Dynamic Wireless Charging of Autonomous Vehicles

Demonstration of inductive power transfer as enabling technology for self-sufficient energy supply to autonomous electric vehicles by a small-scale self-driving truck model

Giuseppe Guidi, Anastasios M. Lekkas, Jon Eivind Stranden and Jon Are Suul

Recent developments towards self-driving cars combined with technology for wireless inductive power transfer can enable electric vehicles that are fully autonomous with respect to operation and energy requirements. Furthermore, technology for wireless opportunity charging or dynamic on-road inductive power transfer can allow for autonomous electric vehicles with infinite driving range. This article discusses the general potential for combined utilization of the technological progress towards self-driving vehicles and the capability for autonomous energy supply to electric vehicles enabled by dynamic on-road wireless power transfer. For illustrating the potential for utilization of such solutions in the electrification of road transport, a small-scale demonstration model of an electrical truck is built, based on adaptations of a replica in scale 1/14. This model allows for transparent and easily accessible demonstration of the operating principles of the technology and the main functionality of dynamic wireless charging as well as basic self-driving functionality. It is also briefly discussed how the demonstrated technology scales for such a small-size low-cost models and what parts of the system can be realistically studied. Results showing basic path-tracking functionality of the demonstration model along a defined track that includes two ground-side coil sections for dynamic inductive power transfer are presented as illustration of the demonstrated functionality.

Autonomous vehicles and electrification of transport

Autonomous vehicles, and especially autonomous cars have been researched for many years, with one of the earliest examples dating back to 1925. It was an invention by Francis Houdina and involved remote control operation in the streets of Manhattan through thick traffic. Despite several milestones over the decades that followed, it was not until 1994 that a self-driving car was tested in public traffic. This test was the result of years of effort by German aerospace engineer Ernst Dickmanns and his team, who modified two Mercedes 500 SEL cars and deployed them in the streets of Paris as part of the *Prometheus* project. Each car was equipped with two cameras with different focal lengths and were able to navigate and change lanes through traffic. In 1995 Dickmanns' cars travelled autonomously from Munich in Germany to Copenhagen in Denmark, and back, while reaching speeds higher than 175 km/h. Although human drivers took over in situations that the cars were not designed to handle, such as road construction sites, 95% of the driving was performed autonomously. During the same year, the “No Hands Across America” trip from Pittsburgh to San Diego was completed by roboticists Pomerleau and Jochen of Carnegie Mellon University. The car achieved an autonomy percentage of 98.2%, however, the car’s onboard system was responsible only for steering while the human drivers controlled the throttle. Their design approach was also different from Dickmanns', as it was a continuation of Pomerleau’s vision since 1989, where he had used a fully-connected neural network to build the Autonomous Land Vehicle in a Neural Network (ALVINN) system. Pomerleau’s and Jochen’s system was therefore designed to learn instead of being explicitly pre-programmed to handle every possible situation on the road. In 2005, the first fully-autonomous trip took place as part of the DARPA challenge, which involved a 212km race through the Mojave Desert. Stanford

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university was the winning team with their car *Stanley* finishing the race first in 6h and 53min. Among the 23 contestants, 5 completed the race, hence giving a strong message that self-driving cars could become a reality. Stanford's team also relied on machine learning, including methods such as decision trees and support vector machines, to enhance the car's perception system and ability for decision making under uncertainty.

Even with several successful demonstrations of capability for autonomous operation, massively produced and deployed fully-autonomous cars did not seem likely to become reality until very recently. One main bottleneck had been the lack of sufficiently reliable and robust perception and situational awareness systems, which would allow the vehicle to understand its environment, including detection of the road, other cars, pedestrians, cyclists, animals and anything else that might find its way in the vehicle's surroundings. Such information would then enable the vehicle to assess its current situation, calculate possible risks, and select its next actions accordingly. Due to the highly uncertain nature of the environments in which cars operate, especially in urban and rural areas, such tasks, which can be handled easily by human drivers, remained infeasible even for the most advanced traditional perception methods.

Recent breakthroughs within the AI subfield of deep learning (DL), which has been fueled by the availability of high computing power and large datasets, hold promise for developing better computer vision systems that can achieve superhuman performance in many areas. The first DL breakthrough in computer vision came in 2012, when the deep neural network *AlexNet* surpassed all previous approaches on *ImageNet*, a collection of image data representing 1000 different classes. Since then, the achievements of DL in computer vision include facial recognition, detecting skin cancer at dermatologist level using clinical data, and learning to perform image segmentation in diverse environments. Naturally, perception systems for autonomous cars have relied heavily on DL the last years. In most cases, deep convolutional neural networks (CNNs) are tasked to detect and track objects of interest in camera images, where they have so far performed better compared to conventional computer vision approaches due to their ability to learn from huge datasets and generalize beyond them. In other cases, like the so-called "end-to-end" approaches, a CNN is assigned to learn the entire processing pipeline needed to steer an automobile. This was the approach implemented by NVIDIA's *DAVE-2* in 2016*,* where pixels of images from a single front-facing camera were mapped directly to steering commands. Interestingly, NVIDIA's approach built directly upon Pomerleau's work from 1989. Currently, many experts believe that self-driving cars are just a few years away, and big industry players such as Google, Mercedes, Tesla, Uber, NVIDIA, Toyota, and many more, are investing heavily to make the fully-autonomous car era a reality.

Notwithstanding the importance of perception systems as a necessity to enable autonomous vehicles, self-driving cars do not involve one single technology. They constitute a complex set of technologies, all of which need to be advanced and eventually integrated into a unified system that must be suitable for fulfilling practical needs of transportation. Thus, future practical applications of self-driving technology must also provide convenient interfaces to the users and ensure practical energy availability to fulfill the transport needs. In this context, the recent developments of technology for self-driving cars is coinciding with the emerging electrification of vehicles driven by the need to reduce emission from transportation. Indeed, battery-electric propulsion is directly enabling zero tail-pipe emission of autonomous vehicles with the main limitation being the driving range limited by the battery capacity. However, emerging technology for wireless inductive power transfer can enable autonomy in terms of energy supply with battery charging managed autonomously controlled by the vehicle without human intervention. Thus, wireless battery charging can enable fully autonomous long-term operation of electric vehicles.

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Wireless inductive power transfer as enabling technology for fully autonomous electric vehicles

Compared to fuel-based vehicles or electric vehicles with plug-based charging, solutions for wireless inductive power transfer allow for easily automated and fully autonomous battery charging of electric vehicles. After extensive research and development efforts during the last two decades, practical solutions for wireless power transfer are emerging as a convenient, reliable and flexible technology for battery charging. Although the solutions currently being commercialized for electric vehicles are mainly intended for conventional driver-operated cars and busses, the technology can clearly be utilized by a wide range of battery-electric autonomous systems. Indeed, wireless charging is a perfect match for fully autonomous battery-electric vehicles, and it is easy to foresee solutions where electric cars with self-driving capability can manage the charging required to cover their own energy demand. For this purpose, the car would only have to drive to the nearest available wireless charging point and could effectively utilize available idling time to ensure that the battery will be sufficiently charged before the next transport assignments. Such solutions are applicable for privately owned autonomous cars as well as for autonomous taxis or other vehicles contributing to the public transport system.

Even with the rapidly ongoing development of electric vehicles, battery-electric propulsion is still considered by a large part of the general public as unsuitable for long distance driving due to the limited onboard energy storage capability and the time needed for recharging. Although limitations of battery capacity, charging time and driving range might become largely an issue of cost for privately owned cars, weight, size and charging time of batteries are still imposing significant challenges for electrification of commercial vehicles with long required operating range and few opportunities for battery charging. One possible approach for avoiding the limitations of driving range in electric vehicles is to enable the power transfer to the vehicle, for propulsion and/or battery charging, directly from the road infrastructure during regular operation. Thus, recent research and development efforts have led to the proposal of several solutions for "electric road" technology and "roadway-powered electric vehicles." Although conductive solutions based on sliding contacts are also being developed and demonstrated, with several conductive concepts being tested in Sweden, solutions for contactless dynamic power transfer have several advantages in terms of flexibility, safety and reliability due to the avoidance of any mechanical or electrical contact. Indeed, the infrastructure for such systems can be embedded in the road without any visible interface at the surface. However, the cost of such solutions is still a significant challenge, and the technical solutions that have emerged from the work of different research groups are still not standardized in a way that can ensure interoperability in an open environment as public roads. Therefore, several demonstration projects for various concepts allowing for dynamic wireless charging of electric vehicles have been initiated or are currently under development, with the intention to gain experience while supporting the technology development needed before such systems will become commercially applicable in larger scale.

Notable activities have for instance been initiated in South Korea, where several concepts for dynamic or quasi-dynamic wireless charging of cars, busses and trains have been demonstrated. In smaller scale, several demonstration facilities have been recently developed for testing of technology in controlled environments, for instance in France and Italy within the EU Project FABRIC, and in testing facilities associated with Utah State University. Numerous other research groups have also developed smaller test facilities for supporting academic and/or industrial development activities related to the design, control and operation of such systems.

Since most demonstration projects have been limited to relatively low power levels suitable for small vehicles, only few projects have studied the infrastructure needed for electrification of heavy vehicles by on-road charging. As one exception, Bombardier in Germany demonstrated already in 2012-2014 a concept for dynamic wireless charging of a truck at power levels up to 200 kW as part of a Swedish research project on electric road technology. The development towards technology demonstrations have continued in Sweden, and plans for the first large-scale demonstration of dynamic charging technology on a public road are now being confirmed. The planned system is already under

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construction based on technology supplied by the Israeli company Electreon, with intended commissioning during 2020, and will include 1.4 km of public roads with the possibility for dynamic charging of a truck and a bus.

The existing and planned demonstration projects for electric road solutions can be expected to bring the technology forward towards future commercial applications, but the time required before potential large-scale utilization will be realistic is still uncertain. Although most research groups involved in the technical developments of inductive power transfer for electric vehicles are predicting future synergies with self-driving technology, the combined operation of such technologies has not been widely studied. Thus, a scaled laboratory model that can be utilized for demonstrating both technologies in a laboratory environment is presented in this article and utilized to illustrate some simple examples of potential operation.

Figure 1 Small-scale truck model equipped for autonomous driving and wireless charging

Small-scale truck model for demonstration of wireless charging and autonomous driving

One obvious challenge with on-road wireless power transfer systems is that they are expensive to build and operate. Therefore, even large and well-funded research and demonstration initiatives like the EU 7th FP FABRIC project have only constructed relatively short test sites that, in spite of being rather impressive, cannot demonstrate the full potential of the technology. Large-scale test-tracks also tend to lack flexibility; upgrades are difficult and expensive, making it virtually impossible to use the sites as benchmark for new solutions based on the rapidly evolving underlying technologies. Small-scale models, on the other hand, are easy to build and modify and are ideal for research, testing and demonstration of basic functionality and for comparing alternative options.

As a low-cost platform for research and demonstration activities, a small-scale model of an electric truck with wireless charging capability is presented in the following. A rather accurate replica of a conventional diesel truck, in scale 1:14, available as an off-the-shelf radio-controlled model from Tamiya, has been used as basis for the development. The model, as shown in Figure 1, came equipped with battery-operated servo-drives greatly simplifying the conversion to self-driving and the implementation of a dynamic inductive charging system. The model was then converted to operate with wireless inductive charging by integrating a receiving coil with the corresponding resonance capacitor and a converter for interfacing with the onboard battery.

A self-driving system based on the embedded system-on-module (SoM) Nvidia Jetson TX2 was also developed and mounted on the truck model. The sensor package mainly consists of a LiDAR and a camera. The LiDAR has a distance range of 0.15-12m and a maximum scan rate of 15Hz, while the camera has a maximum resolution of 1920 x 1080 pixels. The control signals for the traction and steering from the original radio-control interface have been replaced by a microcontroller that generates pulse width modulated (PWM) signals as references for the original servo motor drive system of the truck model.

The self-driving system software stack consists of ROS, OpenCV and Keras running on top of TensorFlow. ROS is used as the main framework for enabling hardware integration with the LiDAR, the microcontroller and a joystick for manual driving, and functions as a peer-to-peer network of processes (nodes) that can communicate via message passing (topics). OpenCV is used to capture and process images from the camera.

Scaling considerations for electric vehicles and wireless charging systems

When scaling-down reality, fidelity must always be questioned: what aspects of the systems can be accurately replicated and studied and what characteristics will be lost in the miniaturization process? It is easy to argue that downscaling has limited influence on the fundamental behaviour of self-driving systems, being the latter a purely geometrical and logical problem. Thus, the main issue for the developed truck model is just that the size of commercially available sensors is relatively large compared to the vehicle while they will be insignificant for a full-scale truck. However, the scaling of the inductive power transfer system requires deeper analysis.

A fundamental result of coupled circuit theory is that the maximum theoretical efficiency at which non-radiative power can be transferred between two coils can be expressed solely in terms of the quality factor of the coils Q and the mutual coupling coefficient k:

$$\eta_{\max} = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2} \; ; \qquad Q = \frac{\omega \cdot L_{coil}}{R_{coil}} \tag{1}$$

Crucially, it turns out that the basic factors determining the power transfer of resonant inductive charging, namely the magnetic coupling and the quality factors of the coils, are invariant with geometrical scaling. More specifically, the scaled-down version of a given multi-coil system will give rise to the same electromagnetic field pattern of the original system, and the power transfer between coils will take place at exactly the same theoretical efficiency, albeit at a power level reduced by the cube of the geometric scaling factor and at a resonant frequency equal to the square of the one of the original system. This very convenient scaling property has been exploited when deciding to build the small-scale demonstration model.

It must be pointed out that while scaling down the macroscopic details of the coils by a factor of fourteen poses no challenges, there are some important microscopic details that cannot be easily (or practically) reproduced, leading to loss of fidelity. Most notably, the very many thin insulated copper strands forming the coil conductors (Litz-wires) of typical resonant coils cannot be scaled, typically resulting in lower efficiency for the reduced-scale model. This factor, combined with the increased losses in magnetic materials and in the power electronics converters, often calls for operation of the reduced-scale model at a frequency lower than what would follow from the ideal geometrical scaling. Lower operating frequency, however, results in lower theoretical efficiency for the inductive power transfer process, as immediately seen in (1).

Perfect geometry and frequency scaling also cause changes of properties related to heat management, since the cooling performance is proportional to the exposed surfaces, while the heat to be disposed of is proportional to the volume. This means that all things being equal, the actual full-scale system would be more challenging to cool than the small-scale model.

The biggest drawback of the scaled-down model is that it cannot be used to directly gather reliable information about the energy balance of the driving/charging process. This is partly due to the difference in efficiency of the wireless charging system discussed above, but mainly because the driving effort – the power required for driving the truck along a given route – does not scale with the same law as the inductive charging power. Even worse, different components of the total driving power (aerodynamic drag, road friction, drivetrain friction, slope climbing, etc.) scale according to different laws that are sometimes difficult to assess. Thus, the scaled truck model will not have the same ratio between the average and peak power requirements as a real system, and the operation of the model should not be directly utilized to evaluate the operation of dynamic wireless charging systems in terms of influence on available driving range or on the infrastructure requirements for ensuring long term energy balance of the vehicle. However, comparative analysis of some general trends and characteristics can be relevant, especially for comparing design strategies and control methods based on similar system configurations.

Given the nature of the application, the total amount of energy that can be transferred to the on-board battery for a unit length of travelled distance is arguably the most important criterion, besides cost, for comparison of different solutions. Such energy transfer capability depends on several factors, including the design of the road coils (shape, length, mutual distance, etc.), the capability of the converters in terms of maximum voltages and currents and the performance of the control methods used to regulate the power flow under variable loading and coupling conditions resulting from driving. Therefore, rather than simply looking at the maximum transfer efficiency given by (1), the overall energy transfer per-unit length of road should be considered. Indicating with e_{in} the total energy supplied by the utility grid to the road-side infrastructure, normalized to the road distance, the energy transfer efficiency can be expressed as:

$$\eta_{road} = \frac{e_{batt}\left[kWh/km\right]}{e_{in}\left[kWh/km\right]} \leq 1 \tag{2}$$

Although the energy efficiency of a small-scale model will differ from a full-scale system, comparative analysis of energy transfer efficiency can reveal relevant differences between various concepts for dynamic wireless charging. When evaluating this figure, the accuracy of the driving pattern (i.e. the alignment between on-board and on-road coils) will also have an impact. Thus, self-driving solutions also imply the potential for more accurate and consistent positioning of the vehicle when passing the road-side coils and thereby improved utilization of the infrastructure compared to manual driving.

Electromagnetic design of dynamic wireless charging system

A wide range of system configurations for dynamic wireless charging have been proposed in the literature and several different concepts have already been deployed in existing demonstrators. However, a dynamic charging system can be implemented using rather simple coil shapes while still obtaining operational characteristics and performances that are largely comparable to more complex arrangements. For the presented small-scale demonstration, rectangular-shaped planar coils have been employed due to their simple structure. A plate of magnetic material (ferrite) is placed behind each coil to improve the quality factor as well as the mutual coupling, ensuring a reasonably high power transfer efficiency. As usual in resonant inductive power transfer systems, Litz-wires are used for the coils to limit losses at the target resonant frequency.

The size of the on-board coil is largely determined by the available space on the vehicle. On the other hand, the design of the coils for the road-side infrastructure has a fundamental degree of freedom in the length of each section that can be independently energized. Long sections result in simplified power supply (lower number of power electronics converters and/or simpler switching network), but normally result in lower efficiency. Moreover, long energized sections can create challenges with control of the electromagnetic emissions and can be difficult to manage when vehicles that are not equipped for wireless charging are mixed with charging vehicles in the normal traffic flow.

Small, discrete, road-side coils – ideally with the same size as the on-board coil – yield the highest theoretical efficiency, when car and road coil are perfectly aligned. However, frequent end-coil effects due to the vehicle motion cause pulsating power flow and effective reduction of both overall efficiency and total energy transfer. End-coil effects can be avoided by overlapping adjacent coils (multi-coil systems), at the expense of increased cost in terms of more required materials and more complex power supply.

The trade-off between coil length and efficiency can be qualitatively and quantitatively evaluated in the case of simple rectangular coils. As an example, consider a road coil section of length l_0 that is at least twice the length of the on-board coil in the direction of travel, having self-inductance $L_{P,0}$ and resistance $R_{P,0}$. Extending the coil length to $l > l_0$ result in new inductance and resistance values for the road coil given approximately by:

$$R_P(l) \approx R_{P,0} \cdot \frac{l}{l_0}; \quad L_P(l) \approx L_{P,0} \cdot \frac{l}{l_0} \qquad \Rightarrow \quad Q_P(l) \approx Q_{P,0} \tag{3}$$

The quality factor of the road coil is therefore approximately independent of its length. The mutual flux is also approximately independent of the length of the road coil, since the latter is anyway much longer than the on-board coil. The coupling factor ca then be expressed as:

$$k(l) = \frac{M(l)}{\sqrt{L_P(l) \cdot L_S}} \approx k_0 \cdot \sqrt{\frac{l_0}{l}} \tag{4}$$

The change in maximum efficiency due to the extended length can be evaluated by the fundamental equation (1). Some numerical examples are shown in Figure 2, by assuming reasonable values for the quality factors and three different values for the initial coupling coefficient.

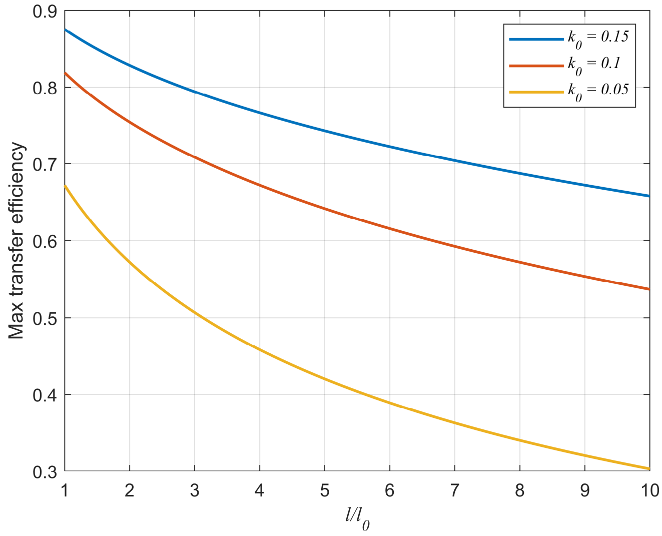


Figure 2 Impact of road-side coil length on the maximum power transfer efficiency of dynamic wireless charging systems

For designing the presented small-scale demonstration platform, reference target specifications for a full-scale dynamic charging system have been assumed according to Table 1. These specifications are based on the general expected requirements in terms of power consumption for a future electrified heavy vehicle, its actual size and the necessary clearance between the receiving coil mounted on the vehicle and the road surface. A wide range of values was allowed for the road coil length, as different design concepts should be tested. The operating frequency of the system has not been specified, as at present no standard has been established for such systems. Although most conventional static wireless EV charging systems operate in the standard frequency window 80-90 kHz, it is possible that systems requiring considerably higher power levels will be operated at reduced frequency, possibly in the order of 20 kHz as for instance used by the first high power systems demonstrated for busses and trams.

Table 1 Assumed specifications of a full-scale dynamic charging system for an electric truck

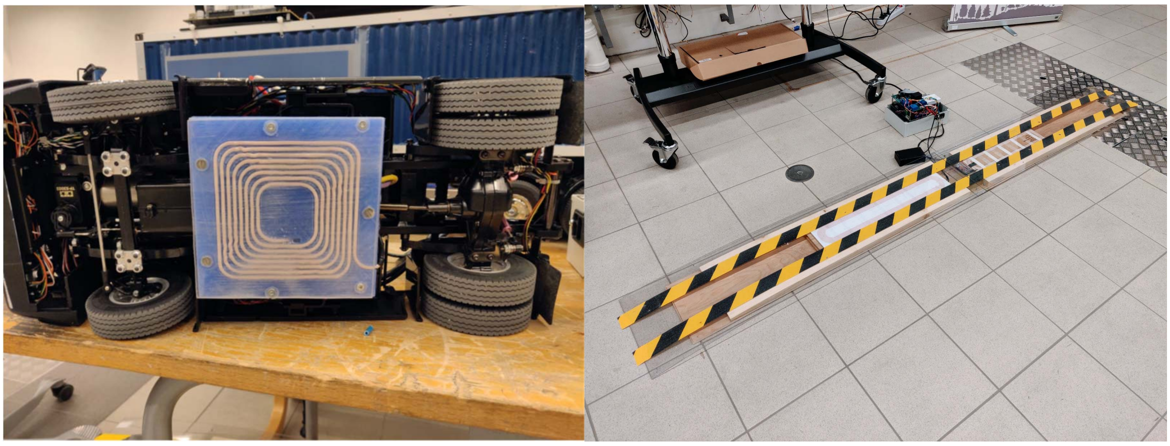
Nominal power, P_0	200 *kW*
On-board coil max planar size	1.4 *m* by 1.4 *m*
Road coil max width	1.4 *m*
Road coil length	5.0 – 15.0 *m*
Coil-to-coil min clearance	0.3 *m*

The scaled-down inductive road testbed, including one on-board coil and two different road-side coils was designed and built, with parameters reported in Table 2. Note that the nominal charging power as well as the size of the coils are scaled according to the 1:14 ratio of the truck model, as discussed in a previous section. On the other hand, the operating frequency of the small-scale model has been chosen rather arbitrarily, since following the ideal scaling law (196:1) would have resulted in a very high value that would have presented significant practical challenges, without giving much additional insight. A picture of the coil mounted on the small-scale truck model is shown in Figure 3 (a).

The intention of having two different designs of the road coils was to illustrate the flexibility of the concept, showing the interoperability of different designs, as long as they are tuned to the same resonant frequency. Thus, the further intention of the small-scale demonstration platform is also that designs based on coils with different shapes and even with different flux patterns can be investigated. In the presented system, one coil was designed with focus on high efficiency (road-side coil 1), using more copper for the winding and high-grade ferrites. The other coil (road-side coil 2) has instead been designed for low cost, resulting in lower quality factor and consequently lower transfer efficiency. A picture of the two coils mounted side-by side as a two-coil dynamic charging lane for the small-scale truck model is shown in Figure 3 (b).

Table 2 Parameters of designed coils for the small-scale truck model

Nominal power, P_0	75 *W*
Nominal I/O voltages, $V_{dc,in}$ $V_{dc,out}$	12.0 *V*, 7.4 *V*
Nominal operating frequency	75 *kHz*
Vehicle-side coil	
Planar dimensions	100 *mm* by 100 *mm*
Self-inductance (above road-side coil), L_2,	7.9 *μH*
Quality factor *Q* (at 75 kHz)	163
Road-side coil 1	
Planar dimensions	570 *mm* by 100 *mm*
Equivalent length in full-scale	8.0 *m*
Self-inductance (with no pick-up), L_1,	37.0 *μH*
Quality factor *Q* (at 75 kHz)	293
Road-side coil 2	
Planar dimensions	440 *mm* by 100 *mm*
Equivalent length in full-scale	6.2 *m*
Self-inductance (with no pick-up), L_1,	31.0 *μH*
Quality factor *Q* (at 75 kHz)	143
Coupling conditions	
Airgap distance	22 mm
Coupling factor, *k* (centered, max coupling)	0.16, 0.18



(a)-Vehicle-side coil (b)-Road-side coils

Figure 3 Picture of the vehicle-side coil and the two road-side coils designed for the small-scale demonstration platform – the two road-side coils mounted side-by side in a short road section for dynamic wireless charging.

Power conversion topology and control

Due to the considerable airgap distance between transmitting and receiving coils, the system for inductive power transfer can be regarded as a poorly coupled transformer with a very high leakage flux causing high consumption of reactive power compared to the active power that can be transferred between the coils. Thus, high efficiency and reasonable rating of the power electronic converters can only be achieved by using resonant networks with capacitive compensation at both sides of the charging system for supplying the reactive power demands of the coils. Series-series (SS) compensation, as shown in Figure 4, is usually preferred for high power applications, and this topology was assumed for the basic design of the developed system. In the SS topology, the resonant capacitors will impose a high voltage on the coils, which will reduce the required current rating of coils and capacitors compared to parallel compensation. This compensation topology also has the advantage that the resonance frequency is not affected by the loading conditions and is rather insensitive to variations in the coupling between the two coils. Furthermore, the SS topology allows for designing the system based on a standard H-bridge voltage source converter topology for driving the power transfer.

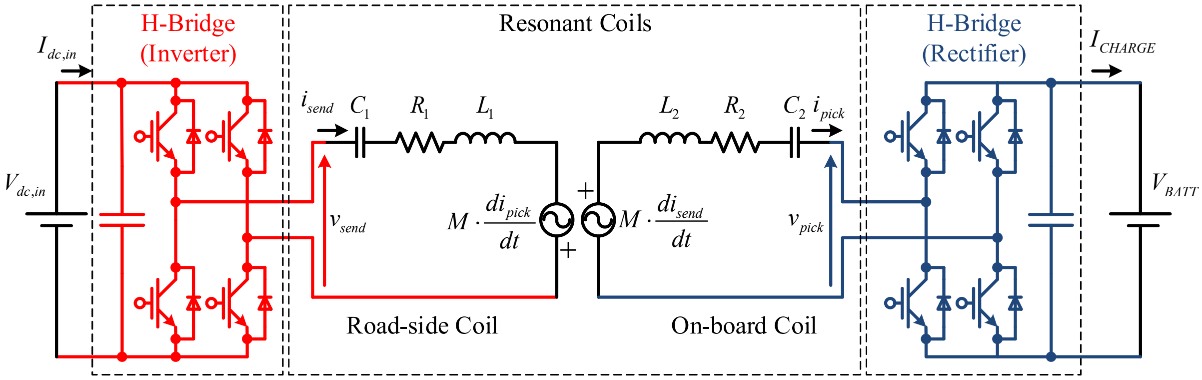


Figure 4 Circuit diagram of topology for series-series compensated inductive power transfer system

The tuned series LC circuits at both sides of the system have a strong band-pass filtering effects on the currents. Thus, when operating close to the resonance frequency, the currents become essentially sinusoidal in spite of the square-wave voltages applied by the converters, as shown in the oscilloscope screenshots of Figure 5. Operation close to the resonance frequency also implies that fundamental components of voltage and current at either side of the system will be in phase. As a result, square-wave operation of the sending-side converter (see Figure 5-(a)) will lead to close to zero-current switching of the semiconductor devices, thereby limiting the conversion losses of the system.

(a)-Square-wave operation on both sides

(b)-Voltage regulation on both sides

Figure 5 Operating voltage and current waveform of the SS-compensated resonant coils (Red: Sending Voltage; Yellow: Pickup Voltage; Green: Sending Current; Cyan: Pickup Current)

Several methods can be used to dynamically regulate the power to be transferred to the on-board battery while the vehicle is passing the road-side coils. One option is to have a passive rectifier on-board (the receiving-side H-bridge in Figure 4 consisting only of diodes) and use the road-side converter to modulate the sending voltage, thus regulating the power flow. This method has the obvious advantage of minimizing cost for the vehicle owner but has several significant drawbacks. Real-time feedback from the on-board battery to the road-side inverter is required for power flow regulation and to ensure that safety limits are never exceeded. Moreover, the efficiency of the power transfer is fixed by the hardware and cannot be independently regulated. Adding a degree of controllability on the vehicle allows for local regulation of the battery charging current, meaning that the on-board system is able to manage and protect itself, independently of the excitation of the road-side coil. Moreover, coordination between the two sides gives the possibility to optimize the efficiency of the power transfer process for all possible loading and coupling conditions. The situation in which both sending and pickup converters are operated in voltage regulation mode to achieve maximum control flexibility is depicted in Figure 5-(b). Note that the active H-bridge implemented on-board of the truck prototype, as shown in Figure 4, gives full control over the load impedance (active and reactive parts) within the capabilities of the converter thus also allowing for fine tuning of the pickup resonant frequency. The H-bridge converter can also obviously be operated as a diode rectifier, making it possible to investigate a wide range of control methods without having to redesign the hardware.

Implemented functions for autonomous operation

Two methods for self-driving have been implemented and tested with the truck model; a Simultaneous Localization and Mapping (SLAM)-based method with a path tracking algorithm and a supervised machine-learning method.

For the SLAM-based path tracking, Hector SLAM developed by Team Hector from the Technische Universität Darmstadt, was chosen as the preferred method. Hector SLAM represents an odometry-free SLAM solution for ROS and has been used to obtain a map of the environment and to estimate the pose of the vehicle. For simple demonstration purposes, a waypoint logging node has been written to manually record a reference path for the small-scale truck model to follow. This is combined with the popular Pure Pursuit steering controller to enable autonomous path tracking. Pure Pursuit receives the recorded path in the form of a list of waypoints over the ROS network. It then calculates the appropriate curvature with a corresponding steering angle so that the vehicle can move from its current position to a look-ahead goal point on the reference path. The forward velocity is set to a fixed value. As the vehicle moves forward, it will also push the goal point forward on the path with a predefined look-ahead distance. For this implementation, the tracking of the driving path depends only on the LiDAR, while the camera is only used for monitoring and obstacle detection. The implementation enables the truck model to autonomously follow the recorded path, operating in a closed loop. Thus, this function enables very convenient demonstration, where the autonomous truck model can be left to operate continuously on a path that includes the dynamic wireless charging section. Thus, if sufficiently long road-side coil sections are introduced in the path to ensure average energy balance, the truck-model could be left to operate continuously on a defined track, with theoretically "infinite" driving range.

As an example of autonomous operation, Figure 6 shows a case where the initial reference path recorded by the LiDAR is shown in red, while the trajectory of the truck when autonomously tracking this path for 5 laps is shown in blue. As indicated by the figure, the path tracking algorithm has reasonably accurate and consistent performance, and the system can be left to operate continuously on the path.

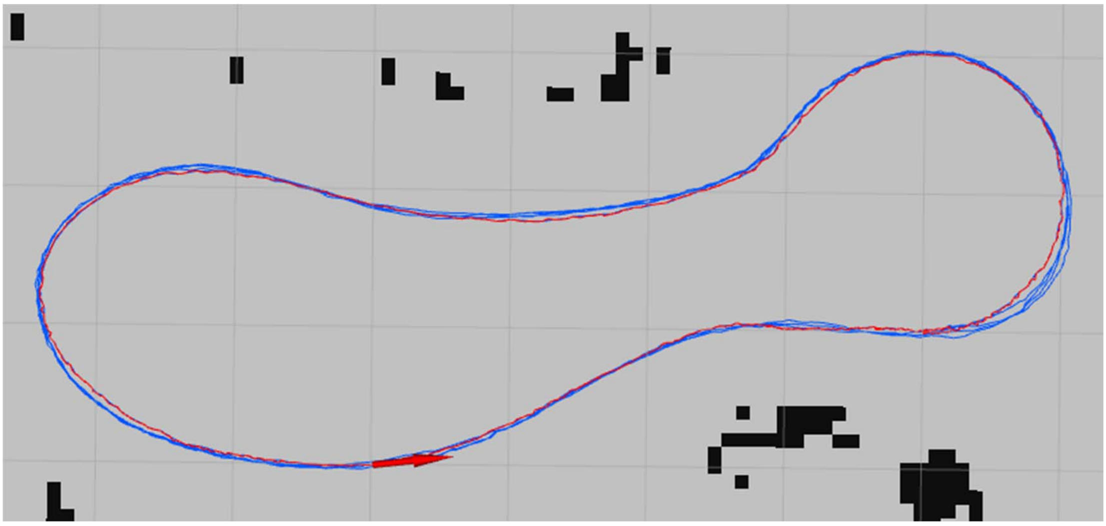


Figure 6 Example of position trajectory of the autonomous truck model when operated with path tracking

A convolutional neural network inspired by the Nvidia DAVE-2 self-driving car has also been implemented for the truck model with Keras as a separate mode to enable camera-based autonomous driving. This is useful for achieving autonomous driving in large, open areas where the LiDAR is out of range. The network has been trained on camera images and steering angle data from manually driving the truck on a visible track marked on the floor. When the training process is complete the truck can drive itself on the track by outputting a steering angle from the corresponding incoming camera images. For brevity, no explicit results are shown here, but similar performance as with the SLAM-based path tracking was achieved when operating on a clearly marked track.

Autonomous operation with dynamic wireless charging

For demonstration of autonomous operation with dynamic wireless charging, the small-scale truck model was programmed to operate with the SLAM-based path-tracking algorithm on a closed path including the two road-side coil sections described in the previous sections. A picture of the truck when driving on the road-side coils is shown in Figure 7. In Figure 8, the receiving current from the charger is plotted as a function of the position of the small-scale truck over three laps. For recording these results, position data from the path tracking algorithm and current measurements from the on-board charging system were saved to a ROS-bag and resampled at 10Hz. In the figure, the radius of the circles marking the path is proportional to the charging current of the battery. Two distinct areas show where the charging coils are placed along the path. There is some noise from the onboard charger system, so small current values are visible even when the truck is not driving across the charger. However, the figure clearly shows how the battery of the truck model is being charged when passing the two road-side coils, while there is a small period of zero transferred power between the two coil sections.

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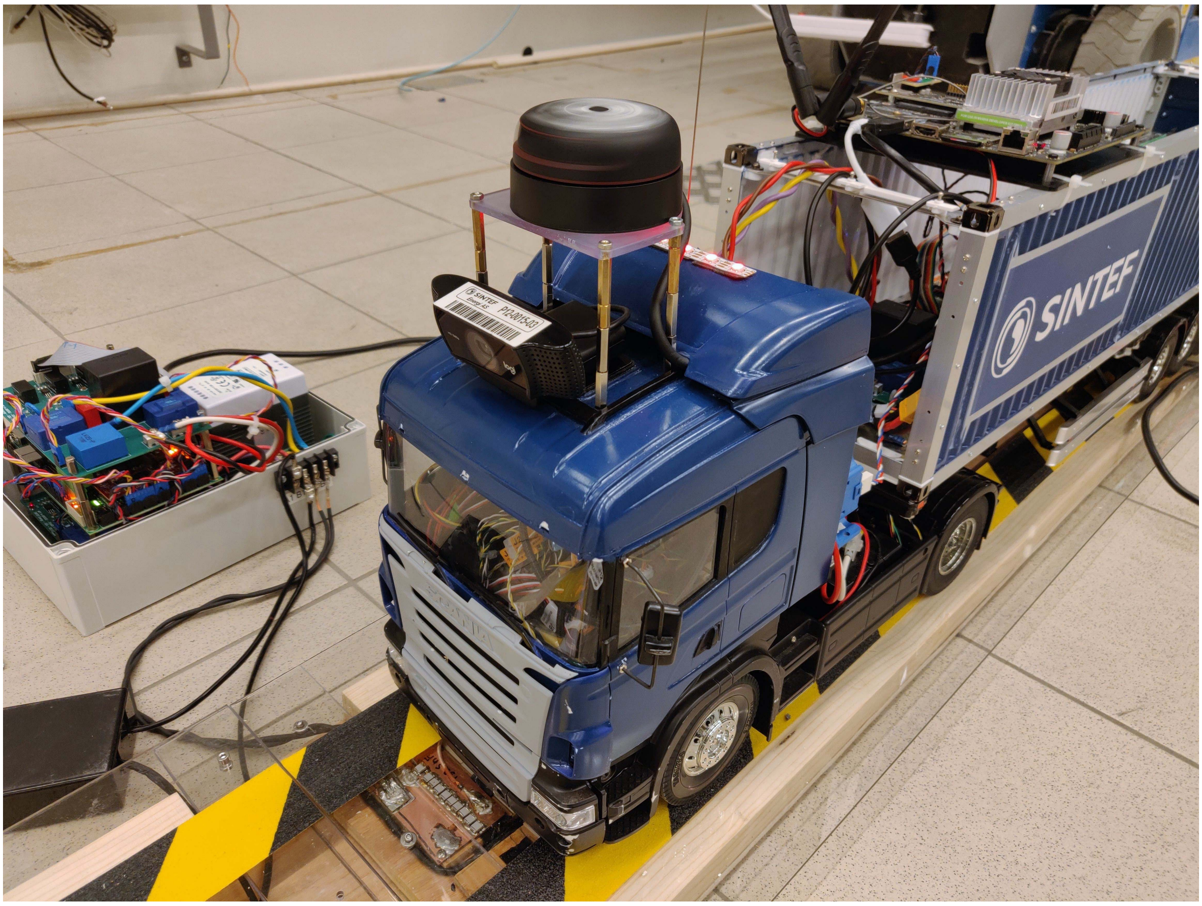

Figure 7 Small-scale truck model when autonomously driving on the road-side coil sections for wireless charging

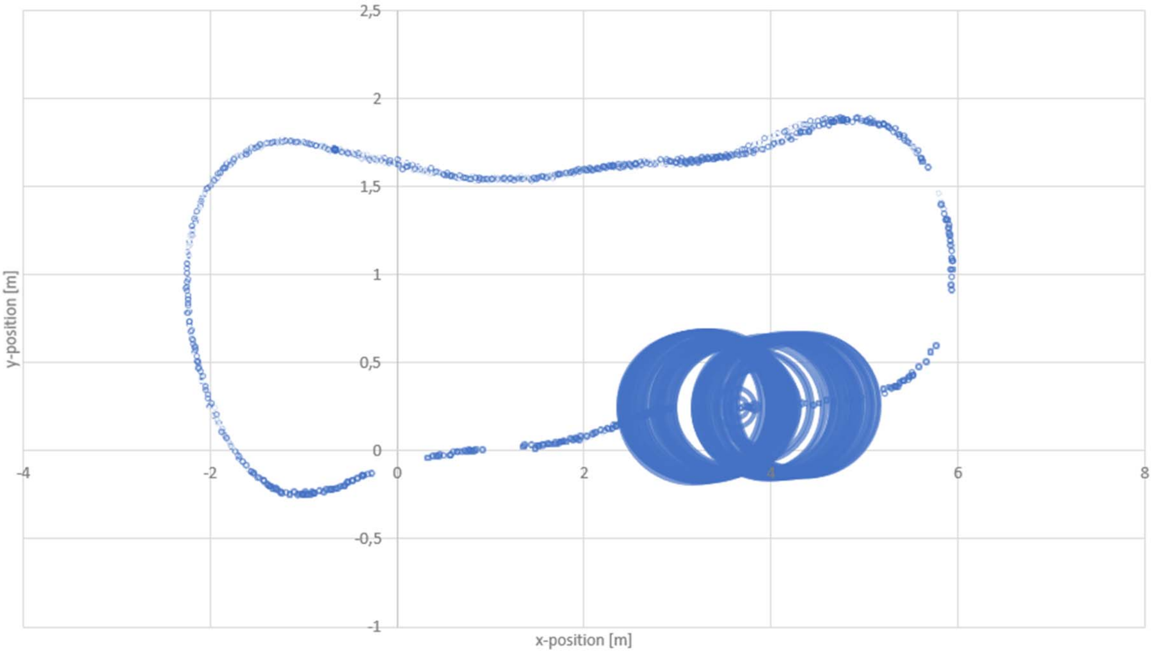

Figure 8 Position trajectory of the autonomous truck model when operated with path tracking for three rounds on a closed path including the two coil sections for wireless charging, with charging current indicated by the diameter of the circles

In Figure 9, the time-response of three measurements from the on-board charging system is shown, namely the current consumption of the on-board system, the battery voltage and the wireless charging current resulting from rectification of the current in the on-board coil. The truck was driven for three rounds, hence the three sections with the double set of peaks for the charging current, one for each round when the charger was passed. It can be observed that charge is received from each of the two coils, with the inversion of the current consumption and a temporary increase in battery voltage. It can also be noted that there is a small increase in the total onboard current consumption before reaching the first coil, resulting from the truck model driving up the ramp to the elevated "road" surface constructed above the two coil sections.

The amplitude of the current consumption and charge current varies when the truck is driving over the charging area, since the transmitted power is depending on the position. The LiDAR-based positioning and tracking system is not perfect, and the vehicle was driven manually when the reference path was recorded, making it hard to optimize the power transfer. A method for optimal placement of the truck according to the power transfer capability of the wireless charging system should be developed in order to maximize the energy transferred to the on-board battery or the overall energy transfer efficiency.

The average time taken to run across one induction coil was measured to about 1.3 second (An average of 13 samples at 10Hz). It is noted that the overall effect of driving across the charger at this speed is not enough to increase the amount of energy stored in the battery by any significance. This will make the vehicle eventually run out of energy if kept driving for too long. This limitation can obviously be easily avoided by extending the charging area with more coils or by allowing the truck to stop or slow down when passing the coils.

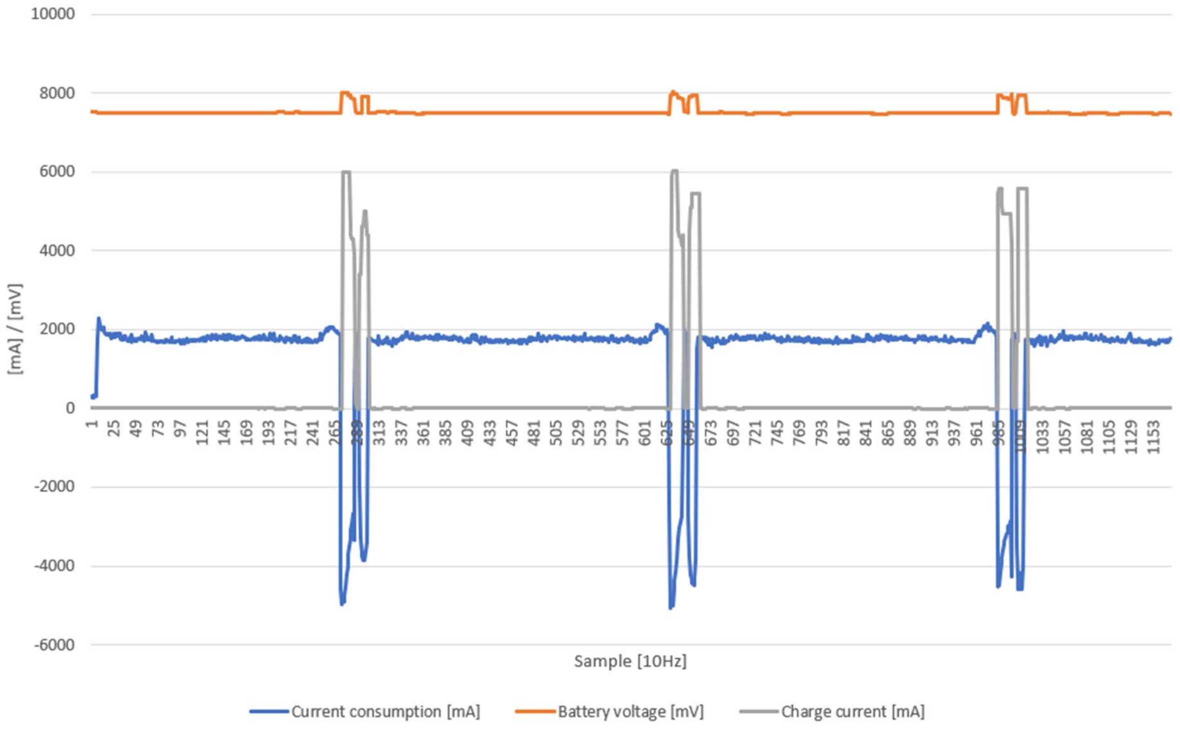

Figure 9 Battery current and voltage measurements from the on-board charging system during three laps of autonomous driving with path tracking

These results clearly show how the presented small-scale model is suitable for demonstrating the combined utilization of self-driving technology and concepts for dynamic wireless power transfer. Thus, the model serves as a convenient and low-cost platform for further research and demonstration activities related to self-driving technology as well as concepts and control methods for dynamic wireless charging.

Conclusion

Technology for wireless inductive power transfer is a perfect match for ensuring energy supply and enabling fully autonomous operation of electric vehicles. This article has presented a small-scale platform for research and demonstration of self-driving functionality for electric vehicles combined with dynamic wireless charging technology. The model is based on a detailed replica of a long-haul truck in scale 1/14. The original radio-controlled model has been retrofitted with a sensor package including a LiDAR and a camera, and the self-driving functionality was implemented on a Nvidia Jetson TX2 system. A dedicated microcontroller was utilized as the interface between the TX2 unit and the already existing servo drive system on the small-scale truck model. Furthermore, the truck model was equipped with a wireless charging coil, the corresponding resonant circuit and the conversion system for charging the onboard battery. Two different road-side coil sections for dynamic inductive power transfer with their associated resonant circuits and power converters were also constructed. General considerations on the scaling of electric vehicles and charging systems as well as basic trade-offs in the design of dynamic inductive power transfer technology have been presented as background for the development of the small-scale demonstration platform. Results showing autonomous operation of the small-scale model by tracking a predefined path including the two developed coil sections for the dynamic charging are presented to illustrate the combined operation of self-driving technology and wireless inductive power transfer. Thus, the presented model can serve as a convenient and low-cost platform for development, testing evaluation of self-driving technology as well as solutions for dynamic inductive power transfer.

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Authors

Giuseppe Guidi (giuseppe.guidi@sintef.no) is with SINTEF Energy Research, Trondheim, Norway

Anastasios M. Lekkas (anastasios.lekkas@ntnu.no) is with the Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway.

Jon Eivind Stranden (joneivinds@gmail.com) was with the Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway and is now with Q-Free ASA.

Jon Are Suul (Jon.A.Suul@sintef.no) is with SINTEF Energy Research, Trondheim, Norway and also with the Department of Engineering Cybernetics, Norwegian University of Science and Technology, Trondheim, Norway.

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