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A systematic review of charging infrastructure location problem for electric vehicles

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ABSTRACT

With the evolving demand for sustainable mobility, adequate charging infrastructure for electric vehicles (EVs) has been growing steadily and wireless power transfer (WPT) technology has been seen as an efficient alternative for EV charging while maintaining seamless traffic flow. This paper reviews the modelling challenges in terms of both static (plug-in) charging (SC) and wireless charging (WC) facilities in a transportation network in terms of system integration, focusing on the evolution of the WPT technology. The first part of the paper provides an overview of all the major progress and achievements made by different research organisations in the area of WPT technology for EV charging. These technologies are ranked based on two indices, namely technological readiness level and system readiness level. The optimal location of WC 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 maximise the network flow and minimise the overall system cost. The second part of the paper assesses different modelling approaches used to analyse the network and locate the charging infrastructure for static and WC 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 WC infrastructure allocation problem. Finally, future research directions in this field are discussed based on the knowledge gaps identified from the existing literature.

Abbreviations: EV, electric vehicle; WPT, wireless power transfer; IPT, inductive power transfer; PATH, partners for advanced transit and highways; OLEV, on-line electric vehicle; KAIST, Korean Advanced Institute of Science and Technology; WC, wireless charging; SWC, stationary wireless charging; DWC, dynamic wireless charging; SC, static plug-in charging; TRL, technology readiness level; SRL, system readiness level; CILP, charging infrastructure location

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problem; GA, genetic algorithm; SOC, state of charge; FCLM, flow capturing location model; FRLM, flow refuelling location model; PPP, public–private partnership; GHG, greenhouse gas

1. Introduction

An electrified road can be defined as 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 (WC) system. A wirelessly charged EV is the one in which charging is done through wireless power transfer (WPT) technology, without any physical contact with the vehicle. WPT technology has evolved since the late 1980s when a pilot test of the IPT charging system was first carried out by California PATH (Covic & Boys, 2013b). The first attempt to develop a commercial IPT system, operating at high frequency was carried out in the mid-1990s at the 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 (Boys, Covic, & Green, 2000). In 1998, a first commercial IPT system was successfully tested for EV movement at Rotorua Thermal Park in New Zealand (Covic, Elliott, Stielau, Green, & Boys, 2000), followed by commercial bus charging developments in association with Conductix-Wampfler in Europe and USA (Boys & Covic, 2015). Subsequently, various researchers investigated the different pick-up topologies for battery charging using loosely coupled IPT for EV charging (Stielau, Boys, Covic, & Elliott, 2000; Boys et al., 2000; Stielau & Covic, 2000; Sheng, Sreenivasan, Sharp, Wilson, & Ranjitkar, 2000). In 2005, a 2 kW prototype IPT system with a grid to battery efficiency of over 85% was developed for private vehicles at the University of Auckland. Later, the first commercialised dynamic IPT charging system known as OLEV was developed by KAIST, South Korea (Huh, Lee, Lee, Cho, & Rim, 2011).

Various studies have been dedicated to the optimal design of primary IPT pads and power transfer efficiencies (Budhia, Covic, & Boys, 2010; Budhia, Boys, Covic, & Huang, 2013; Nagendra, Covic, & Boys, 2014; Lin, Covic, & Boys, 2015) to maximise the energy received by EVs. Figure 1 shows a basic IPT charging system for an EV. Based on the type of use, WC has been divided into the following three categories (Jang, Jeong, & Lee, 2016a; Zaheer, Naith, Beh, & Covic, 2017).

- Stationary: Charging while EV is stationary for a longer period.
- Quasi-dynamic/semi-dynamic: Charging while EV moves at very low speed, for example, at taxi rand and close to traffic signals.
- Dynamic: Charging while EV is in full motion.

SWC provides power wirelessly to an EV when the vehicle stands still, e.g. parking locations, while quasi-dynamic or semi-dynamic charging are designed to charge EVs when the vehicle is moving at very low speed, e.g. at a taxi rank, signalised 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.

There have been a number of excellent reviews over the past five years on WPT technology for EV charging; however, these are often technology-based and focussed on the

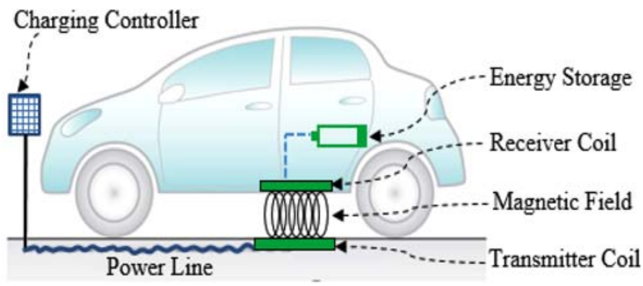

Figure 1. Wireless EV charging system.

electromagnetic or power electronics aspects. Covic and Boys (2013a) summarise the challenges to create low-cost inductively coupled EVs operating under stringent conditions in terms of pad size and efficiency, whereas Fisher, Farley, Gao, Bai, and TSE (2014) discuss the organisational involvement in WC system and suggest the necessity of safety standards for WPT implementation. An overview of existing WPT infrastructure and recommendations on the support system for fault diagnostics, power control and maintenance of the WPT system is given by Brecher and Arthur (2014). Gil and Taiber (2014) focus their study on recent advancements in WPT for EV charging in regard to power electronics. Chen, Taylor, and Kringos (2015) organise their study based on various aspects of E-Road infrastructure, design structure, maintenance and performance issues. Bi, Kan, Mi, Zhang, and Zhao (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 the power electronics of high power WPT system and recommend the cohesive usage of a frequency range for passenger battery EVs. Ahmad, Alam, and Chaban (2018) provide the characteristics and standards of different WC systems. Panchal, Stegen, and Lu (2018) provide an overview of different electromagnetic components used in WPT systems and a comparative assessment of wireless vehicle-to-grid and plug-in vehicle-to-grid architectures. Machura and Li (2019) also discuss various technological components within WPT and recommend the application of high-temperature superconductors for WPT. Although there are concerns over the safety and health hazards associated with WC systems due to roadway electrification and radiation level, those issues are mostly related to the components used in IPT system and the system embedment on the pavement. Jiang, Brazis, Tabaddor, and Bablo (2012) highlighted the safety considerations of high power wireless charger for EVs due to electromagnetic field exposure, electrical shock and fire hazards.

All of the above studies cover a detailed discussion on WPT technological components and their limitations along with potential solutions. However, Jang (2018) reviewed studies on the charging infrastructure allocation, cost–benefit analyses, billing, pricing and other infrastructure facilities for WC, the study was constrained to operational and system aspects of WC only. Some of the limitations observed in the review paper are as follows.

- Absence of holistic representation of charging infrastructure location modelling approach irrespective of the technology involved, i.e. plug-in or wireless.

- Absence of WPT technology and the charging allocation model categorisation based on their technology readiness and system integration potential.
- Need to study key similarities and differences between static (plug-in) charging (SC) and WC as far as charging facility location modelling is concerned.
- Systematic classification of empirical and simulation modelling approach, used in charging infrastructure allocation problem.

This study focuses on the above areas by making a systematic review of existing literature on charging infrastructure location problem. The objective of this study is as follows.

- To categorise the research on WPT technology based on technological readiness level (TRL) and system readiness level (SRL) scale.
- To study different real-world integration challenges posed by SC and WC infrastructure location models for EV charging and its technological readiness.
- To provide an economic analysis of WC and its future applications.

The reason behind studying both SC and WC infrastructure location problem is due to the following reasons.

- Firstly, the WC and SC infrastructure location problems are not vastly different since both problems are based on flow capturing or flow refuelling location model.
- Secondly, most of the models developed for WC facility allocation are inspired by SC infrastructure models due to the similarity in the methodological approach.

Overall, the paper is organised 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 WC, respectively. Section 6 delivers discusses and recommends future research areas for WC modelling.

2. Review technique

A structured review approach is followed to collect literature relevant to the study objectives. A combination of keywords and phrases are used to search the literature using various databases. The relevant research papers are shortlisted based on the following screening criteria. A total of 1400 articles are recovered with duplication of the file in multiple search engines. Figure 2 presents the general statistics of these search results. A total of 99 articles were finally selected from the pool of papers for the literature review using the screening strategy shown in Figure 3.

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 categorise all wireless EV charging

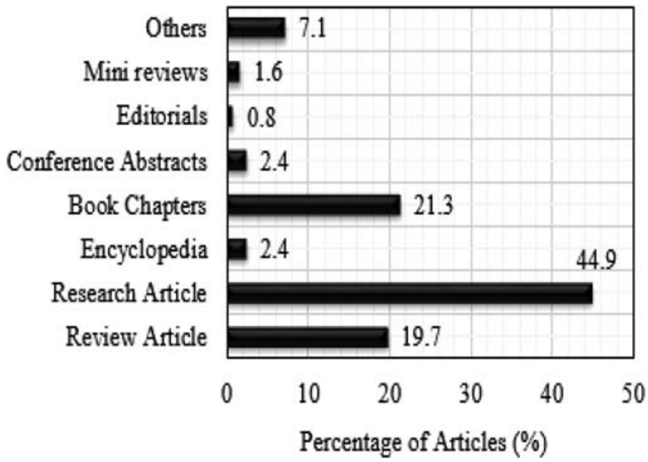

Figure 2. Summary of search results.

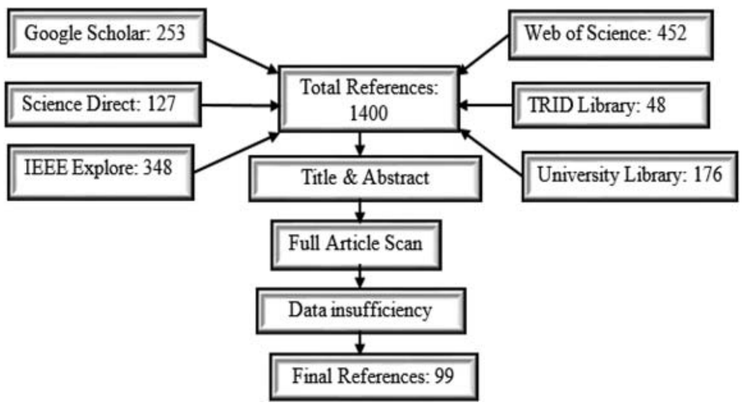

Figure 3. Screening strategy for literature review articles.

solutions based on a scale developed by the National Aeronautics and Space Administration, known as TRL and SRL (Sauser, Marquez, Verma, & Gove, 2006). TRL 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 has a maximum score of 5 for the highest level of integration of a developed technology with existing technology. Table 1 presents an overview of the SRL ranking system.

Several organisations and research groups have been working on the development of WC prototypes for EVs; however, they are underdeveloped and require rigorous testing. Table 2 presents a summary of research activities conducted by different organisations 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. As the focus of this paper is to get an overview of the present WPT technology market potential and their system readiness, individual

Table 1. SRL definitions (Sauser et al., 2006)

SRL	Name	Definition
5	*Operations & Support*	Execute a support program that meets operational 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

components such as electromagnetic characteristics and power electronics aspects have not been considered separately as they have already been reviewed by previous studies as mentioned before.

IPT technology has been categorised under SRL 5 due to its technology maturity and the highest level of system integration, whereas KAIST-OLEV and WaveIPT have been grouped under SRL4 due to partial achievement of wireless technology, not covering all the spectrum. The model developed under the PATH program is categorised 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 SRL2 or SRL3.

A number of prototypes that are categorised as TRL6 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 categorised as TRL7. Only a few prototypes, developed by KAIST-OLEV and Momentum Dynamics and WaveIPT have been successfully tested and implemented in a real-world environment and hence categorised as TRL8. IPT technology (formerly Conductix-Wampfler) has been delivering solutions for over 17 years into the market successfully across Europe and the USA, and are TRL9 systems.

4. Overview of CILP

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 minimise the infrastructure cost and optimise network traffic flow. The modelling approaches used to evaluate charging infrastructure can be broadly categorised 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.

Table 2. Research activities in wireless charging technology for EVs

Organisation/ 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 3 inch	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 11 kw power at energy transfer efficiency up to 94% (WiTricity, 2019)	Designed for stationary WC of EVs at a parking lot	TRL7	SRL3	https://witricity.com/
KAIST-OLEV	Lab	Bus	DWC	The first commercial DWC system with 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 metres wide, 25 cm thick charging pads with the capability to charge 200 kWh battery capacity EV in a few minutes (Brecher & 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 120 kW power at an energy transfer efficiency of 97% in a 6 inch air gap (Onar et al., 2016; Miller et al., 2015)	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 systems at 3.7 and 50 kW, meant for passenger cars and commercial vehicles	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 50 kW with 2.1m vehicle displacement (Ahmad et al., 2018)	For DWC, the operating speed of the bus was 10 kmph which was very low	TRL6	SRL2	NA
Qualcomm-Halo	Lab	Car	SWC and DWC	SWC capable of delivering up to 11 kW at 94% efficiency. DWC capable up to 20 kW above 80% efficiency at highway speed (120 km/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 6.5 kw, Efficiency 80–90%, Speed 50 km/h	Allowable limit of misalignment is 30 cm (Italy test site) (Guglielmi, 2018)	TRL7	SRL2	https://www.fabric-project.eu/

(*Continued*)

Table 2. Continued.

Organisation/ Research project	Labs/ Consortium	Vehicle type	Application type	Major highlights	Setbacks/future scope	TRL	SRL	Official site
WaveIPT	Lab	Bus	SWC	Transfer from 50 kW up to 250 kW 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 50 ke 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 (1–1000 kW) in various applications including EV cars, buses, tram and port equipment	Commercialisation of OLEV systems, product offerings based on WiTricity's DRIVE 11 design, which delivers 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 300 kW power with an air gap of 13 cm	Fully tested and operational systems for over 17 years in multiple countries	TRL 9	SRL5	https://ipt-technology.com/
ElectReon	Lab	All	SWC and DWC	SWC system charges a fully electric 40 tonne truck and trailer wirelessly at a test facility near Stockholm with 20 kW power transmission at 90% efficiency	Planning to test the DWC system in Bus on public roads	TRL8	SRL4	https://www.electreon.com/about

- **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 both SC and WC infrastructure. The microscopic modelling approach is by far the most popular modelling approach followed by the macroscopic approach, while the mesoscopic approach is rarely used. Although nanoscopic modelling approach which deals with the driver and vehicle interaction at a very detailed closed-loop system scale, there is no study in this area as far as CILP is concerned.

4.1 SC infrastructure problem

For widespread uptake of EVs, a reasonable number of charging stations at convenient locations are essential. The CILP is a two-stage problem; firstly, looking at the optimisation of the charging infrastructure cost and secondly, the optimisation of the network flow. Although a great deal of research work has been devoted to this area, each model is too specific in addressing certain issues and there is an urgent need for a holistic approach to resolving the problems for large-scale adoption of EVs. The overall findings from the existing research on the SC infrastructure location problem are shown in Table 4.

The TRL categorisation of various models found in the literature is done based on the model applicability and feasibility for large-scale implementation of SC infrastructure in a transportation network, combined with TRL guidelines. As most of the models are only validated using real-world data but not demonstrated in the transportation network, they are categorised at TRL5. Some models have been categorised as TRL6 due to the advanced nature of the model and its suitability and validation for a larger network. A smaller number are classed as TRL4 as their application is limited to a virtual network.

4.2 WC infrastructure location problem

A WC system is best suited for public transport and private vehicles taking a longer transit route as it can provide charging while the vehicle is on the move. Although the WPT

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

Modelling approach	Percentage of research (approx.)	Observed findings
Microscopic	32 papers (60%)	• Predominantly fixed route with a known journey time • In case of overlapping of routes, the approach becomes obsolete • Absence of Driver Uncertainty, only EV Bus type
Mesoscopic	2 papers (4%)	• Consideration of small traffic network by incorporating individual driver behaviour • Energy modelling in combination with traffic parameters
Macroscopic	19 papers (36%)	• Location of charging infrastructure affects the route choice, thus traffic flow • Unreasonable assumptions in design framework such as fixed SOC level, fixed origin–destination

Table 4. Summary of research in the SC simulation modelling approach

Modelling Approach	References	Case study	Key considerations and limitations	TRL
Microscopic	Acha, Dam, and Shah (2012)	Repast city (Virtual Model)	An agent-based model to emulate the EV driver's travel pattern for optimal charging, able to solve the spatial and temporal difficulty in mobile load transfer	TRL4
	Viswanathan et al. (2016)	Singapore	The optimal location for charging station based on daily energy consumption rate, trip location and trip length, large scale EV adoption possible without changing the existing driver behaviour	TRL6
	He, Yang, Tang, and Huang (2018)	Nguyen–Dupuis and Sioux-falls network	Bi-level model to optimise the charging station location using route choice user equilibrium, energy consumption in EVs is distance-dependent	TRL5
	Ge, Feng, and Liu (2011)	Virtual model	Grid partition method for locating charging station using traffic density and charging station capacity, limited to the local road network and traffic density was not considered	TRL4
	He, Yin, and Zhou (2015)	Sioux-falls network	SC station locations based on driver's decision parameters such as adjustments, interaction in the transportation network and a recharging decision within a budget, traffic congestion at the charging stations were not ignored	TRL5
	Xi, Sioshansi, and Marano (2013)	Ohio	Establish the relationship between service rates and the chargers deployed in the network	TRL5
	Sathaye and Kelly (2013)	Texas	Public charging infrastructure location based on demand uncertainty, continuous optimisation can be applied to large-scale infrastructure deployment	TRL6
	Nie and Ghamami (2013)	Chicago	At a reasonable level of service, fast-charging stations are required to minimise the social cost to achieve battery savings and promote EV adoption	TRL6
	Worley, Klabjan, and Sweda (2012)	Chicago	Discrete integer model based on the classic vehicle routing problem by gathering demand data with vehicle range and power consumption for light-duty electric trucks	TRL5
	He, Wu, Yin, and Guan (2013)	Sioux-falls and IEEE-118 Bus system	Equilibrium analysis framework for investigating the interactions between route choice, electricity price in a coupled transportation and power network system, failed to consider the time-varying demand for travel and electricity	TRL5
	Baouche, Billot, Trigui, and Faouzi (2014)	Lyon metropolitan area	Minimise the trip energy consumption and total location cost subjected to mobility energy demand	TRL5
	Wang and Lin (2013)	Penghu Island, Taiwan	Capacitated multiple recharging station location under cost-effective facility planning	TRL5
	Shahraki, Cai, Turkay, and Xu (2015)	Beijing	Optimal location strategy by maximising the vehicle mile travelled	TRL6
	Liu, Wen, and Ledwich (2013)	IEEE-123 Node	A modified primal-dual interior-point algorithm through a two-step screening method, able to reduce network loss and improve the voltage profile	TRL4
	Frade, Ribeiro, Goncalves, and Antunes (2011)	Lisbon	Maximal covering model for parked vehicles	TRL5
	Dong, Mu, Jia, Wu, and Yu (2016)	Hainan Island, China	Spatial and temporal planning model based on origin–destination analysis on a freeway by considering the uncertainty in battery characteristic and transportation behaviour	TRL6
	Liu, Zhang, Ji, and Li (2012)	Beijing	Particle swarm optimisation model to solve CILP by considering EV type, battery characteristics, charging time and charging environment	TRL5
	Xylia, Leduc, Patrizio, Kraxner, and Silveira (2017)	Stockholm, Sweden	10–15% of bus stops require charging infrastructure based on minimum cost or energy consumption	TRL6

	Chung and Kwon (2015)	South Korea	Charging demand, waiting time and variable charging time were not considered	TRL5
Macroscopic	Xiong, Gan, Miao, and Bazaan (2018)	Singapore	A heuristic approach to the CILP to minimise the scalability issue for Singapore city, able to capture the strategic charging behaviour by EV drivers	TRL6
	Barzani et al. (2014)	Tehran	Mixed-integer non-linear model using GA to minimise the total cost including station development and electrification cost	TRL5
	Hess et al. (2012)	Vienna, Italy	Mobility model that considers a change between vehicular mobility and navigation to the nearest charging station on demand	TRL5
	Dong, Liu, and Lin (2014)	Greater Seattle metropolitan	No change in the activity pattern when drivers switch from gasoline to EV	TRL5
	Li, Huang, and Mason (2016)	South Carolina	Multi-period multipath refuelling location model based on GA to fulfil origin–destination trips	TRL6
	Chen et al. (2016)	Beijing	Effect of local constraints from the supply and demand side to optimise the EV charging station location	TRL6
	Jia, Hu, Song, and Luo (2012)	Stockholm, Sweden	Mixed-integer quadratic model to minimise the integrated cost of investment and operation subject to charging demand	TRL5
	Andrews, Dogu, Hobby, Jin, and Tucci (2013)	Chicago and Seattle	Based on EVs who are unable to complete the trip with only home charging	TRL5
	Chen, Kocklman, and Khan (2013)	Seattle	Minimise the EV user's cost while accessing the station by penalising the unmet demand	TRL6
	Lam, Leung, and Chu (2014)	Hong Kong	Non-deterministic polynomial-time complete based on charging station coverage and convenience of drivers to solve the CILP	TRL6
	Wang, Huang, Zhang, and Xia (2010)	Chengdu	Multi-objective planning model by considering charging demand, power grid distribution and charging station characters	TRL5
	Ip, Fong, and Liu (2010)	Macau Peninsula	Cluster analysis to solve CILP in dense traffic concentrations	TRL5
	Wu and Sioshansi (2017)	Central Ohio	Stochastic flow capturing location model in a two-stage integer program focused on location optimisation rather than charging load balance at the station	TRL6

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 perspective. Several considerations need to be made when analysing the feasibility of such a system, such as:

- The placement and serviceability of the power tracks for maximising the traffic network flow.
- The cost and quantity of the WC infrastructure for a given transit network.
- The effect of WC lanes on existing traffic movement.
- The possible reduction in battery size for an EV using WC when compared with SC.

The categorisation of the modelling approach is based on the type of simulation model used in the literature for analysing the network under which different optimisation approaches are used to locate the WC sections, as shown in Figure 4.

The amount of charge that an EV receives from the power track is dependent upon several factors such as battery capacity, energy transfer efficiency, IPT power and the time spent by EV on the charging lane. To solve the WC infrastructure problem, EV user behaviour needs to be studied thoroughly. As has already been discussed in the SC infrastructure problem, the optimisation of system cost and network flow are the two major objectives which need to be fulfilled to solve these CILP. Some of the existing studies on WC infrastructure location modelling have been discussed in the following sections.

4.2.1 Macroscopic modelling

Riemann, Wang, and Busch (2017) 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, Alaoui, and Boukachour (2016) used particle-swarm optimisation technique to find the minimum total investment cost for the OLEV system with multiple route environments. The proposed model demonstrated the robustness of the solution against the non-linear optimisation technique. Another study by Chen, He, and Yin (2016) proposed a new user equilibrium model to optimise the WC location by an active set algorithm.

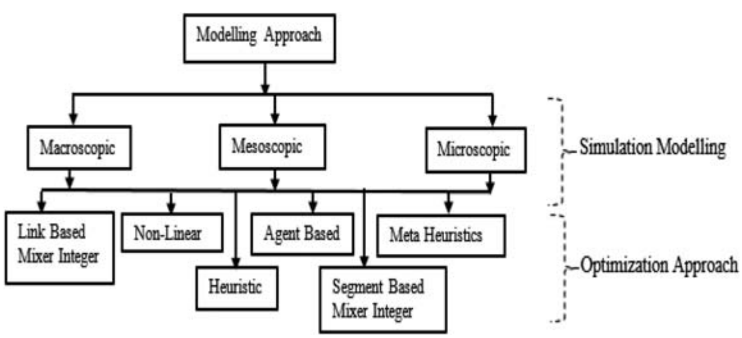

Figure 4. Modelling approaches used for the WC infrastructure location problem.

In the same year, Fuller (2016) developed an optimisation model to minimise 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 minimising the social cost using Sioux-falls network. Two shortest pathfinding problems for WC and SC were developed in their study. Using the Manhattan city road network data, Ushijima-Mwesigwa, Khan, Chowdhury, and Safro (2017) proposed an integer programming model to find the optimal location of WC by minimising the driving range anxiety and maximising the battery range per charge. The proposed models in their research were able to minimise the infeasible routes by improving various centrality-based heuristics.

4.2.2 Mesoscopic modelling

This approach is one of the least explored areas in WC infrastructure modelling. Deflorio, Pinna, Castello, and Cantello (2016) investigated the daily energy demand of EVs on motorways subject to the availability of a WC facility under different levels 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 the use of a WC lane at a higher speed would be beneficial both for drivers and energy operators as a percentage of EVs in the traffic mix plays a critical role in it. In a subsequent study, Deflorio and Castello (2017) analysed the traffic and energy performance of a WC system for freight EVs by using a mesoscopic modelling approach while updating the traffic and energy data of simulated EVs at the nodes.

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, Jang, and Jeong (2012) analysed the key parameters in an automated WC facility as provided by OLEV. They were pioneers in introducing microscopic modelling approach for assessing the optimal allocation of the WC 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, Jang, and Kum (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, Suh, and Kim (2016b) 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, Liu, and Yin (2017) investigated the required charging facility deployment along a traffic corridor to analyse the competitiveness of charging lanes. In contrast to the earlier work by Riemann et al. (2017), 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 optimisation model for EVs required larger batteries when compared with the deterministic approach. Later Hwang, Jang, Ko, and Lee (2018) proposed an algorithm for the optimal location of a WC 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, Broihan, Jang, Hecker, and Feuerle (2018) analysed the location planning problem of a WC system, embedded in airfield pavement on the taxiways and minimised the total capital cost of the necessary installed inductive transfer units and power supply units required for apron buses on the airfield side. A graph-based optimisation 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. Liu, Song, and He (2018) reported on a case study conducted in Salt Lake City, Utah, considering a fixed route with all the buses having a base station where EVs start and terminate their service loops. Their model demonstrated feasible solutions and was robust against uncertainty in energy consumption. Mourhim, Alaoui, and Boukachour (2019) proposed a Pareto efficient allocation of WC infrastructure in a multipath network in the port of Le Havre, UK. Mohamed, Meintz, and Zhu (2019) studied the optimal allocation of WC lanes for shared automated EV in an automated mobile district and found that well-positioned WC chargers with high output power could provide a sustainable and cost-effective solution for seamless EV movement. Most recently, He, Yang, Tang, and Huang (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 the WC infrastructure.

4.2.4 Discussion

As noted, the majority of the research related to the WC 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 WC because of the high approximations involved in a much larger network. Table 5 summarises studies related to WC infrastructure modelling and suitability based on the TRL scale.

As can be seen in the table, half of the studies on the WC infrastructure problem are based on a hypothetical scenario and the models are not validated with real-world data, hence they are categorised as TRL4. On the other hand, only a very few studies

Table 5. Summary of WC simulation modelling approaches

Modelling approach	References	Case study	Key considerations	TRL
Macroscopic	Riemann et al. (2017)	Hypothetical	Use of maximal flow covering approach for optimal charging location	TRL5
	Mourhim et al. (2016)	Hypothetical	Total investment cost optimisation for the OLEV system	TRL4
	Chen et al. (2016)	Hypothetical	User equilibrium model for optimisation of a wireless charging station	TRL5
	Fuller (2016)	California, USA	Minimise charging infrastructure cost subjected to battery capacity and charging level	TRL6
	Ushijima-Mwesigwa et al. (2017)	Manhattan, USA	Reduction of driving range anxiety by maximising battery range	TRL6
	Liu and Wang (2017)	Hypothetical	Tri-level model by minimising the social cost	TRL5
Mesoscopic	Deflorio et al. (2016)	Hypothetical	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 and charging opportunity under DWC facility for freight distribution service	TRL6
Microscopic	Ko et al. (2012)	Seoul, Korea	Assessment of key parameters in the WC facility as provided in OLEV	TRL7
	Jang, Jeong, and Ko (2015)	Seoul, Korea	Determination of the most economical battery size and power track location by considering power and cost factor	TRL7
	Jang, Suh, and Kim (2016b)	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 and variable energy consumption	TRL6
	Chen et al. (2017)	Hypothetical	Cost equilibrium for optimal charging infrastructure in the case of public and private provision	TRL4
	Helber et al. (2018)	Hypothetical	Location planning of wireless charging station for Airside buses by minimising total capital cost	TRL4
	Kosmanos et al. (2018)	Hypothetical	Introduction of inter-vehicle communication strategy for reduction of battery size and improving range	TRL4
	Liu et al. (2018)	Hypothetical	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 swarm optimisation technique for trade-off cost between battery and power transmitter	TRL6
	Mohamed et al. (2019)	Hypothetical	WC infrastructure allocation for SAEV in an AMD based on multi-objective optimisation	TRL4
	He et al. (2020)	Hypothetical	Effect of WC lanes on road capacity and driver's route choice behaviour	TRL5

have done some level of validation but in a limited environment by providing slightly better results over TRL4. Those studies are categorised as TRL5, for example, the studies conducted by Riemann et al. (2017) 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, Suh and Kim (2016b) and Hwang et al. (2018) in South Korea using the OLEV system are classified under TRL7.

4.3 Review findings

Most of the studies on SC stations allocation revolve around two distinctive modelling approaches: FCLM and FRLM. The FRLM model refers to an extension of FCLM model (Hodgson, 1990) as developed by Kuby and Lim (2015). Research studies on WC are mostly deterministic in nature and few limitations found out from the existing literature are as follows:

- 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 WC lanes in a transportation network. Hence, the model performance is unpredictable.
- In almost 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 contribute high emissions to the pollution statistics. Hence, there is a need to consider private vehicles in the charging infrastructure modelling.
- Economical WC systems need to be assessed carefully to evaluate the economic feasibility of using continuous or several staggered charging lanes over each targeted road section.

Although there are a few similarities in infrastructure modelling approach between SC and WC, key differences as observed from the literature are –

- Studies on SC infrastructure modelling have been more stochastic based on capturing spatial trips and driving uncertainty, whereas WC studies have been more deterministic in nature.
- FCLM and FRLM models which are predominantly used in SC are not used frequently in WC due to its inability in predicting the dynamic nature of traffic growth.
- Inaccurate estimations of EV charging facilities based on current scenarios have been observed using SC models, whereas WC models produce fairly good results.
- SC model validations are more real-world oriented, whereas WC model validations are done using IEEE Bus system, Ngyuen–Dupius network and Sioux-falls network which are hypothetical in nature.
- Researches on SC infrastructure modelling are either micro-allocation and macro-allocation-based, whereas hybrid models such as mesoscopic models in addition to the above two have also been explored in WC modelling.

Unlike the SWC location problem which is similar to SC problem in terms of infrastructure modelling, DWC facility problem has its own challenges such as network safety and efficiency. Firstly, as the DWC lane placements are adjacent to non-charging lanes and EV driver's intent to switch to charging lanes can be governed by several factors such as availability of charging lanes, charging cost, reduction in travel time remaining distance to destination etc., modelling becomes tougher as the frequent lane change affects the network safety invariably. Secondly, it affects the efficiency of the transportation network, e.g. in arterial roads, where speed is comparatively lower than the motorways, increase in EV traffic in combination with lane manoeuvring to charging lane can create unnecessary queue delay for non-EVs. As the DWC infrastructure is meant for fast and moderately moving EVs without sacrificing their overall travel time, it makes it more difficult to strategically locate the DWC facility so that network efficiency can be maximised. Hence, it is important to consider those factors into modelling while optimising the DWC location from the driver's perspective.

5. Economic evaluation 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:

- Study of operational cost, expenditures and economic benefits of wireless charging.
- Validation of the transportation model and optimisation technique.

The first objective deals with a cost–benefit analysis such as investment cost, operational cost and benefits from battery size reduction, the IPT charger and safe operation, whereas the latter deals with a traffic model evaluation and the various optimisation technique validation.

5.1 Economic viability of WC infrastructure

As discussed earlier, economic feasibility is concerned with the break-even analysis of cost and benefit. Several studies have investigated the economic implications of WC on system benefits through empirical models and suggested optimal strategies for WC system longevity. Table 6 summarises the economic study that has been carried out regarding the WC infrastructure.

5.2 Summary

More recently, a large body of research has emphasised the economic impact of wireless charging. While the majority have focused on dynamic WPT due to its potential benefits, a few studies have targeted on life cycle cost optimisation of WC of EVs. In other words, during the last decade, the priority has been given to the infrastructure cost minimisation for a successful WC system integration in the road network, largely due to its high investment cost. However, monetary benefits in terms of value-of-time or timesaving and reduction in delay have yet to be covered in such economic analyses. Although several studies have identified the economic potential and sustainability of the WC system, there still lacks a holistic picture to better understand the large-scale economic assessment and sensitivity analysis of the 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

Table 6. Summary of economic study on wireless charging

References	Modelling strategy	Study output	Transit type	Case study
Cao et al. (2012)	Charging cost minimisation based on energy demand	Optimised charging pattern has a significant benefit in reducing cost and flattening the load curve	Passenger EV	Hypothetical
Ko and Jang (2013)	Investment cost optimisation based on battery size and power transmitter	Reduction in infrastructure cost	OLEV	Seoul Grand Park
Ko, Jang, and Lee (2015)	Investment cost optimisation based on battery size and power transmitter	Reliability analysis of key design parameters for commercially viable OLEV system	OLEV	Seoul, South Korea
Jeong et al. (2015)	Infrastructure cost optimisation based on energy demand and battery power level	Cost-saving from reduced battery size and benefits from the extension of battery life	OLEV	Gumi City, South Korea
Bi, Song, Kleine, Mi, and Keoleian (2015)	Life cycle assessment of SC and SWC based on cumulative energy demand	Electric grid mix difference between day and night can reduce more GHG emissions for SWC	EV bus	Michigan, USA
Jang et al. (2015)	Investment cost optimisation	Benefits from cost reduction and an increase in system performance through stable energy supply	OLEV	KAIST, South Korea
Fuller (2016)	Estimation of levelled cost of energy based on the life of charging infrastructure, total capital cost and supplied electricity	Tiered price scheme for DWC infrastructure to encourage wide usage by EV drivers	Passenger EV car	California, USA
Shekhar, Prasanth, Bauer, and Bolech (2016)	Infrastructure cost optimisation based on the driving range	Increase in IPT power can reduce infrastructure cost	Articulated EV bus	North-Holland
Jang et al. (2016b)	Investment cost optimisation for three types of the WC system	DWC system is not economical for short-range operations	OLEV	KAIST and Gumi City, South Korea
Park and Jeong (2017)	Infrastructure cost minimisation of the OLEV system and comparison with the plug-in hybrid EV system for EV penetration	OLEVs are not cost-effective if battery price goes down, but the infrastructure can be used for EVs by adding pick-up devices	OLEV	Seoul, South Korea
Bi, Keoleian, and Ersal (2018)	Multi-objective life cycle optimisation model for characterisation of trade-offs between the cost of WC lane and benefits of battery downsizing	Benefits from minimal GHG emissions and improved energy consumption rate	EV bus	University of Michigan, USA
Manshadi, Khodayar, Abdelghany, and Uster (2018)	Minimisation of travel time cost and electricity consumption cost based on user equilibrium traffic assignment	Impact of battery size on the total travel cost of EVs with DWC	EV bus	IEEE-30 Bus system
Limb et al. (2019)	Energy consumption model based on WPT implementation and EV adoption	Sizeable economic benefits in savings under conservative electricity and fuelling cost projection using DWC	All EV types	USA
Sheng et al. (2000)	The economic viability of the DWC system using the PPP model by incorporating net present value framework	Benefits from PPP model for DWC system while private investors receive 12.5% return under 15 year concession period	All EV types	New Zealand

integration. Only a few studies have focused on the limitations of different solutions for charging infrastructure location issues in operational environments such as Jang (2018). The present study has taken a holistic approach to categorise various WPT technologies based on two indices. Namely, their TRL and SRL. The paper then assessed different 4modelling techniques used to optimise the location of WC facilities and has provided a synopsis of different socio-economic studies related to the infrastructure allocation problem.

Instead, a multitude of challenges and knowledge gaps have been identified in the existing literature which requires further research. These are listed below.

(1) *Inclusion of stochastic modelling*: 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 WC system installation procedure.
(2) *Hybrid modelling Approach:* In the case of charging infrastructure modelling, the microscopic modelling approach has been largely explored, 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 large-scale deployment of a WC installation.
(3) *Private vehicle consideration:* Many studies have relied on EV bus types for model development and validation. However, in most developed countries where cars take a significant share of the traffic mix and people prefer cars over the buses 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, the assessment of the long-term efficiency of the system is critical.
(5) *Integration of smart solutions for WC*: Studies on connected automated vehicles, V2G, V2V 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. As studies have shown, EVs can be used as an energy storage device for WC due to bi-directional power transfer between EV and grid.

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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