**Real-world applications and selected case studies**

Public transit buses

Chattanooga Area Regional Transportation  
Authority (CARTA) project, a short ‘‘opportunity charge” of 1 min  
at 60 kW can extend the range by approximately 1 mile  
( 1.61 km) so that multiple charges in a day would release the  
range constraint to cover the required daily route of 100 miles  
( 161 km), which otherwise requires battery swapping during  
the day [60].  
Another obstacle for the expansion of traditional pure electric  
transit buses lies in the battery size, cost, and life. For a longrange all-electric bus, the battery pack can comprise about 26%  
of the weight and 39% of the total cost of the bus

Among  
the various bus projects, the KAIST On-Line Electric Vehicle (OLEV)  
project in Korea has advanced technologies that allow buses to  
charge either while stationary or in motion to significantly downsize the battery. Beginning in 2009, the OLEV research group developed and applied the Shaped Magnetic Field in Resonance (SMFIR)  
technology in buses and a tram to demonstrate the dynamic wireless charging of EVs as a commercially viable approach [57]. The  
battery installed on a Gumi City bus is less than one-fifth the size  
of a normal conductively charged electric bus battery, which significantly reduces the procurement cost of OLEVs [11]. As a result of  
dynamic wireless charging, the state of charge (SOC) of an OLEV  
battery can be kept in a narrow 40–60% SOC band that may help  
extend the battery life, instead of the large 20–90% SOC swing of  
a normal conductively charged electric bus [66].

Passenger cars

As early as 2012, the U.S. Department of Transportation recognized the emergence of WPT for EV applications and identified  
the need to understand the implications of dynamic wireless  
charging of EVs on U.S. highways [13]. In 2015, Utah State University built an advanced test facility for dynamic wireless charging  
[67]. Dynamic WPT may enable unlimited range extension for  
EVs [13]. EVs can run continuously without stopping in areas with  
available dynamic WPT infrastructure. Also, the battery capacity  
could be reduced to below 20% of a conventional EV battery [68].  
Several feasibility studies were conducted to test the idea of  
deploying a dedicated WPT lane on major roadways for inmotion charging. ORNL partnered with three other U.S. Department of Energy laboratories and conducted a feasibility analysis  
of dynamic wireless charging using traffic data from Atlanta, GA  
[69]. The power requirement versus the vehicle speed profile was  
characterized using data from Argonne National Laboratory’s chassis dynamometer testing facility and field tests of advanced vehicles at Idaho National Laboratory. A vehicle speed of 40 miles per  
hour ( 64.37 km/h) was selected to meet the minimal speed  
requirements for operational status of typical commuter roadways,  
which corresponds to a power transfer level of 25 kW. This power  
level is required to sustain vehicle travel and maintain the SOC. A  
higher power transfer level and relatively higher power from the  
vehicle propulsion system is required for greater speeds. The arterial routes that maximize roadway electrification return on investment were identified by using information from the National  
Renewables Energy Laboratory, including the most frequently traveled roadways based on vehicle miles traveled (VMT) and representative traffic volumes versus time of day. The 1% of arterial  
roads in Atlanta where 17% of VMT took place were selected as  
the most desirable road segments for charging. The infrastructure  
proposed to support this system included 12 transformers and  
inverters per mile (1 mile 1.61 km) with a 100-m maximum distance between inverter and coil

In Europe, another feasibility study being conducted  
with test sites in France, Italy, and Sweden is the feasibility analysis and development of on-road charging solutions for future electric vehicles (also called FABRIC). The project duration is from  
January 2014 to December 2017 with a total cost of 9 million Euros  
and it seeks to pave the way for large scale deployment of electromobility. It is supported and co-funded by the European Union in  
the Seventh Framework Programme for Research, Technological  
Development and Demonstration, European Council for Automotive R&D (EUCAR) and ERTICO-ITS Europe

**Research on WPT for EV**

*3.1. Korean Institute of Advanced Technology (KAIST)*

*3.2. Oak Ridge National Laboratory (ORNL)*

*3.3. University of Auckland (UoA)*

*Commercial and non-commercial WPT projects*

One early adopter was PATH (Partners for Advanced  
Transit and Highways). It is a programme founded in 1986 and led by  
the University of California, Berkeley. One research project run by  
PATH focussed on dynamic charging for EVs. In 1994, it developed the  
first prototype of such system [206]. It transferred 60 kW over a two  
inch air gap and achieved 60% transfer efficiency

Two recent European projects were FABRIC and UNPLUGGED.  
FABRIC (Feasibility analysis and development of on-road charging solutions for future EVs) is a project that started in 2014 and ran until the  
end of 2017. It was mostly funded by the European Commission and  
comprised 24 members [208]. Its main objective was to investigate the  
feasibility of DWPT technologies for EV range extension as well as efficiency of DWPT. Deliveries include analysis of existing solutions for  
DWPT and their technical feasibility [209–211]. DWPT systems of  
Qualcomm Halo and PoliTo as well as Seat were tested in three different  
test sites, France, Italy and Sweden [212].  
The second project called UNPLUGGED, ran from 2012 until 2015.  
It examined the impact of WPT of EVs on customers in urban areas and  
the feasibility of DWPT for range extension [213]. As the FABRIC

project, it was funded by the European Commission and was conducted  
by a consortium of 17 partners [214]. Technical and economic feasibility analysis of the DWPT project have been published in 2013 and  
2015 [215,216]. As part of the project two prototypes of a wireless  
charging system were built.

Besides consortia-run projects, there are also a wide range of companies using WPT. The majority are using this technology for lowpower appliances. However, a few companies offer products for EVs.  
The main companies include WiTricity and HaloIPT. Both companies  
are based on research conducted at universities and were later formed  
by researching staff of Massachusetts Institute of Technology (MIT) and  
UoA, respectively. WiTricity is focussing its production on stationary  
charging system of EV. It offers a wide range of different power levels  
up to 11 kW with efficiencies of up to 94% [219]. HaloIPT was acquired  
by Qualcomm in 2011 and is now part of the wireless charging solution  
offered by Qualcomm. Qualcomm Halo offers stationary charging pads  
in power levels of 3.3 kW, 6.6 kW, and 7 kW with efficiencies higher  
than 90% [220]

**4. Health and safety concerns**The use of time-varying currents and voltages, particularly at higher  
power levels, brings certain risks and concerns to health and safety (H&  
S). However, these risks are well known due to their usage in other  
fields and can therefore be addressed. They include electromagnetic  
field exposure, electrical shock, and fire hazards [221]. Hence, the  
bigger challenge with H&S in WPT is the public perception of the safe  
employment rather than any actual challenge for the system [222]. The  
high-frequency currents in the system produce varying magnetic and  
electric fields. Due to the low coupling between coils, the share of  
leakage field is high. It causes undesirable electromagnetic interference  
and field exposure, which not only lowers the system efficiency, but  
also leads to safety risks. To limit the impact of magnetic and electric  
fields on employees and for the public in general, the International  
Commission on Non-Ionizing Radiation Protection (ICNIRP) proposed a  
guideline for field limitations [223,224]. The reference levels of electric  
and magnetic fields for public and occupational exposure are shown in  
Fig. 15.  
In the late 2000s, the World Health Organization (WHO) presented  
a report that stated there was a lack of scientific evidence for health  
risks caused by fields with a frequency below 100 kHz [225]. Since  
then, the amount of research on low-frequency magnetic and electric  
fields has increased but it is difficult to study the long-term effects of  
magnetic radiation. Short-term effects and biological response can be  
studied by using experiments on animals, mainly mice [226]. A study  
conducted by Nishimura, et al. could not observe any changes in reproductive organs of rats during and after magnetic field exposure with  
frequencies of 20 kHz and 60 kHz [227]. The investigated magnetic  
fields had a higher field intensity but a lower frequency than currently  
present in WPT. It is therefore difficult to gauge possible impacts on the  
human body.  
With the aid of anatomical models of humans, it is possible to assess  
the impact of external magnetic field exposure on humans [228–230].  
These models are based on MRI-scanned human bodies and include  
properties of multiple different tissues, organs, and body fluids [31]. By  
coupling the anatomical model and the magnetic field generated by the  
WPT system, a tool is obtained to investigate the impact of magnetic  
field exposure. A person can interact with the wireless charging system

**7. Costs of WPT**

Currently EVs are more expensive than conventional ICE-vehicles due  
to the large on-board battery packs. While using stationary wireless  
charging, the conventional plug-in charging system is substituted with a  
charging pad installed in the ground.

highways and motorways. For example, between 2016 and 2017, 65%  
(212 billion miles) of the driven miles in the UK were located on 13%  
(~32,000 miles) of the road length [276]. This means that much of the  
daily driven mileage can be covered by installing DWPT on these key  
roads. In general, the economic feasibility of a DWPT system depends  
on road coverage, power level, EV penetration rate, and battery size

a case study based on a bus service in North Holland was investigated. The bus service included 25 buses, five of which were kept  
as redundancy. Each bus was equipped with a 500 kWh battery pack  
and was expected to drive 400 km/day, split into ten 40 km long services with six minute breaks. Along the service, there were 24 stops of  
20 s each. The Urban Dynamometer Driving Schedule (UDDS) standard  
driving cycle was utilised and a climate model predicted the auxiliary  
power consumption of each bus to be 25 kW. Under these conditions the  
SoC dropped to 68.66% after the first 40 km. The required SoC of the  
on-board battery to achieve a total of 400 km was calculated to be 87%.  
A combination of stationary charging and dynamic charging was used  
to remove the discrepancy between actual and required SoC. Fig. 20  
depicts the variation in the final SoC and achievable driving range of  
the bus depending on the stationary charging power on each stop. The  
SoC can be increased to 77.7% when a 200 kW stationary system is  
used. As this is still below the required SoC, an additional DWPT system  
must be deployed.

**4.3. Other applications**  
Wireless charging can also be applicable for other transportation modes that require continuous fixed-route operations, such  
as harbor, airport, rail systems, and theme parks. Transporting  
commodities from shipping ports to nearby distribution zones is  
often referred to as drayage operations. ‘‘Zero emission” drayage  
operations are the long term goal of many large port cities and  
wireless charging can help these vehicles operate continuously  
and enhance regional sustainable mobility in densely populated  
areas. The Port of Long Beach in Los Angeles, CA is identified as a  
candidate for such an implementation to combat the pollution  
and energy consumption related to the intense drayage operations