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Article

Wireless Charging of Electric Taxis: Understanding the Facilitators and Barriers to Its Introduction

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Abstract: The shift to electric vehicles has brought about the potential to reduce the environmental damage caused by road transport. However, several challenges prevent wider adoption of electric vehicles, such as: a lack of charging facilities, long charging times, limited range, and the inconvenience of cable charging. These barriers are more pronounced for taxis, which generally cover longer distances than regular cars and have fewer opportunities for recharging. This research aims to evaluate wireless charging for range extended electric taxis, as a strategy to minimise these challenges and facilitate the electrification of fleets. A mixed methods approach, combining quantitative vehicle tracking with qualitative interviews and focus groups with drivers and local authority representatives, provided an understanding of ‘facilitators’ and ‘barriers’ to the introduction of wireless chargers in London and Nottingham, UK. Results indicated that current wired charging infrastructure does not facilitate recharging opportunities during taxi working hours, causing longer shifts or lower earnings. Drivers reported running on a range extender petrol engine once the battery is depleted, limiting the environmental benefits of electric taxis. We conclude that wireless chargers could facilitate the increased driving range of existing electric taxis if installed where drivers stop more often. The results support the implementation of opportunistic, short but frequent charging boosts (known as choko-choko) as part of policies to alleviate the barriers to the introduction of wireless charging of electric taxis, and foster more sustainable means of road transportation.

Keywords: electric vehicles; wireless chargers; taxi; user experience; human-factors

1. Introduction

Transport is currently responsible for 40% of the energy use in the UK, and road transport contributes to the larger share of this figure [1]. Electric vehicles (EVs) are being promoted as one important strategy to reduce the environmental damage caused by CO₂ emissions [2–6]. An EV is, on average, five times more efficient than an equivalent car powered by an internal combustion engine [3]. The exact environmental benefits from EVs will depend on the source of electricity providing power to EVs and the level of electrification of these vehicles [7]. The consequent impact of EVs will therefore depend on clean sources and high electrification, but also on public acceptance and adoption of these technologies.

Cities around the world are introducing electric taxis (ETs) as clean and more sustainable transport services [8–10]. One particular transport service that has the potential for significant improvement in this regard are taxis. Even though taxis generally account for less than 1% of vehicles, they may be responsible for more than 9% of the pollutants in the air within cities [11]. Taxis are important actors

in the process of reducing carbon emissions and pollution as fleets have been growing steadily in diverse cities [12,13]. Taxis cover longer distances than regular vehicles and generally work in densely populated areas where pollution levels are more critical [8,11,14,15]. Replacing conventional internal combustion engine taxis by ETs is likely to reduce the carbon emissions in city centres [16]. Therefore, tackling the environmental impact caused by taxis addresses a large part of the urban air pollution and CO₂ emissions.

The ideal design of chargers for ETs and the location of charging stations may be different from regular cars given the peculiar scenarios of use, work routines, driver behaviours, and preferences [17,18]. This work proposes wireless charging [19] as a method to provide additional charge so ETs can have enough power for their work shifts.

1.1. Charging Infrastructure

While EV technology is developing steadily, the lack of charging infrastructure, long charging times, and limited battery capacity are opportunities for improvement [20–23]. While capacity, charging speeds and prices of batteries have improved steadily in recent years [24,25], larger batteries are still heavier and constitute a significant proportion of an electric vehicle's cost [14,20]. Furthermore, charging speeds and capacity are often limited to prevent battery damage [26,27].

A recent report indicates a need for more reliable recharging infrastructure to help foster the adoption of electrified transport systems [28]. New regulations against internal combustion engines mean that EU countries will have to prioritise electric charging points; therefore, much more charging infrastructure is required to keep pace with the increasing demand for EVs [29]. Charging infrastructure is perceived as the most important aspect influencing the adoption of EVs; therefore, more effort is needed to provide easy access to charging facilities [30,31].

Although numerous cities create public policies motivating the adoption of EVs [32], there are restrictions on where chargers can be installed; for example, to preserve historic areas, avoid street clutter, or prevent accidents with trailing cables [33]. These policies and regulations combined with house characteristics mean that some vehicles cannot be recharged overnight. Approximately 44% of taxi and private hire drivers in London declared themselves to be unable to install a charger at home [34] and will have to find alternative methods to recharge their batteries.

Previous research indicates a lack of parking space for EVs where they could be charged [35]. Analysis of charging data indicates that often vehicles are left connected to the charger for longer than needed, and “a significant proportion of the charging sessions last longer than one day” [36]. Consequently, conflicts may emerge when a vehicle needs charging, but the charging spaces are taken up by vehicles already at full charge, but left plugged in. Users want chargers conveniently placed on their routes, and readily available so they do not have to wait [37].

It is possible that these conflicts and sub-optimal use of chargers results from the idea that charging infrastructure needs to support charge patterns of a single, continuous full-charge. Studies that have considered the optimal locations for charging infrastructure all use mathematical models to predict based on the assumption that a vehicle will require a charge as close to full as possible [38–40]. Hence, the results would suggest that locations where vehicles frequently stop for longer durations are ideal candidates for the placement of chargers [41–45].

While this may be suitable for private passenger vehicles, this may be an inappropriate model for taxi drivers, as evidenced in the next section.

1.2. Electric Taxis

Journey tracking data from conventional taxis show that the majority of current taxis would be unable to run on battery because of a shortage of convenient charging stations and because taxis are often used for more than one daily shift by different drivers [46]. Indeed, studies on earlier deployments of ETs indicate that they are generally charged between three and five times per day [47]. Even taxi drivers working with long-range electric cars such as the Tesla Model S report that they spend around

1.5 h per working shift charging their vehicles [8]. This would suggest that the current models of facilitating charging for private vehicles, do not apply to ETs.

Taxi drivers require charging stations sited at different locations in comparison with regular EVs. It is suggested that taxis should be charged within city centres [44], but there are restrictions on land use that prevent the installation of chargers in specific locations [33]. The ideal type of charging facility may be influenced by the specific operational modes adopted by drivers. One driver may use more than one operational mode during a shift, for example taking dispatch calls, picking up street-hail passengers, waiting at ranks, or responding to requests on applications, depending on the demand or local regulations [17,18].

Not Enough Charge

In large metropolitan areas, taxi drivers can cover from 137 to 168 miles daily on average (220 to 270 km) [9,46], making it a challenge for current vehicle battery capacity. It is suggested that, if chargers are readily available, idle time can be used by drivers to recharge their batteries without losing revenue [48]. However, for most cases, the regular waiting times and breaks are not enough to provide the charge needed for a shift, forcing taxi drivers to proceed charging and dismiss customer trips [38]. If batteries are running low and a driver has to stop for an emergency charging, several subsequent occupied trips will probably be missed [46]. In large cities, detour charging will be inevitable, meaning that taxi drivers will have to look for chargers far from their work places, particularly for those equipped with small-range batteries [49].

One study simulated the performance of different capacities and indicated that ETs require batteries of 60–90 kWh to meet power requirements, achieve optimal profits, and generate limited carbon dioxide emissions [14,20]. However, when considering the most popular electric taxi sold in the UK, the LEVC TX, this is equipped with a 31 kWh battery—which evidently would not provide the capacity required to meet the estimated power requirements [50].

The three approaches to solving this challenge would be to either increase the capacity of the battery, swap entire battery packs once a vehicle is depleted [51], or enable the opportunity for taxis to be recharged more easily during a shift. Larger batteries, as discussed previously, would add additional cost and weight to the vehicle, while battery swapping would require unproven infrastructure that is likely to be expensive.

This would suggest that providing drivers with more opportunities to charge their vehicle may provide the solution. It has been suggested that drivers may be reluctant to stop and plug their vehicle in to charge, if the stop is expected to be less than 30 min [46]. Consequently, ET drivers specifically schedule longer stops when their vehicles need charge [21,46]. It is also anticipated that ET drivers will opt to charge their vehicles in less profitable periods of the day and avoid losing potential fares if they still can drive [52].

Ultimately, taxi drivers have a few opportunities for long charges, but a large number of short breaks; for example, during the dwell times between passengers, which, in New York, USA, are about 30 per day on average [46,53]. These numerous short breaks offer the opportunity for small boosts of charge. Inspired by the Japanese expression “choko-choko”—translated as little by little, with short steps but constantly on the move [54]—there is the possibility of making use of these small breaks for recharging vehicles several times throughout a day. There is already the habit of recharging EVs in small doses a few times a day [9,47], contrary to combustion fuel vehicles, which are refilled completely when the tank is getting empty [55]. The question that focussed around how shorter, more easily engaged charging can be facilitated.

The evidence would suggest that there is an opportunity to explore solutions that can provide more convenient and easier to engage charging methods, to address the key concerns regarding the adoption of ETs. One such technology that may address this is wireless charging.

1.3. Wireless Charging

With various challenges surrounding the charging of EVs, there is the need to develop innovative solutions that could improve the infrastructure and functionality of these charging facilities [56]. One promising innovation is the wireless charging technology [57]. Wireless charging, in this paper, is defined as a method of transferring energy at distance without wires, via inductive power transmission [19]. This can be considered one key advantage over the use of cable charging, as the driver is not required to step out of their vehicle and plug in a cable, in order to begin the charging process [58]. Wireless chargers can also be placed on or below road surfaces [59], enabling installation where cabled charging may not physically be possible [33]. Small but frequent recharging instances could help reduce the range anxiety [60] and provide ETs with enough charge for a full working shift without the need for long breaks.

Wireless charging has been commercially available for portable electronic devices for some time [61], but recent developments are making it possible to provide enough power to charge large vehicles [62–65]. Wireless charging of vehicles has been considered as an option for domestic charging, especially for residences without off-street parking [33].

Some projects have considered laying wireless chargers on the road so vehicles could be charged whilst in movement [66–69]. Even though there are some successful installations for public transport, dynamic wireless technology is not yet mature or commercially viable for wider implementation. Therefore, this project considers only static wireless chargers.

The potential to install wireless chargers is enormous, but there are technical, commercial and operational challenges that need to be acknowledged. For example, static wireless charging requires the vehicle to be stopped at the same location for some time. A precise alignment between transmission and receiver pads is needed for the charge to be efficient [70,71]. This is made more challenging by the fact that natural parking positions vary remarkably [72]. In addition, the power transfer capacity of wireless chargers is limited [65] compared to modern rapid cabled chargers [23].

While the evidence would suggest that wireless chargers are a potential solution to the challenge of providing an appropriate charging infrastructure for ETs, there are challenges around its implementation.

1.4. User Research

The proposition of new technology is often faced with challenges, both on the technical implementation and from the human factors perspective. Customer behavioural and emotional aspects represent barriers to the adoption and acceptance of EVs [73]. A large number of user studies evaluating acceptance of EVs are based on surveys in which respondents select their options on ranking scales or state their preferences from a list of choices [74]. These surveys are often conducted “with participants who have had no direct experience of EVs on which to base their responses” [75].

Qualitative methods such as interviews and focus groups with actual users can provide a rich picture of existing scenarios and experiences. Researchers can observe or track the activities that individuals perform in their real contexts to understand current behaviours and issues [76]. The design of technological innovations has to consider users’ actual behaviours and opinions of how they experience interactions with these technologies to increase acceptance and adoption [77]. Prospective users can contribute to the design of innovations via human factors research, so the development team can understand people’s needs and limitations early on. Through user research, it is possible to understand potential challenges and address those that could prevent the smooth adoption of such systems.

1.5. Aim and Objectives

Despite the potential benefits of wireless charging for electric taxi operation, the operational details, feasibility, and user acceptance of this method are still unknown. Hence, this research aimed:

- To inform the design of future wireless electric vehicle chargers by using a mixed methods methodology to define the challenges of this new technology for taxi drivers

Across both a quantitative and qualitative method, this study addressed the aim by:

- Quantitatively collecting and analysing taxi driving patterns in Nottingham (UK) to define current driving behaviour and inform the locations for wireless chargers
- Using a qualitative workshop to explore and design solutions to the challenges faced by taxi drivers by the introduction of electric taxis
- To combine results from both methodologies to inform the design of future wireless chargers for electric taxis

Human factors methods were brought alongside transport geography to answer these questions. This study aims at gathering information about behaviours and attitudes of ET drivers and local authorities in relation to wireless charging of EVs and understanding the challenges to the introduction of innovative wireless vehicle charging technology within two UK cities.

2. Materials and Methods

In this chapter, both the quantitative and qualitative portions of the study are reported. Given that the adoption of EVs and availability of chargers vary notably between regions of the country [78,79], taxis and drivers from both Nottingham and London were recruited. Nottingham is a medium city in the UK with approximately 321,000 inhabitants, 411 registered taxis (21 of them electric), 1000 private hire vehicles [80] and 104 charging points [81]. London has almost 9 million inhabitants, 21,000 taxis (2450 electric), 88,000 private hire vehicles [13,82] and 7316 charging points [83].

By taking taxi drivers from both medium and large cities, the aim was to ensure a more balanced representation of drivers could be achieved.

2.1. Quantitative Study

In order to understand how taxi drivers currently use their vehicles, 10 conventional taxis performing operations in Nottingham were monitored in 2018. The primary objective of this stage was to understand driving patterns to inform where wireless chargers for electric taxis can be appropriately placed.

A device named 'Clear Capture', custom-built for this study, was used to log the duty cycles of the selected taxis. The information collected included the location of the vehicle and its speed for a minimum of 30 days. The Clear Capture devices collected data automatically and transmitted it wirelessly to the researchers. The tracking devices logged an overall 19,925 miles (32,067 km) from 10 taxis working in Nottingham. The work was carried out over 30 to 60 days for each vehicle (mean 41 days), resulting in 9764 logged hours. On average, taxis covered 49 miles (78.8 km) per day.

Given the objective was to determine the optimal locations for wireless chargers, based on where taxis were typically stationary, heatmaps were produced by specific software in order to display the tracking data in the context of the city map. Best known for plotting eye-tracking data on a multi-coloured map, heatmaps can also be used to analyse movements of people or vehicles, and provide a useful diagrammatic form of the data [77]. Based on this evidence, the locations for electric taxi wireless chargers could be justified.

2.2. Qualitative Study

Once the optimal locations for wireless chargers had been quantitatively established, the next objective was to explore the wider user experience factors of the technology, through a more holistic lens. This was achieved using in-depth semi-structured interviews, conducted in person, with nine taxi drivers and five local authority representatives from Nottingham City Council. All taxi drivers were owners of the new electric London taxi (Figure 1), manufactured by LEVC, having been driving it for at least 2 months. The vehicle has a battery capacity of 31 kWh and a range of 80.6 miles [50].



Figure 1. Electric hackney carriage “black cab” licensed in Nottingham, manufactured by LEVC.

This method enabled the freedom to explore themes and motivations in a way that was not possible with the initial quantitative analysis [78,84].

Furthermore, one focus group was conducted in person with four taxi drivers (Table 1). Each individual interview and the focus group both lasted approximately 1 h. The recruitment was a convenience and snowball sampling strategy intermediated by the Nottingham City Council and Transport for London.

Table 1. Sample. Qualitative and quantitative data sources, vehicle tracking and participant type.

Data Type	Source	Quantity
Vehicle Tracking	Nottingham	10
In-depth semi-structured interviews with electric taxi drivers	Nottingham	4
	London	5
Focus group with electric taxi drivers	London	4
In-depth semi-structured interviews with local authority representatives	Nottingham	5
Total		28

Qualitative Data Collection and Analysis

Topics for the interviews and focus groups involved the overall working scenario, such as the advantages or disadvantages of working with an ET instead of a diesel vehicle. The researcher then asked a number of questions to understand how participants charge their vehicles, both overnight and during the work shift. Other questions were placed to investigate how the taxi ranks work, the time spent on ranks and the frequency of visits to the same ranks.

Halfway through the activity, the researchers gave information about wireless chargers, describing how they work and sharing details such as the expected charge speed. This process was illustrated via a photo of a prototype of the wireless charger (Figure 2). The main aspects of the technology were described, such as the absence of cables, the need to park exactly over a specific position to optimise charge, and the limitation of power transfer to prevent overheating the pads. Participants were asked to give their impressions about the system, comment on possible challenges, and give suggestions to the design and installation of the technology.



Figure 2. Prototype wireless charging pad under the car (Source: IHI).

Sheets of paper, marker pens, and miniature cars were used to illustrate the dynamics of the system and work as prompts for drivers to explain their point of view, such as during the negotiation between cars on taxi ranks (Figure 3). These issues are particularly problematic if considering that diesel taxis may have to use the same ranks as ETs, therefore parking on the bays where the wireless chargers are installed. Drivers were asked to describe their impressions of these issues, and to propose ways of solving it.

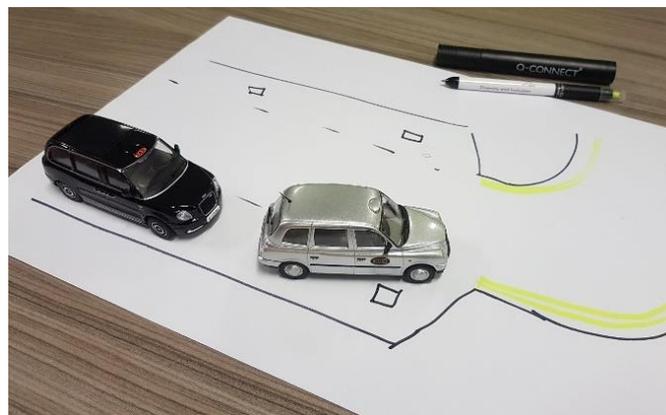


Figure 3. Miniature cars and drawings used during interviews and focus groups to represent taxi ranks and illustrate the dynamics that the drivers have to perform; for example, during the negotiation of spaces between regular diesel taxis (silver) and the new electric taxis (black).

A structured analytical process was followed to minimise the risk of introducing bias in the results. Qualitative data was collected, such as opinions, suggestions, attitudes, and behaviours concerning electric chargers and EVs. Furthermore, researchers took field notes of any relevant points made by participants during the activities. The notes were de-identified and transcribed to a Word document. The software NVivo was used for qualitative data analysis. NVivo enabled the organisation of the codes into categories and themes. Established methods of qualitative coding were used, as described in [85,86]. Grounded theory was used to analyse participant's statements. Multiple cycles of qualitative coding were run to capture as many of the themes as possible. This was carried out independently by two qualitative researchers at the University of Warwick and Coventry University. The results of the coding were then assimilated and brought together to find repeated patterns of meaning, which were analysed in terms of frequency and importance, following established qualitative methodology [87].

3. Results

This section presents the results obtained from the two data collection methods: the quantitative (based on vehicle tracking devices) and qualitative (interviews and focus groups with taxi drivers and local authorities). The log devices installed in taxis provided a picture of the patterns of work performed by taxi drivers, and this result allowed the simulation of hypothetical scenarios of the installation of wireless chargers for taxis. The thematic analysis of qualitative data allowed the understanding of challenges faced by drivers of ETs and an evaluation of the acceptance of wireless chargers. These results combined indicated guidelines for the design and location of wireless chargers for ETs presented below.

3.1. Quantitative Study

Analysis of the tracked data produced a heatmap showing where the taxis often stop (Figure 4). The image was produced using a sum of cumulative time for all vehicles as logged using the tracking devices. Each occurrence was registered if approximately longer than 3 min but shorter than 30 min. This range was selected to avoid registering quick stops (such as traffic lights or to pick up passengers), and to avoid long instances when wired charging would be more suitable.

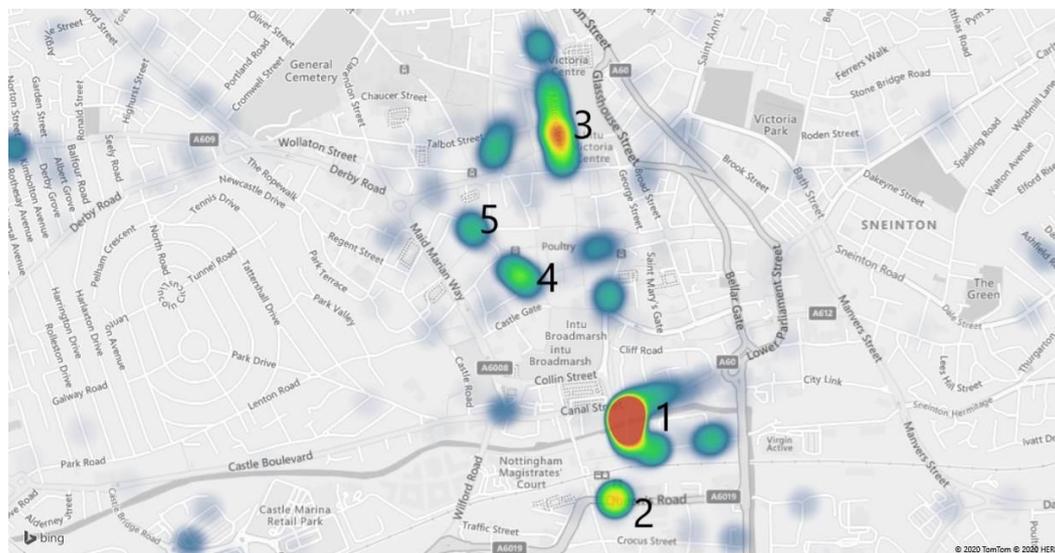


Figure 4. Heatmap showing locations of all 10 tracked taxis in Nottingham. The red areas represent higher cumulative time stopped. The numbers correspond to: 1—Trent Street (taxi rank outside the main train station), 2—Queens Road (not an official rank), 3—Milton Street rank, 4—Wheeler Gate rank, and 5—Long Row West rank.

The heatmap shows the stop locations that are mostly used by the logged vehicles and gives an indication of the possible locations for wireless charging devices. Where taxis stop more often, that represent opportunities for choko-choko charging. Figure 4 shows that the Trent Street taxi rank is the most frequently used location within Nottingham. This rank is located outside the main train station. The average wait time for all logged taxis was calculated at 20 min. Average wait times of 17 min and 10 min were recorded at the Milton Street and Wheeler Gate, respectively, which are the second and third most frequently used taxi ranks within Nottingham.

Over a random period of approximately 12 h, from evening to morning on a weekday, we can observe the speed and stopping patterns of vehicle 1, as shown in Figure 5. Matching this information with the vehicle's location, we noticed that this taxi returned to the same taxi rank seven times over the selected period. If Trent Street taxi rank were fitted with wireless charging infrastructure, it would provide seven short charging opportunities.

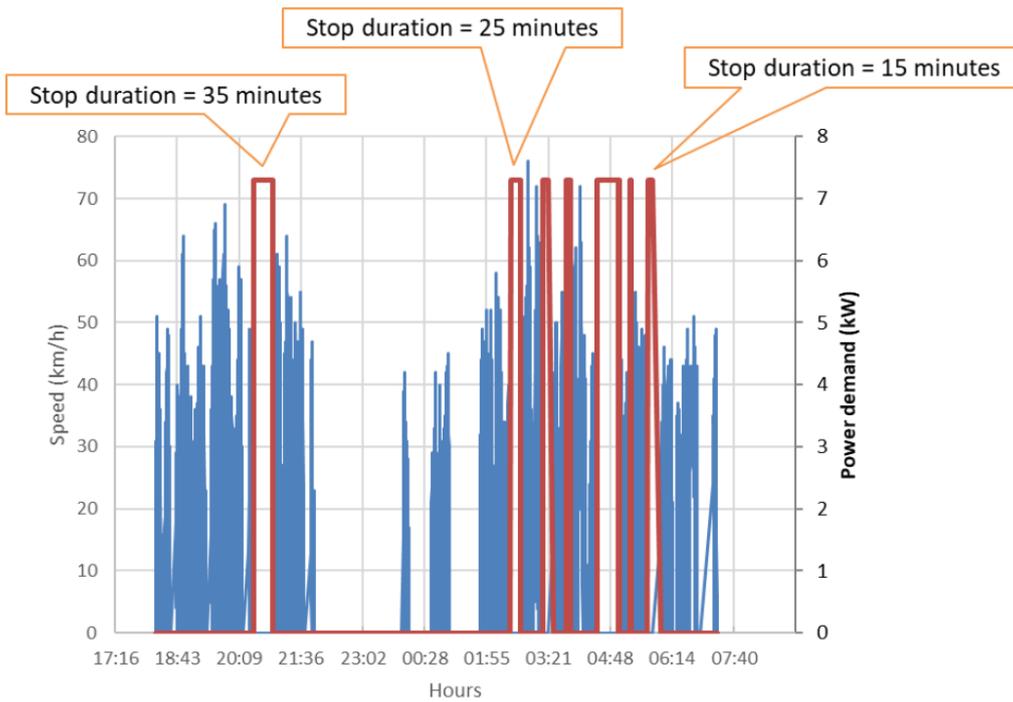


Figure 5. Speed and stopping profile of one tracked taxi (vehicle 1) over 12 h. The occasions when the vehicle was stopped at Trent Street taxi rank (outside main train station, Nottingham) are highlighted in red, indicating some potential for wireless charging.

Figure 6 considers the installation of wireless chargers at different places within the city centre, where taxis stop more often. With the provision of 7.2 kW power supply from these chargers, the short visits to Trent Street taxi rank would provide a maximum of 12 kW, the equivalent of 30% of a 40 kWh battery (red line). This charge would provide an additional range of 30 miles (48 km) based on the average energy consumption of 0.25 kWh/km.

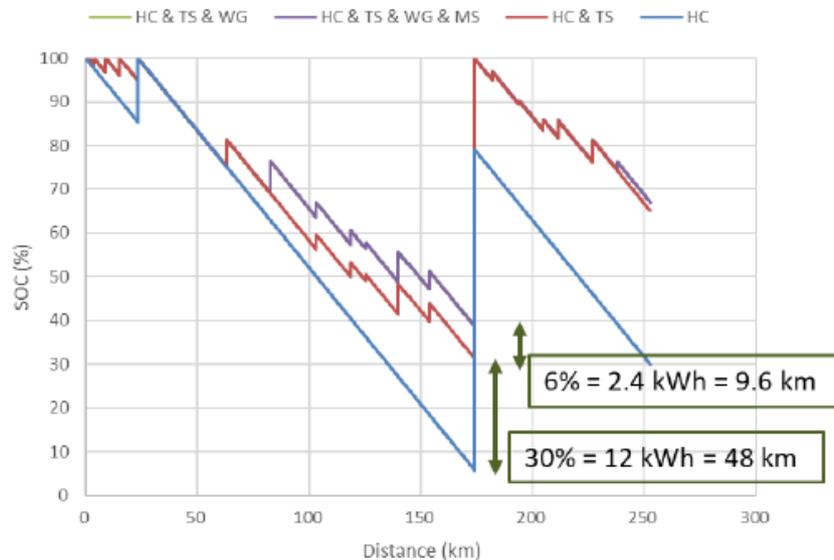


Figure 6. State of charge (SOC) of vehicle 1, if equipped with a 40 kWh battery. It compares different combinations of charging methods. The SOC generated by a 3.3 kW home charge (HC) in blue is compared with the addition of wireless chargers at Trent Street (TS), Wheeler Gate (WG) and Milton Street (MS) in Nottingham, UK.

3.2. Qualitative Study

From the qualitative data analysis of interviews and focus groups, the themes mentioned by participants were classified into two main areas: those that are positive to wireless charging points, in terms of being motivators or facilitators to the implementation of wireless chargers, and those that represent barriers to the proposed chargers. A summary of the key qualitative results can be seen below in Figure 7.

Facilitators	Barriers
<ul style="list-style-type: none"> • Limited battery capacity • Time is money • Limited charging facilities • Street furniture • Taxi and rest rank waiting time • Cable charging inconvenience 	<ul style="list-style-type: none"> • Limited charging speed • Costs • Short time at taxi ranks • Hailing • Safety

Figure 7. Summary of Results.

3.2.1. Facilitators

A number of positive aspects were gathered from this study, which motivate the implementation of wireless chargers of ETs. These items indicate that there is potential for wireless chargers to improve the experience of taxi drivers, facilitate the charging process, and benefit their work routines. These items are listed as follows:

Limited Capacity of the Battery

Taxi drivers mentioned they could not work for a full day's shift with one charge. The mileage obtained by our participants was not as good as promised by the dealer or the manufacturer: the vehicle's brochure claims a range of 80.6 miles with a full charge [50], but the majority of participants currently obtain on average half this figure. Two drivers mentioned that limited range happens probably because the top and bottom 20% of the battery are not accessible to improve its longevity. The electricity consumption is more problematic in winter, when drivers have to use the heating system to improve the working conditions in the vehicle and to make it more comfortable for passengers. Taxi drivers mentioned that they sometimes switch on the range-extender petrol engine to warm up the vehicle in the morning and save the battery. Participants reported the need to charge their vehicles once or twice during the work shift. Taxi driver 04 (T04) said that he starts his work with a full battery, but based on his previous experience, he found that *"by 1 or 2PM that charge is gone."* To address this (T04) commented, *"so I recharge it at lunchtime."* The charging is often combined with a coffee break, lunch, dinner, or other activities such as a walk.

Time is Money

Drivers mentioned that, for charging during the working shift, they have to drive to a place with rapid chargers and plug in their vehicles. Adding the recharging time and the detour, it means that approximately *"two hours of the working day are lost charging,"* (T02). One common concern is that the time spent charging the vehicle is time not earning fares, with the feeling that, meanwhile, the diesel taxis are working. Given the higher fares, some drivers in London even considered it more worthwhile to drive using the range extension, therefore burning petrol, instead of being away from the streets charging the vehicle. T08 mentioned that he uses the charging points at Q Park during a 20 or 30-min scheduled break, and later on, *"if it trips up to petrol then that will be it."* T09 complements, saying that

“you can end up driving through 3 or 4 charging stations and lose 2 h, then I think I could go to a petrol station, put £5 and off you go”.

Limited Charging Facilities

Some drivers mentioned difficulties in charging their vehicles, both overnight and during the working shift. Not all drivers have chargers at home because of their house characteristics: terraced houses without off-street parking, or blocks of flats where the installation of home chargers is problematic. Therefore, these drivers have to either park the car away from home by a charger and walk back, or use rapid chargers installed in other places in the city before their work shifts. Drivers mention that sometimes there are frictions around chargers. For T05, street charging is crucial: *“Someone may pull beside and see that I’m already on 85% and think I’ll be off shortly . . . and I have to say ‘no, I need 100%, I don’t have a charger at home’”.*

Participants mentioned that they often have to drive five miles away from their place of work near the main train station (Nottingham) or drive through a few charging stations until finding one available in the city centre (London). Drivers mentioned that the smartphone applications are not very accurate to tell if a charging station is being used since there is a delay of about 5 min for the information to be updated. The general impression is that the lack of charging points is getting worse with time, with more ETs and passenger cars on the streets, and not many new charging points. T09, one of the first drivers to adopt the ET in London, said, *“when there were 200 of us, I used Polar to have charge for the second half of the day . . . I used to have my own favourite charger hidden on top of a car park, not many people knew about it”.*

City council staff in Nottingham mentioned the reasons for the limited availability of wired charging points in central areas, and that is difficult to install chargers in new places. It is necessary to have access to the land, in an area with enough energy supply, and a good location that is close to transport hubs and guarantees safety to drivers, pedestrians, the charger, and the cars. However, sometimes it is difficult to tick all these boxes.

Street Furniture

City planners mentioned concerns regarding the use of pavements and other usable areas within the city centre. There is considerable resistance to allow more street furniture to be installed on the streets. The existing totems for cabled chargers are considered bulky, ugly, and subject to vandalism. Participants were favourable to the idea of a charger on the tarmac, if it minimises the need for adding more ‘clutter’ on the pavement. Nottingham City Council staff 04 (C04) mentioned that *“the council is mindful of street furniture, how they look and how they are maintained”.*

Waiting Time at Taxi Ranks and Rest Ranks

Taxi drivers mentioned that they are stopped at taxi ranks for different lengths of time, from 10, 20 min, to one hour or even longer. There are occasions during the day when they stop at other places, for example, the ‘green huts’ rest ranks in London.

At Trent Street, in Nottingham, there are two lanes for the taxi rank, at opposite sides of the road (Figure 8). The pick-up point is only on the main lane. Participants mentioned that the second lane works as an overflow, where drivers can use when the primary line is long. T01 explains that *“the taxi rank line works on a first come first served basis, but we have a gentlemen’s agreement.”* T02 complements: *“There’s method in the madness, we know who is where in the queue. We take note of the last car and we follow them. We usually get the number of the car in front, when they move away we take that place”.*

When waiting at small taxi ranks, for example in front of supermarkets or hotels, the wait can be long. That may be one of the reasons for small taxi ranks in London being rarely used. Sometimes there is the feeling of wasting time and being subject to luck. T08 said that *“when it’s slow on the streets, there’s more ranking, to avoid be driving around. You may see that you stop here and someone stops a couple of blocks further, and it’s the same as if we were all driving around”.*



Figure 8. Trent St, Nottingham, with the main taxi rank (left) and overflow lane (right).

Participants reported that the waiting time at airports such as Heathrow is usually extremely long. Taxis have to wait at a feeder car park and can stay there from a minimum of 2 h, which can be up to 5 h at times.

Cable Charging Can Be Inconvenient

Taxi drivers mentioned that cable charging is sometimes inconvenient, requiring the driver to leave their vehicle, connect the leads, and authorise the charge using a membership or credit card. Similarly, once finished, the process has to be repeated in reverse. This process can be troublesome with bad weather and be unsafe in specific parts of the city. In addition, with cable charging, they are unable to just drive off, as it can take some time to disconnect and be able to go.

These concerns resonated with opinions of taxi drivers in London, who exposed safety concerns around cabled chargers. Especially drivers who work evenings and nights said that some chargers are placed in ‘dodgy’ areas, not very safe for taxis to stay parked there at night. Participants also mentioned the general knowledge that taxi drivers always carry cash in their vehicles. T05 illustrates: *“Some places are unnerving, you see a guy there, he may be a nice chap, but we’re vulnerable. We have to go out, connect the cable, and can’t just drive off if needed”*.

3.2.2. Barriers

Some challenges to wireless charging of ETs were mentioned by our participants. These barriers represent obstacles to the implementation of wireless chargers in general, from the perspective of taxi drivers and city planners. These risks need to be acknowledged and, if possible, addressed or mitigated prior to the implementation of a real-world trial.

Limited Charge Speed

Drivers mentioned that the expected charging speed of 7 kw is slow. Participant 04 in the focus group (F04) said that *“with a 7 kw charger, you stay there 10 or 20 min, then if you put the foot down or the heat on, it’s gone like that [snaps finger].”* Others acknowledged that it is ‘better than nothing’, but this

cannot be seen as a method to fully charge the battery as it would take a few hours. Similar speeds are only used by taxi drivers if they are charging their vehicles overnight at home or in the city when they want to use the cabled charging points “*as cheap street parking,*” (T07).

Costs

Drivers were quick to point out that the wireless charging technology would require a receptor on the vehicle, which would come with a cost. The installation of such device would also require time off, as the vehicle would have to be driven to a garage or dealer for the installation of hardware and software. From their experience, every charging point on their vehicles and any accessories such as the taximeter had to be paid separately, and they believe that will be the same with the wireless receptor. Taxi drivers self-declared to be very cost-sensitive, and understand that the investment should be compensated somehow.

Short Time at Taxi Ranks

At some train stations, such as “*St Pancras, there may be 100 taxis going through the rank in 30 min*” (T08), therefore the vehicles keep moving forward frequently. Some drivers mentioned using technology to optimise the wait time as they consult live train arrival times via smartphone applications. Others mentioned the use of WhatsApp groups and Twitter feeds where fellow drivers inform when there is high demand for taxis at specific stations.

Participants said there are regulations specifying that taxis have to move forward once the first vehicle in the queue leaves the rank. Keeping large gaps can potentially create “*untold hassle*” (T07). Drivers described that when there is a gap, there may be conflicts because drivers joining the back of a full taxi stand cannot be ‘over-ranking’, when they are outside the designated rank area.

Hailing

One main difference between Nottingham and London is that none of the drivers from London in our sample said they stay at taxi ranks very often. They may do sometimes if they drive a passenger to a station, the line is not very long, it has been difficult to find jobs being hailed on the streets, or other drivers shared the information of high demand at a particular station. Drivers seemed more comfortable driving around central London to be hailed on the street.

Safety

The implementation of wireless chargers will require hardware and software modifications on the vehicle, which motivated the preoccupation that it should not impose risks for the car and users. City council staff mentioned a few concerns regarding the safety of the devices and the need for it to comply with existing regulations. Concerning the pad located on the ground, it should be robust, endure heavy vehicles, be weatherproof, and resist oil and other substances. It should not have protrusions to minimise the risk of accidents to pedestrians and other road users. Participants also expressed concerns in relation to the safety of the magnetic field produced by the pads, and wanted to know if the equipment would cause any hazards to other road users, pedestrians, cyclists, pushchairs, or electric wheelchairs. City council staff were also concerned that these modifications in the car should not void the warranty nor affect the vehicle insurance. The licensing of taxis may require a confirmation from the manufacturer that adaptation is safe.

4. Discussion

4.1. Suitable for Certain Places

The combination of vehicle location data and stopping patterns in Nottingham, UK showed that drivers work mostly from the Trent Street taxi rank. Hence, our results would suggest that deployment of the wireless charging infrastructure at Trent Street could facilitate the electrification of taxi operations in the city. Wireless chargers exclusive for ETs are being proposed for taxi ranks

in certain cities [57]. However, vehicles on a traditional taxi rank will not be able to stay over a pad for long, as they “must move up on ranks to fill vacancies as they occur” [88]. However, there are other places where wireless technology would be more suitable, where taxis can stay for longer in the same position. A few pads could be installed on the overflow rank, where vehicles stay stationary for prolonged periods. Short boosts of charge during work shifts could minimise the known issues of lack of charging facilities and range anxiety [30,31,60]. The 20 min spent at Trent Street taxi rank on average seemed reasonable for the use of wireless charging as an option to minimise these issues. Furthermore, there is the convenience of just quickly stopping the vehicle over a pad [89] whilst still remaining available for hire immediately. The ease of use of wireless charger may foster its use even for very short bursts. Previous research tends to use 30 min as the minimum wait time that would be worth the effort of connecting an ET to a cabled charger [21,46].

4.2. More Charge Is Needed

During interviews and focus groups, our participants mentioned a range of factors motivating the implementation of innovative charging methods. For example, that charge obtained overnight is not enough to last a full working shift with the LEVC taxis. The real-world range of 40 miles or even the promised 80 miles seem modest in comparison to the generally accepted landmark of 200 miles range [24]. Participants reported conflicts with fellow drivers at charging points, which are not in abundance [35,90]. Some taxi drivers are unable to install chargers at home [34] and are therefore more dependent on public street chargers.

The range extension feature of the new black cabs guarantees that drivers do not need to reject long-distance customers, as occasionally happens with drivers using battery-only vehicles [8,9]. Some participants from London reported that they tend to switch to the range extender once the battery runs flat because the high fares in the city tend to compensate for the fuel costs. This behaviour may be negating the sustainable benefits of an EV, which makes adamant that a solution is found to the limited charging opportunities for these vehicles.

ETs can be worthwhile if drivers can find charging stations without difficulty and if “financial losses due to missed passenger trips are negligible” [38]. Participants reported long detours to find a charging station and to have longer breaks while the vehicle is recharging. These drivers are therefore having longer work shifts to obtain the same number of occupied journeys and to collect the same fares as their colleagues driving diesel-powered taxis. Some cities implement strategies to compensate for this lost time; for example, Stockholm, where ETs can jump the queue at airports and have priority on booking applications [8]. However, the current research suggests that these approaches may not be necessary once wireless chargers are installed where taxis currently wait for passengers.

4.3. Particular Scenario in Every City

Charging opportunities can be evaluated as a trade-off between the energy obtained, time spent, and cost [91]. These factors will depend on the specific scenarios for every driver, including time available, locations they find themselves at, and passenger demand, which can change with the time of the day. It is important to notice that the average driven distances of taxis in Nottingham are modest comparing to larger cities such as New York, Beijing or Seoul [9,46,92]. Therefore, it is crucial to provide convenient charging facilities for taxi drivers whenever possible within their working areas and during their working shifts, particularly in locations where taxis cover long distances.

4.4. Avoid Driving around

As described by our participants, they tend to drive through specific busy roads in the city centre to be hailed by prospective passengers. Drivers are then counting on that moment of luck when a passenger will wave. Similar results were observed in New York, where taxi drivers tend to find passengers by ‘cruising’ Manhattan [46,53]. This preferred behaviour represents one barrier to charging during work shifts, cause congestions and extra energy use.

Our results indicate that there is a possibility of a significant change in driving behaviours among taxi drivers in London. Some small ranks in the city centre are not frequently used, partially because of the perceived long time for a passenger to appear. Having a wireless charger installed at these small ranks can motivate taxi drivers to be stopped there while waiting for a passenger to come over. It will also reduce the feeling of 'sunk cost', the time invested in the wait for passengers [93]. If using these ranks, time would be better spent if they were also charging their vehicles and likely to get a job at the end of the wait. If more drivers adopt the smaller taxi ranks, there is less driving around to hail passengers, less congestion, and lower collective carbon emissions. However, government planning, policies, subsidies, and incentives may have to get into the equation to motivate these changes [7,94,95].

4.5. Future of Taxis

There are projections indicating that taxis could become automated in the future, once the driverless technology is mature enough [96]. Range anxiety could affect occupants, who will also want to charge their personal devices within the vehicle [97]. The corded charging of automated vehicles may require specific infrastructure and a dedicated attendant to connect cables onto vehicles at charging station sites. This manual process will incur in extra costs that can make electric automated vehicles less competitive than those running on petrol [98]. Driverless cars could also be charged if a robotic arm connects the cable to the vehicle [14], but that will require mechanical parts and processes. It is natural to expect that automated, self-driving vehicles should be charged automatically, without human intervention. Therefore, wireless technology will play an important part in the recharging of these vehicles [63].

4.6. Suggestions

The combination of quantitative and qualitative data obtained during this research allows us to provide some suggestions for the installation of innovative charging facilities for ETs. Wireless charging seems to be one of the technological solutions to minimise the challenges surrounding battery charge. Those could be installed on taxi ranks such as on Trent Street, outside the main train station in Nottingham. Drivers wait for several minutes there, and arrangements between drivers could allow the secondary lane to be used preferably for charging.

Other locations, where drivers take breaks, could also be used for wireless charging. One of the 'green huts', around Russell Square, has parking for 10 taxis, but there is no clear division to the pavement. This location seems not suitable for cabled rapid chargers due to trip hazards and because it is a conservation area [33]. Wireless chargers could be installed using existing approved shapes from companies that already provide hardware for the roads, for example the bolt-on speed bumps.

Heathrow airport seemed an additional location for installing these chargers, given the long wait and the fact that drivers stay at a feeder car park before being directed to the terminal ranks. Wireless chargers at the car park would provide charge without the need for cabled connections.

The overarching suggestion is that wireless chargers should provide good cost-benefit, ideally making taxi drivers spend less on running costs, and allowing them to earn more fares. From the interviews and focus groups, we observed that taxi drivers are very cost-sensitive but also very opinionated. During our contacts, they seemed passionate about the profession, with a wealth of knowledge about negative and positive issues related to their cars, keen to contribute to the project and help the trade. They took this research as an opportunity to vent frustration caused by the issues they experience with their ETs. Therefore, the last suggestion is that any technological improvement should be introduced with care. Trade organisations may present certain resistance to change if improvements benefit only specific groups in detriment of others.

4.7. Limitations and Future Work

To produce the quantitative results presented in this article, we had to make a few assumptions. For example, Figure 6 shows the hypothetical state of charge (SOC) as the example vehicle drives

around the city. For simplification, we consider that the SOC reduces linearly and proportionally to the distance travelled. We acknowledge that in a real-world scenario, the SOC will be influenced by a number of factors such as the geography of the route, the speed of the vehicle, temperature, and driver behaviour. Simulations and projections also consider the average scenarios of battery capacity, energy use and charger availability. Quantitative methods alone often fail to account for individual issues and personal circumstances, which were only uncovered with a deeper analysis of qualitative data. We intended to minimise these drawbacks, combining two different research methods, namely the vehicle tracking with the human factors research presented here.

Another limitation from our research is that the tracking of taxis was made on traditional diesel-powered vehicles. With ETs being deployed progressively in diverse cities, future research should track these specific vehicles [10,47]. This will make possible to have a detailed picture of actual driver behaviours, but focusing on the specific particularities of EVs within the cities in question. After combining this information with interviews, it will be possible to better define the locations for wireless charging facilities.

It should be mentioned that these results are based on a scenario whereby charging times at taxi ranks equal wait times. This is true when the ET under investigation stops in a taxi space with wireless charger facilities, such as the overflow lane at Trent Street, Nottingham. In a busy rank scenario, charging time will differ from wait time as other taxis may be occupying the charging bays. More research is needed to evaluate the real-world feasibility of the proposed technology and the locations suggested.

Wireless charging technology has promising potential, but some open questions need addressing, for example health assurances [64,89]. The electromagnetic fields generated during wireless power transfer can be harmful between the charging pads and cause foreign objects to heat up quickly [71]. Future projects should make sure the technology is proven safe prior to large-scale deployments. Next steps should also evaluate the technical feasibility and cost-benefit analysis to make sure there are long-term economic benefits for using wireless chargers, similarly to projections made for cabled charging [99]. Lastly, studies for siting charging points could add wireless charging of electric taxis to their models in order to optimise their locations [38–40,44].

5. Conclusions

Electric vehicles bring about the potential to reduce greenhouse gas emissions and contribute to a cleaner and more efficient transport systems. In particular, taxis present an ideal opportunity for the implementation of EVs. However, ensuring electric taxis are able to meet the range demands of taxi drivers during their work shifts is critical to its success. Solutions such as increasing the number of cable charging facilities or faster charging, suit the driving patterns of regular drivers but not the patterns of taxi drivers. These solutions are also expensive and require the use of large amounts of space, which may be limited in urban environments. In comparison, wireless charging may support the stop-start nature of taxi driving and reduce urban 'clutter'.

This research used a combination of quantitative and qualitative methods, which provided useful data logs from real-world taxi journeys, together with textual accounts from drivers of ETs. The results obtained by tracking taxis indicate that Nottingham could be a potential pilot location for deploying a wireless charging infrastructure for ETs. The results of the current study aggregated human factors research to the tracking of vehicles to suggest more accurately the ideal location of charging stations.

Wireless charging has the potential to mitigate current issues of ET operations, including the limited capacity of the on-board battery, long charging times using conductive-based systems, scarce charging facilities, and the inconvenience of performing cable charging. However, some barriers to the introduction of wireless charging of ETs were identified. Those include technology limitations, costs, and short times available for charging. Some taxi drivers do not work from taxi ranks at all, making the technology unsuitable, unless there is a radical change of behaviours.

Our results indicated that wireless charging of ETs can be a feasible technology to supply charge during work shifts without long detours to find a charger, and therefore could be part of policies tackling carbon emissions in urban areas. Convenience, speed of connection/disconnection, and removing the need to plug-in cables in the rain and cold are some additional benefits of wireless charging. It is expected that, eventually, the technology will reduce street clutter as well as hazards caused by trailing leads. Finally, wireless charging is fundamental as an enabling component to ensure that zero emission capable vehicles achieve their potential for true emission free driving in our city centres.

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