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The Versailles-Satory charging infrastructure for Dynamic Wireless Power Transfer systems testing

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Summary

An experimental road concept has been implemented in Versailles-Satory, France, by the French research Institute VEDECOM. Its design aims at providing a convenient test facility to develop and assess the performances of Dynamic Wireless Power Transfer (DWPT) prototype systems for Electric Vehicle (EV). A first system developed by Qualcomm CDMA Technologies GmbH (Qualcomm) was implemented and integrated in the VEDECOM experimental track and in two prototype Renault cars in the framework of the FABRIC European project [1]. This paper describes the original experimental investigations aiming to characterize the performances of such a prototype system in real driving conditions. One prototype vehicle was defined and implemented with a complete instrumentation enabling collection of energy transfer, misalignments and air gap data. Results are presented and discussed in a large range of real driving conditions. The demonstrations performed during the FABRIC project have shown feasibility of DWPT in different use cases, including high power (20 kW), from stationary to high speed (100 km/h) and with two cars scenario.

Keywords: wireless charging, dynamic charging, infrastructure, demonstration, instrumentation

1 Introduction

Even though electro mobility penetration levels worldwide are currently not high, the trend is upward, and carmakers will introduce more and more electric models to the market within the next years. Research during the recent years focuses on reducing the charging time for static stations (wired and wireless) and in parallel explores the transition from static charging to stationary and dynamic or “on-the-go” charging. The latter alleviates many of the perceived EV charging issues, in particular charging time since there is no need to stop charging [2, 3, 4]. At the same time investments in EV charging infrastructure continue to grow as it can be seen in [5]. Different summaries of the state-of-the-art in ongoing research on wireless charging EVs outlining the many technical multidisciplinary challenges have recently been published [6, 7, 8, 9]. The scientific and technological objective of FABRIC EC-project was to conduct feasibility analysis of on-road charging technologies for long-term electric vehicle range extension. FABRIC use cases [10, 11, 12] were demonstrated in Suza (Italy) by Politecnico de Torino and in Versailles-Satory by VEDECOM. This paper presents the main results and conclusions for the Versailles-Satory DWPT solution and provides future prospective on some use cases which could benefit from this technology.

2 The Versailles-Satory charging infrastructure concept and implementation

The experimental test lane implemented for the FABRIC project was integrated in the test track infrastructure in the Versailles-Satory test site. The charging lane concept aimed to develop, evaluate an original DWPT system provided by Qualcomm. The general track configuration is described in Fig. 1 below:

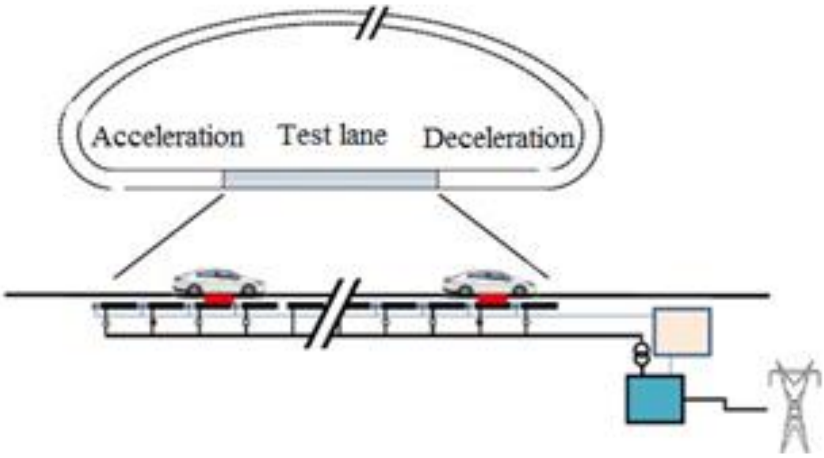


Figure 1: Complete road configuration concept for the Versailles-Satory test site

This experimental charging lane concept was developed to meet the different FABRIC project use cases expectations. Initially it was planned that the equipped length would allow simultaneous presence of two vehicles and analysis of the various transitions and the stabilization of charging. A minimum length of 100 meters for speeds of minimum 60 km/h and with an effort to reach 80 km/h. Various power levels were to be tested, the target was to experiment a power flow up to 20 kW at high speed. As a complement to any electric on and off-board data measurement, precise positioning of cars and magnetic field emissions measurement close to the track would be available for data logging.

Due to the technology designed by Qualcomm, a part of the power electronic had to be close to the emitter coils. Therefore it was necessary to have easy access to all components integrated beneath the road surface. The available space was finally set to a cavity 80 cm wide and 20 cm deep formed by a precast central trench, as can be seen in Fig 2(a). In order to close this cavity, a special study was conducted in cooperation with IFSTTAR. Different design constraints were set: no presence of iron elements, resistance in worst case braking scenarios, smallest thickness, friction equivalent to road surface, easy opening and closing. These were solved through simulation and testing finally considering 3 cm thick bolted covers made in highly reinforced glass-fiber material. The final integrated charging lane can be seen on Fig. 2(b).

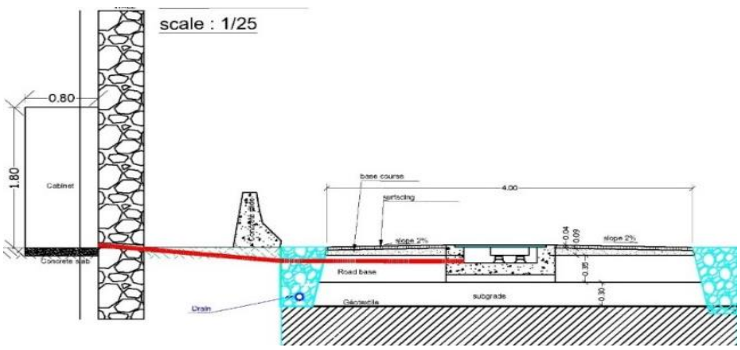


Figure 2(a): Precast trench-based road concept

Figure 2(b): View of the experimental road in 2017

3 Electric infrastructure, vehicle instrumentation and demonstrations

The DWPT primary system is supplied by a1000 V DC electrical distribution with 50 kW power along the test lane as shown in Fig. 3(a). The secondary coils deliver energy to the battery through a Qualcomm power converter as shown in light blue in Fig 3(b).

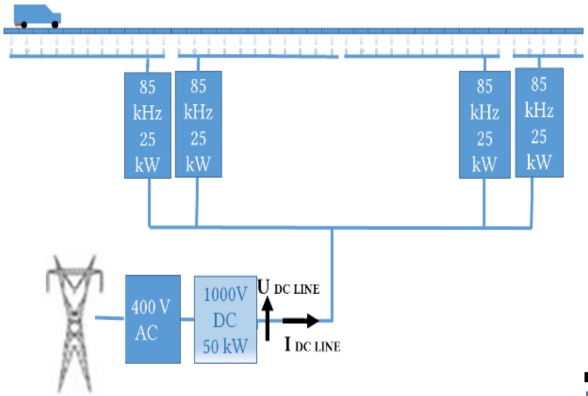


Figure 3(a): Schematic of the electric infrastructure associated with the charging lane

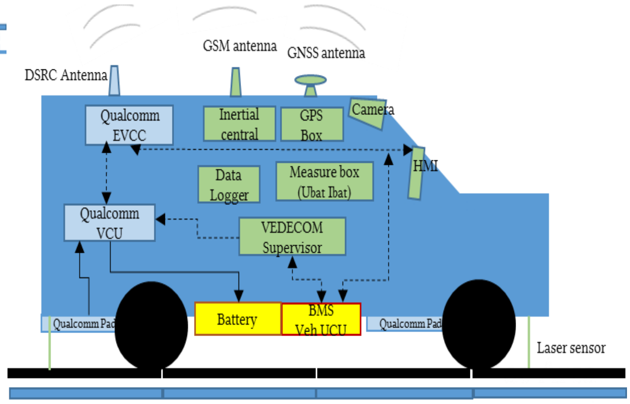


Figure 3(b): Car DWPT system components (in light blue) and main additional equipment (in green)

Additional equipment displayed in green on Fig 3(b) provided the following data:

- electric measurements (charging current and battery voltage in the measure box)
- misalignment measurements (through GPS-RTK system)
- air gap measurements (using four vertical laser sensors)

The control/command data exchange between the infrastructure supervision room and the car was done through a Direct Short-Range Communication (DSRC) antenna. All information was displayed in the car on an HMI integrating also a real-time misalignment feedback graphic interface (based on a lane detection system developed according the methodology background of [13]) as shown in Figure 4.

Figure 4: Alignment feed-back system integrated in the HMI developed for the FABRIC project

The DWPT system was implemented in two car prototypes which can be viewed on Fig. 5(a) and 5(b):

Figure 5(a): View of the first car prototype (the coils system and power electronics components embedded below the road covers can be seen)

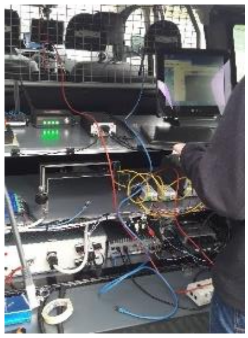


Figure 5(b): View of the second car prototype with the full instrumentation

Between March and October 2017, the following dynamic charging performances were demonstrated publicly several times, i.e.:

- at different power levels up to 20 kW
- up to 100 km/h speed,

- with two prototype cars
- according to the different FABRIC use cases (stationary…)

The experimental testing lane can be seen in operations at [14] and [15] resumes the project demonstrations and findings.

4 Main results for the Versailles-Satory site

4.1 Main EM Safety & Performance results

As defined with the FABRIC consortium, the requirements for the DWPT system commissioning have been referring to ICNIPR 2010 [16] in terms of maximum ElectroMagnetic Fields (EMF) exposure, which was thoroughly characterized at different stages of integration of the system. The measurement points and test results for tests inside the car are shown in Fig. 6(a) & Fig. 6 (b).

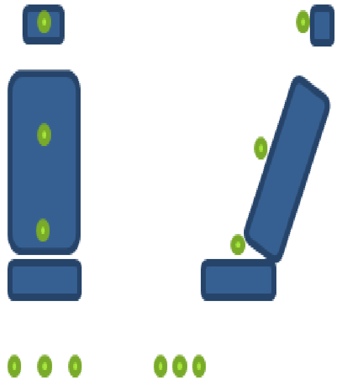


Figure 6(a): Intra vehicle measurement points inside the EV

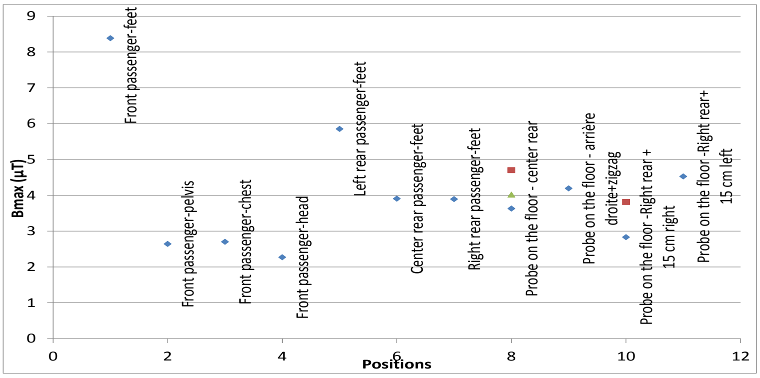


Figure 6(b): Measurement results at 20 kW showing values below 27 µT for the operating frequency of the DWPT system (85 kHz)

Outside the vehicle, the EMF levels were measured in different charging use cases with a common FABRIC project methodology as shown in Fig.7 (a) and Fig.7 (b):

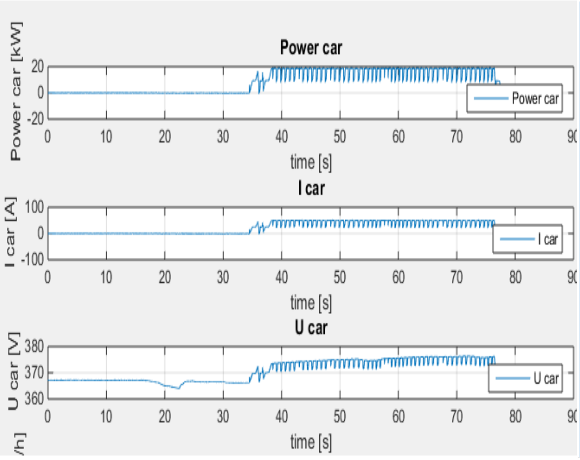
Figure 7(a): Experimental set up EMF emissions measurements

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 7(b): test results in different conditions for extra vehicle EMF assessment

Levels obtained for the different tested use cases shown in Fig.7 (b) were below the values recommended by [16]. In addition, some ElectroMagnetic Compatibility (EMC) verifications were conducted without detected significant impact on basic car functions.

The system performances have been assessed in many real driving conditions with all the instrumentation initially planned. Car and grid electric measurements were performed in different misalignment, speed and air gap dynamic conditions. A study of the impact of these parameters was conducted through a 54 tests plan. An example of voltage and current shapes can be seen in Fig. 8(a) as well as the impact of speed and misalignment on efficiency in Fig. 8(b).



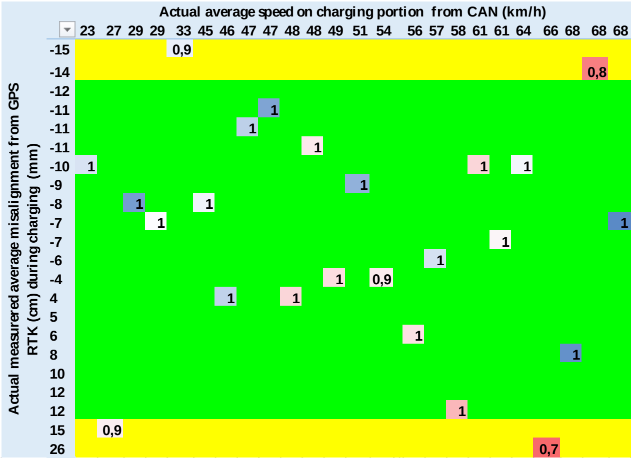


Figure 8(a): Example of on-board electric measurement showing ripple induced by primary coils subsections separations (test at 10 km/h , 20 kW)

Figure 8(b): 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

We observe that the efficiency indicator in Fig. 8(b) is relatively constant while the average misalignment does not exceed +/- 12 cm from the optimal driving position. However, with greater average misalignment, this indicator decreases significantly in particular at highest tested speed.

4.2 Additional system characterizations

In the automotive field, radiated EM emissions measurements are carried out in a static situation by positioning the vehicle on a chassis dynamometer. However, with the dynamic induction charging system, a measurement method must be adopted to measure the radiated EM emissions of the complete "vehicle and dynamic charging infrastructure" system. In the railway field, the EN 50121-2 standard [17] is dedicated to the radiated EM emissions measurement of the railway system as a whole and this standard includes limits to be respected. We have therefore adopted the same measurement method and performed comparisons with the limits applied to the railway system.

As mentioned in [17], radiated EM emissions were measured 10 m away from the road center at the passage of the vehicle at maximum charging power (20 kW), with a dedicated magnetic antenna for 10kHz to 30MHz frequencies. The configuration of the spectrum analyzer connected to the antenna (sweep time, number of points, resolution bandwidth…) was also in compliance with [17].

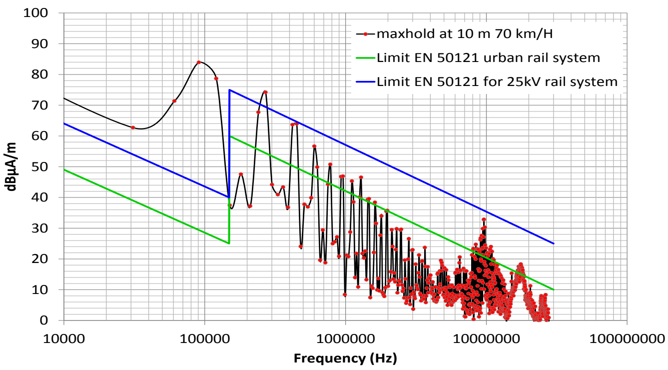


Figure 9: Radiated emissions measured 10 m away from the system

From Fig. 9 we observe that for the frequencies between 150 kHz and 30 MHz, the emissions clearly exceed the limit applied for URBAN railway system. Nevertheless, considering the limit for 25 kV rail system, only the third harmonic exceeds the limit. Radiated electromagnetic emissions could be characterized in the same way in a future standard for DWPT systems.

An additional possibility, given by the instrumentation presented in Fig. 3(b), was to measure in real time the distance of four points located at each corner of the vehicle. Therefore, we could compute the air gap variation during charge. This additional feature enabled us to determine experimentally a dynamic air gap value. In order to observe and study the effect of increasing air gap on the power received by the battery, a simple two step test using different duckboard layers was set up as shown in Fig.10.

Figure 10: Two steps tests using different duckboard layers

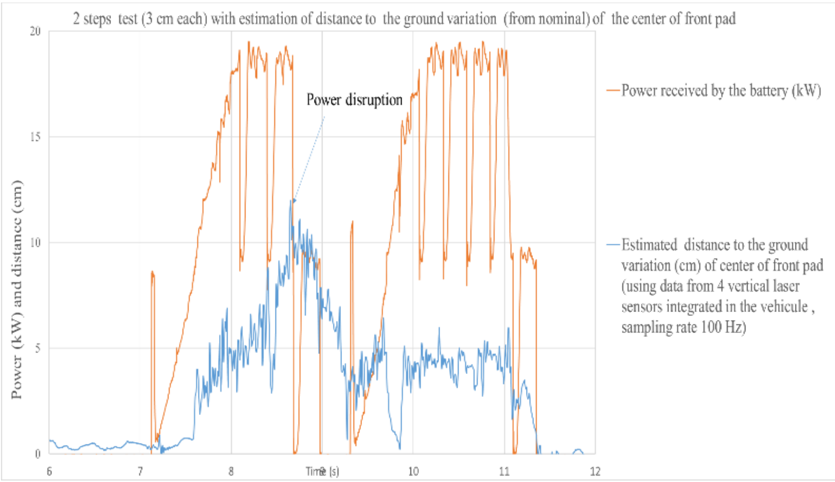


Figure 11- Experimental dynamic airgap variation measurement correlated with power received by the battery

From Fig. 11 we can observe that the transmitted power level is not influenced by total air gap increase of 10 cm from the nominal conditions (the total air gap includes car vibrations while driving over the duckboard layers).

5 Versailles-Satory demonstration conclusions

5.1 Feasibility, safety and performance for the Versailles-Satory site demonstrations

The VEDECOM experimental track concept for implementing and developing DWPT charging solutions has proven to be an appropriate tool for such specific early prototypes tune-up, validation and demonstration.

Concerning EMF exposure, the prototype system meets applicable requirements [16] inside and outside the vehicle. No EMC impact on car components was assessed during more than a year of monitored exploitation.

On the tested Qualcomm early prototype dedicated to feasibility demonstration, the total efficiency measured, grid to battery, reached around 70% using methodology elaborated within the FABRIC project (DC to DC).

The very early nature of this prototype, and its first feasibility demonstration purpose, shall be emphasized to explain this relatively low result. Further prototypes will integrate many simplifications, optimized architecture and components for power distribution etc. A minimum of 80 % efficiency in functional conditions (airgap and misalignment) is considered as a reasonably realistic target for a next prototype definition. The ripple on the output current and voltage signals could also be further reduced. The optimum level will be a trade-off between system cost and efficiency, and vehicle battery life.

The Lane Keeping Assistant was a great asset to ensure maximal charge performance during tests. Further developments should investigate fully automated trajectory control, possibly using the actual magnetic field detection.

All the instrumentation has served their initial purpose. It is interesting to note that the thematic of vehicle misalignment is generating recent research activities, in particular with the use of LIDAR-based technologies [18].

5.2 FABRIC activities towards future Standardization

Should this type of technology be integrated in real circulated roads in the future, it will necessarily have to follow a standardization process. An overview of the different standardization related items linked with DWPT has been presented in [19] and recalled in Fig. 12:

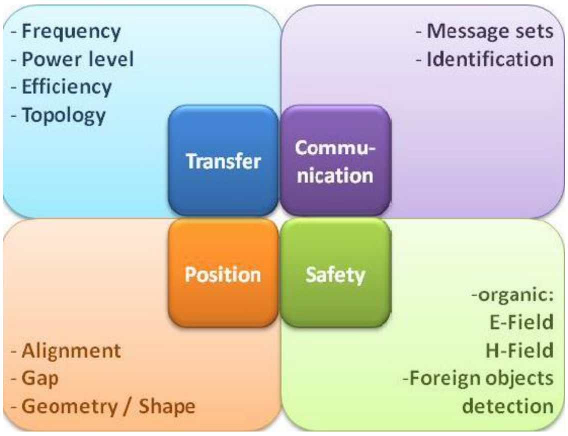


Figure 12: Topics related to inductive charging standardization from [19]

A consistent frame of International Standards is in an advanced phase of development by ISO, IEC, SAE and UL. The elaboration of these standards is performed in interactive collaboration, with the aim of achieving effective harmonization among them. A detailed updated status can be found in the FABRIC deliverables, D55.4 [20]. FABRIC has brought test method proposals to assess safety and performance which have been deployed in two test sites, some of which can pave the way for future standardization.

5.3 FABRIC demonstrations in link with other pilot studies

The main DWPT pilot demonstrations compiled from [6, 7, 8, 9] are presented in Table 1.

Table 1: Main DWPT system demonstrations and conclusions

Project/Main Institute/year/vehicle type	Power	Efficiency	Conclusions
PATH/UCBerkeley/1980-1990/ Bus	60 kW	60%	Lower power efficiency
OLEV/KAIST/2013/ bus	Up to 100 kW	Up to 85 %	First commercialized dynamic wireless charging bus is the On-Line Electric Vehicle (OLEV, 2013),
Primove/Bombardier/2013/ Buses & trucks	Up to 200 kW	Above 85 %	PRIMOVE system for buses has been tested and deployed in many cities in Europe
Nissan research Center/2013/car	1kW	90%	
China (since 2014)			Many demonstrations have been reported in China since 2014 [16] , some near locations for the next 2022 Olympic games in Bejin.
SELECT/Utah state Univ./2016/Buses and cars	30 kW		400m test track with 75m precast trenches and power panels for embedding coils roadway-scale demonstration and pilot projects
ONRL/2016/car	20 kW	90%	Laboratory conditions
UNPLUGGED/VICTORIA/2016/Bus	50 kW		For Buses 10 segmented wireless charging infrastructure systems with a total length of 300m were installed
FABRIC/Satory/2017/Car	20 kW, 2 cars up to 100 km/h	70%	Experimental instrumented Qualcomm-Halo DWPT system (100 m VEDECOM reconfigurable experimental track)
FABRIC/Suza/ (2017)/Car	11 kW	up to 85 %	2 different DWPT solutions embedded in real road

6 Prospective for DWPT technology applied to EVs

6.1 Overview

The massive planned current deployment of EVs and the related charging infrastructure [21] in Europe opens the way to innovative and competitive charging solutions. Among the current charging solutions, DWPT for EVs now appears as one demonstrated alternative option (Table 1). Business perspectives have been developed in the FABRIC project and will soon be available publicly. As a matter of fact, the favorable conditions for developing DWPT systems are economically uncertain to predict at present. Nevertheless, a short overview on its potential future deployment can be made.

6.2 The mature charging technologies

The most mature charging technology for EVs is currently wired charging. Slow wired charging options in public or private places develop at a high pace in Europe. Fast (up to 100 kW) and superfast chargers (> 150 kW) are currently deployed all over Europe along highway networks. Theses chargers should be able to address EV mass market within the next years.

Premium EV users can also experiment wireless static recharge technology.

6.3 The eRoad alternative solutions

Different ground conductive charging solutions exist [9]. Some of these have been tested in real road in Sweden [22]. Overhead conductive charging solutions are currently also tested in real circulated roads, however only for trucks [23]. These solutions typically offer a range of charging power greater than 200 kW.

WPT which initially was dedicated to static wireless charging is now in competition as a solution for dynamic charging (DWPT) since its feasibility has been demonstrated for a wide range of use cases by different projects (Table 1). Therefore, real road demonstrations can be envisioned in a few years, provided sufficient improvements are realized.

First of all, safety in terms of human EMF exposure and EMC with car electronics are pre-requisite to be assessed at every step of future DWPT system development. This is correlated with the maximum functional charging power level defined for the system. Since typical light EV requires around 25 kW motive power at 130 km/h [24], it can be proposed in a first approach to double at least this level, i.e. 50 kW. Any excess power can be used to recharge the battery, or by the powertrain to face more severe driving conditions (slope, strong wind …). However, this level should be improved further to match the levels of the other challenging technologies (up to 200 kW) so the performance and infrastructure costs can be comparable.

Regarding these costs, a first estimation of 3 M€/km/lane has been found through different approaches within the FABRIC project. In addition, a set of conditions must be reached, among which the most critical is to achieve a critical mass of vehicles equipped with DWPT technology crossing the eRoads daily and the avoidance of the chicken and eggs effect, since the lack of infrastructure will discourage potential buyers of DWPT vehicles whose costs will be higher than those of conventional electric, as described in [20].

One other issue to address is interoperability. Given the state of the art performed in FABRIC deliverable [25], a list of parameters can be set as shown in Table 2:

Table 2: Main DWPT interoperability parameters

Communication	Construction and geometry	Electromagnetic
Method (carrier)	Coil geometry	Operational frequency
Protocols	Lateral misalignment tolerance	Magnetic field intensity
Guiding system	Air gap and tolerances	Achievable secondary coil voltage
	Achievable vehicle velocity	Power rating and power

Theoretical explorations of this subject, as done in FABRIC, should be followed by experimental collaborative investigations, aiming at specifying interoperable receiver/emitter sub systems, developing test methods and providing extensive demonstrations in different use cases.

Further development of this technology in real circulated roads would also require sufficient reliability. Different possible mission profiles should be discussed, a first basis is proposed below:

- 24h/24h serviceability for any power electronic system and energy delivering
- for the emitter part embedded in the road, the minimum required by road operators is typically 15 years of embedment in traditional road

Once these technical developments are done, the essential driving factor for the technology to take off in some specific real use cases is to satisfy some economic profitability which could emerge from a conjunction of favorable conditions. Some examples of the potential favorable use case for this technology can be listed in Table 3.

Table 3: Main favorable conditions for real use cases development involving DWPT

Potential Deployment scenario	Possible DWPT system road integration	Potentially favorable factors for DWPT systems real deployment
All (generic)	Dedicated lanes	EM safety, EMC, reliability assessed (test methods) Standard approved Vehicle trajectory control (autonomous driving) Wide vehicle interoperability (infrastructure costs can be shared to a wide diversity of users) Static/stationary/dynamic compatibility
Urban	Shared bus lanes	Vehicle interoperability: car, urban busses, taxis, Light Duty Vehicles (LDV) … Cities Policies (Internal Combustion Engine vehicles restrictions, less land imprint of charging infrastructure)
Interurban	Shared lanes	Vehicle interoperability: car, busses, taxis, LDV… Charging/dropping spots close to public transport stations Possibility to extend the mobility services in complementarity to existing inter urban transports.
Long distance	Shared Highway lanes	Vehicle interoperability from car to heavy duty truck Local REN production, storage and distribution

7 General conclusions

DWPT feasibility has been fully demonstrated in compliance with FABRIC project objectives and use cases, in the Versailles-Satory test track. The demonstration has shown that this technology is feasible in different use cases, including high power (20 kW), from stationary to high speed (100 km/h) and two cars scenario. This first step is encouraging, a further step should be a demonstration in real circulated road with an efficiency target greater than 80 % (without misalignment). Advanced trajectory control offered by autonomous driving is needed so any driver can remain in the optimal charging conditions.

The different demonstrations and experimental knowledge capitalized within the FABRIC project (from measurement methods to billing and business aspects), have shown that some use cases are potentially rational and could be studied further provided favorable conditions (see Table 3). Therefore, more pre-industrial investigations are needed to allow DWPT system maturation and complete standardization (test methods for EM safety, interoperability and reliability in particular) as well as user acceptance studies.

This technology is in competition with a wide range of more or less mature other charging solutions. New battery technologies and increasing capacity installed in EVs will accept higher charging power. Increasing the power can also have a positive impact to reduce infrastructure cost since more energy can be delivered at the same speed [26].

The best compromise should be found as a trade-off between maximal acceptable power compatible with EMF safety considerations. The urban use case could be the more interesting since vehicle diversity can be considered as the most important and the energy charged per unit of length is also the most important due to lower speeds than other use cases.

As a matter of fact, this new era of electric mobility spawns many innovative ideas. The number of use cases with potentially "en-route" charging technology including DWPT has indeed never been so worth investigating and assessing since they could provide substantial societal benefits and new business opportunities in reasonable time prospective, as well as encouraging wider interest for EV adoption. EV could even be considered as "energy carriers" in the future. Reversible static (or even dynamic) WPT systems could charge from renewable energy production zones in remote areas and can discharge in urban smart grids [27].

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