energy operators as EV percentage plays a critical role in it. In a subsequent study, Deflorio and Castello (2017) analysed the traffic and energy performance of DWC system for freight EVs by using mesoscopic modelling approach while updating the traffic and energy data of simulated EVs at the nodes**. Figure 6** shows the modelling framework for vehicle trajectories while moving in the charging lane.

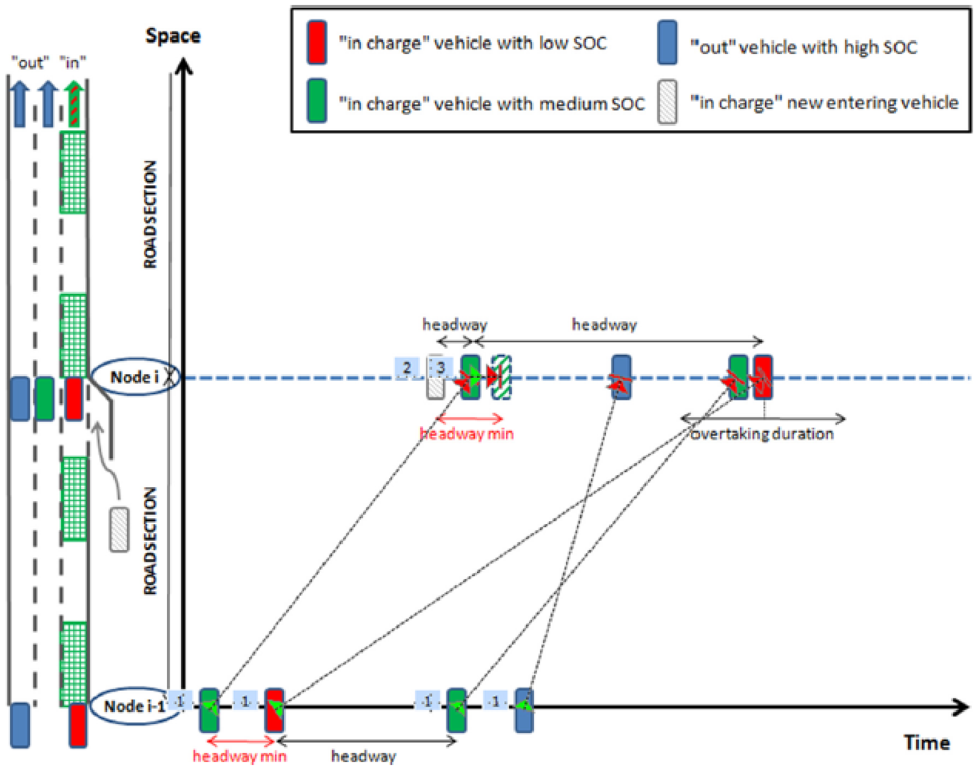

Figure 6. Modelling of vehicle trajectories in WC lane (Deflorio et al, 2017)

One limitation from their model is that it is applicable for EVs, operating at a relatively low speed by guaranteeing a minimum SOC level. There is a need for more research in this area to assess the significance of this approach for charging infrastructure modelling.

4.2.3 Microscopic Modelling

After their successful demonstration of OLEV in Gumi City in 2009, Ko et al. (2012) analysed the key parameters in an automated wireless charging facility as provided in OLEV. They were pioneers in introducing microscopic modelling approach for assessing the optimal allocation of DWC infrastructure. However, one major weakness in their study was that the transit route and the charging location were assumed to be fixed. In a subsequent study, Jeong et al. (2015) determined the most economical battery size and power track allocation by considering cost factors and power requirements. Their analysis also focused on OLEVs and used a deterministic approach. It was limited to a predefined route and as such this study could not capture the stochastic nature of a vehicle driving cycle as well as traffic patterns.

Jang et al. (2016) analysed the WC of OLEVs with and without intermittent charging based on battery capacity and found an optimal solution for battery size and infrastructure location. Chen et al. (2017) investigated the charging facility deployment along a traffic corridor to analyse the competitiveness of charging lanes. In contrast to the earlier work by Reimann et al. (2015), their work was based on an analysis of charging facilities and route choice equilibrium for EVs. Their study concluded that charging lane operation was economically viable based on the existing IPT technology for EV charging.

A study carried out by Liu and Song (2017) made a relative comparison of the proposed deterministic and stochastic model using EV bus data, running in Utah State University campus with unknown energy consumption rates and travel times. The findings concluded that a robust optimization model for EVs required larger batteries as compared to the deterministic approach. Later Hwang et al. (2018) proposed an algorithm for the optimal location of DWC System operating in multiple route environments. Their approach was not restricted to a single route, rather it was a combination of several single routes sharing common roads.

Helber et al. (2018) analysed the location planning problem of DWC system, embedded in airfield pavement on the taxiways and minimized the total capital cost of the necessary installed inductive transfer units and power supply units required for apron buses on airfield side. A graph-based optimization shortest path algorithm was proposed by Kosmanos et al. (2018) for intelligent routing of EVs through an inter-vehicle communication system. Their study suggested that the integration of modern techniques to IPT could improve range anxiety as well as help in battery size reduction..

Another study on the DWC modelling approach in Salt Lake City, Utah by Liu et al. (2018) considered a fixed route with all the buses having a base station where EVs start and terminate their service loops. Their proposed model demonstrated feasible solutions and was robust against uncertainty in energy consumption. Mouhrim et al (2019) proposed a Pareto efficient allocation of WC infrastructure in a multipath network in port of Le Havre, UK. Mohamed et al. (2019) studied the optimal allocation of WC lanes for shared automated EV (SAEV) in an automated mobility district (AMD) and found that well positioned WC chargers with high output power could provide sustainable and cost-effective solution for seamless EV movement. Most recently, He et al (2020) analysed the adverse effect of WC lanes on roadway capacity and suggested that charging EVs will affect the equilibrium path flows and link flow pattern.

Although microscopic modelling approach has largely been used in previous literature, most of the studies have not considered real time factors such as driving behaviour and traffic network uncertainty. Indeed, these factors could be important determinants in identifying the optimal location of DWC.

4.2.4 Discussion

As noted, the majority of the research related to DWC infrastructure problem tends to focus on using microscopic modelling approach mainly due to its convenience and accuracy in analysing a small network. However, this approach fails to estimate large scale deployment of DWC because of the high approximation involved in a much larger network. **Table 4** summarizes studies related to DWC infrastructure modelling and suitability based on TRL scale.

Table 4. Summary of research in the dynamic wireless charging modelling approach

Modelling Approach	References	Study location	Key considerations	TRL

Macroscopic	Reimann et al. (2015)	Hypothetical Network)	Use of maximal flow covering approach for optimal charging location	TRL5
	Mourhim et al. (2016)	Hypothetical Network	Total investment cost optimization for the OLEV system	TRL4
	Chen et al. (2016)	Hypothetical Network	User equilibrium model for optimization of a wireless charging station	TRL5
	Fuller (2016)	California, USA	Minimize charging infrastructure cost subjected to battery capacity & charging level	TRL6
	Ushijima-Mwesigwa et al. (2017)	Manhattan, USA	Reduction of driving range anxiety by maximizing battery range	TRL6
	Liu and Wang (2017)	Hypothetical Network	Tri-level model by minimizing the social cost	TRL5
Mesoscopic	Deflorio et al. (2016)	Hypothetical Network	Daily energy estimation on motorways in case of a wireless charging system	TRL4
	Deflorio and Castello (2017)	Turin, Italy	Traffic modelling by considering energy requirements & charging opportunity under dynamic charging facility for freight distribution service	TRL6
Microscopic	Ko et al. (2012)	Seoul, Korea	Assessment of key parameters in wireless charging facility as provided in OLEV	TRL7
	Jeong et al. (2015)	Seoul, Korea	Determination of the most economical battery size and power track location by considering power and cost factor	TRL7
	Jang et al. (2016)	KAIST, Korea	Identification of optimal battery size and charging infrastructure for OLEV buses	TRL7
	Liu and Song (2017)	Utah State University, USA	Probabilistic approach with multiple routes having unknown travel time & variable energy consumption	TRL6
	Chen et al. (2017)	Hypothetical Network	Cost equilibrium for optimal charging infrastructure in case of public & private provision	TRL4
	Helber et al. (2018)	Hypothetical Network	Location planning of wireless charging station for Airside buses by minimizing total capital cost	TRL4
	Kosmanos et al. (2018)	Hypothetical Network	Introduction of inter-vehicle communication strategy for reduction of battery size and improving range	TRL4
	Liu et al. (2018)	Hypothetical Network	Deterministic approach with uncertainty in energy consumption	TRL4
	Hwang et al. (2018)	Gumi City, Korea	Combination of multiple single routes sharing common road segments having identical batteries	TRL7
	Mourhim et al. (2019)	Port of Le Havre, UK	Allocation of WC infrastructure based on multi-objective particle swam optimization technique for trading-off cost between battery and power transmitter	TRL6
	Mohamed et al. (2019)	Hypothetical Network	WC infrastructure allocation for SAEV in an AMD based on multi-objective optimization	TRL4
	He et al. (2020)	Hypothetical Network	Effect of WC lanes on road capacity and driver's route choice behaviour	TRL5

As can be seen in the table, half of the studies on DWC infrastructure problem are based on a hypothetical scenario and the models are not validated with real-world data, hence they are categorized as TRL4. On the other hand, only a very few studies have done some level of validation but in a limited environment by providing slightly better results over TRL4. Those studies are categorized as TRL5, for example the studies conducted by Reimann et al. (2015) and Chen et al. (2016).

Some modelling approaches have validated the model by considering various traffic and roadway characteristics from a real-word network. These studies are classified as TRL6 as they use traffic simulation models to produce reasonable results in terms of model acceptance. A handful of literature have developed system prototypes and demonstrated the model in a real-world environment. Studies like Ko et al. (2012), Jeong et al. (2015), Jang et al. (2016) and Hwang et al. (2018) in South Korea using OLEV system are classified under TRL 7.

4.3 Review findings

Most of the studies on static recharging stations allocation revolve around two distinctive modelling approaches: flow capturing location model (FCLM) and flow refuelling location model (FRLM). A FRLM model refers to an extension of FCLM model (Hodgson, 1990) and is developed by Kuby and Lim (2015). Two major problems associated with those models are- the identification of future EV charging demand in the study locations (as there is a high uncertainty involved in terms of EV growth rate) and inaccurate estimation of EV charging facility based on the current scenario. All afore said models are capable of capturing spatial travel trips but they are deterministic and not flexible in terms of the dynamic nature of traffic growth.

As discussed earlier, SC causes unnecessary delay at charging stations and inconvenience to the EV drivers, DWC is definitely the way forward step for large scale adoption of EVs. However, most of the research studies on DWC are deterministic. Although the majority of the research deals with the optimal allocation of WC infrastructure, some of the limitations found in those studies include-

- Most of the studies are focused on a fixed route with known driving time and traffic pattern which is practically infeasible as the driver’s decisions are dynamic.
- Mesoscopic traffic modelling is still unexplored in the area of optimal allocation of DWC lanes in a transportation network. Hence the model performance is unpredictable.
- In all most all cases, bus transit networks are modelled given they have defined routes and schedules, however in a real-world application, private cars dominate the vehicle fleet for most developed countries and they also contribute high emission to the pollution statistics. Hence, there is a need to consider private vehicles in charging infrastructure modelling.
- Economical DWC sections need to be assessed carefully to evaluate the feasibility of using a continuous or several staggered charging lanes from an economic point of view.

5. Economic analysis of wireless charging infrastructure

The economic approach in the field of EV charging facility has been used as a useful tool to achieve two broad objectives:

(1) Study operational cost, expenditures and economic benefits of wireless charging

(2) Validate the transportation model and optimization technique.

The first objective deals with a cost-benefit analysis such as investment cost, the installation cost of charging facility and operational cost involved over time whereas the latter deals with a traffic model evaluation and the various optimization technique validation.

5.1 Economic viability of wireless charging infrastructure

As discussed earlier, economic analysis is concerned with various cost components involved in the process of developing WC infrastructure. The cost-benefit technique serves two purposes. Firstly, the estimation of infrastructure cost, initial investment and EV fleets and secondly, the operational cost and other economic implications on the system over a longer duration. **Table 5** summarizes the economic study that has been carried out regarding WC infrastructure.

Table 5. Summary of Economic Study on wireless charging

References	Modelling Strategy	Transit Type	Study Location
Schroeder and Traber (2011)	Estimation of the rate on investment (ROI) subjected to annual net profit and levelled investment cost for DC fast-charging stations	All EV type	Germany
Cao et al. (2012)	Charging cost minimization based on energy demand	Passenger EV	Hypothetical Network
Ko and Jang (2013)	Investment cost optimization based on battery size and power transmitter	OLEV Bus	Seoul Grand park
Ko et al. (2015)	Investment cost optimization based on battery size and power transmitter	OLEV Bus	Seoul, South Korea
Jeong et al. (2015)	Infrastructure cost optimization based on energy demand and battery power level	OLEV Bus	Gumi City, South Korea
Bi et al. (2015)	Life Cycle Assessment (LCA) of plug-in and stationary wireless charging based on cumulative energy demand	EV Bus	Michigan. USA
Jang et al. (2015)	Investment cost optimization	OLEV Bus	KAIST, South Korea
Fuller (2016)	Estimation of levelled cost of energy (LCOE) based on the life of charging infrastructure, total capital cost and supplied electricity	Passenger EV Car	California, USA
Shekhar et al. (2016)	Infrastructure Cost optimization based on the driving range	Articulated EV Bus	North-Holland
Jang et al. (2016)	Investment cost optimization using the cost of battery size and charging infrastructure for three types of the wireless charging system	OLEV Bus	KAIST and Gumi City, South Korea
Park and Jeong (2017)	Infrastructure cost minimization of the OLEV system and comparison with the Plug-in Hybrid EV system for EV penetration	OLEV Bus	Seoul, South Korea

Bi et al. (2018)	Multi-objective life cycle optimization model for characterization of trade-offs between the cost of wireless charging lane and benefits of battery downsizing	EV Bus	University of Michigan, USA
Manshadi et al. (2018)	Minimization of travel time cost and electricity consumption cost based on User-Equilibrium (UE) traffic assignment	EV Bus	IEEE-30 Bus system
Limb et al. (2019)	Energy consumption model based on WPT implementation and EV adoption	All EV Types	USA
Sheng et al. (2020)	Economic viability of DWC system using Public-private-partnership (PPP) model by incorporating net present value (NPV) framework	All EV Types	New Zealand

5.2 Summary

More recently, a large body of research has emphasised the economic impact of wireless charging. While the majority have focussed on dynamic WPT due to its potential benefits, a few studies have targeted on life cycle cost optimization of WC of EVs. In other words, during the last decade, the priority has been given to the infrastructure cost minimization for a successful DWC system integration in the road network, largely due to its high investment cost. Although several studies have identified the economic potential and sustainability of the DWC system, there still lacks a holistic picture to better understand the large scale economic assessment and sensitivity analysis of the DWC system.

6. Concluding remarks and future research directions

This paper has presented a review of the evolution of WPT technology over the years and discussed particular issues related to its infrastructure allocation in terms of real-world integration. Various WPT technologies are ranked based on two indices. Namely; their technological readiness level (TRL) and their system readiness level (SRL). The paper then assessed different modelling techniques used to optimize the location of static charging and dynamic wireless charging facilities and has provided a synopsis of different socio-economic studies related to the DWC infrastructure allocation problem.

A multitude of challenges and knowledge gaps have been identified in the existing literatures which require further research. These are listed below.

(1) *Inclusion of driving uncertainty*: It was found that most of the literature focused on a fixed route with known journey time, however in the real-world, drivers do take an instantaneous decision depending on various factors such as traffic flow, journey time and side friction. Therefore, instead of taking a deterministic approach, a probabilistic approach would be effective in modelling a more realistic DWC system installation procedure.

(2) *Hybrid modelling Approach:* In the case of charging infrastructure modelling, the microscopic modelling approach has been largely explored in comparison to another approach as discussed in section 4. However mesoscopic modelling has not been used for the same purpose. Hence it would be interesting to develop a hybrid model for a large scale deployment of a DWC installation.

(3) *Private vehicle consideration:* Many studies have relied on EV Bus type for model development and validation. However in most developed countries where cars take a significant share in the traffic mix and people prefer car over the bus for their long and short distance travel, there is a need to consider private vehicle types for testing WPT technology.

(4) *Assessment of Long-term benefits*: Although many researchers have done a considerable amount of research in the area of economic analysis of WPT technologies, those studies tend to reflect the immediate benefits of the system. For example battery life and health have been considered to evaluate the economic aspects of the WPT system, but in the long-run battery health gets reduced and there will be a need for replacement as well. Therefore, assessment of long-term efficiency of the system is critical.

(5) *Connected and automated vehicle (CAV) for wireless charging*: As the need of intelligent transportation system (ITS) for sustainable mobility is progressively increasing, studies on CAVs for wireless charging will help accelerated growth in the deployment of WPT technology as it improves driving performance, charging lane precision and energy transfer efficiency.

The improvements in WPT technology in coming years in the above mentioned research areas will determine how crucial this technology is for promoting electrified road infrastructure and improving sustainable transportation mobility.

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