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Charging of eTaxis by inductive power transfer: Lessons learned from demonstration of wireless charging for taxi operations

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Summary

Transport sector electrification is a critical step towards alleviating climate change and air pollution concerns. Public transport is an important sub-sector with high densities of taxis operating in urban areas. Given the duty cycles of taxis and the required recharging time during a shift, or for vehicles that are double shifted, wireless charging is a potential enabling technology for moving further towards electrified taxi (eTaxi) operations. Wireless Charging of Electric Taxis (WiCET) is a demonstration project of wireless chargers retrofitted to eTaxis with charging infrastructure installed at the main taxi rank in Nottingham, UK to enable frequent charging boosts. The results presented discuss the project consortium experiences and lessons learned to date during the planning and preparation phase retrofitting two types of eTaxis for wireless charging.

Keywords: wireless charging, demonstration, public transport, ULEV (ultra-low emission vehicle,) user behaviour

1 Introduction

Shifting the transport sector away from the dominance of internal combustion engines to zero emission alternatives is imperative for mitigating the worst effects of climate change and tackling public health concerns from air pollution. Many countries are committing to ending the sale of petrol and diesel vehicles in the 2030s. Taxis are a significant vehicle group typically operating in population centres and Hackney carriages, where a taxi may be hailed as well as using taxi ranks, normally have high duty cycles and may also be double shifted by multiple drivers over an extended regular usage period. Conductive charging normally requires the vehicle to be taken out of fee earning service, as it is not generally practical to co-locate conductive chargers with taxi ranks in which taxis intermittently move forward in a queue over short time intervals. Wireless charging potentially offers an opportunity for “on-the-stop” top-up charging boosts as wirelessly equipped eTaxis pass over charging pads installed in a rank.

Wireless Charging of Electric Taxis (WiCET)[1] is a consortium project seeking to demonstrate wireless charging equipment installed in taxis ranks to understand the opportunity, practicality and business case for the technology to support the industry transition towards electrified taxi operations, both for full battery electric vehicles (BEVs) and plug-in hybrids (PHEVs). WiCET is unique in its introduction of wireless power transfer (WPT) technology for the first time to eTaxis in the UK, utilising two approved eTaxi vehicles: the LEVC TX (LEVC), and Dynamo-Nissan E-NV200 (Dynamo) retrofitted with wireless charging technology. It is among a small number of studies worldwide looking at wireless charging of taxis[2-4].

A wireless charging concept for eTaxi operation is shown (figure 1) in which a taxi rank is equipped with a suitably rated grid supply. Control boards provide power electronics and control/communications facilities to ground assembly pads (GAs) installed in the wait areas of the taxi rank. Vehicle receiver assemblies (VAs) enable the vehicle to identify itself for billing and back-office functionality along with power receiving electronics. This provides an approach for opportunistic wireless charging during wait times between customers via regular top-ups.

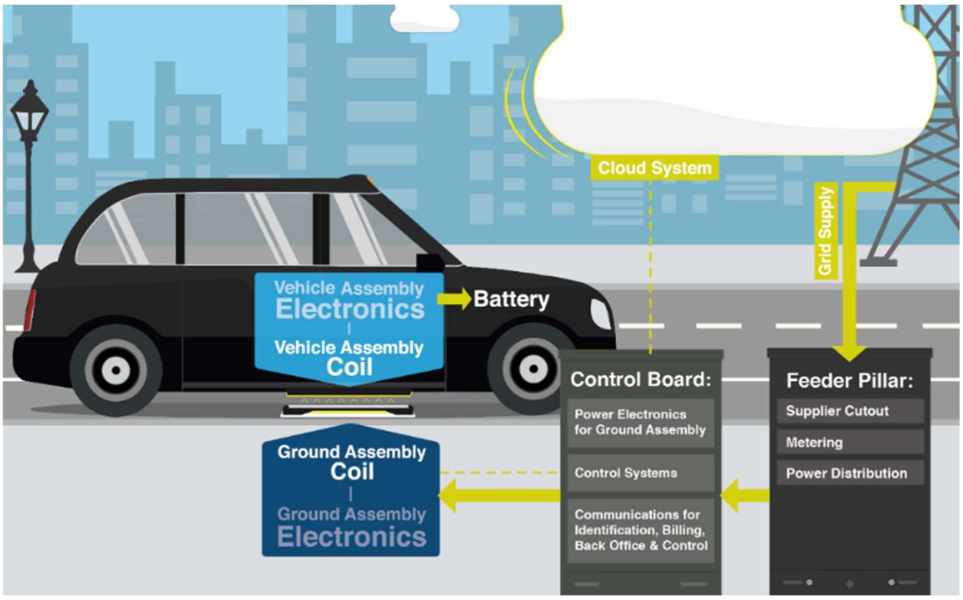

Figure 1: Outline concept of a wireless charging system for eTaxis

1.1 Project Structure

The WiCET project was initially planned into two stages: 1) a preparation and internal piloting phase with baseline data collection to study and develop the eTaxi WPT concept; 2) a public demonstration phase for piloting real world usage and acceptance of the solution. The planned project approach has been impacted by: project commencement aligning with the COVID-19 pandemic, limitations of the wireless technology including issues surrounding the overall technology integration, and supply of wireless hardware being impacted by the global semiconductor shortages. These concerns have meant that the project structure and approach had to be adapted to extend certain activities and to iterate the approach taken for key components.

The private pilot site was in-situ from June-2021 to May-2022 and has allowed the engineering and systems integration work to take place along with testing activities at a private Nottingham City Council authority venue (figure 2). The pilot work involved initial retrofitting and systems integration for both the Dynamo and LEVC vehicles using pre-series WPT hardware.

The public demonstration in the main taxi rank will use an evolution of the WPT hardware complete with revised vehicle integration and suitable driver controls and visual interfaces for usage and alignment.

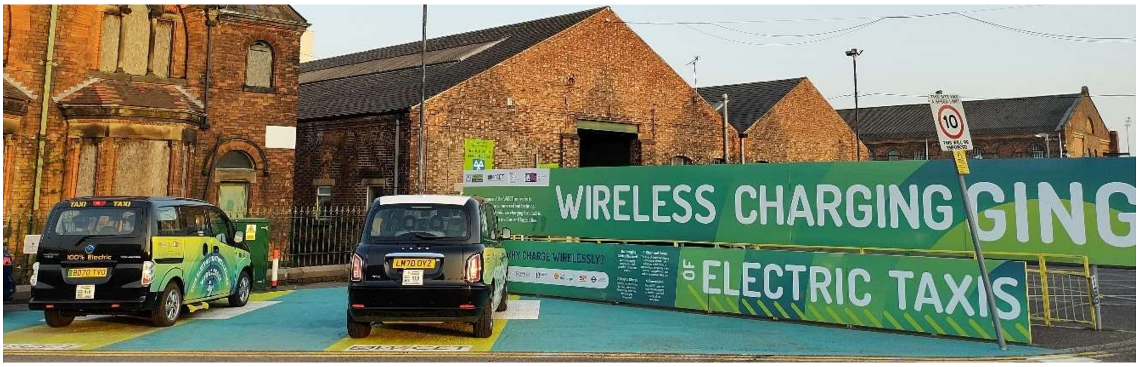

Figure 2: WPT installed at the Nottingham Eastcroft private pilot site

2 WiCET Highlighted WPT Features

2.1 SAE J2954 Power Classes

The ratified version of SAE J2954[5] defines WPT power classes to align with SAE J1772[6] AC power levels up to class WPT3 (11.1 kVA). The WiCET project approach to adopt hardware aligned to the standard restricts WPT power levels to WPT3 and correspondingly this could limit the practical benefits for drivers and the realisable business case.

Future versions of SAE J2954 may provision for WPT4 (22 kVA) and WPT5 (60 kVA) providing a standards and technology roadmap that is more beneficial for drivers and allows optimisation of the ground infrastructure deployment in a taxi rank to enhance the business case.

To illustrate this, figure 3 models the delivered electrical energy (kWh) to the DC battery system in the car for different scenarios. In this model the taxi rank is configured with 12 vehicle bays, of which five are equipped with wireless charging. The model assumes a transfer time to align, initiate and ramp up charging of 30 seconds and a mains 50 Hz AC to on-vehicle DC system transfer efficiency of 90% which is representative of the expected performance determined in the WiCET private pilot testing.

The blue line shows the delivered energy at an input power of 11.1 kVA for different taxi rank visit durations in which the queue time is equal for every space in the rank. In this scenario a mean visit duration of 13:11, (as seen during the baselining phase, discussed later), would deliver just 0.50 kWh. More realistically the taxi rank won't have all spaces occupied most of the time and with the wireless charging equipment installed towards the front of the rank a greater proportion of a visit duration is likely over the wireless charging hardware. The orange line shows the scenario in which the proportion of time over a wireless bay is double that of a non-wireless bay which for a mean duration visit would result in a delivered energy of 0.87 kWh. Increasing the nominal supply power to 22 kVA (WPT4) and 60 kVA (WPT5) increases the energy delivered to 1.73 kWh (grey line) and 4.73 kWh (yellow line) respectively for a mean duration taxi rank visit.

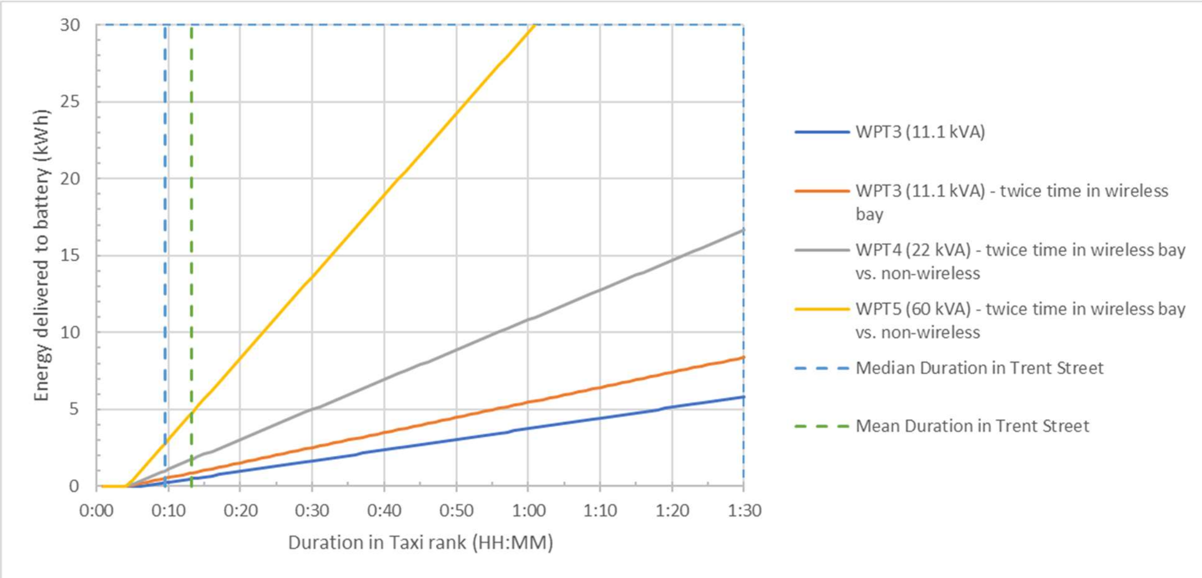

Figure 3: Modelled taxi rank energy delivery for different WPT power levels in a 12-space taxi rank with five WPT spaces, 90% AC to DC system power efficiency and 30 second space-to-space transition.

Surveys and driver discussion research by the WiCET project suggests that typically drivers will organise and arrange themselves according to informal queuing arrangements so that a driver will know which other drivers they followed into a taxi rank regardless of the physical queue itself. For instance, the Trent Street taxi rank (figure 4) currently runs down both sides of the street with one side used for the main queue and the other for overflow arrangements at busy times. With a proportion of the spaces in a taxi rank equipped with wireless charging it may be possible that queuing arrangements can be organised to maximise the charging opportunity for drivers who need to do so. The public demonstration of WiCET will only install wireless charging equipment in five spaces on one side of Trent Street, so understanding driver queuing arrangements and how much charging benefit is possible for each visit, despite limited WPT power, is an objective of the study.

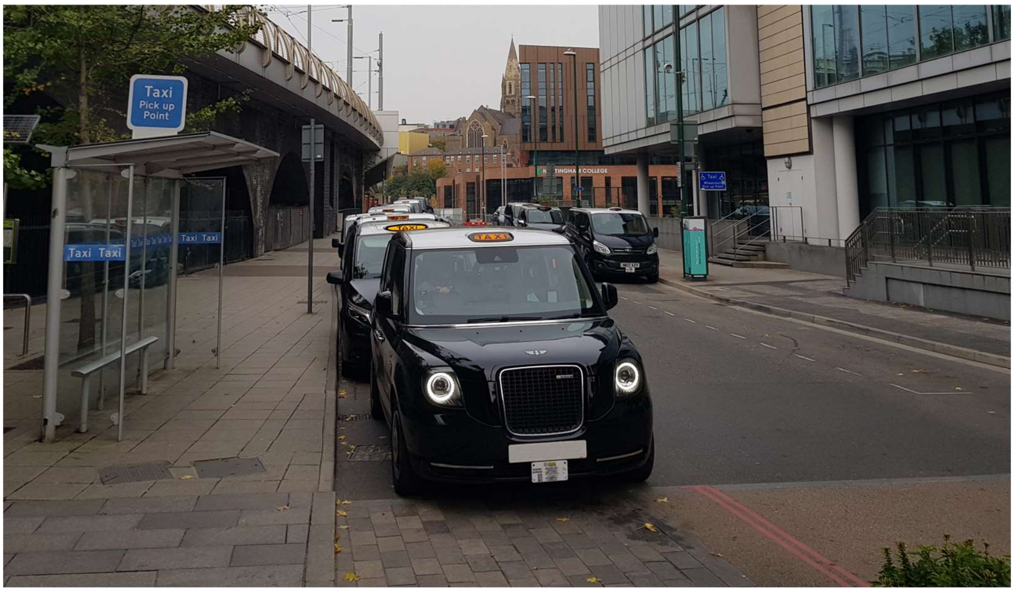

Figure 4: Nottingham Trent Street taxi rank configuration (2020)

2.2 Efficiency of WPT System

SAE J2954[4] defines that system efficiency is measured from the AC grid connection to the HV battery connection and shall be ≥80% over the full range of variations. The private pilot site tests considered good alignment at different heights of Z to test the extremities of the SAE J2954 Z1 range, as well as different X - longitudinal along the vehicle, and Y - lateral across the vehicle, alignments, and misalignments within the allowable limits of the standard (ΔX ±75 mm, ΔY ±100 mm). Typically, system efficiencies observed ranged from 87% at extremes of misalignment to 92% with good alignment.

2.3 Living Object Protection Systems

Inductive power transfer systems generate electromagnetic field emissions surrounding the transmitting and receiving coils. Generally, the field emissions will increase with increasing wireless power levels, with some variances due to different WPT system designs. The current regulatory position in the UK aligns occupational exposure limits with those presented in ICNIRP 2010[7] via statutory legislation[8], while for general public exposure there is a government policy position to comply with the more restrictive limits in ICNIRP 1998[9] in terms of a 1999 EU recommendation[10].

At the transfer power adopted by the WiCET project (11 kVA) the fields extend at a level above the ICNIRP 1998 values beyond the vehicle perimeter. Protecting living beings from harm in this zone requires a living object protection arrangement (figure 5). The LOP arrangement for the WiCET demonstration requires a protection perimeter necessitating extra ground side infrastructure and inhibiting taxi vehicle egress from the rank. Future opportunity for on-vehicle LOP arrangements, either directly embedded into the WPT hardware or vehicle sensing arrangements, would enable a simpler, more practical user experience with possible cost advantages.

The WiCET project is already having discussions, and continuing to engage, with stakeholders to achieve clarity and understand the route to harmonization and simplification of the regulatory environment for general public and occupational exposure limits and achieving technical compliance.

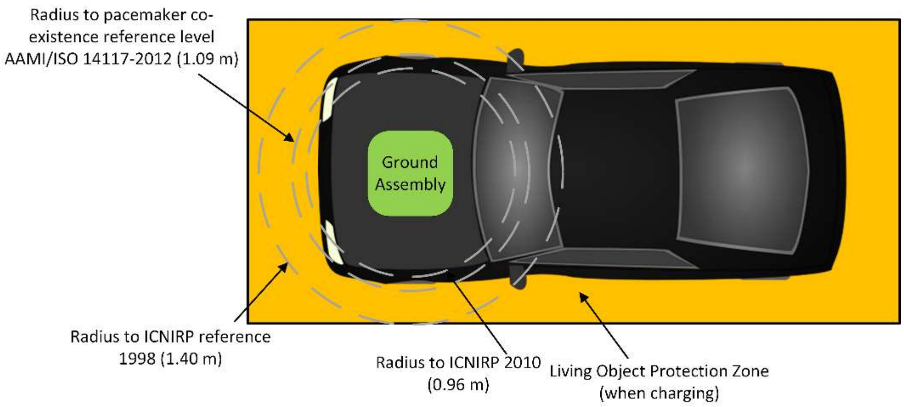

Figure 5: Living object protection zone for each taxi rank space (front VA mounting position)

3 Wireless Hardware Vehicle Integration

Retrofitting of WPT hardware into donor vehicles requires integration of mechanical (fixings, bracketry, shields), Electrical (power, and communications), controls and cooling systems. The WiCET project has implemented this for two different donor vehicle types using an approach which, as far as possible, is universal in terms of the integration approach and system components.

The approach for integration of the DC charging voltage and on-vehicle charging control has been via the CHAdeMO system within the vehicle. The reason for this is that CHAdeMO has a well specified communications standard and is a common interface to both the Dynamo and LEVC vehicles (the main two ultra-low emission vehicles licensed for use as a Hackney carriage taxi in London). The controls and communication integration requires a universal vehicle interface unit (VIU) operating between the vehicle communications, the WPT hardware controls, and the CHAdeMO system. For power integration a power distribution module (PDM) is required.

3.1 Ground Clearance

Ensuring adequate ground clearance of WPT hardware when fitted to small passenger vehicles is essential. In the UK speed bumps, curbs, and other highway ground features can routinely extend above the nominal ground plane by as much as 100 mm e.g. [11,12].

At the same time the fitness for purpose guidance for licenced taxi vehicles places requirements that must be met for the height of passenger door entranceways above ground to ensure accessibility needs are met.[13]. This limits the overall vehicle ride height and additionally sets the defined height of the vehicle receiver assembly (VA) to the Z1 height class as defined in SAE J2954[5] (100 to 150 mm).

These two requirements create constraints which can be challenging for the retrofit packaging of the wireless VA. In the WiCET project, initial vehicle integration packaging work for a private pilot testing phase focussed on integrating the VA near the front of the vehicle to maximise driver control for lateral vehicle alignment (across the width of the car). For both vehicle types used within the project, this location is restrictive - ensuring adequate clearance of the upper surfaces of the VA to dynamic movements of drivetrain components, while also avoiding interaction of the electromagnetic shield surrounding the VA with front axles, suspension arms, steering etc. Figure 6 shows images of the initial VA positioning and ground clearance in the private pilot phase. For both vehicle types at kerb weight this mounting location yielded clearance distances of the VA to ground of approximately 100 mm. Additionally, as the load of the vehicle approaches gross vehicle weight (GVW), there will be some compression of the front suspension to further reduce this clearance distance.

Project investigation work using wear blocks and a variety of test drives showed clearly the mounting position was vulnerable to costly damage to the VA and shield and that the ground clearance was insufficient.

Figure 6: Photos from the private pilot showing side and front views of VA and EM shield mounted using a front position on the vehicle, with limited ground clearance.

For the main public demonstration, the VA position, on both vehicles, has had to be repackaged further back towards the rear situated behind the traction battery such as the diagram for the LEVC in figure 7. This position allows for a much greater ground clearance of approximately 150 mm at kerb weight. At GVW the suspension travel towards the back of the vehicle will be more substantial, however the overall ground clearance should remain in the 100 to 150 mm Z1 range of SAE J2954 and events charging at GVW are unlikely. The revised position represents a compromise as a taxi driver has reduced control for lateral alignment of the VA with respect to the GA, however it is anticipated that visual cues purposely included in the taxi rank as well as the extended length of the taxi rank should guide drivers to ensure good general lateral alignment. A further complexity is that the LEVC, as a range-extended hybrid electric vehicle, has an exhaust system running along the length of the vehicle which requires the main electromagnetic shield to be profiled around it, as well as the exhaust tubing itself needing wrap around electromagnetic shielding. Additionally, the VA must be marginally offset from the vehicle centre line to avoid the exhaust.

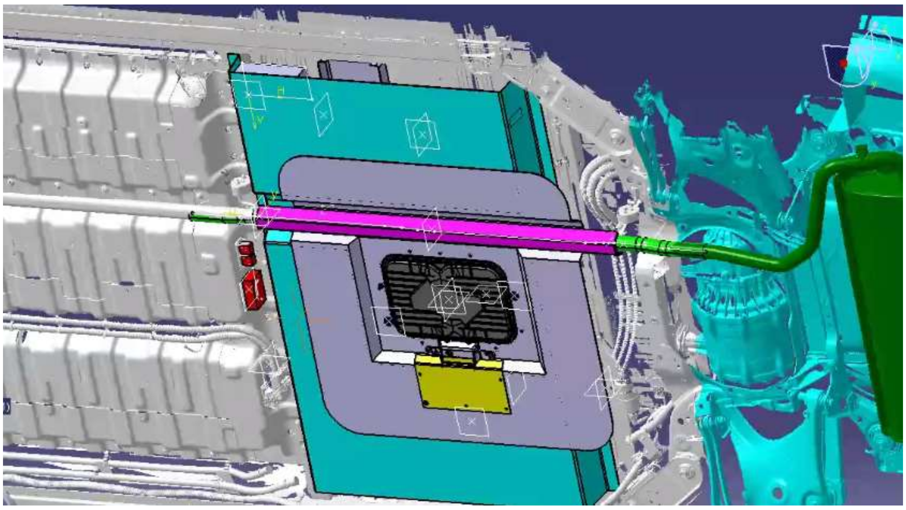

Figure 7: Concept illustration of the revised VA and electromagnetic shield packaging for the LEVC showing positioning behind the traction battery pack and the approach to accommodate the exhaust of the internal combustion engine

4 Design of Taxi Rank

The taxi rank design for the WiCET public demonstration involves some modification to a conventional taxi rank to accommodate the WPT hardware. Apart from the incoming electrical supply to site, this includes LOP system fence and light curtain components as well as power electronic and communications wall boxes for each wireless ground pad.

4.1 Impact of Longitudinal Vehicle Retrofit Position on Ground Infrastructure

The space utilisation efficiency of static wireless systems will be compromised by differing longitudinal mounting positions of the VA system on different vehicles. For wireless charging, the VA needs to align accurately with the GA. If different vehicles have different relative longitudinal VA mounting positions the length of the wireless charging bay needs to be extended, with the worst-case scenario being with the VA mounting position on some vehicles near the front, while on others it is near the rear. In this sort of application dynamic or semi-dynamic wireless charging systems may have an advantage as accurate longitudinal alignment is not required allowing more efficient usage of available space.

4.2 Development of Vehicle Identification Approaches for Back-Office Billing Systems

Vehicle identifiers are encoded into the close-range signalling between the VA and the GA. The GA hardware has an open chargepoint protocol (OCPP) implementation allowing the GA system to interact with a conventional back office. In the demonstration the OCPP vehicle identification will have secondary support from a camera vision recognition system (VRS).

Charging transactions for each GA deployed in a taxi rank may be short duration with limited energy transfer. Consequently, the back-office systems work to aggregate charging transactions from a series of GAs installed in a taxi rank into a single charging station transaction for each visit to the taxi rank that is more meaningful for the user. The vehicle identification approach coupled with OCPP will enable WiCET to deploy a billing and payments system for participating taxi drivers using wireless during the public demonstration phase.

5 Baseline Data Collection

5.1 Data Collection and Reduction

The preparation and private piloting phase of the project included collection of telemetry data prior to vehicle conversion to enable identification of baseline usage behaviours of the vehicles. The data collection systems recorded telemetry parameters from the CAN systems of the vehicles, GNSS positioning data as well as the taxi availability and fare status from the taximeter. A total of five vehicles (three LEVC and two Dynamo) were utilised by 15 taxi drivers over a period of 91 calendar days in normal operation for 391 operational taxi days.

Extensive sets of high-frequency telemetry data have been reduced into a set of allowable summary statuses which together fully describe the vehicle over an entire duration. Table 1 shows a description of the defined allowable states of the taxi vehicles. Each state contains a range of parameters such as durations, distances travelled, speeds, change in state-of-charge, energy. Note: the vehicles in the baselining phase were unconverted, so the “In Rank – Wireless Charging” state is not seen.

Table1: Statuses describing taxi operation

State	Description
AC Charging	The taxi is connected to a public AC charger
AC Home Charging	The taxi is attached to a Mode 2 or Mode 3 home charging outlet.
DC Charging	The taxis is attached to a DC charging system
For Hire – Moving	The taxi is being driven with the “for hire” light on
For Hire – Static	The taxi is stationary with the “for hire” light on
Hired	The taxi fare meter is running (“for hire” light is off).
In Rank – Not Charging	The taxi is located in a recognised Nottingham taxi rank and not charging.
In Rank – Wireless Charging	The taxi is located in a recognised Nottingham taxi rank and wirelessly charging
Non-Work – Moving	The taxi is moving with the fare meter off and the “for hire” light is off.
Non-Work - Static	The taxi is stationary with the fare meter off and the “for hire” light is off.

5.2 Baseline Data Analysis

Nottingham is a medium-sized UK city, which, including suburbs, has a population of approximately 750,000. Within the city there are 31 taxi ranks in 24 defined localities, of which just under half are designated for part-time evening use. The baselining analysis reveals that only a small number of the taxi ranks are used with any regularity as shown in figure 8. The most used taxi rank is Trent Street, which is adjacent to the main railway station and was visited by the five taxis just over 20 times each day. Two other relatively well used taxi ranks are Milton Street and Wheeler Gate which saw over eight and seven visits per day respectively during the baselining period.

If Nottingham, and the usage behaviours of the monitored taxi drivers, is representative of other similar cities, then while there may be numerous defined taxi ranks, actual taxi rank usage tends to be dominated by a small number of key locations. Other taxi rank locations will likely have insufficient usage for a viable business case to exist for wireless charging.

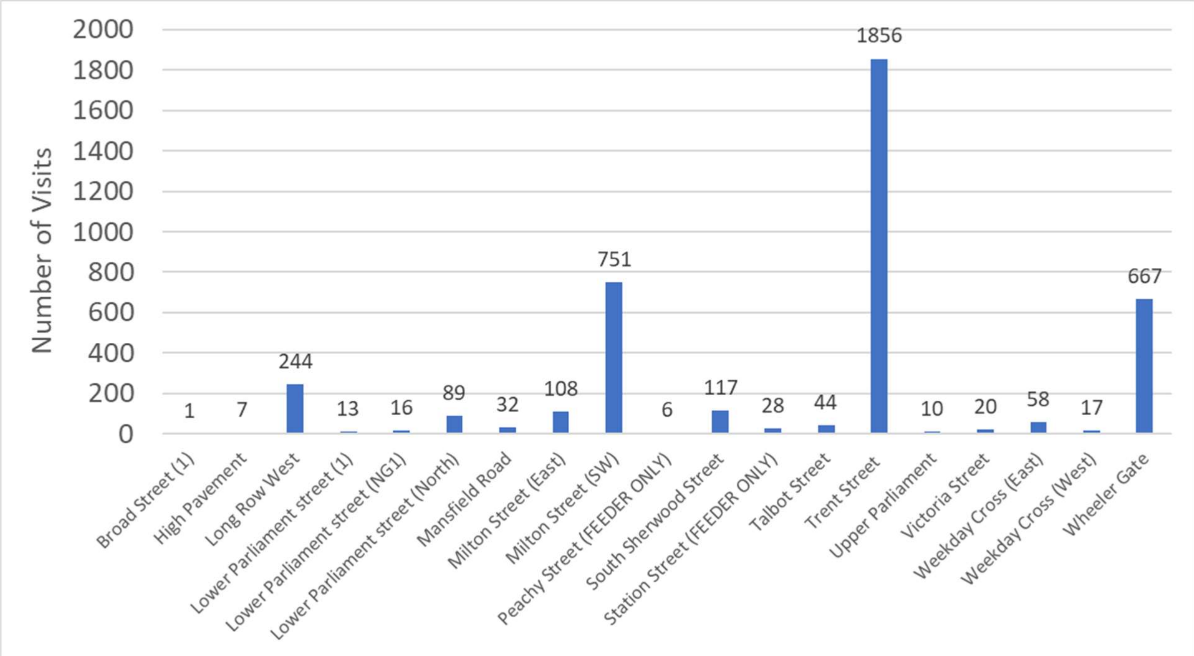

Figure 8: Cumulative visit for each taxi rank in Nottingham during the baselining phase.

For the vehicles and drivers that participated in the baselining phase there were 391 days in which the taxi was driven at least 1 km. Overall the telemetry data shows median and mean daily distances per vehicles of 108 and 126 km respectively – the mean distance is influenced by some days with very high travel distances. The average daily distance travelled is at the limits of, or exceeding, the 100.6 - 126 km pure EV WLTP range (combined and city) of the LEVC [14].

Figure 9 shows the daily travel distances for all recorded taxi days during the baselining phase. For the Dynamo, on over 20% of days the 200 km WLTP EV range[15] would be insufficient for the full day's journey requirement. For the LEVC an achieved range of 100.6 km would be insufficient on 58% of days and additional charging would be required.

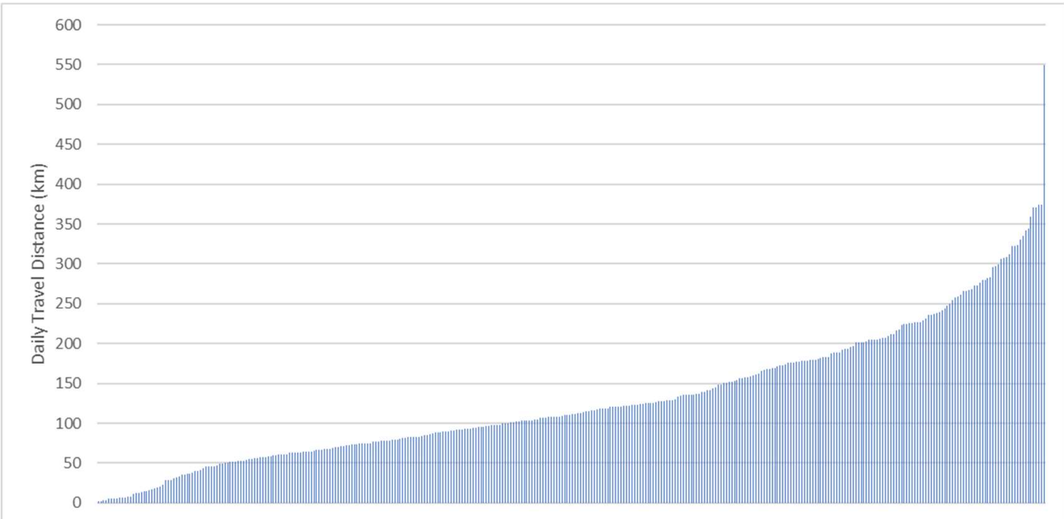

Figure 9: Ordered daily travel distances during baselining phase.

Initial analysis of recorded trips during the baseline phase reveals that they are typically short, averaging less than 5 km overall, and typical journey durations of less than ten minutes - a taxi driver's day will typically be made up of many short journeys. What the baselining data analysis has revealed is that from the taximeter statuses, hired (fare-paying) journeys make up a relatively modest proportion of the journeys, both in terms of total distance (24%) and of occurrences (17%) (table 2). Based on fare rates this is unlikely to be a viable economic income for a driver. It is known that some drivers also work providing bookable private hire services in which the taxi meter is not used and the trip and distance will be recorded as a "Non-work – moving" state. Further research is required engaging taxis drivers with surveys during the main public demonstration phase, however initial indications suggest that a Hackney Carriage Taxi/Private Hire hybrid operation is common. Increasing private hire operation would be expected to impact the economics of wireless charging in taxi ranks and should lead to wider consideration of suitable charging locations and use cases for wireless charging.

Table 2: Breakdown of trip states, distances, and occurrences during the WiCET baselining phase.

State	Description	Average Trip Distance (km)	% of total distance in state	Total occurrences	% of occurrence in state
For Hire – Moving	The taxi is being driven with the "for hire" light on	3.51	30.7	5061	43
Hired	The taxi fare meter is running ("for hire" light is off).	5.94	24.0	2002	17
Non-work – Moving	The taxi is moving with the fare meter off and the "for hire" light is off.	5.79	45.2	4670	40
Overall		4.85		11,733	

6 Next Steps

The WiCET project is scheduled for the main public demonstration to commence in August 2022. Donor vehicles are to be converted during the period Mar 2022 – July 2022 with the taxi rank conversion installation scheduled in July 2022. The public demonstration will run using nine eTaxis (5x LEVC, 4x Dynamo) for four months providing licenced Nottingham taxi drivers the opportunity to try wireless charging technology and engaged to provide feedback on their experience at regular intervals through user surveys.

All vehicles will record telemetry data, and additionally usage and energy delivered through the wireless GAs will be monitored. This will be used to provide evidence for further analysis and business case development for medium cities like Nottingham as well as looking at key drivers and sensitivities when extrapolating for much larger cities with more diverse and complex driver behaviours like London.

7 Conclusion

A key objective of the WiCET project has been to integrate WPT hardware into more than one eTaxi type to show the broader applicability of wireless charging, but also to understand the wider interoperability challenges that begin to emerge attempting to do so. It is possible to engineer solutions on a vehicle-by-vehicle basis, however achieving this cost-effectively at scale is unlikely to be realistic for eTaxis that were not designed to be WPT ready. This is because extra interfacing components are required for control, management, and independent cooling, as well as high levels of intervention necessary for fitting the components, and routing cables and hoses between them. It should be possible to gain considerable advantages to the on-vehicle cost basis if future EVs licenced for taxi use are designed and built with WPT already integrated or “wireless ready” for simplified “bolt-on, plug-in” hardware retrofit.

If static WPT systems are to be used, consistent VA positioning along the length of the vehicle will be required if there is to be efficient use of the streetscape space. This offers a potential benefit for dynamic wireless concepts in addition to charging while the vehicle is moving.

The modelling completed for WiCET so far indicates that an average duration taxi rank visit will deliver less than 1 kWh. Given a typical trip distance is approximately 5 km with more than one trip expected for every visit that occurs to the taxi rank it is expected that the practical and economic opportunity for wireless charging will benefit from higher power classes than are currently defined in SAE J2954.

The future of wireless charging for eTaxis, as well as many other applications, will depend on a simple, efficient infrastructure design. WPT systems will need to avoid additional street-clutter and street disruption, by minimising the size and intrusion of infrastructure components including; wallbox units, LOP systems, passive protection systems and the wireless ground pads in the street.

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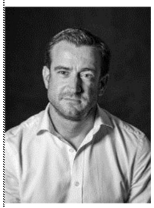

Richard Sander is an experienced engineer and technical programme manager with an extensive background of over 20 years in the automotive industry, developing and delivering new technologies and systems into production, with particular specialism in chassis elements. At Cenex, Richard is a lead project delivery manager for wireless charging and energy systems innovation projects.