WIRELESS POWER TRANSFER FOR ELECTRIC VEHICLES
TASK 26
FINAL REPORT

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Task 26 Operating Agent

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PARTICIPANTS

The task was open to any member country that wanted to join. Participating members were expected to set aside an appropriate amount of time to support activities that may be required in addition to attending meetings.

Member Countries

Task 26 members included the following countries. Because of the long duration of the task, not all countries were represented for the complete duration of the task.

- Denmark
- France
- Germany
- South Korea
- Spain
- Sweden
- Switzerland
- The Netherlands
- United Kingdom
- United States

Companies and Institutes

Task 26 members and final report contributors were representatives of the following companies and laboratories. Because of the long duration of the task, not all companies were represented for the complete duration of the task.

Members	Contributors
BRUSA	Idaho National Laboratory
CIRCE	Institute of Communication & Computer Systems (ICCS)
DTU	INTIS
Floading b.v.	Investment and Development Agency of Latvia (LIAA)
KEPCO	Politecnico di Torino (POLITO)
NTB	TRL
Oak Ridge National Laboratory	U.S. Department of Energy
Qualcomm	VEDECOM
Ricardo	Wireless Advanced Vehicle Electrification (WAVE)
Schneider Electric	
Viktoria (now called RISE)	

Duration

Task 26 was approved during the spring 2014 Hybrid & Electric Vehicle Technology Collaboration Programme (HEV TCP) Executive Committee (ExCo) for a duration of 2 years. During the fall 2016 ExCo meeting, the operating agent requested and was granted a 2-year extension. Listed participants include both initial members and members whose participation was for only a portion of the task's duration.

EXECUTIVE SUMMARY

Wireless Power Transfer (WPT) technologies will enhance the functionality of electric vehicles (EVs) in useable range or hours of use, convenience and even vehicle architecture. Though static WPT charging systems (parked vehicles) are now commercially available in limited numbers, both opportunity (charging at natural stopping points but not parking) and dynamic (charging in motion) systems have also been demonstrated. The deployment of complementary technologies (like self-parking) will invoke new expectations and further development in WPT.

The recent improvements in high power static WPT will change the business model for commercial vehicles, which often require extended daily operating times when compared to light duty vehicles (LDVs). Given the higher power levels and increase in commercial WPT applications, the task also investigated resulting impacts to the electricity grid.

The absence of standards limits WPT commercialization. The lack of international standards has slowed the commercialization of the WPT technologies and limited vehicle product offerings to the public. Even without firm international standards for the technology, research and development (R&D) of high power and dynamic WPT is increasing, as these systems have additional deployment opportunities in the commercial electric vehicle and autonomous vehicle (AV) spaces. The numerous safety and interoperability specifications complicate matters for technology developers because the operating frequencies and power levels may vary by vehicle category, thereby reducing the planned volume for specialized components. By nature, WPT requires 'wireless' communications to ensure safe power transfer, therefore cybersecurity and communications protocols and standards are added to the list of nearly a dozen WPT related standards.

WPT technologies are globally recognized. A multitude of national organizations and major OEMs have performed and continue to perform large scale R&D as well as demonstrations of WPT. From earlier deployments like the dynamic Online Electric Vehicle (OLEV) applications from KAIST, through the EU's FABRIC consortium demonstrations to the planned "Oslo Project" for fleet EV Taxi opportunity charging, the potential benefits of WPT technologies are everywhere. Brief introductions to projects and the findings from each of the member countries as well as substantial projects from other nations are provided in this report.

The scope of this task was very broad, as are the remaining challenges in the WPT field. Previous research and demonstrations conclude that with proper investment, WPT is a viable technology for static, opportunity (quasi-static), and dynamic charging scenarios. Through continued coordinated research, and a balance of negotiated standards and properly integrated technologies, WPT is poised to enable the next phase of e-mobility by advancing the adoption of EVs and AVs as the world looks for sustainable transportation solutions.

1 INTRODUCTION

Wireless charging of electric vehicles (EVs) is inductive or capacitive power transfer across an air gap (see Figure 1). Power electronics convert grid power to high voltage and a higher frequency that is required for efficient wireless power transfer (WPT). Typical operating frequencies are 10 to 145 kHz.

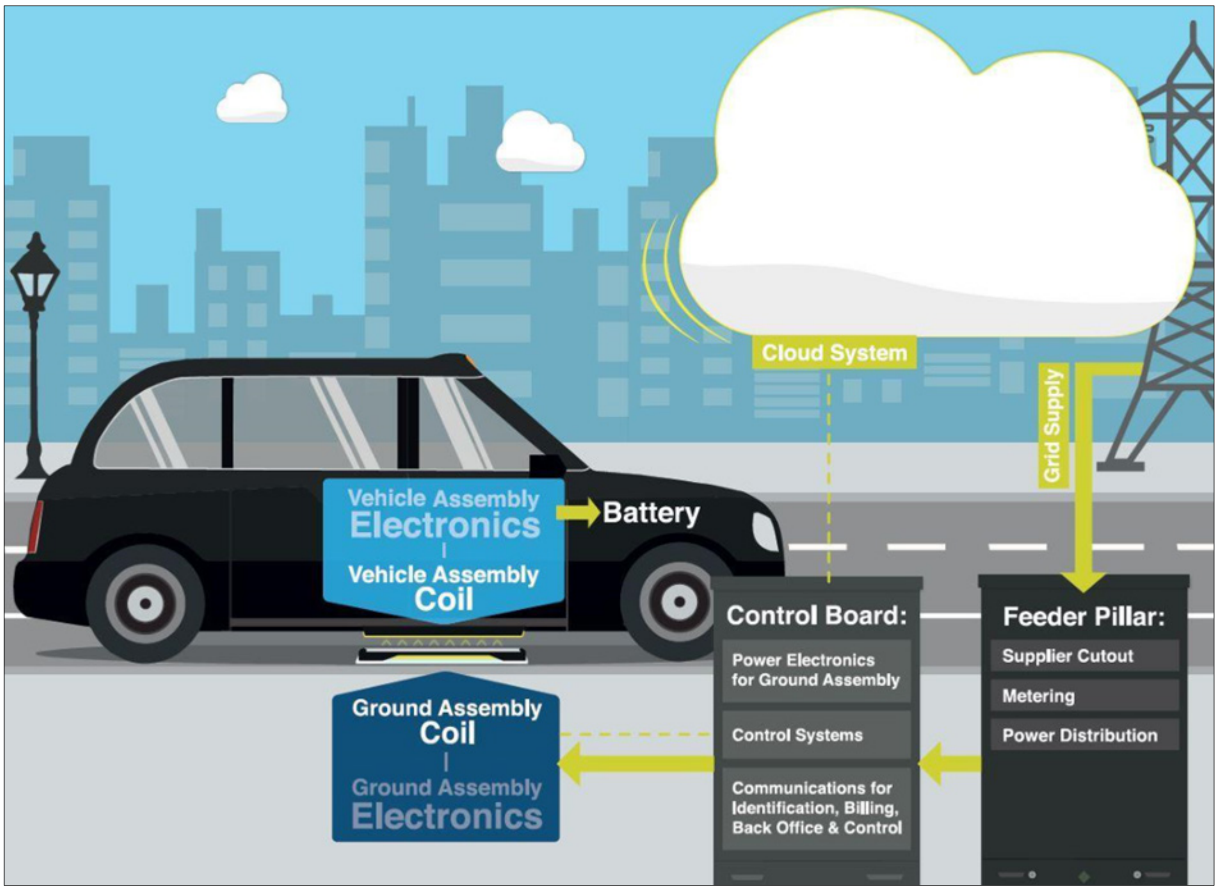


Figure 1. Wireless charging of an EV. (Source: Cenex, Netherlands).

Wireless charging of EVs has the potential to untether EVs from their charger cables and possibly reduce the size of EV batteries. In the future, when vehicles can be charged while in motion, wireless charging has the potential to extend vehicle range for the same battery size used in vehicles today. Research groups in industry, academia, and in national laboratories around the world are working to improve WPT technologies so that EVs can charge by parking over a coupling device (referred to as static charging), by charging at natural stopping points but not parking (referred to as opportunity charging), or even while the vehicle is in motion (called dynamic charging).

However, the standards for WPT vary in different member countries, which limits system interoperability and slows the maturation and adoption of this technology. Task 26 focused on developing a greater global understanding of WPT systems and interoperability through a focused study of WPT technologies being developed in the participating countries. Topics covered by this task included a study of country-based standards (Japan Automobile Research Institute [JARI], Society of Automotive Engineers [SAE], International Organization for Standardization [ISO]/International Electrochemical Commission [IEC]), technical approaches, grid interactions, interoperability, and safety codes for WPT. The focus of the task included provisions to gather information on both passenger vehicle and commercial vehicle applications.

1.1 Objectives

The task addressed many fields of interest in WPT. Areas considered were broad as the task got underway and narrowed in focus as meetings progressed. Task objectives included the following:

- Categorize deployment approaches and requirements for WPT technologies such that participants develop an understanding of what challenges are faced in different countries or markets and what it takes to put this technology into the field in these markets.
- Compare the characteristics of WPT systems being developed in the participating countries, and discuss how to address interoperability concerns.
- Catalog, discuss, and compare standards for WPT in different countries (JARI, SAE, ISO/IEC, etc.).
- Discuss and summarize safety issues regarding misalignment, leakage fields, and debris tolerance and response.
- Catalog potential grid impacts associated with higher levels of WPT.

1.2 Working Method

Task members conducted biannual workshops and supporting conference calls and visited locations of WPT research or deployment activities to gain first-hand knowledge of how this technology is progressing and to inform the committee of new work. Based on information gathered from participating countries, task members identified specific areas of critical interest for off-line research. Collaborators developed conference papers and contributed to ongoing discussions with standards groups.

Task members summarized and shared workshop results among the task participants and presented to the HEV TCP ExCo. The outcome of all discussions in the workshops is a final task report that is available to Task 26 participants, the HEV TCP ExCo, and the public via the HEV TCP website.

1.2.1 Process

The process for how this task operated is as follows.

- Develop an understanding of the challenges faced in various countries or markets.
- Compare current WPT technology development and address interoperability concerns for both static and dynamic systems.

- Identify safety issues arising from misalignment, leakage fields, and debris tolerance and response.
- Establish a repository for the data collected and links to other activities available to the members of the task.

2 APPROACH

The approach used for Task 26 is as follows.

- Coordinate with member countries to identify relevant topics, studies, and demonstrations in the area of WPT of EVs.
- Identify subject matter experts and cutting-edge research in the topics areas to provide further input into task activities.
- Conduct biannual task meetings to visit WPT research entities/activities around the world to gain first-hand knowledge as part of learning and understanding the technologies and to hold in-depth discussions among subject matter experts in the WPT topic areas.
- Inform the ExCo of the work in WPT by both the task and the industry.

This approach allowed task members to gain insight into the research from multiple perspectives such as the SAE standards chair, equipment manufacturers, original equipment manufacturers (OEMs), the European Union (EU) policy officer, and researchers studying the impact of electromagnetic fields (EMFs) on human health.

3 WIRELESS CHARGING TECHNOLOGY OVERVIEW

As shown in Figure 1, a wireless charger consists of two electrical coils, one on the ground and another on the vehicle and associated power conversion systems. Grid voltage is rectified to direct current (DC) voltages sent through a high-frequency inverter and a resonant network, which produces a high-frequency alternating current (AC) voltage supplied to the ground side/primary/transmitter coil. The power is transmitted through the airgap to the vehicle side/secondary/receiver coil, which receives this power through a resonant network and rectifies it to DC to be fed to the vehicle battery. Figure 2 shows these power conversion and transmission stages for a wireless charging system.

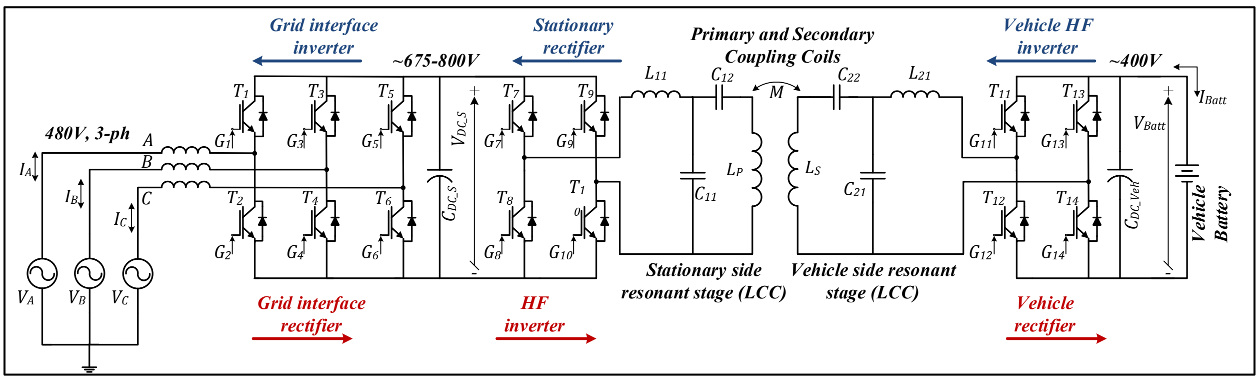


Figure 2. Bidirectional wireless charging circuit diagram with three-phase grid connection. (Source: Oak Ridge National Laboratory, United States).

The ***Grid interface inverter/rectifier*** can be single-phase or three-phase depending on power levels. Figure 2 shows a three-phase grid interface inverter/rectifier with three phase legs and six switches. For a single-phase system, only two phases with four switches would be needed. The main function for this power conversion system is to convert AC grid voltages to variable DC voltages while showing high power factor to the grid and not injecting harmonics into the grid connection.

The ***High Frequency inverter/stationary rectifier*** converts the DC voltages into high-frequency square waves, typically at 85 kHz. Zero voltage switching and zero current switching is the method of turning the switches on and off while either the voltage or the current is zero. This results in higher efficiencies and lower electrical noise.

The ***Stationary side resonant stage*** acts as a filter for converting the square wave into a sinusoidal AC waveform generated by the high frequency (HF) inverter/stationary rectifier to be transmitted by the primary coupling coil using resonance.

The ***Primary coupling coil*** is the stationary coil on the ground. It can be embedded in the pavement/concrete or can sit on the ground depending on the design.

The ***Secondary coupling coil*** is placed on the underside of the vehicle. As it starts lining up with the primary coupling coil, power starts to transfer.

The ***Vehicle side resonant stage*** is a similar tuning circuit as the primary side tuning circuit and functions the same way. In the charging mode, it generates a low impedance path for the voltage received by the secondary coupling coil.

The ***Vehicle HF inverter/vehicle rectifier*** is the rectifier that converts high-frequency AC waveforms received through the resonant network to DC.

Several parameters affect wireless charging design and efficiency. Because this area of research is still in its infancy, multiple solutions are being implemented to demonstrate the effectiveness of wireless charging under a wide range of conditions. One such parameter is the air gap, which is the distance between coils. This has been tested at up to 20 cm. Another parameter is coil design, of which the three primary geometries are D-coil, circular, and square.

Wireless charging is being developed in both stationary and dynamic applications. Dynamic applications are testing charging at speeds between 5–60 miles per hour. Wireless charging technology is also being developed at different power levels. For light-duty vehicles (LDVs), there are efforts to wirelessly charge at power levels between 3–22 kW with plans to move beyond 100kW. ORNL has partnered with Hyundai on a project targeting 300 kW for a LDV. For medium-duty vehicles (MDVs), such as buses and trams, efforts are being made at power levels between 22–250 kW and some transit and Class 6 vehicles are planning to charge at 500 kW. For heavy-duty vehicles (HDVs), such as trams, light rail, and Class 7 and 8 trucks, power levels are between 60–1,000 kW.

Other aspects affecting development of this technology are cybersecurity, safety, grid impacts, and standards. Grid impacts are an important challenge. Task participants catalogued potential grid impacts associated with higher levels of WPT and identified barriers including management of storage assets, business/compensation models, and interoperability. Charging impacts differ according to traffic, season, location, and charging installation properties. Cybersecurity for WPT is continuously evolving as threats change. Areas of emphasis for WPT cybersecurity include exploring vulnerabilities, performing risk analyses, mitigating risks, and performing formal security analyses. Regarding standards, there are two SAE recommended practices related to this area, SAE J2954-1 for LDVs and SAE J2954-2 for HDVs. SAE Recommended Practice J2954 establishes an industry-wide specification that defines acceptable criteria for interoperability, electromagnetic compatibility, EMFs, and minimum performance, safety, and testing for wireless charging of electric and plug-in electric vehicles. There is substantial OEM representation in the development of these recommended practices.

4 CURRENT STATUS OF WIRELESS CHARGING

Faraday demonstrated inductive power transfer in the 19th century, but the demands of WPT in today's transportation sector are more in-line with the visions of Tesla (the inventor, not the car company). When you do an internet search for "wireless charging", the first item to pop-up may be a cell phone or an electric tooth-brush, but WPT applications to power EVs were in development long before these items were invented. From 1996 to 2003 General Motors produced the EV1 which used an inductive paddle and slot charging system. The first dynamic inductive power transfer system was developed up to 8 kW for electric highway systems by Lawrence Berkeley National Laboratory and University of California, Berkeley in 1978[i]. In 1995, a wireless inductive power transfer system was adapted to electrified monorail systems to power roadway based electrical vehicles[ii]. Conductix Wampfler and University of Auckland manufactured the first dynamic wireless charging system[iii]. Other research institutions, including Oak Ridge National Laboratory, have been exploring wireless energy transfer characteristics for very high power and dynamic charging systems[iv].

There have been numerous experimental deployments of static, quasi-static (also referred to as opportunity charging where vehicles are stopped but not parked, such as at a bus stop), and dynamic WPT systems for on-road vehicles. Typically, these were done in controlled environments to ensure accurate experimental data gathering and safety. Each type, or mode, of WPT requires different considerations for safety & various electric or electric magnetic field (EMF) emissions, power transfer levels, coil alignment (required for coil coupling & efficient power transfer) and even communications. The safety of these systems in the public domain is a critical consideration as the fields generated are invisible and there are few agreed upon international standards for exposure limits to the various types of stray field emissions.

Due to the wide scope of possible applications and the cost of developing and deploying a network of WPT systems, one of the first commercially available products for EV charging was an aftermarket static system from Evatran called Plugless Power, from the initial offering for the Nissan Leaf EV, the Plugless Power product offering now includes the first generation Chevy Volt and Tesla model S. The first OEM option to offer a static mode charging was from BMW using WiTricity technology in 2018. This first offering was heavily restricted both in number of customers allowed and the region offered. In 2019 this offer was expanded to include limited customers in California.

Due to the cost of these systems on both the grid-side and the vehicle side, developing the proper market for this technology is also an area in need of study. Much of the focus of current R&D is to enable this technology for safe and robust deployment into the marketplace. The current rise of small autonomous shared vehicles has highlighted the need for an autonomous charging capability, this is due to the fact that AVs are predominantly EVs. The WPT platform provides this capability and the additional ability to provide a low maintenance operation as there are no components of the system which come into contact with the customer. Effort must be undertaken to highlight the use of WPT in the public domain to education the public as to the additional benefits and opportunities provided by this technology.

5 TASK-SPECIFIC TOPIC DISCUSSIONS

Task 26 participants held two workshops per year with each workshop focused on a particular aspect of WPT. The primary benefit was to convene world-wide experts to share WPT cutting-edge information, identify unresolved issues, and discuss a path to resolve said issues. Among other benefits, participation in workshops broadened and deepened attendees' expertise of WPT and related technologies and strengthened working relationships among international collaborators. When possible, workshops were held in conjunction with a conference, an event of relevance to WPT, or with an HEV TCP ExCo meeting. The workshops also included site visits or demonstrations of local WPT sites.

The following subsections describe task-specific findings on key topics associated with WPT of EVs.

5.1 Leading Applications

During the course of Task 26, task members and stakeholders participated in demonstrations during task workshops and in presentations detailing WPT technologies and research and development (R&D). Many leading applications of current WPT technologies were covered during these demonstrations and presentations, including multi-country applications and those at the country level. A leading multi-country application was the EU's Feasibility analysis and development of on-road charging solutions for future electric vehicles (FABRIC), which was co-funded by the EU's 7th Framework Programme (FP7) for research, technological development, and demonstration. The FABRIC consortium consisted of 25 partners from 9 European countries. Partners were from both commercial automotive suppliers and the technology supply and development chain. FABRIC's main objective was to conduct a feasibility analysis of on-road WPT technologies. As part of FABRIC, Qualcomm Halo (acquired by WiTricity in 2019), VEDECOM, and Renault demonstrated their dynamic wireless charging system at up to 20 kW at highway speeds on a 100 m test track.[v] For more information about FABRIC and its demonstrations, see Section 5.7, "Dynamic Wireless Charging."

Other country-specific applications were discussed or presented during Task 26 workshops. In the United States, multiple WPT applications are available for MDVs and HDVs. Wireless Advanced Vehicle Electrification (WAVE) offers a commercially available WPT system of 50 and 250 kW. WAVE worked with an electric bus OEM, BYD, to deliver range-extended battery electric transit buses to the Long Beach (California) Transit Center. The buses perform opportunity charging at 50 kW for 15 minutes to extend their drive time. WAVE has a commercial 250 kW WPT infrastructure running in Antelope Valley, California, serving the Antelope Valley Transit Authority.[vi] Momentum Dynamics has WPT applications in multiple locations, including Wenatchee, Washington, for Link Transit (200 kW); Howard County, Maryland, (50 kW); and Chattanooga, Tennessee's CARTA transit system (200 kW).[vii] The National Renewable Energy Laboratory (NREL), in Colorado, is performing an ongoing demonstration of a wirelessly charged electric shuttle on its campus. A Zenith Motors van was modified with Momentum Dynamics' wireless charging system. The van provides fully electric on-demand service with a battery capacity of 62.1 kWh (it retains the option of using the original on-board conductive charger at 6.6 kW).[viii]

In the LDV space, HEVO Power installed a WPT station pilot in Rotterdam, The Netherlands, in a semipublic municipal area for use by LDVs. The station uses HEVO's wireless technology ground assembly that is flush-mounted with the parking surface. BMW launched an induction charging pilot program for its 530e sedan in Germany in 2018 and in 2019 began looking for 200 interested drivers in the United States. The pilot is available in California for leased vehicles in specific qualifying residential areas across 13 counties. The wireless charging system provides static charging of 3.2 kW with an 85% efficiency rate capable of fully charging the vehicle in 3.5 hours. Plugless Power has a system for Tesla, Nissan, and Chevrolet to be retrofitted for wireless charging,[ix] and Honda introduced a wireless vehicle-to-grid (V2G) system that leverages WiTricity's Drive 11 wireless charging platform.[x] At the fleet level, the city of Oslo in Norway is striving to make their taxis emission-free by 2023. In support of that goal, Fortum and Momentum Dynamics will be installing a wireless charging infrastructure for the city's electric taxis as part of a technology demonstration. Momentum Dynamics' system has been proven on buses and includes both the ground and vehicle assemblies, ensuring interoperability between the ground and vehicle coils. The implementation is intended to be 100% fully automated opportunity charging at taxis stands. With no planned conductive charging, the taxis will always be available and the battery will always be in the preferred state of charge. The number of chargers and taxis to be included in the trial implementation is still being considered; however, deployment is scheduled to begin in the first half of 2020.[xi]

The Oslo project is being seen as a model for high-use EVs. Momentum Dynamics reports that many other cities around the world have expressed an interest in replicating the "Oslo Model" for electric taxi fleets. Note that the same model can be used to support transportation network providers like Lyft and Uber with the capacity to move their fleets to electric drive and, similarly, to support mission-critical last-mile delivery systems.

5.2 Power Levels and Frequencies

Many industries have shown that independence from manufacturers is key to having open market access (e.g., to car OEMs and charging equipment manufacturers). A necessary condition to grow these markets of opportunity charging for all parties is for all parties to not compete on standards. The recommended power and efficiency ratings of J2954-1 are given in Table 1.

Table 1. WPT power classifications of static WPT for LDVs (Reference: SAE J2954 Nov 2017)

	WPT Power Class			
	WPT1	WPT2	WPT3	WPT4
Maximum input Volt Amps	3.7 kVA	7.7kVA	11.1kVA	22kVA
Minimum target efficiency at nominal x,y alignment	>85%	>85%	>85%	TBD
Minimum target efficiency at offset position	>80%	>80%	>80%	TBD

SAE J2954-1 recommends a single nominal frequency of 85 kHz; however, the vehicle assembly (VA) and ground assembly (GA) should always be operated within the frequency range of 81.38 to 90.00 kHz. For systems using frequency tuning to compensate for various operating variations, the operating frequency must remain in this range. This frequency range is defined for the power classes WPT1 – WPT4. For faster charging with charging levels of more than 100 kW, a lower switching frequency of about 20 kHz is more favorable.

However, wireless charging approaches are still in development, and interoperability in the WPT industry is still not fully standardized. The focus for now is to meet the parameter ranges of potential market parties. The EU FABRIC project defined the following interoperability parameters, complete with their existing performance range:

- Operating frequency (15–150 kHz, with a tendency towards 81.38 < ~85 kHz < 90)
- Magnetic compatibility (B, micro T)
- Power levels (kW) WPT1 = 3.7; WPT2 = 7.7; WPT3 = 11.1; WPT4-22
- Single coil: 30; 50; 100; 140; and (multi coils) up to 500 kW; also tests at ~1.5 MW
- Misalignment tolerance (approximate max = 75 mm; see "efficiency levels")
- Nominal air gaps (z = 50–250 mm; z1 = 100–150; z2 = 140–210; z3 = 170–250)
- Various mounting requirements for primary pad (material choices)
- Vehicle pad position (car OEM's agreement)
- Efficiency levels (focus in between 85%–96%)
- Electromagnetic compatibility (EMC) and EMF regulatory compliance (International Special Committee on Radio Interference [CISPR], European Telecommunications Standards Institute [ETSI]) B < 6.5 micro T–28 micro T)
- Radiation protection according to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the "Standard of Building Biology Testing Methods," SBM-2015
- Communications between vehicle and charging infrastructure (beyond ISO 15118 and WLan consensus)

Additionally, the Task 26 group also looked at the following:

- International Telecommunication Union allowance for above harmonic allowance slots for WPT working frequencies (15–150 kHz); Supra harmonics, radio frequency pollution ETSI 300, 300 FCC47; competing opposition by telecomm/broadcasting industries, see Section 5.4, "Safety"
- Grid standards (Workshop 7–Grid Impacts, Newcastle)
- Data security, for example, Intelligent Transport Systems (ITS) (Versailles 2.3)

5.3 Interoperability and Standards

Mass introduction of commercial wireless charging solutions in the EV market is still pending except for BMW's offer as an option. For the lower power levels (3.3, 7.7, and up to 11 kW) performing static charging, the industry has succeeded in separating the supply of the primary and secondary coil(s), both technically and commercially. Recommended practices such as SAE J2954 have been sufficiently developed for manufacturers to interface successfully at the charge points. The topology and material of the coils is compatible for single-coil and multi-coil designs; however, consensus is missing for other designs.

At the higher power levels (22–1,000 kW) for MDVs and HDVs, new standards are also being discussed among parties. Until now, the supplier of these wireless charging solutions have delivered both the primary and secondary coils and the communication solution. Therefore, the bus and truck OEMs have continuously been requested to open their controller area network bus access for WPT suppliers to create a seamless interface between systems. This introduces a cybersecurity vulnerability that is discussed in later sections.

For communications, roaming concepts have been developed successfully for conductive charging solutions as there are now ISO 15118 and Open Charge Point Protocol (OCPP). These standards could be deployed in the wireless world as well to arrange recognition, positioning, smart charging, billing, and accounting.

It is also expected that although HDVs, transit buses, and rail applications will have many of the same parameters for interoperability, safety, EMC, and efficiency, the exact values of those parameters, as well as the parameters for coil(s), vehicle, parking space geometries, and number of phases, may be different. For this reason, a separate HDV, transit bus, and rail document is being created to address the extension of the light-duty principles into this space. Document SAE J2954-2 is still under construction.

The development of SAE J2954-2 will be parallel but remain somewhat behind the J2954-1 Light-Duty Guideline in time to take advantage of the significant work going into the Light-Duty guideline. The SAE J2954-2 Heavy-Duty document will be a separate effort to avoid unnecessary delays in the Light-Duty Guideline required to reconcile and include the HDV requirements.

Wireless charging of HDVs, transit buses, and rail-based EVs pose a number of different challenges for standardization compared with those encountered in supporting LDVs. Some key differences for HDV wireless charging are as follows.

- Power levels are higher, from 22 to 1,000 kW and beyond in the future.
- High power levels are often accompanied by lower operating frequencies (~20 kHz) than for LDV cases (which tend to be at 85 kHz) to better balance high temperature, electronic switching losses vs. coil magnetic and wire loss at these higher power levels.
- Coil geometries are expected to vary from LDV cases and may include multiple power transfer coils with multiphase arrangements on the primary and secondary side to accommodate the higher power level and redundancy for reliability and availability of vehicles.
- HDV parking space geometries differ greatly from LDV cases and are not expected to coexist in the same space with LDV charging spaces.
- Ground clearance will, in general, be greater than LDV cases. However, for example, buses with air-controlled suspension systems could accommodate lower gaps with their “kneeling” facility along the z-axis.
- Rail (streetcars) and transit bus applications may share charging space and equipment.

- EMC/safety requirements and their application will probably differ from LDV cases with more attention to “keep out” areas and greater hazards available with high ground clearance.

Interoperability topic areas and comparison of standards for static solutions are include in Table 2.

Table 2. Interoperability topic areas from SAE J2954 covered in Task 26 workshops

Included in Task 26 Workshops	Subjects mentioned in SAE J2954-1	Relevant section in this report
	Alignment and component location	5.3.1
✓	Power transfer levels	5.3.2
✓	Center frequency operation	5.3.3
✓	Safety issues	5.3.4
	Communications	5.3.5
	Data security	n/a

The ✓denotes topics that received an interoperability label in the Task 26 group during the workshops.

Enthusiastic R&D for dynamic wireless charging is accelerating at many laboratories and test locations worldwide, and the affordability of the concept has already presented economical and (therefore) political challenges. Therefore, the next logical step to define interoperability for dynamic wireless charging is still undetermined.

A new development is a bidirectional charging option in which both the grid and the vehicle can provide each other with energy. At locations where distributed energy production and consumption meet each other, smart charging concepts are in development. A main concern for this technology is working around how loads in congested utility service areas would be met. In areas where vehicle batteries would be discharged to support grid energy, the decline of the battery life has to be taken into account.

5.3.1 Alignment and Component Location

SAE J2954 recommends triangulation for both manual and (future) autonomous alignments. Misalignment causes significant loss in energy transfer efficiency. Low-power fields from three points around the center of the WPT help to adjust the vehicle to an optimum alignment before the energy transfer process starts. Providing both mechanical and visual alignment features on the vehicle so that less skilled drivers are able to properly position vehicles to charge using the WPT technology will help speed up commercial adoption of WPT on EVs.

Coil gap (“z”) has been defined up to 250 mm (10 in.) as well as side-to-side tolerances of 100 mm (4 in.) in the SAE J2954 Recommended Practices document. Although SAE J2954 provides a physical configuration, how the driver achieves the optimal alignment can vary. The tools and features the OEM provides to the driver to ensure the alignment of vehicle and ground coil is within tolerance is a method of differentiating their product from others. Many of the vehicle offerings already have automated parking or parking assist features which distinguishes their product among consumers. These already designed and implemented features can be leveraged by wireless charging systems to facilitate optimum alignment before the energy transfer process starts.

The vehicle OEMs have discussed what position on the vehicle they will recommend for deploying this technology. SAE J2954 defines the ground coil location in a parking spot. The alignment capability should facilitate autonomous driving including (autonomous) smart charging and opportunity charging.

HDVs that already see a positive WPT business case will still be equipped with both primary and secondary coils and other charging equipment by the same manufacturer. In these cases, the vehicle manufacturers could be more cooperative by providing access to their controller area network bus for these wireless charging solutions to get more optimal charging operation. Fewer work-arounds could result in smoother charging processes that are less vulnerable to malfunctions.

5.3.2 Power transfer levels

Interoperability achievements of static WPT for LDVs so far (supported by Recommended Practice SAE J2954, 2016) are shown in Table 3.

Table 3. Interoperability achievements of static WPT for LDVs

Ground Assemblies	Vehicle assemblies (VA)							
	VA WPT1 (<3.3 kW)		VA WPT2 (< 7.7 kW)			VA WPT3 (< 11 kW)		
	Z1	Z2	Z1	Z2	Z3	Z1	Z2	Z3
GA WPT1	+	+	GAlimits	GAlimits	GAlimits	GAlimits	GAlimits	GAlimits
GA WPT2	VAlimits	VAlimits	+	+	+	+	+	+
GA WPT3	VAlimits	VAlimits	+	+	+	+	+	+

Legend:

Zi	air gap levels according standard
+	agreed standard
VA limits	Issues not solved yet for standardization at the vehicle assembly
GA limits	Issues not solved yet for standardization at the ground assembly

The inductive power levels tend to align with conductive charging equipment power levels (e.g., IEC 61851, SAE J3069, and J1772).

Higher power classes above WPT3 have not yet resulted in a standardized interoperability range. For HDVs, the suppliers of the WPT equipment support both the vehicle assemblies (VA) and the ground assemblies (GA).

5.3.3 Center Frequencies Operation

Operation frequencies in WPT range from 15 up to 150 kHz. They tend to focus towards 81.38 kHz < ~85 kHz < 90 kHz as observed in the Task 26 workshops.

Over the duration of the task, a new issue with super harmonics arose in several countries. The WPT of EVs could interfere with the radio/broadcasting spectrum. The broadcasting/telecom industry claim their existing rights at the frequency band and try to increase demands from local authorities to filter the interference of the WPT industry. New rules are being considered that could influence the business case for WPT solutions.

5.3.4 Safety issues

Standards exist to meet safety demands.

ISO 19363, "Electrically propelled road vehicles -- Magnetic field wireless power transfer -- Safety and interoperability requirements," defines the requirements and operation of the on-board vehicle equipment that enables WPT. The electric vehicle communication controller sends the following parameters for service selection:

- EV power circuit power class
- Maximum receivable power
- Maximum secondary (on vehicle) device ground clearance
- Minimum secondary device ground clearance
- Minimum operating frequency
- Maximum operating frequency
- Type of geometry of the secondary device
- Circuit topology
- Fine positioning methods
- Pairing methods
- Initial alignment check methods
- Manufacturer identification

The electric vehicle communication controller expects corresponding information from the supply equipment communication controller, according to IEC 61980-2.

Standard developments: An extended comparison of the developing standards was presented at Workshop 4 (Rotterdam). A short list of standards follows:

<u>IEC 61980: EV WPT systems</u>

Part 1: General requirements (July 2015)
Part 2: Specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to WPT systems
Part 3: Specific requirements for the magnetic field power transfer systems
Part 4: Specific requirements for the electric field power transfer systems
Part 5: Specific requirements for the microwave power transfer systems

<u>ISO 19363: Electrically propelled road vehicles -- Magnetic field wireless power transfer -- Safety and interoperability requirements</u>

<u>ISO 15118: Road vehicles – Vehicle to grid communication interface</u>

Part 6: General information and use-case definition for wireless communication
Part 7: Network and application protocol requirements for wireless communication
Part 8: Physical layer and data link layer requirements for wireless communication

SAE J2954: Wireless Charging of Electric and Plug-in Hybrid Vehicles - light duty (May 2016)

SAE J2954-2 for heavy duty vehicles (in development)

SAE J1773: Electric Vehicle Inductively Coupled Charging (June 2014)

UL 2750: Temperature issues for electronic devices

IEC 63110: management (dis)charging infrastructure and communication gives the development planning in Figure 3.

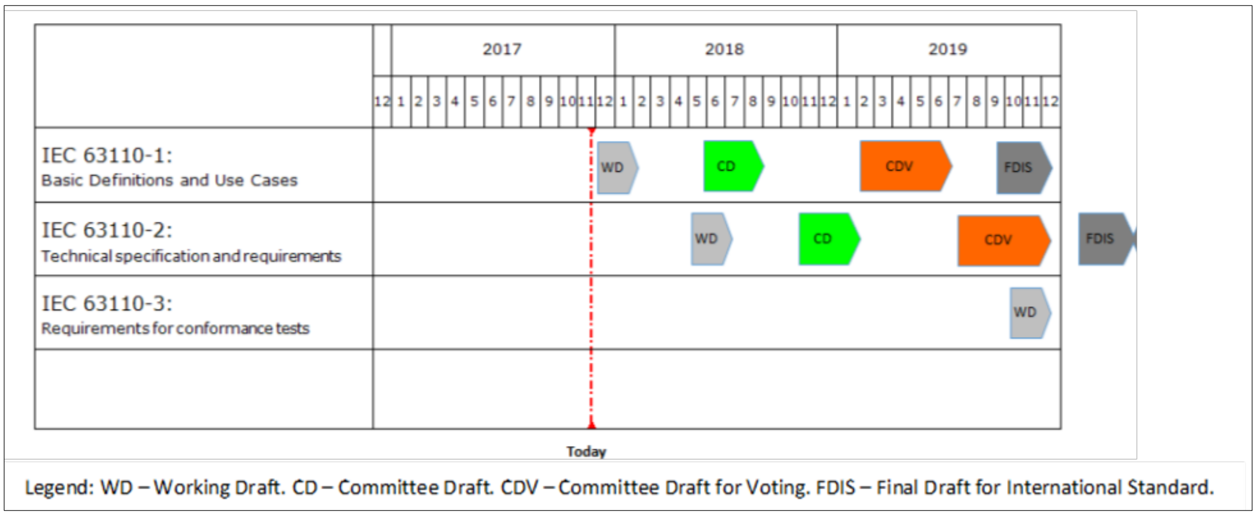


Figure 3. Development planning timeline for the parts of IEC 63110.

For high-power charging at extremely fast charging levels of 350+ kW, a wireless solution can provide safety benefits and eliminate the need for drivers to handle heavy, inflexible charging cables.

The international special committee on radio interference has provided guidelines for EMC, immunity, and vehicle interfaces. CISPR Guidelines 10, 16, and 25 address frequencies between 9 kHz and 18 Ghz for vehicles, boats, and internal combustion engines.

5.3.5 Communications

The operation process and phases of the wireless charging system's use are covered by IEC 61980-2, "Electric vehicle wireless power transfer (WPT) systems - Part 2: Specific requirements for communication between electric road vehicle (EV) and infrastructure" (see Table 4).

Table 4. IEC 61980-2 requirements for communication

Operational Phase	Definition	Additional Applicable Standards
Approaching:	EV detects the supply equipment communication controller communication system	
Recognition:	Unit controller selects charging spot	IEC 61980-1, "Electric vehicle wireless power transfer (WPT) systems - Part 1: General requirements"
Recognition:	Communication is set up	ISO/IEC 15118 series
Fine positioning:	Sequence describing how EV moves from near the supply device to parking	
Positioning methods:	Command and control support several positioning methods	

In addition to communication between the vehicle and the GA, there are more levels of communication between the vehicle and the "environment." Figure 4 shows the different communication levels.

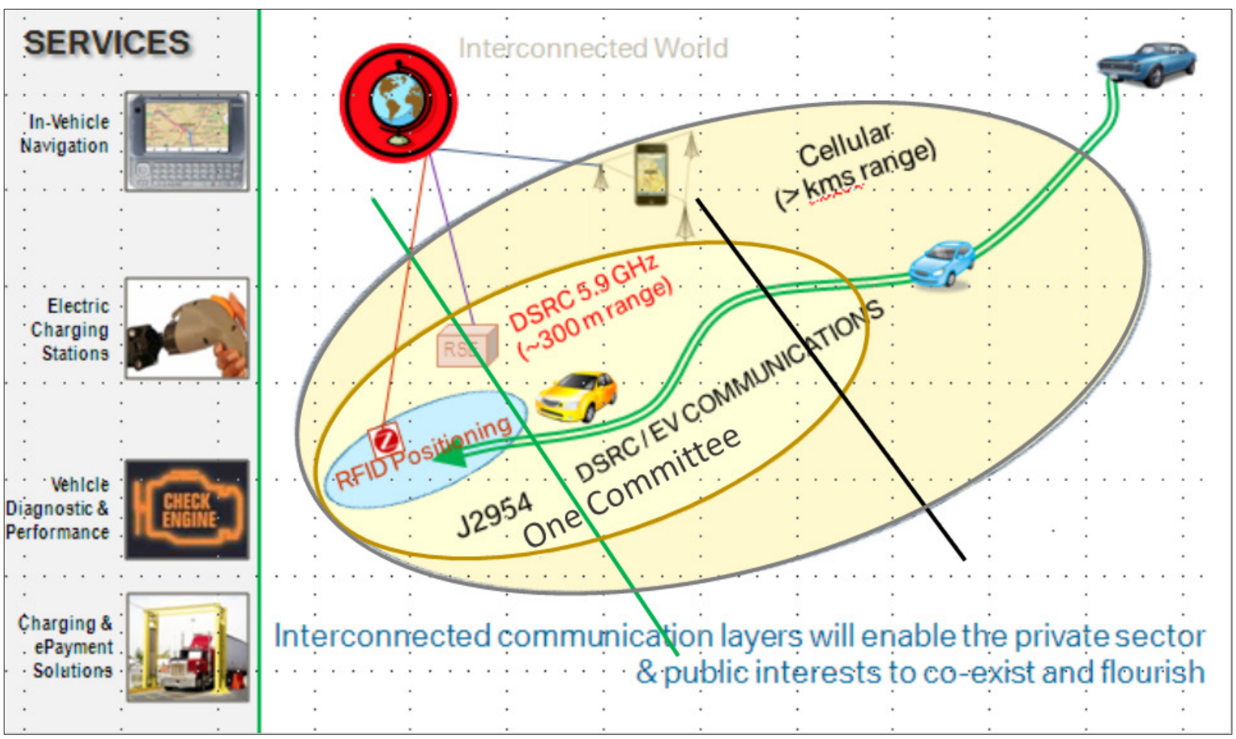


Figure 4. Levels of communication between the vehicle and the environment.

Integration of the charging infrastructure communications and the controller area network bus of a vehicle is now moving forward after several years of hesitation by vehicle OEMs. For example, buses can now use their suspension system to adapt the bus to the desired gap between the primary and secondary coils.

Earlier, WPT system suppliers had to develop "external" devices to the vehicle to adapt the optimal power transfer gap (z-axis). Another development is monitoring of the expected up-time by bidirectional communication of the state of charge status and the data of the battery management system (BMS) by a dual line.

5.4 Safety

The fifth Task 26 workshop focused on the safety of WPT systems. This workshop took place from October 5–6, 2016 in Knoxville, Tennessee, United States. Speakers were sought who have good insight into both the technical and practical challenges associated with the electromagnetic (EM) fields of wireless charging systems and the safety implications of these technologies. With support from the task members, participants reviewed safety from various perspectives.

5.4.1 Key Findings

Discussions were focused on exposure to EM fields from wireless charging systems. Health concerns are generally over thermal effects, electrostimulation, and effects on implanted medical devices. Various organizations regulate the magnetic and electric field exposure limits. Among these, the American Conference on Governmental Industrial Hygienists (ACGIH) defines threshold limit value and the biological exposure index, and these guidelines are mostly followed by government organizations. Limitations defined by ACGIH are given in Figure 5. Note that exposure values are spatially averaged over an area equivalent to a vertical cross section of the human body.

Frequency	Electric Field Strength, E [V/m]	Magnetic Field Strength, H [A/m]
30 kHz–100 kHz	1842	163 [A/m] = 204.4 [µT]
100 kHz–1 MHz	1842	163/f [A/m] = 204.4/f [µT]
1 MHz–30 MHz	1842/f	163/f [A/m] = 204.4/f [µT]

Figure 5. Electric and magnetic field exposure limitations defined by ACGIH.

When the wavelength of the radiation is equal to the dimensions of the human body (1 to 2 m range), then the efficiency of the absorption is maximized, requiring the lowest permitted exposures. E-field and H-field limitations as a function of the frequency (and wavelength) are given in Figure 6.

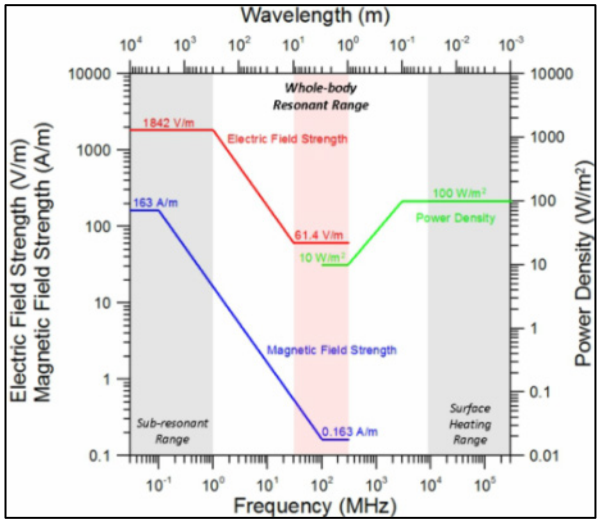


Figure 6. Electric and magnetic field exposure limitations as a function of frequency defined by ACGIH. (Source: [ICNIRP guidelines])

The Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Institute (ANSI) use IEEE C95.1-2005 for radio frequency and microwave frequencies (3 kHz to 300 GHz), which can be used for WPT systems. Furthermore, the Occupational Safety and Health Administration (OSHA) has the OSHA 29 CFR 1910.97, which is based on the 1966 ANSI standard (outdated). This OSHA requirement is only advisory and not regulated. The ICNIRP guidelines limit the electric and magnetic field exposure for 0–300 GHz. SAE J2954 first adopted ICNIRP 2003 guidelines but then relaxed the limits to the ICNIRP 2010 guidelines.

Limitations of the ICNIRP 2010 guidelines are given in Figure 7. Figure 8 shows the limits when there is an implanted medical device or pacemaker in place.

Quantity	ICNIRP 2010 General Public Reference Level Regions 2 and 3 (Peak field strength)
Magnetic field	27 µT or 21 A/m (for 3kHz to 10MHz)
Electric field	83 V/m

Figure 7. EMF exposure standard: Reference levels[xii].

Quantity	ICNIRP 2010 Magnetic Field Limits for implanted medical devices / pacemakers Regions 2 and 3 (Peak field strength)
Magnetic field	15.0 µT or 11.9 A/m (for 3kHz to 10MHz)

Figure 8. EMF exposure standard: Reference levels for implanted medical devices (based on AAMI/ISO 14117-2012 Appendix M).

For wireless EV charger systems, SAE J2954 mainly describes four geometric areas as shown in Figure 9. By using these divided regions, SAE J2954 safety limits are shown up to 11 kW wireless EV charging in Figure 10.

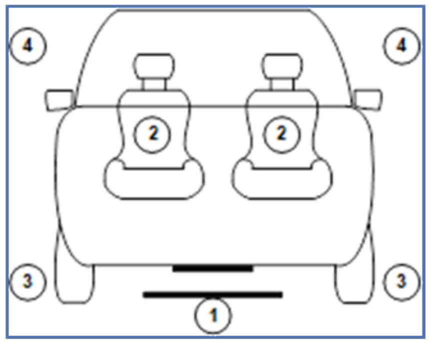


Figure 9. Regions for measurements of field strength as defined by SAE J2954.

Limits	Region	Magnetic field strength H (A/m)	Magnetic flux density B (μT)
ICNRP Standards	2, 3, 4	21	27
Pacemaker / IMD	2, 4	11.9	15

Figure 10. EMF Reference levels for SAE J2954.

IEEE maximum permissible exposure (MPE) limits for magnetic field (B-field) are given in Figure 11 for frequencies of 3 to 5 MHz, which includes the frequency bands commonly used for WPT systems.

Frequency [kHz]	Action level (public exposure)		Persons in controlled areas (occupational exposure)	
	B_{rms} [mT]	H [A/m]	B_{rms} [mT]	H [A/m]
3.35–5,000	0.205	163	0.615	490

Figure 11. Maximum permissible exposure for head and torso: frequency = 3 kHz to 5 MHz.

IEEE MPE Limits for electric field (E-field) are given in Figure 12 for frequencies of 3 to 100 kHz, which includes the frequency bands commonly used for WPT systems.

Frequency [kHz]	Action level (public exposure) E_{rms} [V/m]	Persons in controlled areas (occupational exposure) E_{rms} [V/m]
3.00–100	614	1842

Figure 12. MPE for exposure of head and torso: frequency = 3 to 100 kHz.

The task members identified many issues with the safety of wireless charging systems that still need to be addressed. Those issues are listed subsequently. The order of the points is not reflective of their importance.

- There are no internationally accepted standards on exposure limits. ICNIRP, SAE J2954 and IEEE have published recommendations. Blanket exceptions are made to ICNIRP 1998 for certain products or industries in Europe that would not be possible in the United States if those standards applied. Denmark grid codes are based on International Commission (IC) standards but apply basically only on the transmission lines.
- Adoption of regulations will always be 4 to 5 years behind the actual release of guidelines. For example, Europeans abide by ICNIRP EMF guidelines released in 1998, although the latest version of the EMF guidelines was released in 2010. SAE J2954 references the ICNIRP 2010 guidelines.
- There is no information on the secondary effects of EMF exposure to legacy vehicles.
- No information was presented about the heating effects of the EM fields on metals imbedded in a human body such as plates and screws in legs, or on imbedded devices such as pacemakers.
- These WPT systems are meant to function and not be seen. This presents a situation where there can be EMF exposure to people without their knowledge of the exposure.
- Whether there should be a concern around capacitive charging at 250 kW and 5–6 MHz.
- The Federal Communications Commission operating in the United States considers a WPT system an intentional radiator because of its 85 kHz frequency. This requires that field strength be evaluated at 300 m from the source and within certain V/m limits.
- WPT systems are being designed in a “one size fits all” fashion as driven by OEMs, but placement of systems on each vehicle can vary resulting in different field emissions under various configurations.
- Foreign object and living object detection needs to be done at low cost using automotive qualified parts.

Task 26 members made several recommendations about how work in this area could help address these issues. Those ideas are listed subsequently. The order of the points is not reflective of their importance.

- An international group should be brought together to look at the effects of electric and magnetic fields. This group should reach consensus on these effects.
- Governments should agree to follow the body of evidence for WPT installations.

- Identify someone in the EU, Asia, and North America to look at additive field effects that will inevitably vary with the surroundings and with time. In addition to the wireless charging system, the tire pressure sensor and keyless entry system are some other emitters around the vehicle.
- With help from OEMs and installers, develop the worst case scenario, recognizing that it will have an impact on cost.
- Research which international organizations should be part of an oversight group for the health effects of WPT.

5.5 Installations and Alignment

Inductive WPT research is showing significant potential and promise to charge the battery system of an EV. In general, WPT has two major sections: the sender or primary side, which is generally embedded in the road or parking location, and the receiver or secondary side, which is generally in the vehicle. Public transport companies, being the frontrunners in WPT implementations, are having to coordinate installations with grid owners and road and parking maintenance organizations. GA installations may also depend on the approval of a governmental authority tasked with public safety. Hence the installation process has both technical and procedural challenges. Since the procedural challenges are site specific, it is sufficient to say they exist and the remainder of this section will focus on the technical aspects.

5.5.1 Static and Opportunity Charging

For static charging, the GA is placed in the center of a parking spot when view from side to side. GA can be placed over the pavement, level with the pavement or below the pavement surface. Placement over the pavement is the easiest; however, it could be a tripping hazard in public areas. Installations that are level with the pavement alleviate the tripping hazard and allow for electrical conduit to be underground. In this type of installation, the GA will need to meet the same operating conditions of the road since it can be driven over by vehicles. Installations below the pavement surface offer some protection for the GA but with a higher air gap between the coils. To date there is no convention on whether the GA should be located in the front or back of a parking space. There are several static WPT charging solutions and retro-fit kits already commercially available for light duty passenger vehicles with little need for grid enhancements.

With bus demonstrations, many opportunity charging configurations have located the GA in the front of the bus lane stop. Installation of the GA and associated equipment can take as little as three days; however, the medium voltage power from the grid must already be installed. Figure 13 shows the GA and other components associated with a static or opportunity charging installation.

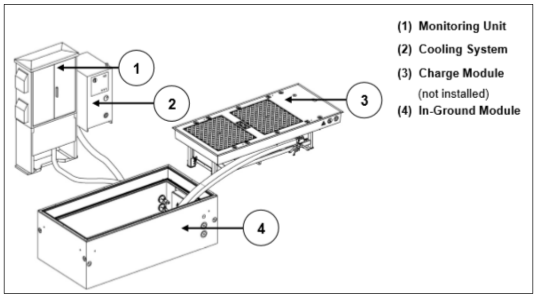


Figure 13. Configuration of an in-ground module to fit in a (double) charge module consisting of two primary WPT coils used for static WPT.

Some factors to study when selecting the GA location are the slope angle for consideration of local ground conditions and sewage systems, stability of the subsoil, frost-proof foundation depth, and maximum slope of the road and the GA. In the case of opportunity or dynamic charging, the GA interacts more with the road construction.

5.5.2 Road Construction Methods

Because a portion of the WPT system is embedded in the road, conventional road construction architectures need to be modified leading to new road constructions (designated as E-roads). Though there is no defined construction methodology for E-roads, existing E-roads have been studied, and four distinct construction architectures have been identified:

1. Trench-based construction (in situ, precast concrete, complete module/concrete bin)
2. Micro-trench–based construction
3. Full lane-width construction, in situ build
4. Full lane-width construction, precast or prefabricated

Trench-based construction incorporates the WPT coils embedded in a trench made in the asphalt layer, which is then covered with precast or in situ–made concrete. Figure 14 (left) shows a cross section of the road for a trench-based electric road implementation. The trench-based construction is quick to complete, has lower initial costs, and allows the use of low-temperature asphalt and nonferrous aggregates in the surface layer. However, it results in the hybrid structure of concrete and asphalt, which is prone to thermal cracking and has high maintenance costs. Compared with trench-based construction, the micro-trench architecture uses narrow, shallow slots in the existing structure, thereby causing minimal damage to the existing road structure. Figure 14 (right) depicts a cross section of road when micro-trench construction tactics are applied. Similar to the trench-based construction, it is quick and cheap to construct. Additionally, it has low maintenance costs. However, in this structure, the WPT coils are more susceptible to damage from road traffic and the depth of the coils are limited to the air gap allowance.

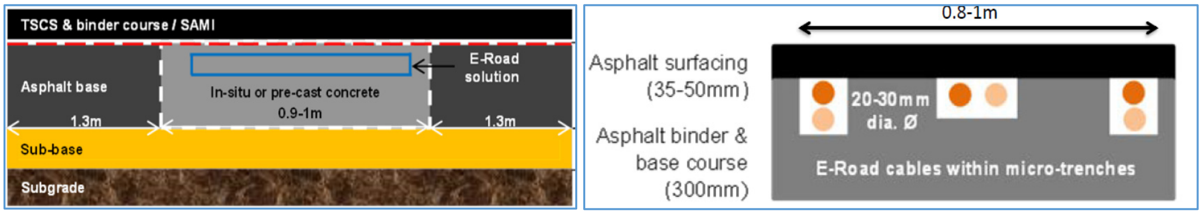


Figure 14. Roadway cross section of trench-based construction (left) and micro-trench–based construction (right).

Trench-based constructions create grooves and trenches in the existing road structure. In contrast, full lane-width constructions are incorporated by embedding the coils in a concrete structure equivalent to the full width of the road, as demonstrated in the road cross section of Figure 15. Full lane-width construction can be in situ build or be precast/prefabricated. In situ build provides the advantages of low maintenance costs, improved quality, and single longitudinal joints at the lane interface. The concrete also protects the WPT coils from the effects of the paving process. However, full lane-width construction takes much longer and might have potential maintenance issues with the transverse joints affecting adjacent lanes. Additionally, its installation requires two lanes of traffic management. One advantage of precast full lane-width construction over in situ build is its installation time. However, the precast concrete slabs are prone to movement under traffic loading.

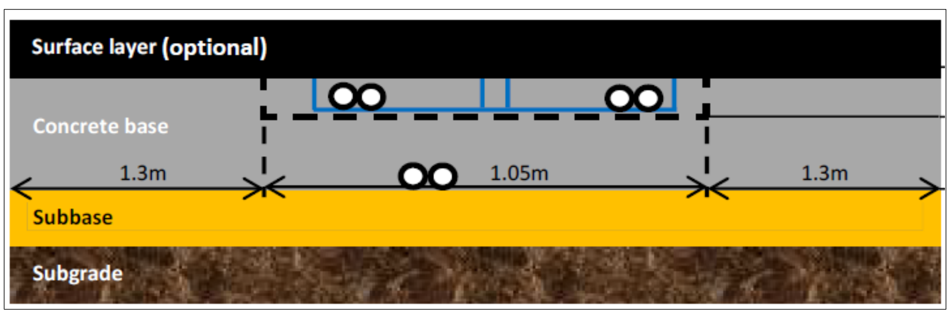


Figure 15. Roadway cross section of full lane-width construction.

Studies from the FABRIC test site POLITO revealed a high capacitive coupling between the embedded WPT coil and the concrete layer. This required insertion of a nonconducting material as dielectric between the embedded coil and ground. Additionally, it was found that the micro-trench–based E-road construction was quick to complete and that the use of cold mix asphalt showed good performance with the WPT equipment.

Laboratory testing at KTH Sweden (findings from WP45) has revealed that there is higher deformation, cracking, and increase of voids at the asphalt/concrete interfaces and corners. Significant failure at the interface is also noted when subjected to cyclic tension and compression testing. Besides laboratory testing, simulation studies revealed that the overlay thickness had a greater effect on the overall structural integrity of the E-road compared with the material stiffness. Joint materials like SAMI, geo-grid, etc., reduced stress at the base of asphalt layer. The bonding at the asphalt interface is extremely crucial for the structural integrity of the E-road.

In summary, conventional road materials are deemed to be suitable for E-roads with low-temperature asphalt and nonferrous aggregates in the surface layers. Nonconductive materials should be used as dielectric between the WPT coils and road materials. Current laboratory testing suggests there are concerns of premature failures at the surface. Good bonding at the interface is key to the overall structural integrity, and the use of joint material at the interface could reduce stress and strain at the interface.

5.5.3 Alignment

Alignment of a vehicle on a WPT point requires precise positioning of the vehicle. The electromagnetic pattern has an optimal efficiency for energy transfer if alignment and gap are within a certain tolerance. Positioning tolerance could be as narrow as 5 cm (x-y axes) and 15–20 cm for the air gap (z-axis). Positioning outside the tolerance window decreases the efficiency to below 85%, which is where most manufacturers switch off the power transfer capability of the coils.

After some training, skilled drivers such as taxi or bus drivers can align their vehicles on the same optimal spot each time. Less experienced drivers, or drivers frequently changing WPT charging locations, often need more assistance. Generally, there are three options in use or in development for assistance: mechanical, visual, and electronic alignment. Mechanical refers to the vehicle's wheel alignment on road markings. Visual means using a camera to align the VA over the GA. Electronic alignment is done with the help of low-voltage sensors or electromagnetic resonance at a low power level just to "find the sweet spot." The integration of wireless charging with automated or self-parking features that are becoming more common on new vehicles, could eliminate the need for the previously discussed alignment methods.

5.6 Bidirectional Systems

5.6.1 Key Findings

Potential impacts on the vehicle battery and the grid from wireless V2G are similar to those from conductive V2G. V2G refers to the reciprocal flow of power between an EV and a recipient that could be, among other possibilities, the grid, a low-voltage microgrid, or a building. In addition to demand shifting and the associated reduced electricity costs attained by avoiding peak tariffs at times of high demand, wireless V2G also introduces the prospect of financial incentives for the consumer through offering frequency regulation and energy storage facilities to the grid.

Potential Impact on Batteries

A key concern has been the impact of V2G operations on the degradation of lithium (Li)-ion batteries, which is central to both EV and V2G operations. Several publications present the results of an experimental study on the impact of V2G operations on Li-ion battery degradation. The results show that additional cycling to discharge EV batteries to the power grid, even at constant power, is detrimental to battery performance. However, a smart control algorithm with an objective of maximizing battery longevity can reverse this. Furthermore, V2G does not involve bulk energy transfers. Only a small percentage of the battery's state of charge is used to support the grid and should therefore have small impact on the EV battery.

Potential Impact on the Grid

Grid impacts have been studied for both unidirectional power flow (V1G) and V2G. The impacts discuss here are for V1G or smart charging and V2G. Analysis concerning the impact on the grid by a coordinated pool of EVs has shown that to date network congestions rarely occurs. Only networks, which already have high loading, can reach their capacity limits because of the further supply of renewable generation or by the simultaneous provision of control reserve from many EVs. EVs as a controllable load allow for deferring power system upgrades. As distributed storage, EVs act as a flexibility source by supporting the local grid, providing demand side response, and allowing for the integration of renewable resources. Taking advantage of this power will require new market rules, but the majority of EVs could provide valuable services to the grid and are often able to respond more quickly than existing power sources. In the long-term, a high portion of EVs might require—even in the case of delivering negative control reserve—extensive network extensions. However, future smart grid technologies might generally increase the hosting capacity of the networks and reduce grid expansion costs.

Regulations and Customer View

To establish a large V2G network, a few challenges must be overcome. V2G needs to find a way to reward EV drivers. Customers will join V2G schemes if they see clear advantages and no disruption in EV use. At the same time, EVs need to be compatible with a bidirectional charging system. Right now, V2G charger costs are still high, and only a few are available on the market. Even more important are the current regulations, standards, and codes that would allow for widespread use of V2G operations. In an ideal world, codes and standards would be the same in every target implementation region for V2G. In actuality, many nuances will cause challenges for customers and vendors.

5.7 Dynamic Wireless Charging

Many stakeholders see dynamic charging deployment as the ultimate objective of wireless charging. This is both the most streamlined and most challenging implementation of wireless charging. Although this is certainly true from a scientific point of view, safety and huge investments in infrastructure still challenge dynamic charging's economical business case. The rollout of EVs is hampered by cost and range. With conductive and static wireless charging, the vehicle must include a large battery, which can be costly to achieve a vehicle range that is acceptable to most consumers. Battery technology will continue to improve, lowering cost and increasing the range of EVs; however, charging while the vehicle is in motion can also address both of these concerns. Dynamic wireless charging permits EVs to accept a charge from a GA installed in the roadway while the vehicle is in motion. If sufficient roads were retrofitted with wireless charging then the EV's battery could be smaller and still provide a range acceptable to consumers. Projects in several countries are looking into this technology. Oak Ridge National Laboratory (ORNL) is working on this technology, and the EU's FABRIC project just demonstrated dynamic wireless charging in Italy and France.

Current research is trying to address many of the technical challenges with this technology, some of which follow:

- Coupling a VA and a GA at driving speeds. The higher the speed the shorter the coupling time, which is a factor in how much power is actually transferred to the vehicle.
- High power transfer rates. To get the most power from each GA, a high power rate is envisioned, but that high power rate needs to be accepted by the battery without negatively affecting battery life.
- Payment. How vehicles would be charged for the power accepted is still not clear as duration and amount of power would vary with traveling speed.
- Interoperability of the system. All vehicles will need to work with a single GA, which presents some challenges.
- Road maintenance. The GAs will need to be robust enough to last as long as the average road maintenance cycle of 10–15 years while being exposed to full vehicle weights and speeds, as well as snow removal equipment and thermal loads.
- Cost. Embedding roads with equipment will be costly. How this initial investment will be paid for and the ownership of the equipment are both new business models that have not been proven.

5.8 Cybersecurity of EV Wireless Charging

Cybersecurity of EVs and charging infrastructure is an important aspect of wireless charging technology and how it is deployed with EVs. Cybersecurity is discussed in this report even though the topic as applied to EVs is not sufficiently developed to dedicate a full workshop to it. The information included here is a summary of the findings by researchers that have been agreed upon by the task members. With advancements in EV charging infrastructure including higher power levels, increased sophistication and automation, smart grid communication, and advanced controls systems, potential negative impacts from an increasing number of cybersecurity vulnerabilities are also escalating. Cybersecurity is typically misunderstood as an issue merely for information technology, but vulnerabilities in physical systems (cyber physical security) could result in even greater impacts to public safety, hardware, the electric grid, service, or data security.

Through research experience, a recommended cybersecurity approach for a more robust EV charging system has been compiled. This recommended methodology assumes that a malicious entity will gain access to the charging infrastructure system with enough time and effort. No connected system is entirely secure from cyberattack. Table 5 lists the recommended cybersecurity components and methods to improve EV charging infrastructure security. This recommended methodology is aligned with the US National Institute of Standards and Technology cybersecurity framework.[xiii]

Table 5. Recommended cybersecurity components and methods to improve EV charging infrastructure security

Category	Methodology
Plan and Prepare	Identify potential system vulnerabilities
	Harden attack surfaces of vulnerabilities
	Develop a methodology to safeguard personal information and data
	Develop a response plan including mitigation strategies and solutions
	Design the system for safe, resilient operation during a cyber event
Attack Response	Identify cyber malicious event
	Execute response plan including communication with stake holders
	Collect data for forensics
Close-Out	Analyze forensics
	Ensure attack vector has been completely closed and the event has ended (not merely dormant)
	Conduct cleanup efforts to get system back to full operation
	Share lessons learned with others in industry

Electrified transportation technology has unique cybersecurity vulnerabilities because it is one of the few technologies that is mobile, publicly accessible, and integrated into the electric grid. DC conductive charging and WPT systems have many common vulnerabilities because the power electronics conversion stages are off-board the vehicle and proper communications between the vehicle and charger are essential for safe charging operation. Because of these unique vulnerabilities of EV charging infrastructure, cybersecurity should be considered early during the design phases of the system to incorporate solutions to reduce the risk of nefarious access, safeguard data and information, and enable a safe minimum state of operation during a cyber event. If cybersecurity is not addressed until late in the development process, often the cost is higher, security implementation is less effective, and the deployment schedule is often impacted.

5.8.1 WPT Cybersecurity Vulnerabilities

In comparison with DC conductive charging systems, WPT systems have additional unique vulnerabilities associated with the wireless controls communication system, EM-field safety systems, and interconnection between the charging system and vehicle powertrain controls system during WPT pairing and alignment operation.

Table 6 lists the WPT cyber physical vulnerabilities and the potential impacts that could result.

Table 6. WPT vulnerabilities and potential impacts

Vulnerability	Impact
Electric grid stability	Sudden and concurrent load shedding of multiple high-power charging systems and an abrupt change in load from stationary energy storage

Vulnerability	Impact
	systems associated with a charge site containing multiple high-power charge systems
Safety hazards for persons with implanted medical devices	A manipulated WPT system operating at full primary coil current with no vehicle present (empty parking spot) results in exposure to a high EM-field if the person walks over a WPT primary coil assembly.
Theft or alteration of data transmitted between the vehicle and the WPT system, including vehicle cargo content, payment information, personally identifiable information	Valuable or important information exchanged between the vehicle, charger, network operator, charge site operator, or other entity
WPT hardware damage or denial of service caused by a malicious external source	Manipulation of the tuning frequency, current request, system status feedback, or other control parameters
Safety or fire hazard resulting from manipulation of the foreign object detection system	Object heating or combustion
Denial of service from malicious falsified information presenting WPT as out of service even though hardware is fully functional	Loss of revenue, discouraged EV drivers, and difficulty in identifying the issue
Manipulation of standardized communications between the vehicle and WPT for WPT pairing, approach, or alignment	Potential unintended vehicle movement

Dynamic wireless power transfer (DWPT) potentially has additional cybersecurity vulnerabilities beyond stationary WPT. These vulnerabilities are yet to be fully identified because of the nature of this developing technology. Though the controls communication systems are not yet standardized, it is anticipated that the communications systems might include dedicated short-range communications and 5G cellular. DWPT vulnerabilities are similar to those of static WPT systems, but additional vulnerabilities could include cross talk between numerous DWPT systems (multiple vehicles on same stretch of DWPT road) and in-motion authentication and payment collection.

5.8.2 WPT Vulnerability Mitigation Strategies and Solutions

For several of the known vulnerabilities for static and DWPT systems, there are tangible and implementable solutions available to improve the security of WPT systems. But research is needed during the design and engineering phases of development to ensure that the potential high impact cyber vulnerabilities are understood and addressed through sound engineering practices.

Encryption is available for many communication protocols. Properly implemented encryption will help to harden the attack vectors for several vulnerabilities as long as the communication rate is not slowed and hindered beyond acceptable levels. For example, open charge point protocol offers encryption[xiv] capabilities to secure communications between the central system and the charge point. Open charge point protocol accomplishes this encryption through keys and authentication.

Using a controls system monitor that identifies anomalies in the controls system communications may help identify a cyber event and initiate the response plan. This mitigation solution can add additional security beyond encryption or other forms of attack surface hardening. An example of a controls system monitor for improved cybersecurity is the Diagnostic Security Module developed by Idaho National Laboratory.[xv] This module monitors communications on the vehicle and charge system to identify message anomalies or other suspect controls system characteristics that indicate possible cyber intrusion or manipulation. In response, this security module can initiate an attack response plan.

Controls systems can use multiple inputs or logic pathways to verify the viability of data used for controls. This will improve the security of the system and enable faster response to an event. For example, if data from a temperature sensor are manipulated by a nefarious cyber actor, the control system may not control coolant flow rate correctly as the temperature increases, resulting in an overtemperature condition and possible hardware damage. If multiple data inputs are used, this could be avoided; for instance, using the measured temperature data as well as the expected temperature rise for a given charge current rate provides additional data. If the two pieces of information drastically differ, then a potential cyber event could be identified.

Although mitigation strategies like those mentioned earlier are an important component of securing WPT, cyber-informed engineering [xvi] practices should be employed during the design, implementation, and installation of a WPT system. The cyber-informed engineering methodology is a framework for bridging the gap between engineering design and cybersecurity to identify cyber vulnerabilities at the earliest stages in the system development life cycle and apply both engineering solutions and information technology to minimize the cyberattack surface across the entire system engineering process. This methodology focuses on aiding engineering staff who traditionally envision, plan, design, implement, operate, and maintain such systems to understand cyber risk (without becoming cyber experts) and on integrating the subject matter expertise of cybersecurity specialists.

Other mitigation strategies and solutions may be available for specific vulnerabilities; however, additional research is required to further improve mitigation solutions for the unique vulnerabilities of WPT for electrified transportation.

5.8.3 Summary of WPT Cybersecurity

Continued research is needed to understand the potential vulnerabilities with WPT for electric transportation. Solutions need to be developed to harden the attack vectors of WPT systems therefore reducing the risks of access and manipulation. Additionally, there is a need to develop methodologies for response and recovery when a cybersecurity event occurs. In general, with increasing system complexity and reliance on control system communications, cybersecurity vulnerabilities increase in quantity and impact magnitude. Hence specific efforts are required during the early design and engineering phases of technology development to understand the potential vulnerabilities and develop strategies and solutions to defend against and respond to a cybersecurity event. Additionally, as cyber adversaries adapt, learn, and change to the new defenses and mitigation solutions, cybersecurity solutions also need to evolve to stay "one step ahead," hence the continuous need to reevaluate vulnerabilities and implement improved solutions.

6 COUNTRY-SPECIFIC PROGRAMS

Task 26 member countries have varying interest and research in the area of wireless charging. This chapter details country-specific WPT programs and activities in the countries that have participated in the task.

6.1 France

The French institute VEDECOM was created in 2014 and is an Institute for Energy Transition established as part of the French government's Investment for the Future Plan. VEDECOM's objective is becoming the leading institute in France for autonomous and connected vehicles and their uses. Since its founding, the institute has grown from 10 founding members to 40 members comprising industry, academia, and local government. Industry members include firms from the automotive, aerospace, and mobility ecosystem sectors.

The research institute's sole focus is individual, carbon-free, and sustainable mobility. To achieve this goal the institute does research in three areas of mobility: vehicle electrification, driving delegation and connectivity, and shared mobility and energy. VEDECOM's wireless charging projects are part of their vehicle electrification research area. The WPT research activities are exploring coupler design, associated power electronics, electric road design, and detection algorithms. Both simulation tools and experimental tests are used to perform research and validate those activities. Task 26 participants witnessed a demonstration during Workshop 6–"Installation and Alignment," at VEDECOM's Satory facility in Versailles. Renault, the French auto manufacturer, provided the vehicle for the dynamic wireless track demonstration witnessed in Versailles, France.

6.2 Germany

Germany is very active in the wireless technology arena with several OEMs working on the technology for EVs. Table 7 details inductive charging stakeholders in Germany.

Table 7. Inductive charging in Germany

Company	Vehicle Class	Development Stage	Product
Blue Inductive	Small industrial vehicles	Available	3 kW inductive charging
BMW	LDV	Available for lease	3 kW
Bombardier/PRIMOVE	Trams/buses	Available	Power transfer up to 200 kW
Bosch	LDV	Project complete	11 kW, Bidirectional charging
Continental	LDV	Under development	11 kW
INTIS	Transit	Under development	500 kW

Table 8 details dynamic charging stakeholders in Germany. Figure 16 is INTIS's 50 kW WPT combined charger prototype.

Table 8. Dynamic wireless charging in Germany

Project	Power (kW)	Air Gap (cm)	Battery Capacity (kWh)	Vehicle Side Voltage (V)	Vehicle/Vehicle Class
Artega	30	15	37	350	Sports car
Autoram	60	15	2	600	Electric bus
BMW	11	13	22	360	LDV
Citroen	30	14	22.5	300	LDV
IPT	Up to 100				Buses
IVECO	12	11	63	270	Electric van
Linde	15	10	50	80	Luggage hauler
Nissan	30	11	24–30	360	LDV
OTS	11	13	35.8	340	
Volkswagen	30	10	36	360	Minivan

Figure 16. 50 kW Combined Charging System (CCS) WPT combined charger prototype. (Courtesy of INTIS.)

6.3 South Korea

Table 9 shows the recent development status of WPT charging technology in the Republic of Korea. A few WPT charging projects for EV and bus charging applications were supported through government R&D funding agencies and industries.

Table 9. WPT in South Korea

Project	Power (kW)	Air Gap	Efficiency (%)	Notes
Korea Electric Power Co. (KEPCO) and Green Power Co. (Static)	6.6	180–220 mm	>90	WPT EV charger system prototype demonstrated successfully at different installation sites in 2018. The AC input was 220 V. The total efficiency of the system was more than 90%.
Korea Advanced Institute of Science and Technology (KAIST) and Renault Samsung Motor (RSM), Static	22	12 cm	>91	Codeveloped a 22 kW WPT charger prototype and tested it using the SM3ZE EV of RSM.
KAIST (Dynamic)	200	200 mm	90	A 200 kW inverter supplies 85 kHz current to a feeder, and a feeder line transfers power to the vehicle.

The following figures provide images and specifications on the WPT projects in the Republic of Korea. Figure 17 and Figure 18 show KEPCO and Green Power Co.'s WPT project specifications and installations. The shapes of the circular type transmitting and receiving coils are optimized, and impedance matching circuits are adjusted to achieve transmission efficiency between coils of more than 97% when the air gap of the transmitting and receiving coils is 200 mm at 85 kHz.

Figure 19 shows KAIST and RSM's 22 kW installation—a four-channel coil system with a three-phase AC WPT system to achieve 22 kW. Figure 20 is KAIST's 200 kW inverter. The inverter input of 380/480 V_{AC} is converted to high frequency suitable for the WPT charging system to supply the required power to feeder line. The power supply system capacity is expandable up to 400 kW. Figure 21 shows KAIST's DWPT installation and specifications.

Specifications

- Input Power: 220V, 1-phase
- Power Factor: > 0.98
- Coil type: Circular
- GA Size: 550 mm x 500 mm x 35 mm, 20 kg
- VA Size: 350 mm x 350 mm x 25 mm, 6 kg
- VA output: DC 300~400 V, 6.6 kW
- Efficiency: >90%, (magnetic gap of 180~220 mm)
- Offset range: ± 100 mm(X), ± 75 mm (Y)
- Frequency: 85 kHz

Figure 17. KEPCO and Green Power Co. general specification of WPT charger prototype and (right) WPT charge vehicle adaptor attached at the bottom of commercial EV (IONIQ).

Figure 18. KEPCO and Green Power Co. installed a 6.6 kW WPT EV charging infrastructure (ground adapter) at parking lots of KEPCO Research Institute (ground surface with concrete, asphalt, blocks).

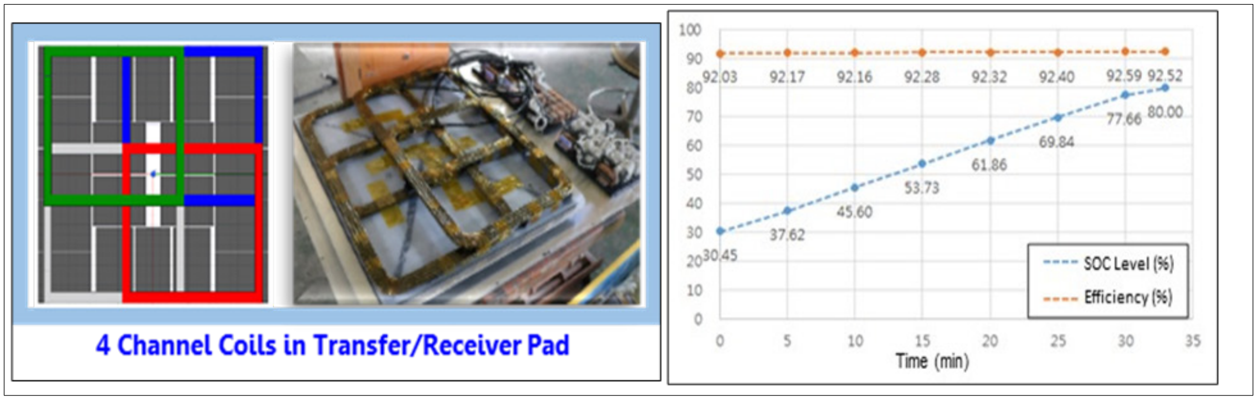
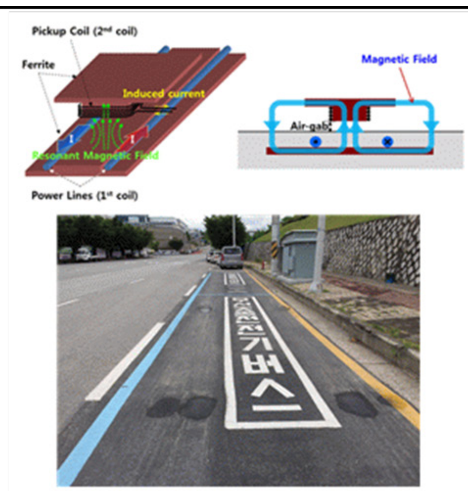


Figure 19. KAIST and RSM four-channel coil system with three-phase AC WPT system (left); charging power and efficiency (right).

Specification (Inverter)
Input voltage: AC 380 ~ 440 V, 50~60Hz
Input current: 300 A
Input Power: 230 kW
Output Voltage: 436 V, 85kHz
Output current: 500 A
Output Power: 218 kW
Conversion Efficiency: 95%
Control modes: CC, CV, CP
Cont. operation time: 2hours max.
Opr. Temperature: -20 ℃ to 50 ℃
Size: W 2400 mm, H 1100 mm, D 900 mm
Weight: 200kg
Cooling: Circulating Water

Figure 20. KAIST's 200 kW inverter and specifications.



Rated Specifications
Input Voltage: 436V
Input Current: 500A
Input Power: 218kW
Frequency: 85kHz
Efficiency: 90% (At 200 mm gap)

Environmental limits
Operating Temperature: -20 ℃ to 50 ℃
Cooling type: Air cooling

Figure 21. Structure of KAIST WPT coil, feeder line, and installed system (left); general specifications of the WPT feeder line (right).

6.4 Spain

In recent years, the government of Spain has developed a set of plans to promote electrical mobility. These plans started with the Program MOVELE in 2014, where no specific funds were allocated to help with the installation of charging points. In the next plans, there were funds allocated to help with infrastructure. However, none of the plans included monetary support for installing inductive charging points.

The MOVEA plan is a part of the strategy to incorporate alternative energy vehicles in Spain from 2014–2020 to unify the different programs and plans aimed at supporting the acquisition of the most efficient vehicles that have been developed so far. This plan was developed by the Ministry of Industry, Energy, and Tourism and by the Ministry of Agriculture, Food, and Environment and aims to continue and unify the PIMA Air Plan and the MOVELE plan to promote vehicles driven by alternative energies. EVs are considered alternatives to gasoline and biofuel vehicles.

Because of these plans, the “new mobility” has become a matter of general interest, as demonstrated by the political agenda of both Europe and Spain in particular as the Spanish government warned on November 13, 2018, that it will prohibit in 2040 the sale of oil cars in the framework of a new law. Because of this law and to make the change less abrupt, the government announced a new plan to promote EVs—the Plan of Integral Support to the Automotive Sector—to facilitate the transition towards a sustainable and connected mobility. The plan supports the sector with an envisioned budget of €2.686 million to be divided among 2019 and 2025, of which €1.739 million is envisioned to boost the implementation of charging points.

At the city level, Madrid has promoted the use of electric buses. Among other bus models, EMT Madrid (the public bus operator) has added five retrofitted units with a range of 200 km, but the most significant novelty is that the buses are capable of inductive charging. Madrid has opted for the inductive system based on technical conditions (efficiency, sustainability, security, and versatility of the system) and urban development. Unlike the conductive solutions, this system has no visual impact on the city because it does not need catenaries or pantographs. The induction charge is carried out by a system of two magnetic coils, one of which is located in the lower part of the bus and the other is recessed in the roadway. In addition, the coil and electrical conduits are recessed in the ground and are covered with a layer of concrete. To guarantee passenger safety, the passenger compartment of the bus is isolated to avoid magnetic radiation inside the vehicle. Moreover, the full charge of the batteries is carried out at night in the garage by means of a conductive system so that the buses start their service with the batteries fully charged. During the journey, opportunity charges are made in less than 8 minutes at various stops along the route.

It is not only the government investing resources in EVs. In 2018, Endesa announced a plan to install 8,500 public charging points in Spain by 2023 and more than 100,000 private charging points for residential and company locations.[xvii] The objective of this plan is to precisely eliminate market concern and facilitate the desire of a large number of Spanish drivers (up to 40%) who declared they would be willing to buy an EV.

On the other hand, more development has been devoted to inductive energy transfer for autonomous ground vehicles.

In the research arena, CIRCE has been active, developing many papers, theses, patents, and projects. Its most important work has occurred over summer 2019. The first wireless project was UNPLUGGED, a European project in the FP7 program with the collaboration of CIRCE. The objective of this project was to develop an inductive charging system for EVs and to study improving the conformity and sustainability of mobility. In particular, researchers investigated how the intelligent inductive charging infrastructure can facilitate the full integration of an EV into the urban road network while improving customer acceptance and the perception of viability. As a part of the project, two intelligent inductive systems where developed. The innovative systems went beyond the current state of the art in terms of power transfer, which allowed intelligent communication between the vehicle and the electrical network. These innovative inductive load systems were tested and evaluated to understand their potential impact on urban mobility and the acceptance of electric mobility. The dynamic charger application was examined for different types of vehicles, such as buses and private passenger vehicles. UNPLUGGED provided evidence and demonstrated the use of inductive charging infrastructure to overcome some of the perceived barriers to electric mobility, such as the range and size of onboard energy storage and the practical difficulties associated with infrastructure (see Figure 22).

Figure 22. EV from UNPLUGGED project.

The most important objectives in this project were as follows:

- Increasing the efficiency and speed of energy transfer
- Optimizing the position of the inductor
- Planning the extension of the electricity network
- Studying and designing the shielding of the magnetic field, with finite element modeling analysis
- Developing the system with an effective cost
- Determining the appropriate location of the charging point

- Finding the means to bill for the energy provided
- Developing the communication system between the EV and the system
- Ensuring the interoperability of communication and the inductive charging system

Another important public project was the national project VICTORIA, which was directed by Endesa with the technical collaboration of CIRCE. This project analyzed the dynamic charge for an electric bus (see Figure 23). The system was tested in a real operation scenario in Málaga, which was the first Andalusian city that used electric power[xviii] in Spain.

The bus was adapted to support induction technology, so it can be charged by conventional method when parked at the bus station at night and be charged statically or dynamically. Partial recharging increases the range of an electrical bus compared with buses that are recharged only at the bus station at the end of the day. The capability to double the range of electric buses without affecting the operating schedules substantially improves the profitability and efficiency of the vehicles.

Figure 23. VICTORIA electric bus.

The main objectives of this project were as follows:

- Eliminate the limitation of the autonomy of the complete EVs
- Reduce the weight and increase the life of the batteries
- Reduce the cost of EVs
- Reduce the costs in the execution of the vehicle load lane
- Increase energy efficiency in the electrical system

Another project was the NUSUR initiative, which was subsidized by the Etogai program of the Basque Government. The result was a compact and fully automatic system of fast installation and easy maintenance for an induction-powered tram. It operates at 50 kW, however the technology used could reach 100 kW. The system was tested on the test track in Zaragoza.

6.5 Switzerland

This section provides an overview of former and recent WPT charging technology projects in Switzerland. A few projects for EV charging applications were supported through government R&D funding agencies and industries.

TOHYCO-Rider Bus Project

Since 1998, the Competence Center Integral Intelligent and Efficient Energy Systems (CC IIEE) has worked on a hybrid bus system with supercapacitors and has realized the TOHYCO-Rider bus (see Figure 24). The concept consisted of a serial hybrid drive, a supercapacitor energy storage of 1.5 kWh, and a fast and contactless charging station WPT. The basic principle was quickly recharging the bus at every bus stop by the WPT charging station. For short rides without WPT, an emergency traction battery (ZEBRA) is integrated. As an option, the system can be extended by an auxiliary power unit for longer distance service. As a prototype, the TOHYCO-Rider Bus was first introduced to the public on December 13, 2002. Once the feasibility of this unique concept was demonstrated, the TOHYCO-Rider bus became semi-industrialized for public service.

Figure 24. TOHYCO-Rider bus.

Blue-Angel III

The development of the Blue-Angel light HEV started in its 1st generation in 1992. In 2006, the 3rd generation redesign began, first as an HEV and later as a full EV with range extender (see Figure 25).

This project presents a V2G system that comprises a plug-in hybrid vehicle, called Blue-Angel III, and a wireless power interface for grid integration. Blue-Angel III uses a Li-ion-supercapacitor energy storage and a wireless power interface, which is based on WPT technology, to facilitate the power exchange between the grid and Blue-Angel III.

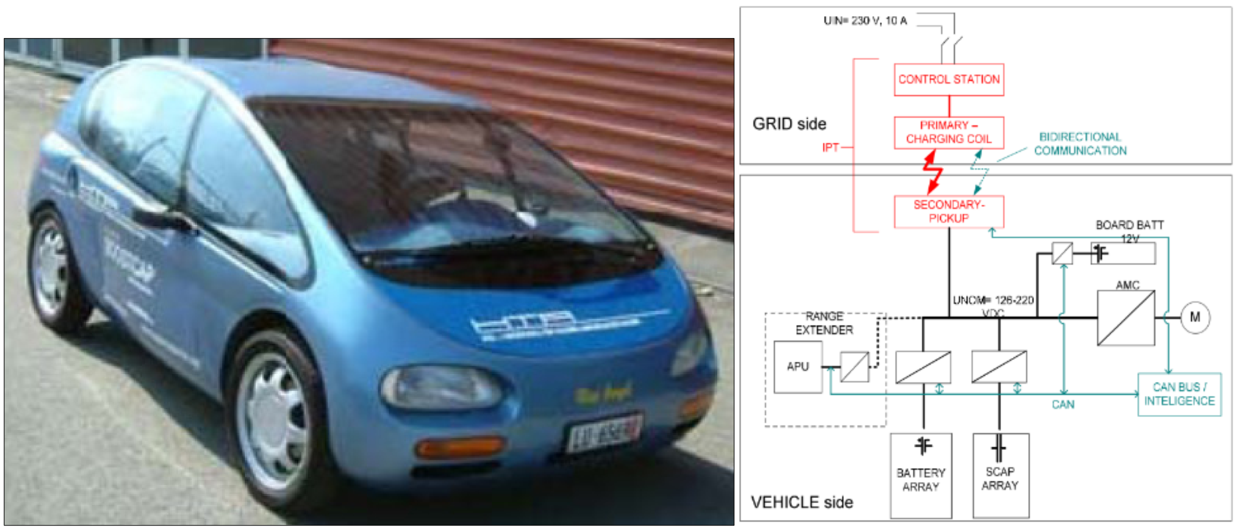


Figure 25. Blue-Angel III and schematic.

The Blue-Angel III has a battery capacity of 15.4 kWh, with an electric range of 210 km. Its fast-charge capability is 35 km in 15 minutes. Figure 26 illustrates its bidirectional WPT system.

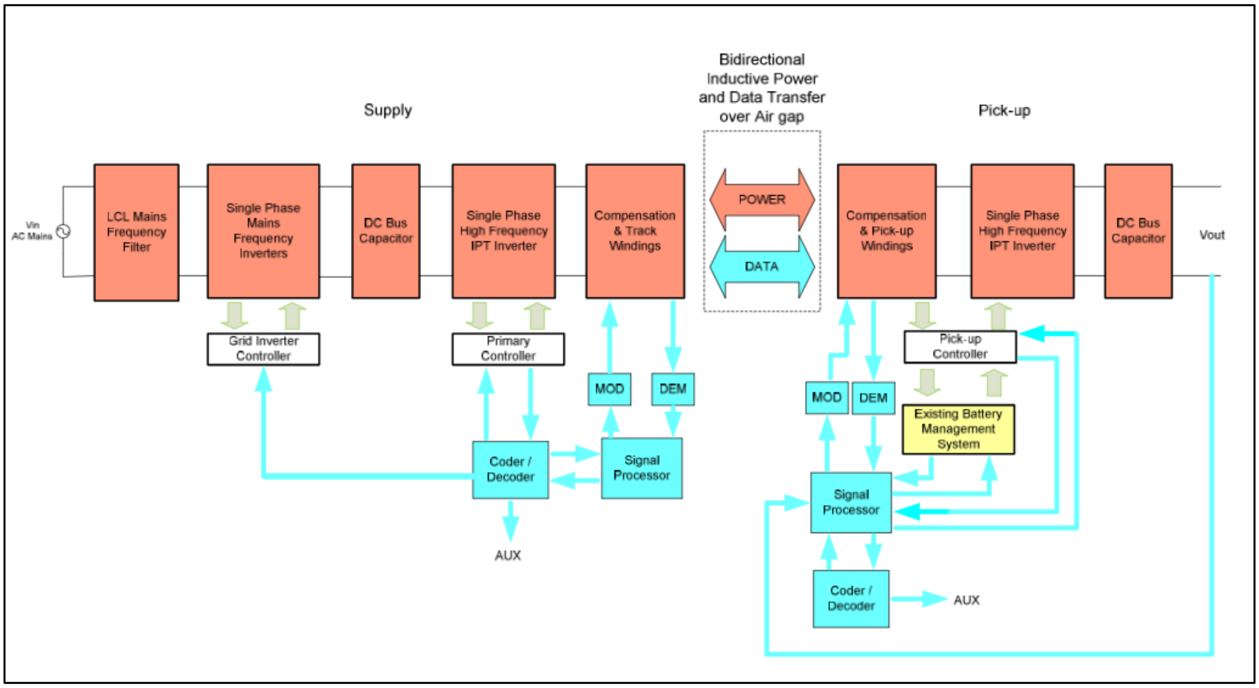


Figure 26. Blue-Angel III bidirectional WPT system.

The bidirectional WPT system consists of two submodules, a primary charging coil or pad located on the grid side, and a secondary pickup coil, which is placed under the EV or Blue-Angel III. The power is transferred from the grid side coil to pick up across an air gap. The primary coil is placed on the grid side and is connected to the grid via an appropriate power converter, while the pickup coil is connected to the vehicle's DC-link, VDC, via an appropriate power converter.

Brusa ICS115

BRUSA's Inductive Charging System (ICS115) is based on the FRAME Technology. It is the first one-box solution with integrated coil and power electronics in the Ground Pad Module as well as in the Car Pad Module (Figure 27).

Figure 27. BRUSA inductive charging system.

Existing implementations of inductive charging systems consist of two current coils: a primary coil located on the floor or, for instance, embedded in the road, and a secondary coil on the underside of the vehicle. The primary side includes a wall box that contains the power electronics and supplies the primary coil. On the vehicle side, besides the secondary coil, a further module is needed, containing a power control unit, AC/DC converter, and other communication components. However, BRUSA has adopted a different approach with its ICS. Instead of using multiple separate components, it has succeeded in integrating all the modules and functions into the coil housings. This means the ICS comprises only the floor plate and vehicle plate. It incorporates a host of safety features, including foreign-object and living-object detection. The charging system activates automatically as soon as the vehicle is in the correct position, with the vehicle and floor plate communicating via the wireless LAN standard 802.11p. The overall system also boasts an efficiency rating of approximately 92%, making it just as efficient as conductive charging systems. Its efficiency is >90% at 130 mm ground clearance, with a charging power of 3.7 kW and an alignment tolerance of +/- 150 mm laterally and +/- 75 mm longitudinally.

6.6 The Netherlands

In The Netherlands, approximately 147,000 LDVs have been registered so far with approximately 39,500 public charging locations. All charging equipment is conductive, although some inductive pilots have been executed. The whole Dutch LDV fleet consists of 8.8 million cars across the country population of 17.3 million inhabitants.

In the HDV segment, the Dutch approach is focused on the full electric conversion of approximately 5,000 diesel buses by 2025. This addresses the whole public bus fleet of The Netherlands. As of 2019, approximately 10% have been transferred to the full electric solution.

The first full electric initiatives were inductive solutions with pilot projects in the cities of 's-Hertogenbosch and Utrecht (2010) designed with 120 kW and 60 kW opportunity chargers, respectively. These projects were followed by a fully commercial operated line at the inner ring in the city of Utrecht, equipped by IPT Technology GmbH (2013). Another inductive charging project is pending in Rotterdam at the time of this report.

However, pricing and existing streetcar infrastructure in cities have made conductive chargers by pantographs more popular in recent years than wireless charging. Given the few public transport companies and the long payback period of these capital-intensive technologies, we anticipate these conductive chargers to be the preference for several more years.

In more countryside areas such as Groningen-Drenthe, the mixture is different (see Figure 28). Hydrogen-fueled vehicles are of interest if there is an appropriate industry in the area to support them.

Figure 28. Four bus types in the country area: highway-, highway + city-, region-, city buses.

For LDVs, EVs are still conductively charged, and there are many charging infrastructure initiatives. Elaad, the knowledge and innovation center in the field of Smart Charging infrastructure in The Netherlands, works to promote and execute interoperability tests for these conductive solutions.

The city council of Rotterdam executed a pilot to facilitate several car brands of their own. Dutch policy is that a charge solution may not exceed 5% of the buying price of a car. Even with the large taxes on new cars, wireless charging is still too costly to install privately.

The distribution grid in The Netherlands is already feeling the effects of distributed renewables and e-mobility growth in the country. Today, interaction with local PV panels on the roofs or energy fields and wind turbines require grid owners to balance the power and performance of stabilization activities. Smart steering and control solutions and stationary battery packs are being implemented to support the expected e-mobility growth.

The transmission grid owner, Tennet, and the gas company of The Netherlands, Gasunie, are joining together to optimize energy distribution. The needs of the commercial EV fleet owners are less of a priority for the grid, and that frustrates the transport companies.

A new management challenge arises where all (public) transport routes come together: traffic bottlenecks (see Figure 29). What (charging) infrastructure will prevail at these spots, to what extent interoperability can facilitate all different modes of transport, and how intelligently the exchange of energy is being distributed among incoming and outgoing transport flows is critical to future transport solutions.

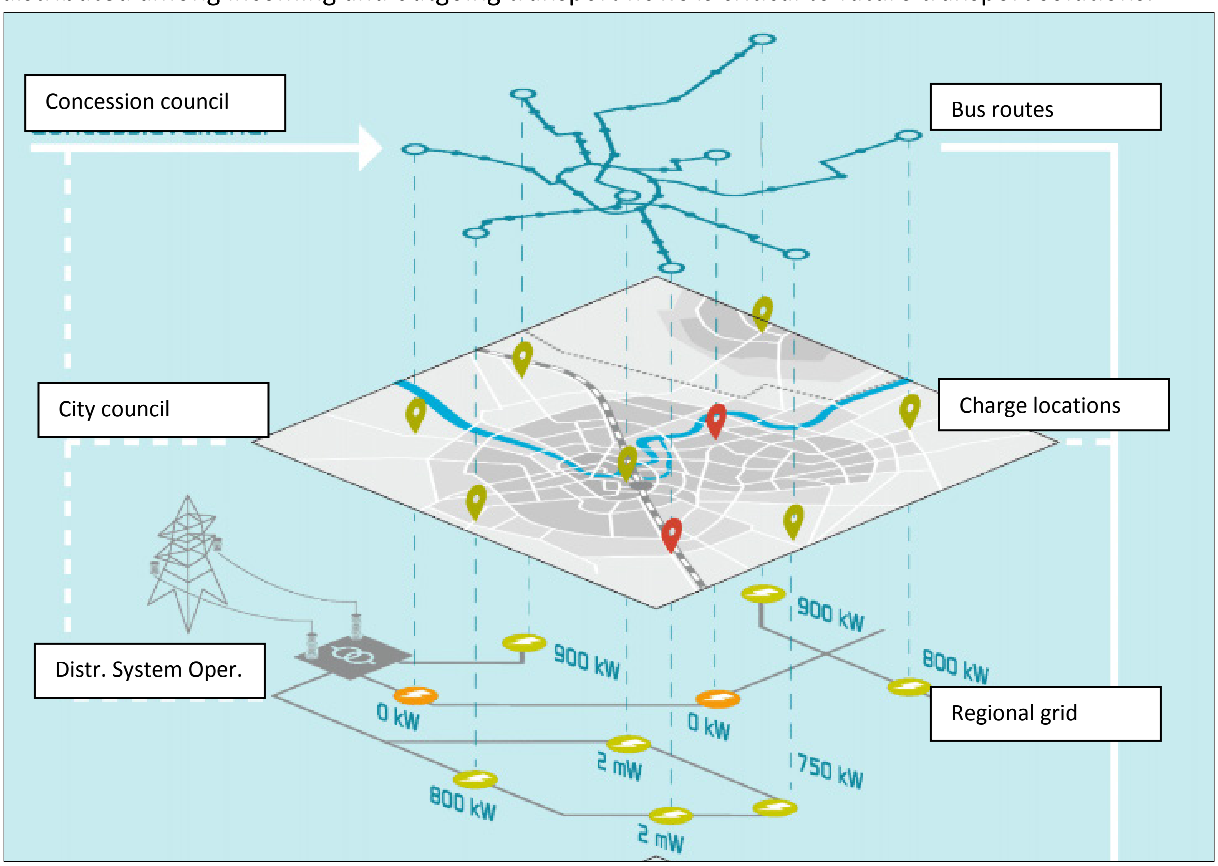


Figure 29. Cooperation at more levels (Source: Stichting Elaad, Netherlands).

Companies active with inductive charging in The Netherlands and abroad:

- EVconsult b.v., Amsterdam, NL. www.evconsult.nl.
- Floading Energy Infra b.v., Amersfoort, NL www.floading.com.

- Prodrive Technologies b.v., Eindhoven, NL www.prodrive-technologies.com.

Stakeholders (both conductive and inductive) in Dutch EV and charging development:

- **DOET:** Dutch Organisation for Electric Transport, www.DoetDoet.nl (Utrecht, NL)
- **Dutch Incert:** Dutch Innovation Centre for Electric Road Transport, www.d-incert.nl (Delft, NL)
- **Elaad:** ElaadNL is the knowledge and innovation center in the field of smart charging infrastructure in The Netherlands and is an initiative of the Dutch grid operators, www.Elaad.nl (Arnhem, NL)
- **Lombox Utrecht**: Implementation of ISO15118-protocol for AC bidirectional charging, www.lomboxnet.nl (Utrecht, NL)
- **NKL: The Netherlands Knowledge Platform for Public Charging Infrastructure EV.** NKL is the platform where government, knowledge institutions, and companies come together to achieve affordable public charging of EVs. http://www.futureofcharging.com/?utm_source=Mailing%20Lijst&utm_medium=email&utm_campaign=We%20have%20to%20run%20fast. www.nklnederland.nl (Utrecht - NL)
- **TNO Automotive:** The Dutch independent gouvernemental organisation for applied sciences reasearch, http://www.tno.nl/, www.automotivecampus.nl (Helmond NL)

Universities active in electrical mobility (both conductive and inductive)**:**

- Technical University Delft — Prof. dr. ir. Pavol Bauer
Prof. dr. D. Gavrila
- Technical University Eindhoven — Drs. Auke Hoekstra
Prof. dr.ir. Maarten Steinbuch
Dr. ir. Carlo van de Weijer
- Technical University Twente

6.7 United Kingdom

The United Kingdom (UK) has been active in both promoting EVs and doing demonstrations of wireless charging. Two historical bus demonstrations are the project in Milton Keynes and the Zero Emission Urban Bus System (ZeEUS) project demonstration in London, which included three buses inductively charged at terminals to top off vehicles during their route.[xix] The UK has two public wireless chargers for LDVs, one in Milton-Keynes and one in Glasgow. In 2018, the Office for Low Emission Vehicles and Innovate UK ran a competition titled “Wireless Electric Vehicle Charging for Commercial Users: Feasibility Studies.” Nine consortiums were given £645K (~$826K USD) to develop business cases and deploy new approaches to EV wireless charging for commercial vehicle users.[xx] Among the recipients was Char.gy, who looked at wireless charging infrastructure. In their study, Char.gy explored the potential for coupling wireless chargers to existing on-street cable chargers to reduce additional infrastructure requirements on the local electricity network operator.[xxi] Their project showed sufficient promise to be awarded a follow-on £2.3M to deploy wireless charging technology on residential streets, thereby removing the need for trailing cables. Electric cars participating in this demonstration would be retrofitted with a charging pad costing £1,000, which the project funds will cover for some participants. Among the areas to benefit from this trial are the London borough of Redbridge Council, parts of Buckinghamshire, and Milton Keynes.[xxii]

Besides the demonstrations, research on EV wireless chargers has been conducted at several universities. Road dynamic wireless EV charging is being studied at Newcastle University, and stationary wireless EV charging is being researched at the University of Warwick. The UK is committed to reforming their transport systems as is reflected in *Future of Mobility: Urban Strategy*, the biggest review into transport in a generation. A separate document, *The Road to Zero*, describes the strategy towards cleaner road transport and to put the UK at the forefront of the design and manufacture of zero-emission vehicles. Among the items described in this file is the £400M Charging Infrastructure Investment Fund to help accelerate charging infrastructure deployment.[xxiii]

6.8 United States

The United States is actively conducting research, development, and demonstrations of wireless charging technology. The following details recent wireless charging technology developments, policies, the companies and universities involved, as well as some of the funding resources in the United States.

Technology Development

Wireless charging research, development, and demonstrations have been ongoing in the United States for nearly a decade. US-based companies such as WiTricity, Evatran LLC, WAVE, and Momentum Dynamics increasingly focus on how to power EVs inductively, while academia researches dynamic WPT on test tracks and how WPT effects the electric grid.

In 2014, WiTricity was awarded a patent for its secure wireless charging technology.[xxiv] This technology includes a ground pad that can be placed on ground or buried in pavement and a vehicle component that is attached to the underside of the vehicle, allowing for wireless charging via electromagnetic resonant coupling between the vehicle and pad. Its charging power is 3.2 kW with an efficiency of 85%. WiTricity partnered with BMW to release the first consumer-ready remote charging system for an EV [xxv] and licensed its technology to OEMs including Honda, Nissan, and Toyota.

Evatran LLC developed aftermarket wireless charging systems for EVs under the Plugless Power brand.[xxvi] Plugless Power inductively charges an EV via a GA and a VA. Another company, Momentum Dynamics, has focused its initial business on fleet operators and wireless charging of MDVs and HDVs such as transit buses. In 2018, it commissioned the first 200 kW wireless charging system for buses in the United States.[xxvii,xxviii] However, the same Momentum system that is used on buses and trucks can also be used on passenger cars (such as the taxis in Oslo).

Utah State University achieved a significant milestone in 2015 with the opening of a DWPT test track in Logan, Utah. The university has been studying DWPT for several years at its Energy Dynamics Laboratory and built the Electric Vehicle & Roadway research facility, the first of its kind in the United States. The facility includes a 4,800 ft^2 research building and an electrified quarter-mile oval test track that allows for R&D into integrating renewable energy sources into an electrified roadway and the grid, electric powertrain design, roadway materials and construction, and security.[xxix]

Companies Involved

Multiple domestic light-duty automakers are involved with wireless charging in the United States. Mercedes-Benz began offering wireless charging for select plug-in electric vehicles in 2018.[xxx] In 2019, BMW brought its inductive charging pilot to California. The pilot was for 200 interested residential customers for inductive charging of the 530e sedan using WiTricity's technology.[xxxi] In 2019, Honda introduced its wireless V2G system, which was developed in partnership with WiTricity. The system allows for wireless charging over WiTricity's Drive 11 charging pad.[xxxii] The Tesla Model S, BMW i3, Nissan Leaf, and the first-generation Chevy Volt can be retrofitted to wirelessly charge using Plugless Power's aftermarket charging system. The charging system varies from 3.3–7.2 kW, with a nominal air gap of 4 in.[xxxiii]

On the medium- and heavy-duty side, Momentum Dynamics has been developing relationships with a number of truck OEMs, as exemplified by the 2018 investment by Volvo Group in the company. BYD has deployed more than 300 electric buses in multiple locations. It partnered with Momentum Dynamics and Indianapolis Public Transportation on installing 300 kW inductive charging points in the city to support an initial installation of 31 buses,[xxxiv] and delivered range-extended battery electric buses together at CARTA, Link Transit, and Howard County, Maryland. Additionally, Momentum Dynamics is working on a project at Martha's Vineyard to have 12 buses capable of wireless charging, which represents one-third of their fleet. WAVE's 50 kW charger was installed adjacent to the Long Beach Convention Center.[xxxv] Antelope Valley Transit Authority (California) deployed BYD electric buses that charge with WAVE's 250 kW chargers.[xxxvi]

R&D Funding

The US Department of Energy (DOE) awards R&D grant funds focusing on WPT. Projects funded by DOE's Vehicle Technologies Office (VTO) include an award to WAVE to develop and deploy high-power, high-speed wireless technology for EV drayage trucks at the Port of Los Angeles. WAVE with its partners Cummins, Schneider Electric, Utah State University, and Total Transportation Services are developing a 500 kW inductive charging system.[xxxvii] VTO also awarded grant funds to CALSTART to build and test a bidirectional wireless power charging system for delivery trucks.[xxxviii]

DOE's national laboratories conduct R&D on wireless charging focusing on high power. ORNL focused on achieving fast charging at the 100 kW and 300 kW power levels with advanced, compact designs focused on user convenience. ORNL is also researching a high-power DWPT system that is viable when applied to real-world traffic conditions in the United States. The activity focuses on developing a compact VA capable of receiving 200+ kW power dynamically.[xxxix] In October 2018, ORNL demonstrated a 120 kW WPT system with 97% efficiency that is comparable with conventional, wired high-power fast-chargers. In the demonstration, power was transferred across a 6 in. air gap between two magnetic coils and a charged battery pack.

The US Department of Transportation's (DOT's) Federal Transit Administration awards low- or no-emission bus grants.[xl] Projects funded by the DOT included an award to the Maryland Transportation Administration for Howard County. The funding supported purchase of three 35 ft. electric buses from BYD and inductive charging equipment from Momentum Dynamics.[xli] Recent awards included $1.75M for the Massachusetts Department of Transportation for purchasing inductive chargers and receiver pads and $3.76M to the Chelan Douglas (Washington) Public Transportation Benefit Area for EV buses and a wireless charging station to replace aging diesel buses.

State-level funding includes the California Energy Commission, which awarded grant funds for two projects at the Port of Los Angeles to demonstrate wireless charging on electric port vehicles. As part of these awards, WAVE partnered with the Hyster-Yale Group, the largest forklift operator in the United States, to demonstrate high-power wireless charging for all-electric container handlers at the Port.[xlii]

6.9 Other Task 26 Countries

6.9.1 Italy

Italy has been active in the research of wireless charging systems. The FABRIC project demonstrated the feasibility of different dynamic WPT systems, one of which, named Charge While Driving, was developed by the electrical engineering group of Politecnico di Torino. The technological innovation of this system has been on the direct embedment in the road pavement of WPT coils that give rise to the variable magnetic field used as a vector for the transfer of energy. This system design aimed at directly integrating transmitter coils without any additional magnetic structure into standard roadwork materials (mainly standard Portland concrete and asphalt) without reinforcing bars to reduce cost. An example of the embedding is show in Figure 30. Reinforcing bars are not typically used on highway infrastructures, hence their absence in this test. [xliii]

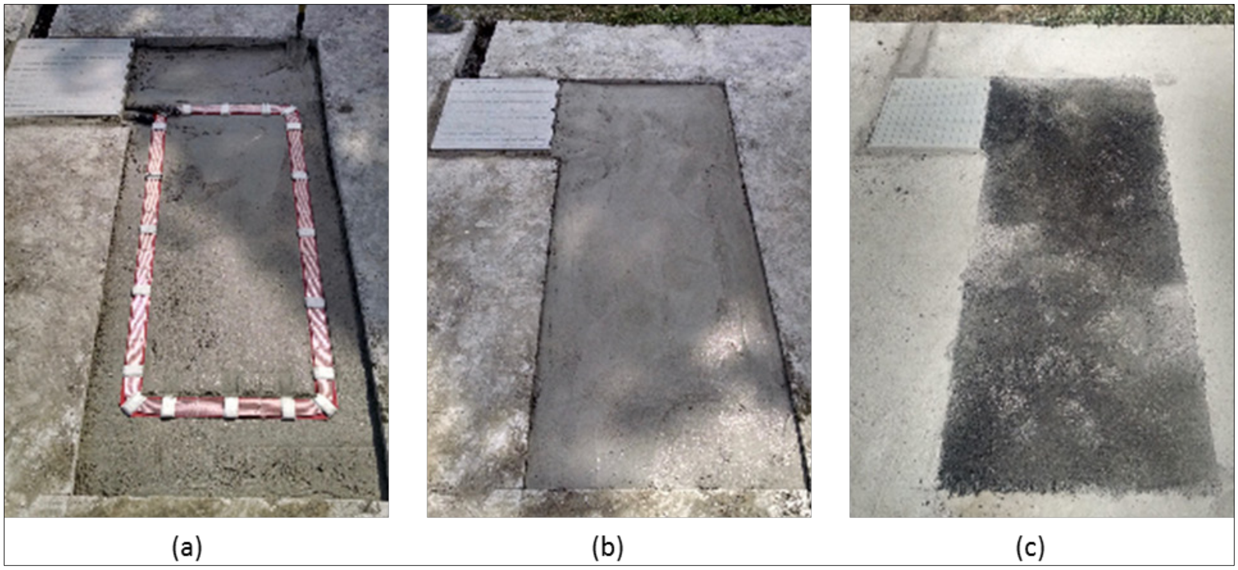


Figure 30. Phases of the coil embedment. Coil placed on the concrete basement (a); coil covered with a second concrete layer (b); coil covered with a final cold asphalt layer (c). (Source: POLITO, Italy)

However, embedding coils presented significant technical issues. The first efforts showed a strong modification in the coil impedance and a significant deviation in the behavior of an inductor. As shown in Figure 31 both the amplitude and the phase of the coil impedance changed with the embedding process particularly as frequency increased.

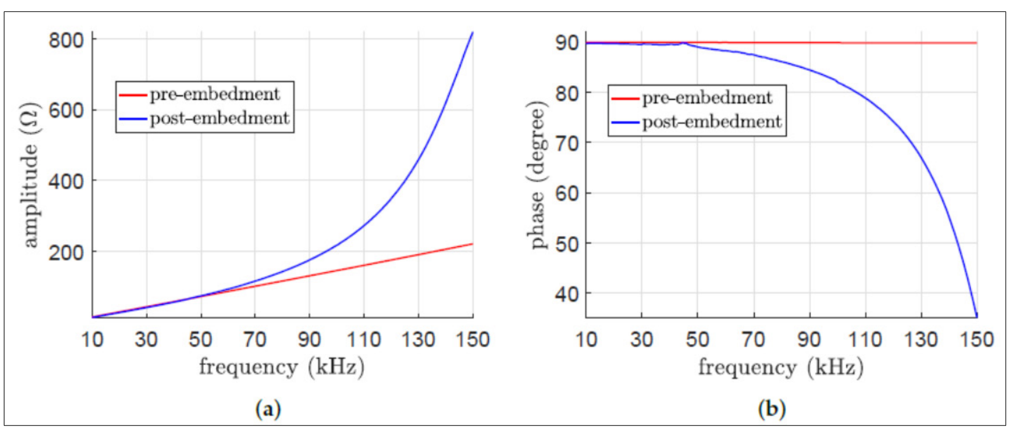


Figure 31. Comparison of amplitude and phase of the coil impedance before (pre) and after (post) embedment measured by means of the LCR meter. Amplitude (a); phase (b). (Source: POLITO, Italy)

Concrete modeling has been challenging because this material is not generally characterized for electromagnetic applications and its composition depends on several factors. Concrete is a complex material that can consist of different chemical mixtures of cements and is usually heterogeneous and porous so that it holds back water. The water content strongly influences the electrical properties of concrete so their values can vary in a wide range.

From a parametric analysis, POLITO determined the following to be true.

- The relative permittivity weakly influences the value of the equivalent impedance of the embedded coil.
- The resistivity value of the concrete strongly influences the overall coil behavior, especially for the highest frequency values.
- The increasing of the spacing between the coil turns does not significantly affect the coil behavior with respect to the variation of the concrete resistivity.
- The overall coil behavior is significantly affected by the thickness of the insulator which separates the copper turns from the concrete. This seems to be the most promising solution.

While FABRIC has been completed, POLITO will continue to do WPT research. It received funding for a novel project, named fASt and Smart charging solutions for full size URban hEavy Duty applications (ASSURED), which is comprised of 39-member consortium from 12 different EU Member States. ASSURED will test six public transport buses, two garbage trucks, one delivery truck, and one light commercial delivery vehicle with the same automatic fast charging, automatic meaning there is no human interaction during the charging process, hence pantographs and wireless charging solutions are being considered in the project[xliv]. This project will test interoperability for buses and trucks across the EU. For Italy's role, POLITO is responsible for a demonstration of energy and cost efficient static wireless charging solutions up to 100 kW for an electric van[xlv]. The project will likely have an operational prototype in 2020.

6.9.2 Latvia

There have been two EV charging projects in Latvia carried out by two companies, TransfoElectric and Lesla. The efforts in Latvia have been focused on bringing down the cost of wireless charging solutions at lower power levels.

TransfoElectric

In 2015–2016, TransfoElectric developed wireless charging for low-speed vehicles with 1 kW charging power and a battery management system for lead-acid battery EVs. The chargers were modified in 2017–2018 to operate in 85 kHz frequency to support the SAE standard. The tests were carried out in cooperation with a representative of a Polish EV manufacturer, Melex, in Latvia. Melex has been developing electric passenger, cargo, and specialty vehicles, such as golf carts, since 1971. The results of the tests showed opportunities for decreasing battery costs for low-speed vehicles fleet operators. In 2018, the company was continuing to develop a 3.5 kW wireless charger for full-size LDVs.

Lesla

Lesla Latvia has developed a low-cost wireless charger technology for a variety of charging powers. Their system provides automatic phase and frequency adjustments between transmitter and receiver, thus significantly decreasing power electronic costs. By using coreless coils, the new system reduces material depletion. As a result, the new technology allows for electrifying much larger road areas and for installing 10 wireless parking spots for the price of one traditional WPT charger.

The initial tests were carried out in 2016–2017 with a 0.6 kW charger for industrial robots. In 2018, the further development of a 3.5 kW charger for stationary charging of EVs was carried out. In 2019, Lesla's sister company in the UK, Lesla Ltd, successfully showcased the technology to complete Phase 1 of the InnovateUK program "Wireless electric vehicle charging for commercial users" in cooperation with Solisco and Keele University.

In 2019, Lesla, in cooperation with eMobility and the Latvia University of Life Sciences and Technology, started a demonstration project for an electric minibus, which will include 11 kW wireless charger development.

6.9.3 Greece

WPT technology development in Greece consists mainly of the activities of academic teams of research institutes or technical universities under grant programs. Deployment or exploitation of such technologies either from the government or companies is limited.

Within the framework of the EU's FP7 for research, technological development, and demonstration, the Institute of Communications and Computer Systems, within the National Technical University of Athens, received funding to coordinate the FABRIC project, a major project aimed at analyzing the feasibility of DWPT for EVs at typical driving speeds. This started at 2014 and was supported by a large number of partners as well as the European Council for Automotive R&D and ERTICO-ITS Europe.

6.9.4 European Union

FP7 was the EU's research and innovation funding program that began in 2007. There were several wireless charging projects developed under FP7 such as FastInCharge, Unplugged, ZeEUS, and FABRIC. Although the program is closed, a few projects are still running. The current program is Horizon 2020, which provides funding over 7 years (2014 to 2020), including €6.3B of which is dedicated to the Transport Challenge.[xlvi]

Two EU projects of note are ZeEUS and FABRIC. In the ZeEUS program, the focus was bringing electrification to the heart of the urban bus network. The project was budgeted €22.5M, with €13.5M provided by the European Commission's Directorate General for Mobility and Transport. Electric bus technologies were tested with different charging infrastructure solutions in 10 demonstration cities across Europe. Several cities tested opportunity charging with WPT including Bruges, Berlin, Braunschweig, London, and Utrecht.

The collaborative FABRIC project was part of the EU FP7 for research, technological development, and demonstration (Grant Agreement No. 605405). The project team consisted of 25 partners and 9 countries. During this project, two sites demonstrated the feasibility of DWPT at 85 kHz in real driving conditions (from stationary to highway speeds) with two different design approaches. The site in Versailles-Satory, France, was operated by VEDECOM, in partnership with Qualcomm CDMA Technologies GmbH

(Qualcomm) and Renault. The other site, in Susa, Italy, was operated by Politecnico di Torino in partnership with CRF, Iren, Saet, Tecnositaf, and the University of Genoa.

The current Horizon 2020 program released a call for proposals in late 2018 focused on user-centric charging infrastructure. Although the selected proposals have not been announced, the call does mention that it is interested in wireless charging technology applications; thus, we anticipate the EU will continue to fund these efforts in the future. Because of the breadth of the FABRIC project and its recent completion, we provide additional details about the project in this chapter.

6.9.4.1 FABRIC

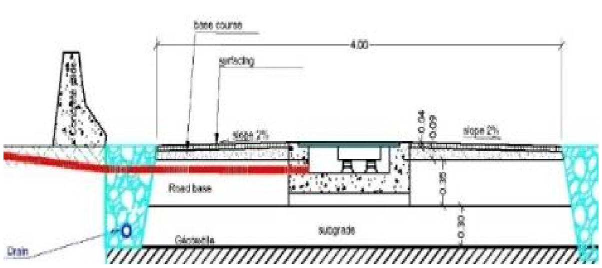
FABRIC was a large-scale integrated project co-funded by the EU FP7, and implemented by 25 partner organizations from 9 European countries.[xlvii] Over these 4 years, the €9M FABRIC project directly addressed the technological feasibility, economic viability, and socio-environmental sustainability of dynamic charging of EVs. Two Task 26 workshops were held in conjunction with FABRIC meetings and demonstrations, one in Versailles-Satory, France, (April 25–26, 2017) and one in Susa, Italy, after the final FABRIC meeting (June 25–26, 2018).

6.9.4.1.1 Versailles–Satory Demonstration Site

The main specifications for the road, electric infrastructure, DWPT system, and car are shown, respectively, in Figure 32, Figure 33, Figure 34, and Figure 35.

<u>Road infrastructure specifications:</u>

- Acceleration and deceleration zone
- Maximum speed 100 km/h
- Central pre-cast trench concept
- Charging lane length: 100 m
- 80*20 cm cavity for coils and their control system
- Non-ferrous covers, 3cm think, easily removable (bolted)



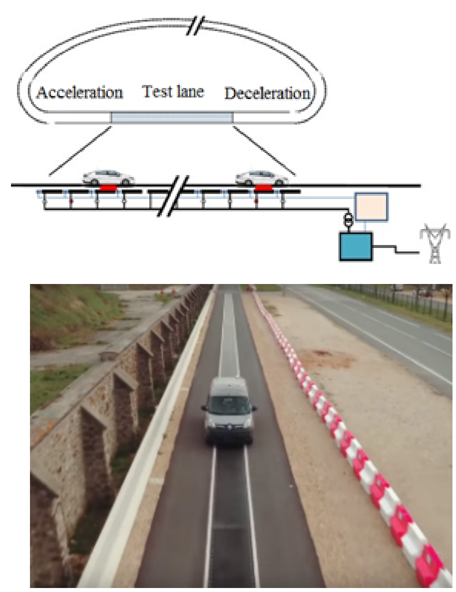


Figure 32. Road infrastructure specifications and cross section of the experimental road (left) and architecture overview and implemented view of the experimental charging road (right).

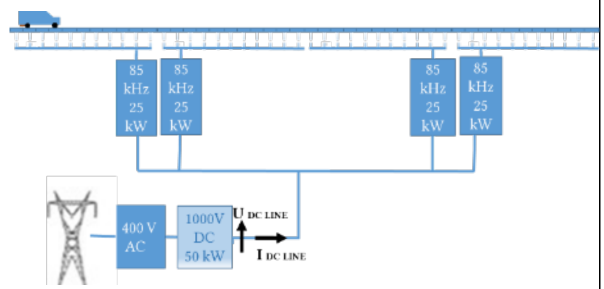
Electrical infrastructure specifications	
- Input of the DWPT system: Available power 50 kW under 1000 V DC after grid connection point - 4 segments 25 m long - Each segment can be powered by one converter at 25 kW - Maximum 2 cars on the charging lane (2 cars on two different segments) - Electric measurements (U_{DCLINE}, $I_{DC\ LINE}$)	

Figure 33. Electrical infrastructure specifications (left) and schematics (right).

Functional DWPT system specifications	
- Frequency: 85 kHz - Maximum Power into the vehicle: 20 kW - Maximum speed while charging 100 km/h - Functional in stationary conditions - Alignment tolerance: +/- 20 cm - Vehicle pad size: 350 *600 mm Note: The design & manufacturing of the DWPT system was performed by Qualcomm-Halo	

Figure 34. General specifications of the DWPT charger (left) and view of one car prototype on the experimental road (one cover has been removed and road embedded components can be seen) (right).

<u>Car additional instrumentation specifications</u>

- Lane Keeping Assistant on dedicated HMI providing alignment feed-back (based on video camera associated with lane detection software with methodology background[xlviii])
- Global Positioning System with Real Time Kinematic (to measure misalignment with centimetric precision)
- 4 lasers transducers integrated in the car (for real time air gap variation measurements)
- Electric measurements (U_{BAT}, I_{BAT})

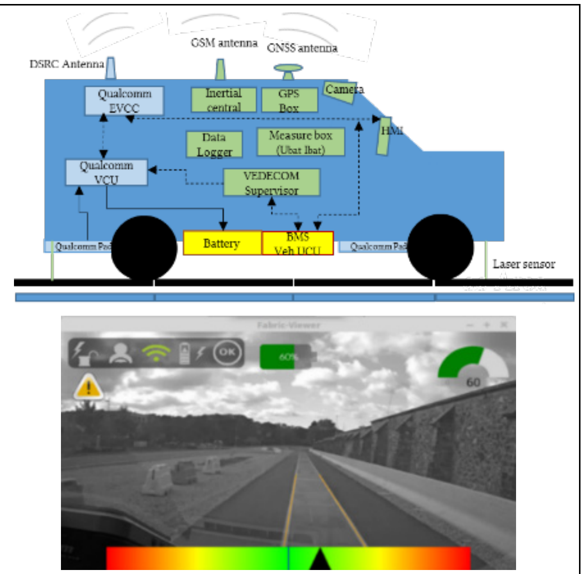


Figure 35. Additional car instrumentation specifications (left) and schematics with real-time misalignment displayed on the human-machine interface (HMI) (right).

6.9.4.1.2 Key Findings from Satory Site

Safety verifications associated with electromagnetic (EM) emissions were conducted through all the development stages (from laboratory testing to integrated system commissioning), using 27 µT at 85 kHz as reference for the maximum admissible magnetic field and common test methods developed within the FABRIC project[xlix] (see Figure 36 and Figure 37).

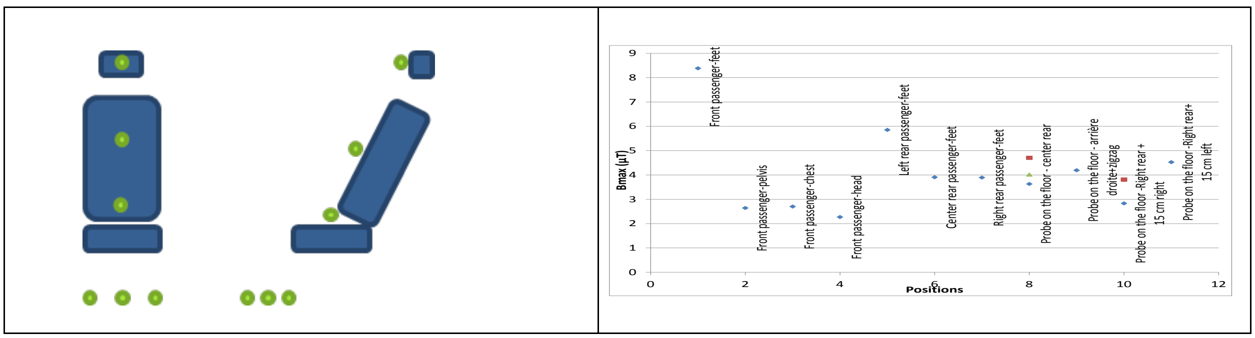


Figure 36. Location of measurement points for inside the vehicle measurements (left) and actual measurement results at 20 kW charging conditions showing values below 27 µT for the operating frequency of the DWPT system (85 kHz) (right).

Car	Driving cond (air gap nominal)	Power (kW)	Speed (km/h)	Probe location (extra vehicle)	Probe location (intra vehicle)	EMF (ICNIRP 2010 compliant)
EV1+EV2	Nominal	18	20	Height: 50 cm Distance to track reference line: 1,5 m		Yes
EV1+EV2	≠ 50 m distance between 2 cars	18	20			Yes
EV1+EV2		18	50			Yes
EV1+EV2		18	70			Yes
EV1+EV2		18	70			Yes
EV2	Stationary 5"	20	5-10-5-STOP			Yes
EV2	Stationary 5"	20	5-10-5-STOP			Yes
EV2	Zig zag	20	20			Yes
EV2	Target 15 cm right	20	40			Yes
EV2	Target 15 cm left	20	40			Yes

Figure 37. Location of measurement points for outside the vehicle measurements (left) and actual test results in different driving conditions for extra vehicle EMF assessment.

The charging integrated infrastructure and the two-car prototypes have been fully operational since April 2017 and operable for more than one year with some maintenance. Renault supplied integrated vehicle prototypes. The tests were performed on a prototype Qualcomm WPT system loaned to VEDECOM and supported by Qualcomm engineers throughout installation and testing. It has demonstrated the original targets many times:

- Charging up to 20 kW
- Charging 1 or 2 cars
- Charging up to 100 km/h
- Charging in stationary conditions

The experimental testing lane can be seen in operations on YouTube and on the FABRIC website, which summarizes the project demonstrations and findings[l,li].

The main performance indicators (DC/DC efficiency and average power received by the battery) were characterized in many real driving conditions defined through a design-of-experiments approach. A 54-test sequence was repeated. Researchers considered influence parameters including misalignment (which proved to be the most significant influence parameter), air gap, and speed. The key results are presented in Figure 38 and Figure 39.

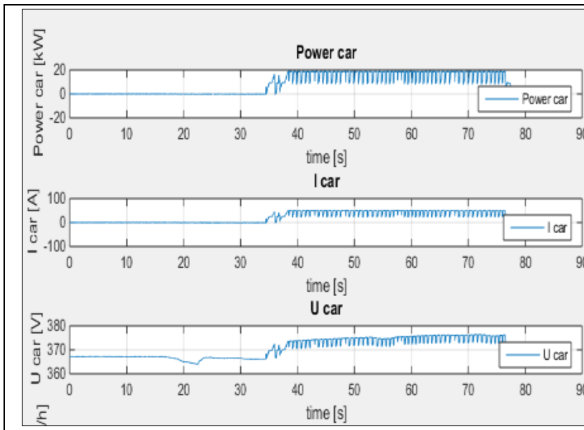


Figure 38. Example of on-board electric measurement showing ripple induced by primary coil subsection separations (test at 10 km/h, 20 kW).

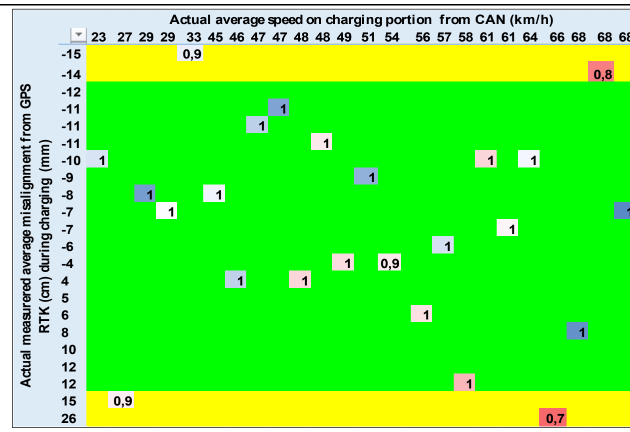


Figure 39. Efficiency indicator values as a function of average speed (horizontal) and average misalignment (vertical). This indicator is calculated as the ratio between the actual efficiency for a test run over the maximum recorded efficiency value.

More explanations and results can be found in the EVS32 conference proceedings, where this project was presented[lii].

6.9.4.1.3 Susa Demonstration Site

The main specifications for the road, electric infrastructure, DWPT system, and car are shown, respectively, in Figure 40–Figure 43. Two solutions based on similar principles have been developed:

- Solution 2 (S2) by POLITO at low-current, high number of turns directly supplied
- Solution 3 (S3) by Saet at high current with a single turn adopting a high-frequency transformer

<u>Road infrastructure specifications:</u>

- Oval track with the two solution
- Maximum speed 90 km/h
- Completely embedded solution
- Charging lanes length: 100m-S2 50m-S3
- Power electronics embedded side the road
- Specific embedment for S2

Figure 40. Road final aspects after embedding (left); sky view of the test track with the positioning of the S2 and S3 solutions and power electronic boxes beside the road for S2.

<u>Electrical infrastructure specifications</u>

- Input of the DWPT system: Available power 50 kW under 600 V DC after grid connection point (S2 & S3)
- (S2) single 100m segment in DC
- Each coil is powered by one converter at 25 kW (S2 & S3)
- Maximum 2 cars on the charging lane
- Electric measurements (U_{DCLINE}, $I_{DC\ LINE}$)

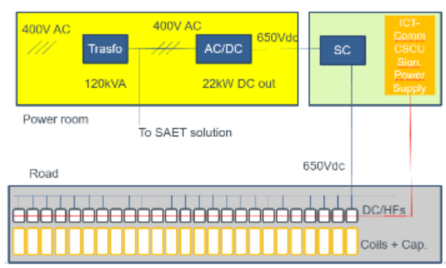


Figure 41. Electrical infrastructure specifications (left) and schematics (right).

Functional DWPT system specifications

- Frequency: 85 kHz
- Maximum Power into the vehicle: 20 kW
- Maximum speed while charging 50 km/h
- Functional in stationary conditions
- Alignment tolerance: +/- 10 cm
- Vehicle pad size: 350 *600 mm

Note: The design & manufacturing of the DWPT system was performed by POLITO

Figure 42. General specifications of the DWPT charger (left) and view of the van prototype on the experimental road (receiver and on board DC/DC converter can be seen) (right).

Car additional instrumentation specifications

- Lane Keeping Assistant on dedicated HMI providing alignment feed-back (based on video camera associated with lane detection software)
- Electric measurements (U_{BAT}, I_{BAT})

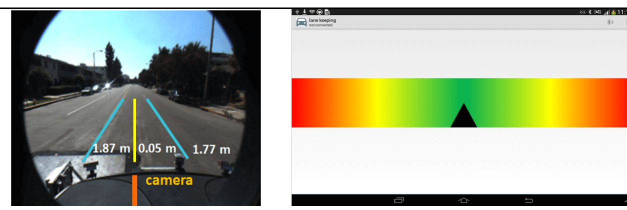


Figure 43. Additional car instrumentation specifications (left) and schematics (right) with real-time misalignment displayed on the HMI.

6.9.4.1.4 Key Findings for Susa Site

The main aspects identified within solutions 2 and 3 were the ground coupling for a realistic embedment, the capacitor compensation solution (patented) for the low-current solution, and the self-regulating power from the onboard control (Figure 44 and Figure 45).

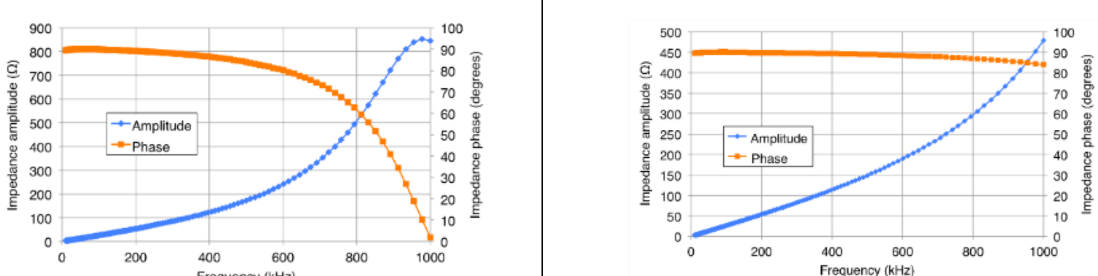


Figure 44. Phase and amplitude of coil impedance for a testing element: embedment without any correction (left) and embedment including adequate materials for insulation and covering (right).

Figure 45. Capacitor shape for the low-current (S2) solution (left) and on-board DC/DC converter for vehicle self-power regulation (right).

The embedding problems have been studied at sub-scale and in detail by embedding a reduced-scale element in the same layout of the final road. It has been proven that the phenomenon shifts versus higher frequencies.

The charging integrated infrastructure and the van prototype were fully operational only at the end of 2017 and were operable for 6 months with some maintenance. The project demonstrated the original targets of working with full temperature in complete embedded conditions, self-identification and on-board power transmission control, charging up to 50 km/h, and charging in stationary conditions. Videos of the experimental testing lane can be seen at web links provided in references l and li, which also summarize the project demonstrations and findings.

The main performance indicators (DC/DC efficiency and average power received by the battery) were characterized in many real driving conditions defined through a design of experiments approach. The team repeated a 54-test sequence and considered the following influence parameters: misalignment (which proved to be the most significant influence parameter), air gap, and speed. The key results are presented in Figure 46 and Figure 47.

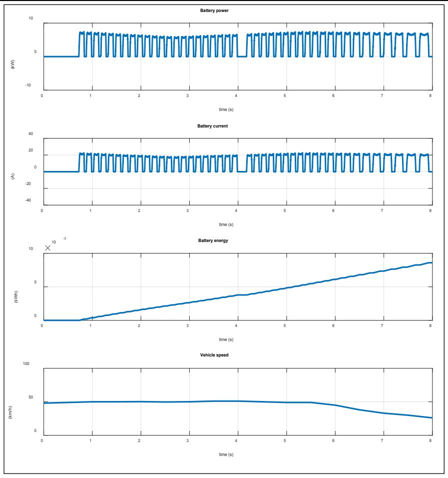


Figure 46. Example of on-board electric measurement showing ripple induced by primary coil subsection separations (test at 50 km/h, 7 kW).

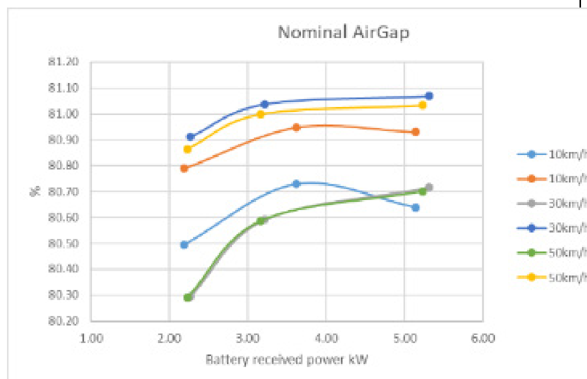


Figure 47. Efficiency values as a function of average speed and battery power.

6.9.4.1.5 Conclusions from FABRIC

The demonstrations performed during the FABRIC project have shown the feasibility of DWPT in different use cases, including high power (20 kW), from stationary to high speed (100 km/h), and with a two-car scenario.[liii]

The following are conclusions based on project experience:

- Easy access to power electronics components installed below the road surface have greatly facilitated continuous improvements and repairs during a trial lasting more than a year in real environmental conditions. Real road integration of future prototypes will necessitate additional work in terms of system architecture and road integration method because the WPT technology based on magnetic resonance could be very sensitive to neighboring materials, magnetic properties, and road integration processes.
- The total energy efficiency of the DWPT is one of the key parameters to decide large implementation of such a system. On the tested Qualcomm prototype, the total efficiency measured, grid to battery, reached about 70% using methodology elaborated within the FABRIC project for the two test sites. Qualcomm expected that an efficiency between 80% and 90% will be practically achievable when the WPT system is matched to the vehicle rather than designed in isolation.
- From a series of 54 tests, when aligned to an average +/- 12 cm, there is no noticeable reduction in the performance of the system with speed in the tested range. Vehicle speed was not an influencing element to the target speed of 50 km/h. Based on estimates, performances should be maintained up to 150 km/h.

- Air gap variation in the range of usual vehicle loading could be managed by the controls within the Qualcomm system and did not significantly affect the charge performance indicators in dynamic conditions.
- No EMC impact on car components was assessed during more than a year of monitored exploitation. However, these aspects should be studied by using appropriate standard methodology in future research.
- The Lane Keep Assist integrated in the HMI solution was a great asset to ensure maximum charging performance. Further developments should investigate fully automated trajectory control.
- Road construction plays a part in the efficiency and reliability of the system. Having a single coil and the same magnetic field strength, the precision of the realized inductances was poor, leading to a poor power transfer capability.
- Coil placement in the GA requires careful consideration to avoid overlap of the fields. Placement choice can result in high ripple on the output current and voltage levels at the battery side. Areas of no power in the GA could mitigate the impacts on the battery.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Through various demonstrations and research programs, in countries throughout the world, WPT technologies have been shown to be a promising method of powering/charging vehicles in multiple scenarios. This task successfully inventoried and studied the international efforts by conducting workshops and meetings to focus on the WPT learnings and standards across the industry. The previous work done in this field has identified key elements and parameters of the technology as well as the system characteristics and sensitivities which are required to build an integrated system:

- High power WPT technologies (100 -- 1,000kW) have been demonstrated which change the previous application boundaries
- Dynamic WPT feasibility studies have shown that large scale deployment has substantial benefit potential with large resource commitments
    - FABRIC results establish recommendations in socio-economic areas as well as technology
    - KAIST dynamic WPT enabled bus routes highlight the ability to reduce battery storage requirements and weight
- WPT center operating frequency agreement (85kHz for power levels below 11kW) will allow for multiple providers to bring technologies to market

The complexity of integrating WPT technologies into an existing transportation system is typically understated. Currently only BMW offers a production vehicle WPT charging option (at 3.3 kW)

- Current state of the WPT related standards are not adequate and require international support to address items such as;
    - Communication standards need to align with emerging AV and connected vehicle efforts
    - Safety standards for related electric and magnetic field exposure
    - EMF exposure to various vehicle electronic required additional research
    - On vehicle coil location flexibility will be required to allow various vehicle architectures
    - Standards for WPT change for categories of vehicles, how will this impact interoperability
- Higher power WPT deployments have additional consideration areas, such as;
    - Grid impacts and benefits need to be studied and tested
    - Bi-directional charging will provide additional opportunities to support Grid variation
    - Peak demand timing will be influenced with additional EVs entering the market
    - Commercial vehicle applications of WPT provide new operating environments, benefitting vehicle range and hours of service

7.2 Recommendations

The previous work done in the WPT research has made great progress to advance WPT and to highlight the potential and capabilities of this enabling technology, however, there is still much work to be done.

Continued support and investigation into the creation of proper international standards is critical to continue the progress in the WPT technologies. With standardization, businesses are more apt to invest as this is an indicator of a technology's maturity and likely deployment (monetization).

Greater adoption of EVs into the marketplace (both LD and commercial) and the future deployment of AVs will add to the positive business scenario for WPT applications. 'Self-park and charge connection' would be enabled by WPT and low speed capable AVs; consumer acceptance of EVs will surely increase as these types of features typify this segment with features that customers will demand. Consumer behavior needs to be researched and understood regarding various enabled WPT technologies. Additional fleet studies should investigate the potential to reduce battery sizing, while increasing hours of service with WPT.

7.3 Next Steps

Of the many forms of WPT technology applicable to vehicle technologies, high power static or opportunity charging (WPT to a vehicle at rest but not in Park) may seem to be the best near term deployment opportunity, as this application would not impact the infrastructure (electrical or road network) like a dynamic WPT would. However, this may not have the greatest impact on the future of e-Mobility. The recognition of increasing freight movement and the ability to electrify this transportation segment, lends to a dynamic scenario which needs continually renewed electric power. Dynamic WPT is a feasible technology in such a scenario. With proper technology interoperability, the electrification of freight transport would have a faster adoption rate and (with supporting policy) would have a greater long-term environmental and economic impact. The case for electrified roadways is being strengthened by the changes in vehicular travel and e-commerce/consumer behavior.

[i] J. G. Bolger, M. I. Green, L. S. Ng, R. I. Wallace. (1978). Tests of the Performance and Characteristics of a Prototype Inductive Power Coupling for Electric Highway Systems. [Online]. Available: http://escholarship.org/uc/item/7fq973bj#page-1.
[ii] G. A. J. Elliott, J. T. Boys, and A. W. Green, "Magnetically coupled systems for power transfer to electric vehicles," in Proc. IEEE Int Conf. Power Electron. Drive Syst., Feb. 1995, pp. 797–801.
[iii] Online. Available: https://www.conductix.us/en/products/inductive-power-transfer-iptr.
[iv] J. M. Miller, P. T. Jones, J.-M. Li, and O. C. Onar, "ORNL experience and challenges facing dynamic wireless power charging of EV's," IEEE Circuits Syst. Mag., vol. 15, no. 2, pp. 40–53, 2nd Quart., 2015.
[v] Online. Available: https://www.qualcomm.com/news/releases/2017/05/18/qualcomm-demonstrates-dynamic-electric-vehicle-charging.
[vi] Online. Available: https://waveipt.com/.
[vii] Online. Available: https://www.momentumdynamics.com/.

[viii] Online. Available: https://www.nrel.gov/news/program/2018/cutting-the-cord-nrel-demonstrates-wirelessly-charged-electric-vehicle.html.
[ix] Online. Available: https://www.pluglesspower.com/shop/.

[x] Online. Available: https://www.greencarcongress.com/2018/12/20181212-hondav2gwpt.html.

[xi] Phone Interview with Judy Talis of Momentum Dynamics, 25 September 2019.
[xii] Online. Available: https://www.icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf. ICNIRP 2010 table 4 (public exposure levels).
[xiii] Online. Available: https://www.nist.gov/cyberframework.
[xiv] Online. Available: https://www.oasis-open.org/committees/download.php/59309/161101%20Security%20Specification%20OCPP%20%28v0.9%29.pdf.

[xv] Online. Available: https://gridmod.labworks.org/projects/gm0163.
[xvi] Online. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:48074806.
[xvii] Online. Available: https://www.endesa.com/en/press/news/d201811-endesa-will-install-charging-points-for-electric-vehicles.html.
[xviii] Online. Available: http://www.caminitodelrey.info/en/4923/coming-of-electricity-used-in-industry.
[xix] Online. Available: https://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-internet.pdf.
[xx] Online. Available: http://www.infrastructure-intelligence.com/article/apr-2019/future-wireless-changing-uk's-approach-ev-charging.
[xxi] Online. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/762905/Wireless_Electric_Vehicle_Charging_for_Commercial_Users_-_FS_-_Competition_Results.pdf and https://www.bbc.com/news/business-48913028.
[xxii] Online. Available: https://www.redbridge.gov.uk/news/july-2019/redbridge-council-first-in-london-to-pilot-wireless-charging-for-electric-cars/.
[xxiii] The Road to Zero. Department for Transport. July 2018.
[xxiv] Online. Available: https://bit.ly/2C8iTM6.
[xxv] Online. Available: https://www.smithsonianmag.com/innovation/wireless-charging-cars-finally-here-180970494/.

[xxvi] Online. Available: https://www.pluglesspower.com/learn/mainstream-electric-cars-are-headed-towards-wireless-charging/.
[xxvii] Online. Available: https://www.greencarcongress.com/2018/04/20180419-momentum.html.
[xxviii] Online. Available: https://www.greencarcongress.com/2018/07/20180715-md.html.
[xxix] Online. Available: https://chargedevs.com/features/utah-state-university-builds-a-dynamic-wireless-charging-test-track/.
[xxx] Online. Available: https://chargedevs.com/features/whats-the-current-state-of-wireless-ev-charging/.
[xxxi] Online. Available: https://www.greencarcongress.com/2019/08/20190810-bmw.html.
[xxxii] Online. Available: https://chargedevs.com/newswire/honda-unveils-two-way-wireless-v2g-energy-management-system/.
[xxxiii] Online. Available: https://www.pluglesspower.com/shop/.
[xxxiv] Online. Available: https://chargedevs.com/newswire/indianapolis-buses-to-use-wireless-inductive-charging/
[xxxv] Online. Available: https://waveipt.com/long-beach-transit-lbt/.
[xxxvi] Online. Available: https://waveipt.com/antelope-valley-transit-authority-avta-2/.
[xxxvii] Online. WAVE's presentation at VTO's 2019 Annual Merit Review is available at https://www.energy.gov/node/4268456.
[xxxviii] Online. CALSTART's presentation at VTO's 2019 Annual Merit Review is available at: https://www.energy.gov/node/4268327.
[xxxix] Online. ORNL's presentation at VTO's 2019 Annual Merit Review is available at: https://www.energy.gov/node/4268345.
[xl] Online. Available: https://www.transit.dot.gov/funding/grants/lowno.
[xli] Online. Available: https://www.businesswire.com/news/home/20170621005848/en/Momentum-Dynamics-Corporation-Howard-County-Maryland-Wireless.
[xlii] Online. Available: https://waveipt.com/port-of-la-pola/.
[xliii] Cirimele, Vincenzo et al. "Challenges in the Electromagnetic Modeling of Road Embedded Wireless Power Transfer." Energies, 12 July 2019.
[xliv] Online. Available. https://egvi.eu/research-project/assured/ .
[xlv] Online. Available. https://assured-project.eu/ .
[xlvi] Online. Available. https://ec.europa.eu/programmes/horizon2020/en/area/transport.
[xlvii] Online. Available. https://www.fabric-project.eu/.
[xlviii] M. Revilloud, D. Gruyer, and M. C. Rahal. "A new multi-agent approach for lane detection and tracking." *In Robotics and Automation (ICRA)*, 2016 IEEE International Conference on Robotics and Automation, pp. 3147–3153.
[xlix] International Commission on Non-Ionizing Radiation Protection, "ICNIRP Guidelines for limiting exposure to time-varying electric and magnetic fields (1 hz–100 khz)," health physics, vol. 99, no. 6, pp. 818–836, 2010.
[l] Online. Available. https://www.youtube.com/watch?v=2t0E4AcVu6o.
[li] Online. Available. https://www.fabric-project.eu/index.php?option=com_k2&view=itemlist&layout=category&task=category&id=46&Itemid=224.
[lii] S. Laporte, G. Coquery, and V. Deniau, The Versailles-Satory charging infrastructure for Dynamic Wireless Power Transfer systems testing, EVS32 Conference, Lyon, May 20–22, 2019.
[liii] Online. Available: https://www.fabric-project.eu/ (FABRIC final use cases (D43.1)).