The Benefits of a Dynamic Wireless Power Transfer System for Electric Vehicles

Elijah A. Murphy

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Abstract

This thesis paper explores the history of wireless power transmission technology, starting from its roots in the 1800s. The paper highlights the innovations made by Michael Faraday, James Clerk Maxwell, Heinrich Hertz, and Nikola Tesla, considered the forefathers of electromagnetics. The paper also explores the concept of electromagnetic induction and how it has made wireless power transmission possible. It explains the principles of wireless charging and its required and suggested components. Finally, the paper focuses on past trials and implementations of in-road wireless charging systems. It argues why a dynamic charging system should implement this type of system by discussing why many consumers chose not to purchase electric vehicles, the efficiency of past systems, and the safety features that have been developed. Wireless charging technology has the potential to revolutionize the automotive industry by providing a convenient and efficient way to charge electric vehicles, reducing range anxiety, and promoting the adoption of sustainable transportation.

History

While utilizing electromagnetic waves might sound like a new concept, it has been researched and experimented with since the early 1800s. In 1831, an English philosopher, Michael Faraday, discovered the relationship between electromagnetic fields and electric circuits, leading him to create Faraday's Equation.[1] (see Technology section). A few years later, a scientist named James Clerk Maxwell extended the work of Faraday and studying the relationship between electric and magnetic fields. After years of experimentation and research, Maxwell published "A Dynamical Theory of the Electromagnetic Field." The primary purpose of this

[1] Al-khalili, "The Birth,".

paper was to publish his four equations of electromagnetism.[2] A few years after the publication of his research, a professor named Hermann von Helmholtz at the University of Berlin showed his students and offered a prize to the student who could prove Maxwell's equation. One of his students, Heinrich Hertz, would prove that Maxwell's equations explain the electromagnetic phenomena.

Hertz, a natural experimentalist and proficient in mathematics, eventually became a professor at the University of Bonn in Germany and, while there, researched electromagnetic waves. He proved that the waves that Maxwell hypothesized were natural and could be replicated. He is the father of radio waves, a massive technological advancement still utilized today. However, due to Hertz's early death at 36, he never fully understood the significance of his discovery. His assistant professor, Wilhelm Bjerknes, continued Hertz's research and, in 1889, gave a lecture at the Exposition Universelle in Paris.[3] One of the audience members was none other than Nikola Tesla. Bjerknes introduced Tesla to Hertz's electromagnetic waves.

Nikola Tesla is considered the father of wireless power transmission. Many people today believe that the world would be different if the scientific community had appreciated Tesla's research more during his time. When Nikola Tesla moved back to New York after living in Austria, he repeated and improved on Hertz's experiments. In 1891, Tesla patented the Tesla coil, which could power lighting systems and other electronic devices without a direct connection. The main demonstration of this work was at the Columbian Exposition at the 1893 Chicago World's Fair. With this invention, Tesla envisioned a world where power was transferred wirelessly across the world, made possible by the conductivity of the Earth's atmosphere. By

[2] Institute of Electrical and Electronics Engineers, "WPT History," IEEE WPT.

[3] Institute of Electrical and Electronics Engineers, "WPT History," IEEE WPT.

having multiple towers across the world, people would be able to tune their devices to use electricity. He moved to Colorado Springs and built the largest Tesla coil, also known as the magnifying transmitter, to pursue the project. He moved back to New York and obtained funding for a second research project in wireless telegraphy. Marconi's radio transmission in 1901 made Tesla expand its goal along with wireless power transmission. Funding problems in 1906 resulted in the end of Tesla's dream of a wireless world.[4]

Today, wireless charging is used for mobile devices, small handheld electronics such as toothbrushes, and in some cases, medical devices. In order for all devices to be charged, an industry standard is used, which defines the amount of voltage, the communication system between the electronic device and the wireless power transmitter, and ensures a safe power transfer. This standard is called Qi (pronounced "chee"). First published in 2008, Qi allows wireless charging to function across thousands of devices.[5]

Wireless Power Transfer Technology

The concept of electromagnetic induction makes wireless charging possible. When electricity flows through a wire, a magnetic field is generated. A magnetic field by itself cannot charge a device wirelessly. However, Michael Faraday proved that a changing magnetic field passing through a loop would create an electromagnetic field that can be utilized to transfer power wirelessly. This change in the magnetic field is the alternation in a current. Therefore,

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[4] Institute of Electrical and Electronics Engineers, "WPT History," IEEE WPT.

[5] About Qi Wireless Power Standard, Wireless Power Consortium.

adding more loops in the wires' coil will increase the voltage output.[6] The voltage output of this field is called the induced voltage, thus why this phenomenon is called induction. Michael Faraday created an equation to calculate the induced voltage:

$$\varepsilon = - N\frac{\Delta\phi}{\Delta t}$$ [7]

- ε represents the induced voltage created by the induction coils.
- N represents the number of loops of wire.
- $\Delta\phi$ represents the change in the magnetic flux, i.e., the change in the total magnetic field which passes through a given area.
- Δt represents the change in time.

This induced voltage can supply electricity to another circuit. In the case of wireless charging, the power is supplied to another set of coils. This is the primary principle behind wireless charging. [8]

Firstly, there must be a wireless power receiver (PRU) (Fig 1.250) and a wireless power transmitter (PTU) (Fig 1.200). The PTU must convert the input electricity into a specific amperage and voltage depending on the PRU's needs. This is why there are sub circuits such as the amplifier to increase the amperage controlled by the driver of the circuit. However, the driver and communication unit are not required for a wireless power transfer (WPT) but for the user's

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[6] Physics Dept. of UCF, "Electromagnetic Induction," Department of Physics, Roldan, Group.

[7] Physics Dept. of UCF, "Electromagnetic Induction," Department of Physics, Roldan Group.

[8] Physics Dept. of UCF, "Electromagnetic Induction," Department of Physics, Roldan Group.

and the electronics' added safety. Once the electricity is transferred from the PTU to the PRU, the rectifier has to convert the alternating current into a direct one, as most handheld devices would require. A DC/DC converter will then change the voltage of the rectified current to a specific voltage. [9]

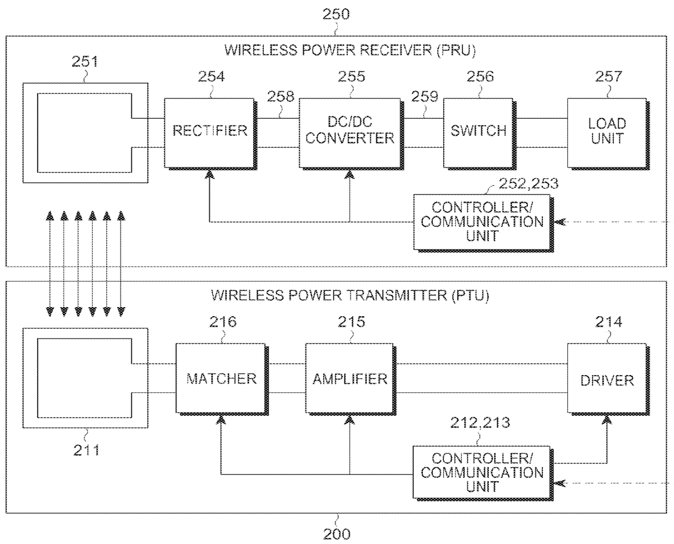

Figure 1. Kyung-Woo Lee et al., U.S. Patent issued Oct. 13, 2020, The basic method of a wireless charger,

Wireless Vehicle Charging

Vehicular wireless charging is an increasingly considered infrastructure project with the rise in electronic vehicle ownership. Wireless charging removes the need for plug-in electric vehicles, which can be dangerous if the wire is damaged, faulty, or tampered with. In addition, wireless charging would be incredibly user-friendly, requiring little to no user interaction to initiate charging. If multiple safety measures (see "Efficiency & Safety") are implemented, then wireless charging could be safer than wired charging since there is no chance of a faulty or

[9] 1. Kyung-Woo Lee et al., Method And Apparatus For Controlling Wireless Charging During Mode Transition Of A Wireless Power Receiving Device, U.S. Patent US 10804746 B2

damaged cable in the hands of the user.[10] Furthermore, wireless charging would be able to calm range anxiety, or the fear of running out of energy, in electric vehicle owners. A study conducted by OnePoll found that only 9% of electric car owners never worry about the range of their vehicles. In another study targeting potential electronic vehicle owners, Autolist found that 44% of their responders had range anxiety. In that same survey, 36% said that there was no local charging infrastructure to support them using an electric vehicle.[11] By implementing a dynamic charging system in the roadways, a large percentage of potential customers would feel more confident in their purchase of electric vehicles.

A dynamic wireless charging system built into a roadway is a challenging task. One way of completing this would be by having a station near the road that takes power from the national energy grid, records the energy consumption, and keeps track of which vehicles use the system. This will allow the owner of the charging system to bill the electric vehicle customer for the electricity used to charge the vehicle. The electricity would go to a section of the road where induction coils are placed slightly under the asphalt (See Fig. 2). A communication unit would activate the charging section when a car requests to be charged. This would heavily reduce the amount of electricity lost; the smaller the charging sections, the less energy lost. If the user requests a charge, there would be a WPT between the induction coils in the road and the induction coils in the pickup system of the car. Within the car, the electricity would be rectified, voltage regulated, then wired into the car's battery. [12]

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[10] Turki et al., "Compact, Safe," [Page 139].

[11] Lekach and Kwanten, "E.V. Survey," Forbes Wheels.

[12] Turki et al., "Compact, Safe," [Page 140–141].

This idea is more than just hypothetical. A team of German electrical engineers at Paul Vahle GmbH & Co. K.G. have created a minimal component design that has been proven to work. They used a 3.7kW power supply and powered induction coils in the road. To control the potential energy leakage, they placed a ferrite plate to contain the fields to a specific size, which stops the electromagnetic field created by the induction coil from reaching the vehicle's body. Not only does this protect the vehicle from underbody overheating due to the induction, but it also protects the occupants from high levels of electromagnetic radiation. They installed aluminum plates that shield high kilohertz frequencies to prevent the electronics within the vehicle from being affected by EMFs. Finally, they used two coils to get the most efficient energy transfer. The primary was a single-layer bipolar planar coil, and the second was a bipolar solenoid coil. This configuration allowed the most effective energy transfer and the highest tolerance to X and Y displacements.[13] However, is more than just a proof of concept. Wireless charging has been used in public transportation in some cities in South Korea.

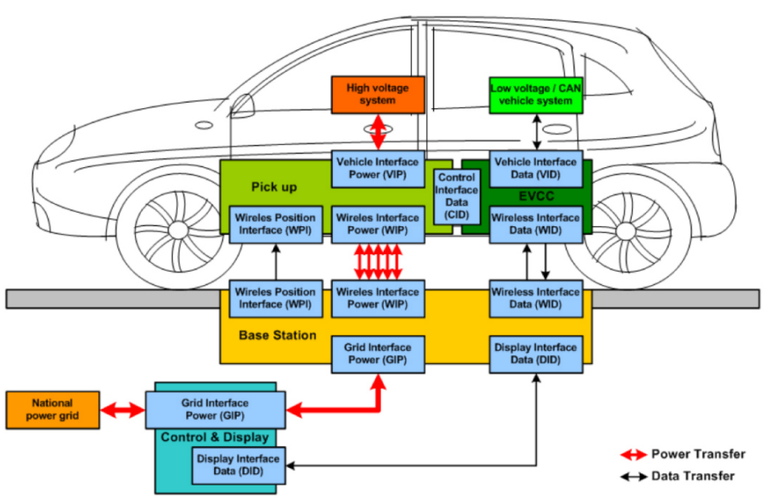

Fig 2. Turki et al. Figure, Published May 2014, System overview of wireless chargers

[13] Turki et al., "Compact, Safe," [Page 141, 149–150].

In 2010, two online electric vehicles (OLEV) were introduced in Gumi, South Korea. These vehicles were modified buses capable of charging wirelessly from charging infrastructure installed under the asphalt of the roads. These buses were among the first successful uses of wireless technology with electric vehicles. South Korea continues to innovate with this technology, most recently with the trials of another bus in Seoul.

Efficiency & Safety

Wireless technology can be safer than wired, but electromagnetic radiation caused by induction is a significant safety concern. The International Commission of Non-Ionizing Radiation Protection (ICNIRP) has set specific electromagnetic radiation ranges that are considered safe for humans. Engineers must consider these ranges when designing these charging systems. A passive method of limiting the EMF's range is using a ferromagnetic plate to limit its size. However, there are more active methods of limiting EMFs. For example, if EMF generators that output a smaller range and flow in the opposite direction of the primary charger were installed on the edge of the in-road charging system, it would cancel out EMFs that would otherwise reach pedestrians (See Fig. 3). In the case of the Korean wirelessly charged buses, this system was installed and was successful at keeping electromagnetic radiation levels significantly below the limits set by the ICNIRP.[14]

[14] Rim and Mi, *Wireless Power*, [Page 179-181]

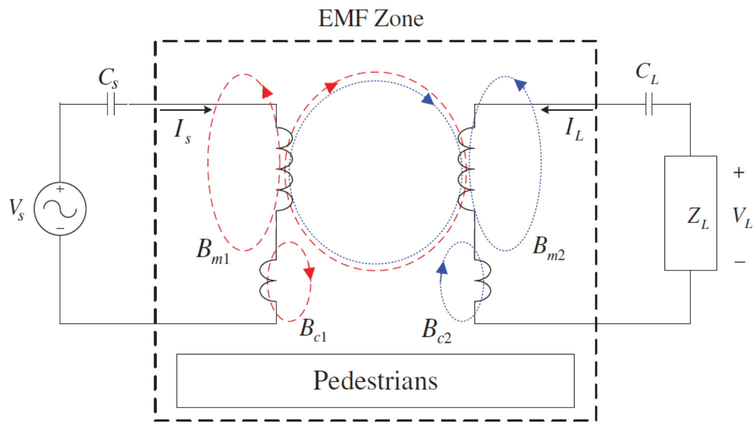

Figure 3. Rim and Mi, Figure 9.22 2017, Independent self-EMF cancelation (ISEC) method for primary and secondary sides, fetching its cancelation current from each primary coil.

One of the major drawbacks when considering WPT is the amount of power lost in the induction process; however, coil configuration and computerized auto-positioning systems would result in a more efficient power transfer. As expected, the efficiency will decline with an increasing distance between the PTU and the PRU.[15] In a project led by the National Technical University of Athens (NTUA), they found that their WPT system had an efficiency of up to 92% at a 90mm air gap. However, an air gap of 9cm is not ideal for a human-operated vehicle due to drifting within the lane. To compensate for this, NTUA designed a positioning mechanism that automatically moves the pickup coil horizontally and vertically to achieve the most efficient power transfer possible (see Fig. 4).[16] In an efficiency test of an A.C. conductive road charging system conducted by ERoadArlanda, they concluded that the efficiency of WPT outputting 80 kilowatts had a minimum efficiency of 93.45% and a maximum efficiency of 96.50%.[17] Despite

[15] Karakitsios et al., "An Integrated," [Page 18].

[16] Karakitsios et al., "An Integrated," [Page 18].

[17] Hellgren and Honeth, "Efficiency of an A.C. Conductive," [Page 38].

this high efficiency, the energy conservation test from road to battery resulted in an 81% efficiency. The reasoning behind this is not the power transfer but the power lost due to rectifying the A.C. current to a D.C. current.[18] While this may sound problematic, this can be improved by creating more efficient rectifier circuits. ERoadArlanda even claims that “The total efficiency is reduced due to the comparatively low efficiency of the particular rectifier unit used and also due to losses in conductors during high current tests. These parts could be enhanced and should be optimized with respect to cost and efficiency.”[19]

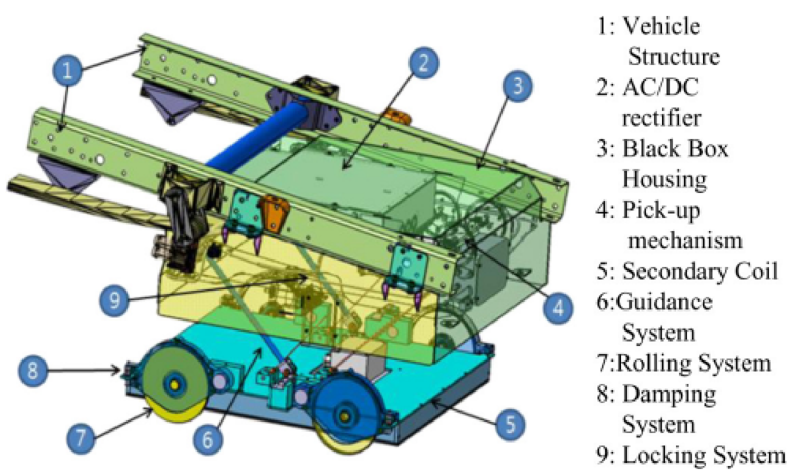

Figure 4. Karakitsios et al., Figure 7, May 2017, The pickup & auto positioning system of the NTUA WPT system.

Conclusion

Wireless power charging systems increase safety and convenience, which convinces people to purchase electric vehicles by reducing range anxiety and increasing charging infrastructure. Lighter, larger batteries might exist someday, lessening issues of range capacity,

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[18] Hellgren and Honeth, "Efficiency of an A.C. Conductive," [Page 38].

[19] Hellgren and Honeth, "Efficiency of an A.C. Conductive," [Page 38-39].

but in the interim decades, induction charging could provide a solution. Wireless charging has the potential to revolutionize the automotive industry by providing an efficient and convenient way to charge electric vehicles.

Furthermore, as seen in South Korea, a dynamic charging system could revolutionize public transportation systems worldwide. Wireless charging has been successful in the cell phone and medical industries, which are all very reliable and safe; thus indicating how wireless charging can be scaled up to more significant use cases. Now more than ever, it is essential to continue to invest in developing and implementing wireless charging systems for electric vehicles to see the benefits of a wireless and sustainable future.

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Hellgren, Mikael, and Nicholas Honeth. "Efficiency of an AC Conductive In-Road Charging System for Electric Vehicles-Analysis of Pilot Project Data." *SAE International Journal of Electrified Vehicles* 9, no. 1 (2020): 27-40. https://www.jstor.org/stable/27041193.
This source discusses an in-road charging system invented by the eRoadArlanda project. Specifically, it mentions the companies developing this system, the limitations, and the project's scope. It shows how their system works and electrical illustrations explaining the circuits necessary to function. Something that must be considered is the conversion of AC power to DC power. The vehicle must have a rectifier to create a direct current, charging a battery. They show results of short circuits, rectification, and energy loss testing. This document contains graphs showing power efficiency by measuring the power output and comparing it to the power absorbed by the vehicle. Short circuit testing was also done in their study. Their system had a 93-96% energy efficiency at a charge power of 80kW; however, it was not an induction charging system but rather a powered rail system. In the case of an unsuccessful pick-up to rail connection, the efficiency can drop significantly. High-quality conductors and rectifiers are required to make the system more efficient; however, they can be expensive. A rectifier in the road system rather than in the vehicle might be better. A communication system must also be implemented into the vehicle to ensure a safe connection.

Institute of Electrical and Electronics Engineers. "Wireless Power Transfer History and State-of-The-Art." IEEE WPT. Accessed February 27, 2023. https://wpt.ieee.org/wpt-history/.

Karakitsios, Ioannis, Evangelos Karfopoulos, Nikolay Madjarov, Aitor Bustillo, Marc Ponsar, Dionisio Del pozo, and Luca Marengo. "An Integrated Approach for Dynamic Charging of Electric Vehicles by Wireless Power Transfer - Lessons Learned from Real-Life Implementation." *SAE International Journal of Alternative Powertrains* 6, no. 1 (2017): 15-24. https://www.jstor.org/stable/26169145.
This source is a report on a complete fast dynamic charging system tested in a real-life example in Douai, France, in 2015. The use of an inductive power transfer module (IPTM) allows a high-wattage current to be passed through an electromagnetic field. This article, unlike other sources, raises issues that I have yet to consider. One of these issues is a misalignment of the receiving and transmitting systems. By having the system off by a few millimeters, the power efficiency drops off in a logarithmic pattern. It also introduces a vertical displacement issue in the system. When the system was 92% efficient, the receiving coil on the electric vehicle was nearly touching the ground. At 20

cm, of total displacement, both in the vertical and horizontal directions, the efficiency dropped to 88%. This requires a mechanism that lowers the receiving coil extremely close to the ground once a charging system is detected for the most power transfer. Furthermore, there must also be a way of controlling the vehicle to stay within the middle of the lane to avoid human error. Another error that was raised was leaked radiation. All secondary winding and positioning materials must be constructed from nonmagnetic materials to avoid negatively affecting nearby electronics. Human safety is essential, and the system they describe is significantly below dangerous levels for humans. The magnetic flux density was measured equal to 13.8µT at a distance of 60cm from the primary coil. INCIRP says that 27µT is the exposure approved for the general public.

Lee, Kyung-Woo, Kang-Ho Byun, Ho-Seong Lee, and Hee-Won Jung. Method And Apparatus For Controlling Wireless Charging During Mode Transition Of A Wireless Power Receiving Device. US Patent US 10804746 B2, filed Mar. 31, 2020, and issued Oct. 13, 2020. Accessed November 21, 2022. https://patents.google.com/patent/US10804746B2/en.
This source is a patent held by Samsung Electronics, which explains the method of controlling wireless charging. It shows multiple diagrams explaining how to construct a wireless charging system and what elements must be used to ensure the system only activates when a receiver is present. This will be incredibly useful for designing both the PRU and the PTU of my wireless car charging system.

Lekach, Sasha, and Alex Kwanten. "EV Survey Shows Range Anxiety High While Charging Costs Remain Low." Forbes Wheels. Last modified June 28, 2022. https://www.forbes.com/wheels/features/ev-range-cost-confidence-survey/.

Merritt, Rick. "Car makers signal interest in wireless charging." EE Times. Last modified October 20, 2010. Accessed February 7, 2023. https://www.eetimes.com/Car-makers-signal-interest-in-wireless-charging/.

Physics Dept. of UCF. "Electromagnetic Induction." Department of Physics, Roldan Group. Last modified April 12, 2010. https://physics.ucf.edu/~roldan/classes/Chap29_PHY2049.pdf.

Rim, Chun T., and Chris Mi. *Wireless Power Transfer for Electric Vehicles and Mobile Devices*. Chichester, West Sussex: Wiley Blackwell, 2017. PDF e-book.
The Institute of Electrical and Electronics Engineers (IEEE) book discusses wireless charging and how it can be incorporated into daily life. Specifically, section 9 discusses a dynamic charging system for road-powered electric vehicles (RPEV). Section 9.2 explains the details and requirements of creating a wireless charging system for these RPEVs. There are multiple parts in the vehicle's road system and onboard systems, such as a 50/60Hz power source, rectifiers, inverters, capacitor banks, and the charge rail. For a system like this to function correctly and safely, the power system cannot be the only requirement but also a control system, an EV system, and a safety system (i.e., active EMF cancelation methods). For these systems to operate, there are multiple factors that the designer must consider, such as a switching frequency, high power and large current, power efficiency, coil design, insulation, resonant frequency variations, and roadway

construction. There are examples of these online electric vehicles (OLEV) being implemented in South Korea as public transportation. A summary of different OLEVs implemented with their efficiency, airgap, EMF, pick-up system, and input power. This chapter presents multiple diagrams that depict system thinking, cross sections of functioning systems, and graphs displaying important comparisons such as airgap vs. efficiency.

TORRES, ROY A. "CAUSES OF ACTION FOR EMF HARM." *Fordham Environmental Law Journal* 5, no. 2 (1994): 403–29. http://www.jstor.org/stable/44174205.
This journal article published by Fordham University in 1994 discusses the legality and safety of electromagnetic fields. They discuss what electromagnetic fields are. Electromagnetic fields are created when electricity flows through a conductor. Electromagnetic fields are everywhere, such as electrical appliances, wires, transformers, or naturally from the earth. These fields penetrate most kinds of material as well as humans. Inside most buildings, a 60Hz magnetic field is created by the appliances and the electrical wires. The rest of this document explains how a legal case involving electromagnetic fields can be rebutted. For example, to defend against a nuisance charge, "the plaintiff has suffered more than a trivial harm." Notably, while discussing a charge of abnormally dangerous activity, the document mentions that a plaintiff cannot prove that electromagnetic fields were the source of harm. This is because no scientific evidence proves that electromagnetic fields can cause problems. Furthermore, due to the overwhelming benefit of providing electricity to a city, the benefits outweigh the negatives. According to Willsey V. Kansas City Power & Light Co., "[F]ear of danger from power lines is necessarily based on pure speculation by an ignorant public and can never be an element of damages even if it affects the market value of the land." This source teaches me how to gauge the safety and legality of installing any EMF-producing device on the road.

Turki, Faical, Andre Körner, Juris Tlatlik, and Alan Brown. "Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles." *SAE International Journal of Alternative Powertrains* 3, no. 1 (2014): 139-51. http://www.jstor.org/stable/26169047.
Regular charging systems for electric vehicles using cables create disadvantages such as depreciation, tampering, loose or faulty cables, and non-value-added user efforts. On the other hand, wireless charging introduces a safe and reliable charging experience. The system convinced consumer adoption and promoted the integration of electric vehicles into the car industry. Furthermore, increased access to the grid allows greater flexibility for power management and battery life length. This article discusses the power class of 3.7kW being the ideal global standardization choice. This article also discusses how wireless charging can be done with minimal components. The pickup coils have 300mm side lengths and low volume and mass. There are problems regarding efficiency and energy loss; however, these can be attributed to vertical and horizontal deviations in the vehicles' placement. For a wireless charger to operate, a magnetic field is required. Usually, this is seen in mobile devices with relatively low energy fields. However, an electric vehicle would require a significantly more powerful version. An issue raised throughout this source is that induction might heat metal in the area. This means a system

would require a way to power down if the metal is present. They introduce a foreign object detection system to monitor the high field area continuously. They also collect data ensuring that living beings are safe near these fields.

Wireless Electric Vehicle Charging Grant Program Act of 2022, H.R. 6546, 117th Cong. (as introduced, Feb. 1, 2022). Accessed February 8, 2023. https://www.congress.gov/bill/117th-congress/house-bill/6546/text?r=63&s=1.
Rep. Lawrence, Brenda L. [D-MI-14] proposed this bill on February 2nd, 2022, to allocate fifty million dollars to establish a wireless electric vehicle charging system in diverse areas. The bill discusses range anxiety, one of the primary barriers to electric vehicle adoption. It also discusses how wireless charging would benefit citizen-owned and public transportation, trucks, fleet vehicles, or autonomous electric vehicles. Furthermore, if a wireless charging system were adopted nationwide, the need for larger and heavier batteries would decline, benefiting both the consumer and the vehicle manufacturers. Section 3 of the bill discusses how the grant program would be established. The Secretary of Transportation (SoT) would work with the Department of Energy to organize this endeavor. Similar to military contracts, grants would be awarded competitively to companies willing "to construct, install, or improve existing wireless charging infrastructure and technology for electric vehicles," (3). The SoT would also publish an annual progress report to the relevant House of Representatives and Senate committees. This report will describe the recipients of these grants, how much funding they received, and reasons for selection. It would also include successes and failures under the program. This bill also requires the SoT to prioritize geographical diversification of where these grants are awarded. The program must create non-intrusive designs that work with existing infrastructure and benefit disadvantaged communities.