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CRITICAL STUDY ON DYNAMIC CHARGING NETWORK SYSTEMS FOR ELECTRIC VEHICLES

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1. INTRODUCTION:

After almost 150 years developing and commercializing internal combustion engines, we have noticed the need to find alternatives to these engines. The huge CO2 and NOx emissions and the fact that fossil fuels aren't unlimited, leads to the search for new engines powered by clean energy. The electric vehicle seems to be nowadays the future of the automotive sector to face the environmental and public health issue [1].

The electric car is a vehicle powered by one or more electric engines that use the electric energy accumulated on rechargeable systems, batteries, and transform it into kinetic energy. These engines can work on direct current (DC) and alternating current (AC) [2].

The electric vehicle has many parts which represents a huge difference between them and the intern combustion cars. These parts are:

- **Electric Engines:** As we have said before, is it possible to have one or more engines that work on AC and DC. This engine uses the electromagnetic rotation discovered by Michael Faraday in 1821 [3].
- **Batteries:** Composed of lithium ions, they store the energy on direct current (DC). If the electric vehicle has an AC engine, the battery is connected to an inverter.
- **Inverter:** Transforms the DC into AC
- **Transformer:** Transforms the AC obtained from the net into DC which is stored by the battery.
- **Controllers:** They check the correct performance of the car and regulate the quantity of energy that receives and recharges the engine [1].

Electric vehicles have plenty of advantages compared to internal combustion cars. The most important are:

- They make almost any noise.
- They are hugely more efficient. As internal combustion cars have an efficiency of 35-40% (This means, these cars can only use 35-40% of the energy that fuel has, the rest is lost in form of heat), electric vehicles have an average efficiency of 88’7%.
- Engines are more compact, lighter and simpler. As they don’t need to burn fuel, they don’t need a refrigeration or oil circuit either.
- Also, engines need reduced maintenance due to their mechanical simplicity.
- The energetic cost per kilometre is less expensive for electric vehicles than internal combustion ones. Moreover, electric vehicles are independent of petroleum, a limited and pollutant source of energy.

On the other hand, they have significant disadvantages, which will avoid the fast expansion of this kind of engines:

- They have less autonomy than internal combustion vehicles and the time needed to complete a static charge isn’t less than thirty minutes (fast charge mode).
- The initial investment for an electric vehicle is usually bigger than internal combustion ones. Nevertheless, in the long term, it is easy to amortize because there are lots of benefits such as less taxes and lower prices of electricity compared to fuel.
- Batteries wear down due to the use of them although the useful life is bigger than a car’s life.

The electric vehicle is not a recent idea, as we can think. This technology dates to the beginnings of the car. At that time, it was uncertain which technology would power the strange carriage of the end of XIX century and beginnings of XX. Some cars were powered by internal combustion engines. Nevertheless, this technology wasn't popular at all because of the noise and the smell these engines caused. There were some attempts with steam and gas, two methods which had a little develop on the Second World War, on the Nazi territory. However, the most surprising thing was that the electricity appeared as a good option to power vehicles [4].

In 1859 Gaston Planté invented the lead-acid rechargeable battery. In 1881 Camille Faure improved the capacity of this battery and Thomas Edison in 1899 proposed to increase even more this capacity, a proof that, on those days, electricity seemed to be the future. One year before, Ferdinand Porsche designed his first vehicle for the company Lohner [4]. This was an electric vehicle powered by two engines assembled directly on the front wheels. These engines could contribute with 7 Horsepower each, this was called "The Lohner-Porsche System" [5]. This system created euphoria in the Europe press causing the first assembly order from E. W. Hart, who wanted a vehicle able to work with two different engines, electric ones and others of internal combustion, a hybrid vehicle. This car was finally presented in Paris in 1900. It had four engines, two of each type, and a lead-acid battery. This battery has a capacity of 270 Amps per Hour and the total of the engines transmitted 56 Horsepower with 4-speed gearbox. It was able to do 59 miles (95 Km) in a row [5]. It was a success and the company sold more than 300 units between 1900 and 1906 [1].

However, 8 years later, when many companies were developing electric and hybrid vehicles, Henry Ford presented the Ford Model T moved by an internal combustion engine. He opted for this type of engine not only because of the price (cheaper car), but also because he wanted to sell freedom and mobility in rural areas and small towns, things that could only be obtained with internal combustion engines, a fact which was proved by Bertha Benz 20 years ago [1].

In 1888, Bertha was the first person to drive a car in a long distance. She drove her husband's invention (Benz Patent-Motorwagen Type III with 2'5 Horsepower) from

Mannheim to Pforzheim covering a total distance of 212 Km going and coming back [6]. Bertha wanted to demonstrate to her husband that their vehicle could be a financial success. And the decisive argument for the Benz vehicles in particular, and the internal combustion engine in general, was that they could stop to refuel in pharmacies. Bertha used a stein remover sold in this establishment, the ligroin (Petroleum Ether, hydrocarbon derived from petroleum) [7], to replenish her car on a cheap and fast way in every part of the country. That was the advantage that internal combustion engines had compared to the electric ones, and nowadays still have [4].

Electric vehicles still need many times to recharge their batteries, even with Fast Charge Mode it is needed about 30 minutes to fill in the battery [2]. It is true that automotive companies are doing their best to increase the autonomy of their batteries, but this autonomy is not enough for long distance travels at this moment. Indeed, there isn´t a solid network of charging points [8]. That´s why some companies are developing projects to help the expansion of this type of cars. Here it is found the union point to the idea of the dynamic charge.

The dynamic charge is a solution to the autonomy of the batteries on the electric vehicles. The idea is to charge the vehicle while driving on the road without the necessity to stop somewhere and fill in the battery. As we will see extended in the next sections, this is a wireless process in which some coils buried under the asphalt induces a magnetic field which is detected by a receiver on the car and transforms it into electric energy. This energy is stored by the battery, which is recharged [9]. The coils will be activated when the car approaches the road through emitters installed on the vehicle and sensors on the road. There are many important factors that influence efficiency such as weather conditions, the position between car and track or the power needed by the vehicle.

Several technical, economic, environmental and societal challenges have to be addressed:

- Design of inductive power transfer coupling coils, cost and materials resources needed for large scale deployment.
- Dynamic vehicle alignment with respect to emitter coils
- Relation between power substation and grid energy supplier
- Impact on the grid and global green-house-gas emission depending on how electricity is supplied.
- Resistance of off-board emitter systems when implemented in a road and submitted to vehicle rolling and various weather conditions
- Safety with respect electromagnetic radiation exposure of human beings and animals, or any foreign object

In the pursuit of the decarbonisation of road transportation and mobility, it is widely recognised that electromobility will prove to be an essential component.

2. TECHNOLOGY DESCRIPTION

In this section we will develop the idea of dynamic charge for electric vehicles. There are two types of dynamic charge:

- Dynamic wireless inductive charge: the vehicle is getting charged without contact between the road and the car
- Dynamic conductive charge: the vehicle charges its battery by contact between the picking-up system and an electrified rail.

On the next pages, the focus will be on wireless inductive charging with the power emitter off-board (Road) and the receiver on-board (Vehicle). It will provide a step forward in the progress of this technology by analysing all factors influencing its development and implementation and assessing the extent to which progress in technologies might provide benefits compared to conventional plug-in charging [10].

The dynamic wireless charge consists in charging the battery of an electric vehicle while driving through a special road [11].

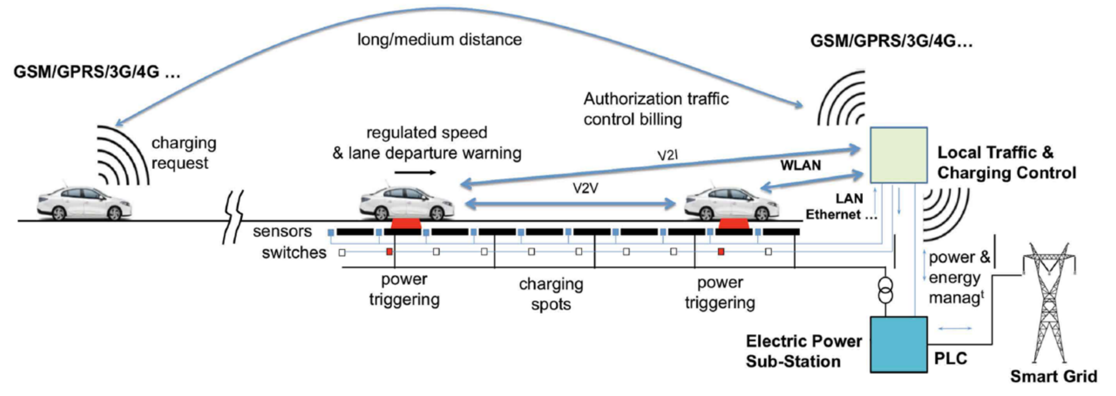

Figure 1. Fabric project system description.

As it can be seen on Figure 1, when the electric vehicle needs to charge the battery, it enters the special rail. However, there is no flowing energy on this rail. The electric vehicle needs to send a wireless signal to a local Charging Control receptor which activates the charging road just before the car begins passing through it. The ICT

(Information and Communications Technology) Charging infrastructure allows to establish this communication.

This charging infrastructure involves an actor responsible for the booking and the economic management of the electric energy provided for the recharge, a Charging Station Control Unit (CSCU), responsible for the communication control of all the actors of the charging area, a PE (Power Electronics), it is the application of solid-state electronics to the control and conversion of electric power [12] management unit (Single Board RIO) [13] and a control unit on vehicle board that interface with the PE on board and communicates the information about the vehicle through a wireless communication thanks to a COHDA Wireless system (COHDA Wireless offers safe vehicle and connected vehicle design solutions for public safety, outdoor, and automotive wireless-based systems) [14].

The electric vehicle, during the approach to the recharge road, gives information about its characteristics for the authentication and authorization to access the area. The charging phases according with the position of the vehicle are [15]:

- **Empty Charging Area:** No vehicle is approaching. Normal execution of tests about PE health are performed.
- **First Entry:** The vehicle requests to be charged. It begins the procedure for authentication.
- **Before Rail:** The vehicle is detected by the COHDA wireless system, and the Charging Station Control Unit starts to handle the authentication process.
- **Authentication:** The vehicle, characterized by an ID number is authorized to pass through the charging road. An Automatic Plate Number Recognition (APNR) camera detects the ID of the vehicle. The charging road will be activated if the APNR checks that the ID has authorization.
- **Approach:** The vehicle is not yet over the charging zone but the first PE on the grid begins with the recognition process.

- **Driving Through:** The vehicle is above the charging area. The PE on the ground identifies the presence of the vehicle and begins to transfer power. The vehicle has been charged.

- **Charge Completed:** The vehicle finishes the recharge as it abandons the charging road.

- **After Charge:** The vehicle is still detected by the COHDA wireless system, and they still exchange data of the charging procedure.

- **Disconnection:** The vehicle is out of the COHDA wireless system detection range (vehicle exits the charging area).

Below, it will be explained more in detail about similar solutions with other phases.

As it has been explained before, once the vehicle approaches the charging road, this is activated and begins to transmit power. The physical principle in which we will base the technology of power transmission is the Magnetic Induction [16].

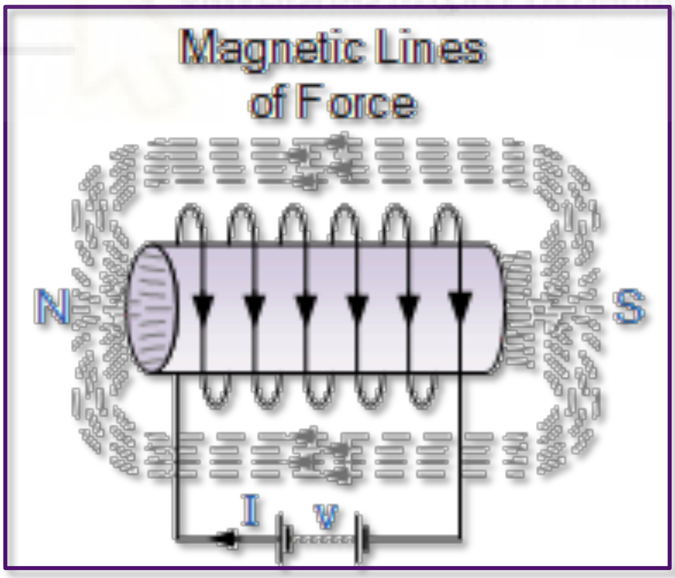

Figure 2. Magnetic induction (AspenCore)

When Direct Current (DC) flows through a long straight conductor, a magnetising force (Figure 2) and a Static Magnetic Field is generated around it [17].

By wounding the cable into a solenoid, this Magnetic Field is hugely intensified, which causes a static magnetic field around itself. The Magnetic Lines of force are attracted by the two sides of the coil, which are the Magnetic Poles of a magnet.

By increasing the wire that is wound into the solenoid having the same DC current passing through it, the Static Magnetic Field strength will enhance. This is an important point in this study because a high Static Magnetic Field strength is needed to be detected by the car and transmit the power.

Nevertheless, if instead of providing a DC current to the coil, it is introduced a magnetic bar inside it moving this bar, a current will be induced in the solenoid due to the physical movement of the magnetic flux inside it.

In addition, if the coil is moved instead of the bar, a current induced is obtained in the solenoid. This process is known as Electromagnetic Induction.

Electromagnetic Induction was discovered by Michael Faraday in 1831 and then, Heinrich Lenz could interpret the direction of the induced electromagnetic force.

The next systems will dispose of two coil circuits, one buried underground (Primary Coil) and another on the vehicle (Secondary Coil). It will provide a current to the Primary Coil underground which will generate a magnetic field. This magnetic field will induct a current on the Secondary Coil assembled on the vehicle which will be stored on the battery recharging this one. Nevertheless, it is not that easy. There are some factors which affect this system:

- **The alignment of the primary coil (vehicle) with the secondary (asphalt).** The more they are aligned, the more power transmission.
- **The coupling time.** The more time passing through the magnetic road, the more power transmission.
- **The air gap between road and car.** The more air gap, the less power transmission.
- **(Speed, number of vehicles)**

Referring to the Primary coil and according to different studies which took place in Italy by the SAET Group in collaboration with the University Politecnico of Torino, if the coils are buried into usual concrete or reinforced concrete, these coils lose their inductive ability. To solve this problem it has been developing a new and magnetic concrete that will be analysed extensively on next sections which maintain the inductive behaviour of the coil and allow the power transfer.

There is also important the way the coils are buried. Instead of doing a hole to put inside the coil (Figure 3) and the magnetic concrete all over it (it can cause power transmission interference and the system would lose efficiency), it is digging a gap with the coil form to embed it. After that, it is filled with the magnetic concrete (Figure 4). With this operation it keeps the inductive behaviour of the Primary Coil facilitating the power transmission.

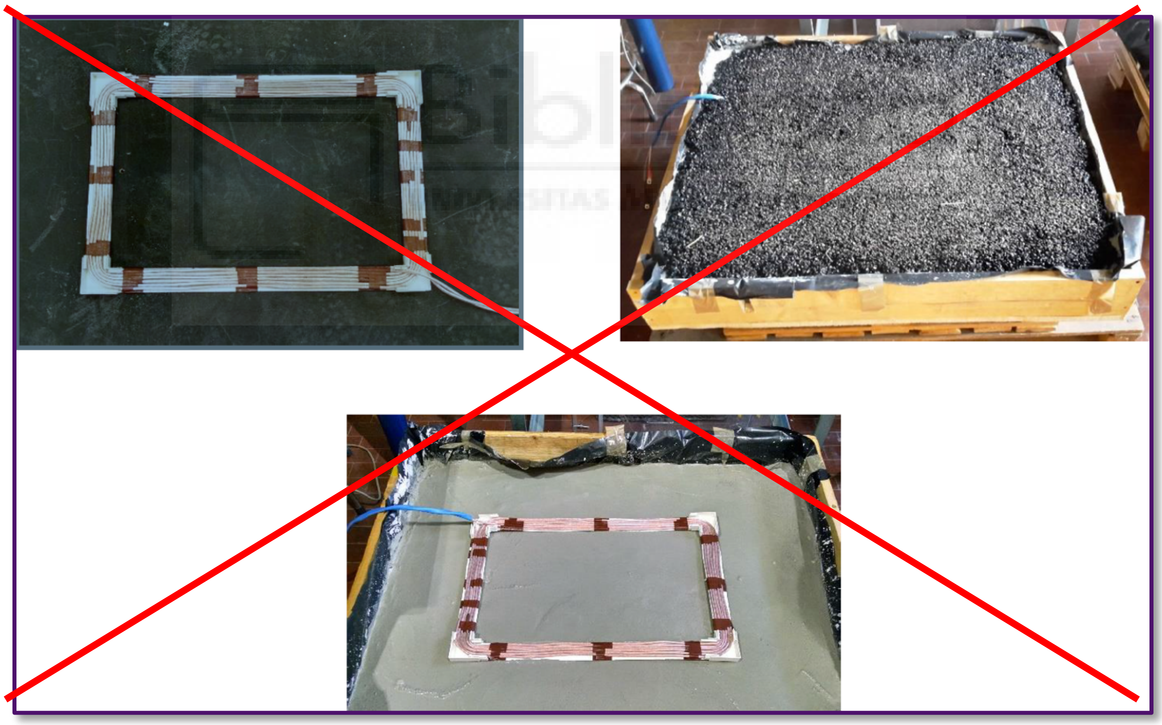

Figure 3. First POLITO embedding method

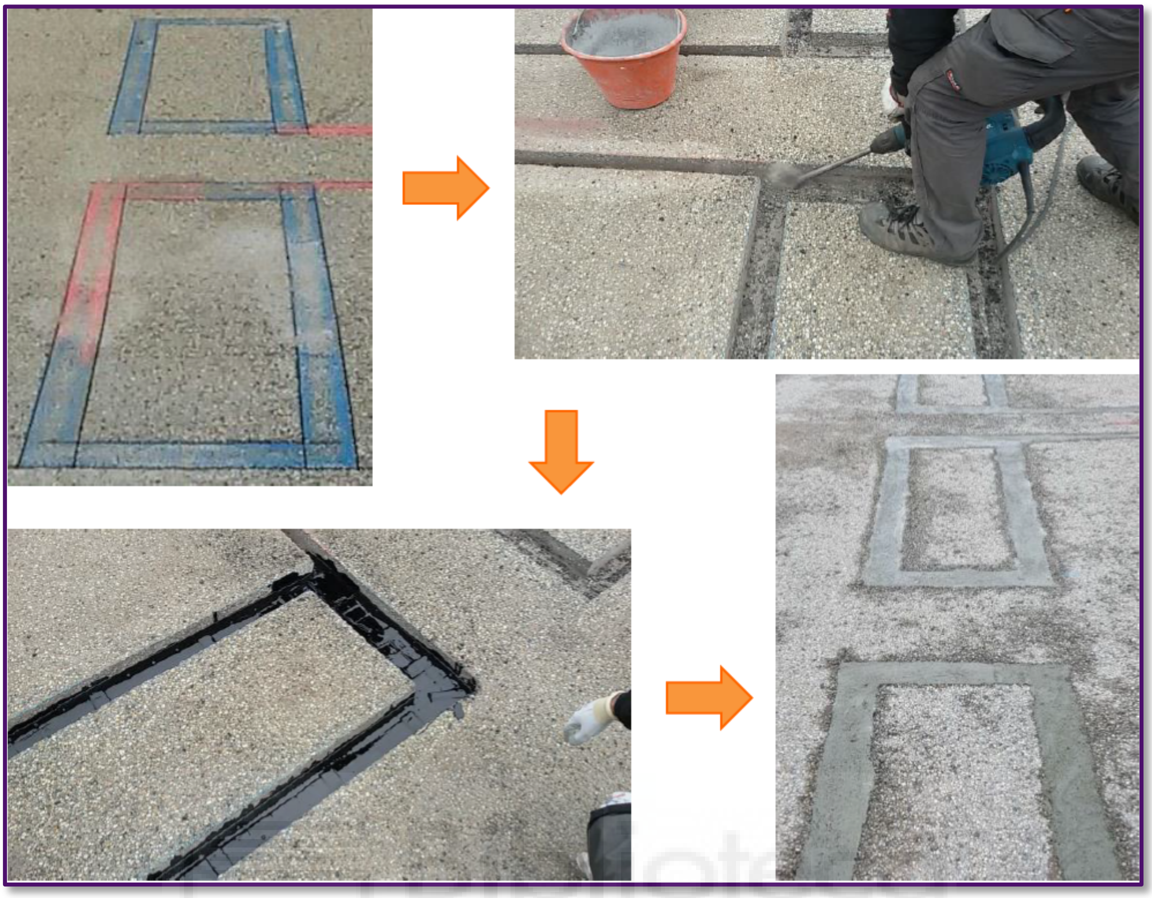

Figure 4. Second POLITO embedding method

As important as how to bury the Primary Coil is the form the ferrite cores acquire [18]. Depending on the form, the coil will generate more or less power. Attending different studies carried out by KAIST (Korean Advanced Institute of Sciences and Technology), these are the results of efficiency depending on the form.

As it can be observed (Table 1), the coil E-type is very efficient, but it transfers low power and needs the Secondary Coil to be very near to the ground (1cm), which can be a problem while driving. It needs a current of 100 Amp.

The second generation could hugely improve the air gap between the primary and secondary coils doubling the amperage to generate a bigger magnetic field, but the power transferred were low.

The third generation highly improves the power that the Primary Coil is able to transfer and keeps the gap between coils. W-Form is at the moment the best option to transmit power and it reduces the use of ferrite on the cores of the Primary Coil [19].

KAIST OLEV						
MODEL	**WEIGHT**	**P. COIL**	**S. COIL**	**AIR GAP**	**EFFICIENCY**	**POWER PICKED-UP**
GENERATION 1 (small cart)	**10 Kg**	**E-Type**	**E-Type**	**1 cm**	**80%**	**3 KW**
GENERATION 2 (bus)	**80 Kg**	**U-Type**	**Long**	**17 cm**	**72%**	**6 KW**
GENERATION 3 (SUV)	**10 Kg**	**W-Type**	**W-Type**	**17 cm**	**71%**	**17 KW**

Table 1. KAIST coil types.

However, the Secondary Coil using the W-Type needs more ferrite to increase the area, allowing a better magnetic flux.

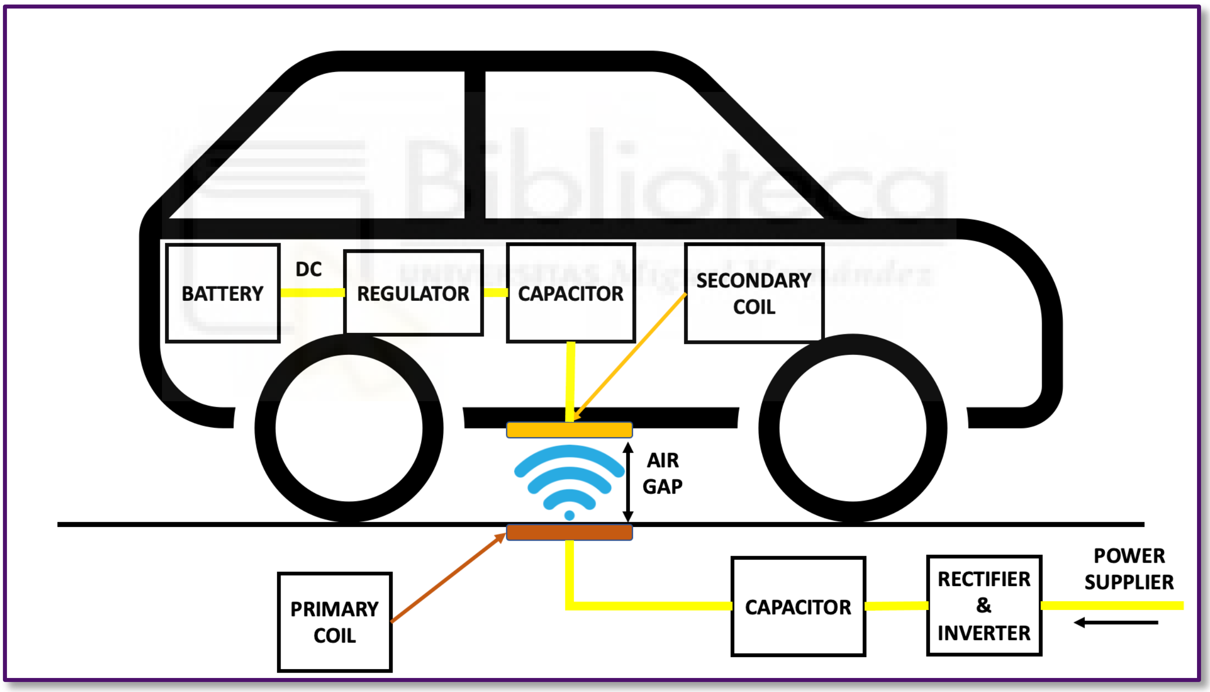

Figure 5. Systems interaction

This Secondary Coils is the most important part of the Receiver, which is the circuit that detects and catches the power transmitted by the Primary Coil embedded on the ground. The receiver is made up of these elements (Figure 5):

- **Secondary Coil:** W-Type (depends on the project).
- **DC-DC Boost Converter:** The Boost Converter is a specific converter in which a DC voltage is transformed into another, but higher, DC voltage. We have a lower

input voltage than at the output one, but the output current will be lower than the input one. This converter has two objectives: power identification and regulation.

- **Compensator capacitor:** The installation of this component is very important to try to reduce or eliminate the reactive energy. Doing this, we increase the active energy (useful energy) with respect to the total one.
- **Rectifier:** It is the element that transforms the AC into DC current.
- **Battery Protection Circuit:** This circuit controls when the battery should not be discharged to avoid any damage to the battery cells, cutting the output voltage; and when the battery doesn’t need more energy because it is sufficiently charged, cutting the input voltage.

Apart of all these elements, it has been added an aluminium shield covering the Receiver to maintain the electromagnetic field controlled on that area, avoiding the interference between it and other electronic devices and, the most important, with people inside the vehicle.

3. ANALYSIS OF DIFFERENT DYNAMIC CHARGING SOLUTIONS:

On the next pages, it will be studied different dynamic charge solutions for vehicles that have taken place in Europe in the last few years. All these prototypes are part of a European joint project that studies the possibility of implementing these systems in the future with the main goal of eliminating the COx emissions. This European joint project is called PROJECT (**Fea**si**b**ility analysis and development of on-**r**oad charg**i**ng solutions for future electric vehi**c**les). It has three different test sites: one in Italy, where two different essays have been made; another one in France and the last one in Sweden. Both tests in Italy and France have developed different dynamic wireless power transfer systems. On the other hand, Sweden has been running a dynamic conductive system.

3.1. The Italian Test Site:

In this country, the FABRIC project has run two similar prototypes by the hand of the SAET group (Engineered Products) and POLITO (Politecnico di Torino University) to achieve a dynamic wireless power transfer.

This test site is located in Susa (Figure 6), close to the Autostrada A-32 Torino – Bardonecchia [20].

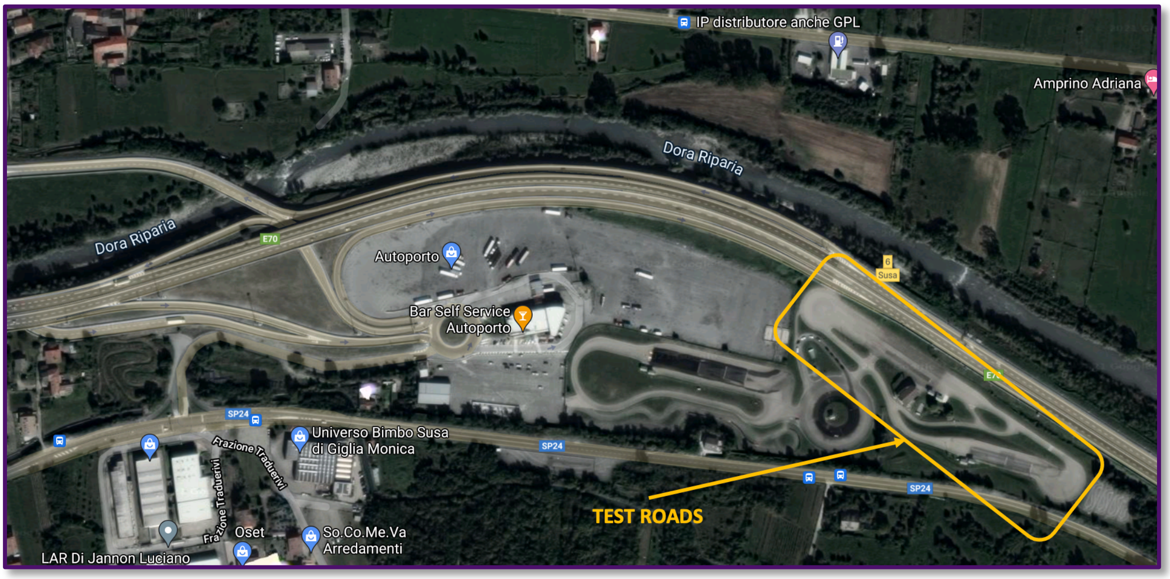

Figure 6. Italian test site.

The two systems implemented (Figure 7) are the POLITO (Politecnico di Torino University) and the SAET solutions. These prototypes have given the opportunity to study the behaviour of a dynamic wireless charge in vehicles and also test the interaction of different factors that may affect the power transfer process.

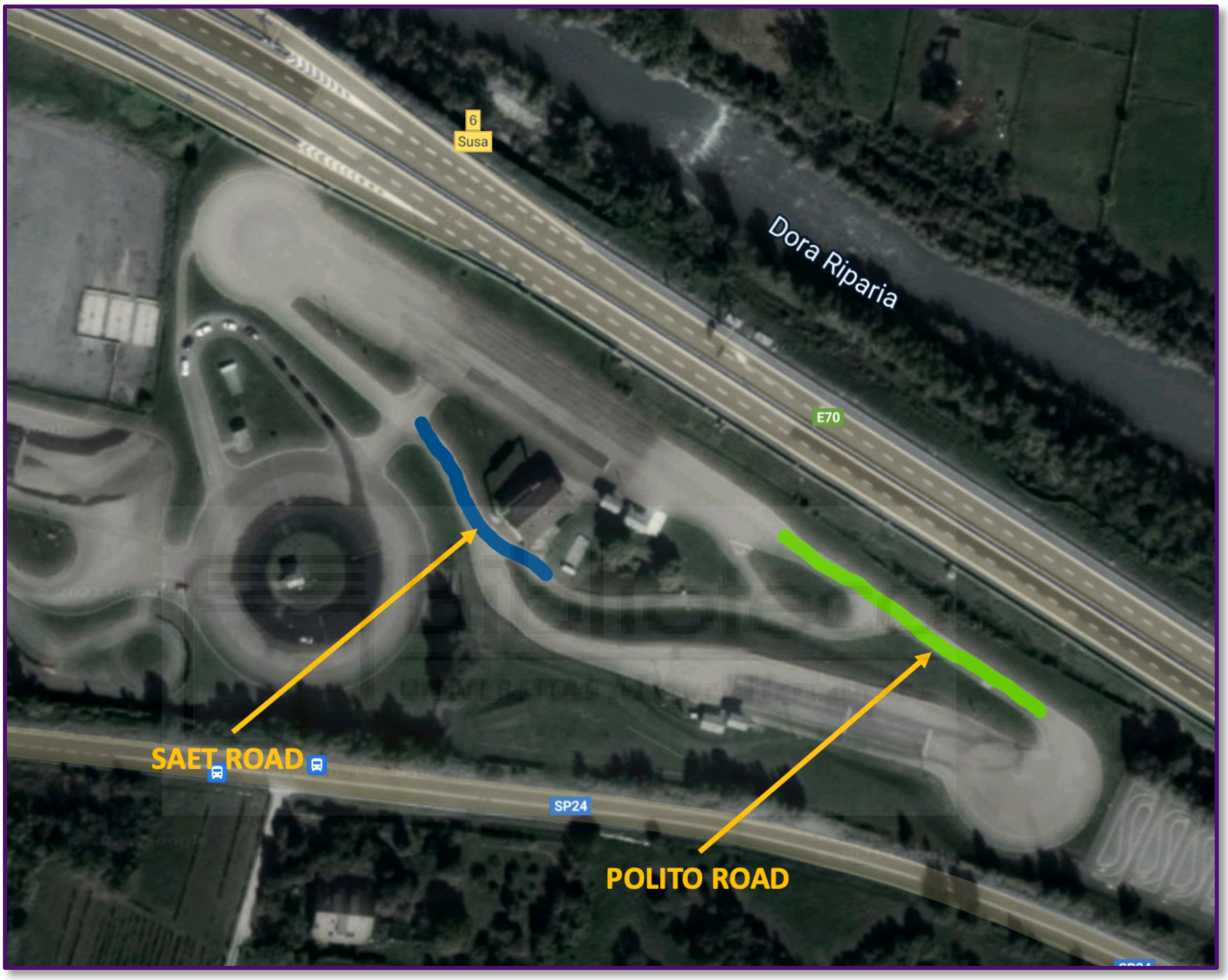

Figure 7. POLITO & SAET roads

Additionally, the construction of both e-roads has given the chance to analyse the maintenance needed by all the mechanisms involved and the management of these systems as well as the construction problems or difficulties.

These two new electromobility solutions have faced day-to-day the integration of primary and secondary coil on the e-road pavement, the connexion with the electric grid or the installation of the ICT (Information and Communications Technology) infrastructure, which controls which vehicle is approaching to the e-road, activates the charging lane and, when the vehicle has passed, the system verifies how was the charging process [21].

For both Italian solutions, the receiver was the same prototype. It has been used an IVECO Daily light duty van with two possible locations to install this secondary coil system (the receiver coil). It could be assembled in the middle of the van (centred) or rear of it as we can see on the image below (Figure 8) [20].

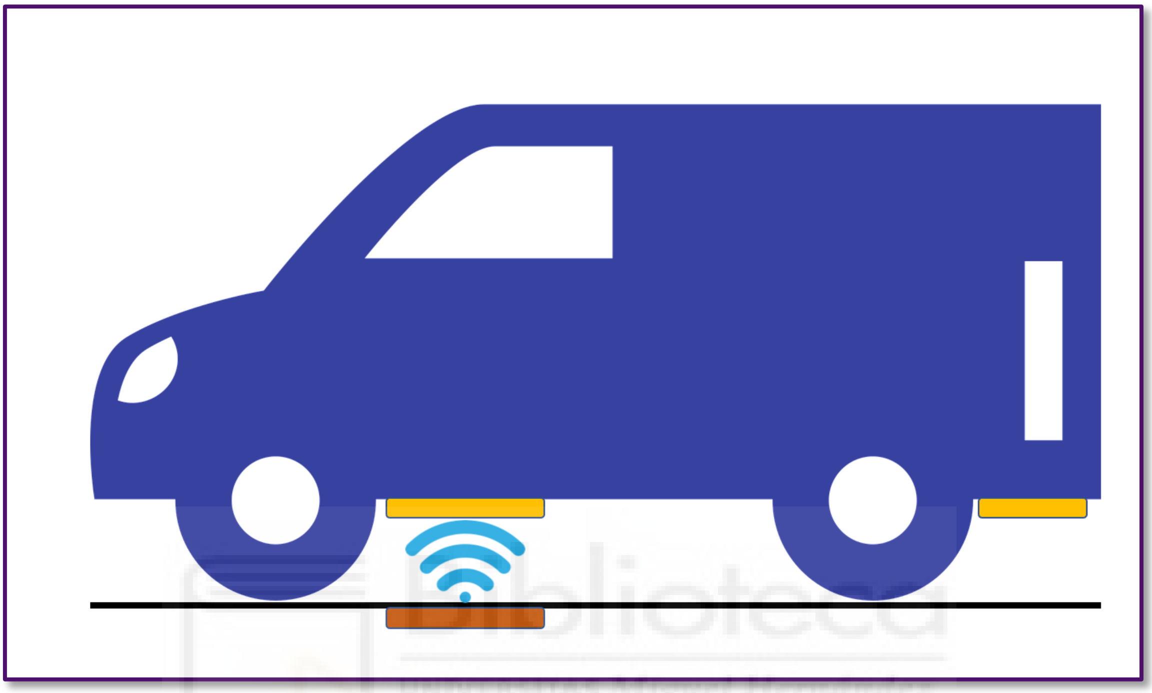

Figure 8. Power transmission.

The properties of the secondary coil and its assembly are as follows [22]:

- The secondary coil structure is 140x80x15 cm within which we can find the proper secondary coil with the dimensions 30x70 cm, ferrite cores and the resonant capacitors.

- This secondary coil has a metal housing that protects humans from the electromagnetic field, which can be dangerous for the human's health and avoids the interaction of this electromagnetic field with other devices. This metal housing is made of aluminium and its design has considered the maximization of power transferred between coils respecting the International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits for electromagnetic field vulnerability.

- In order to improve the power transmission between coils, the secondary coil is assembled with the ferrite cores in a Lexan polycarbonate plaque. This assembly offers better mechanical properties and allows more tolerance in the misalignments between coils without reducing the efficiency of the wireless power transfer.

To complete the secondary coil structure, silent blocks have been added to it. The idea is to reduce all kinds of vibration that can be transferred from the receiver structure to the vehicle.

On the other hand, the main difference between the SAET solution and the POLITO solution can be found on the primary coil, the one that goes embedded on the e-road.

For both solutions there isn’t ferrite on the ground and neither a shielding protection.

Every coil embedded on the road has the same dimensions, 1’5 meters length and 0’5 meters width. Each one is buried 0’5 meters from the next one.

As for the POLITO solution (Figure 9) it has been used 25 coils per branch with two branches, the total length for this proposal is 100 meters. However, the SAET solution is composed of 25 coils but only in one branch, that’s why this e-road length is 50 m [23].

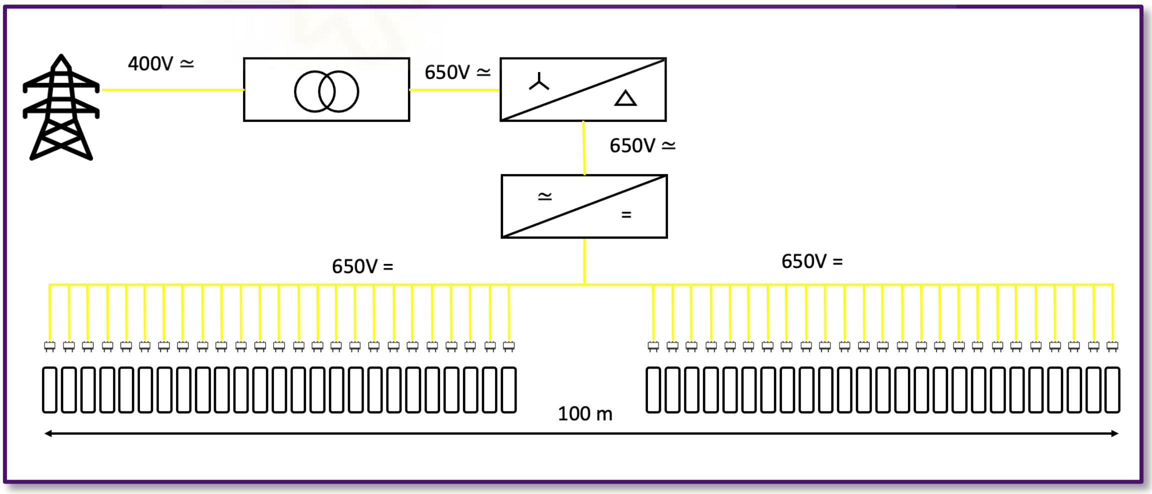

Figure 9. POLITO architecture.

Studying the POLITO solution, we can notice how every coil is formed by multiple winding ones (Figure 10). Each coil is fed by a low voltage (LV) and direct current (DC) provided by H-bridges converters which contain compensator capacity. The LV/HF transmitter has been developed at first as a laboratory prototype in order to make trials with the best fit on the e-road [23].

These H-bridge converters have been designed to work at 20 Kw and 85 kHz without any air-cooling [22].

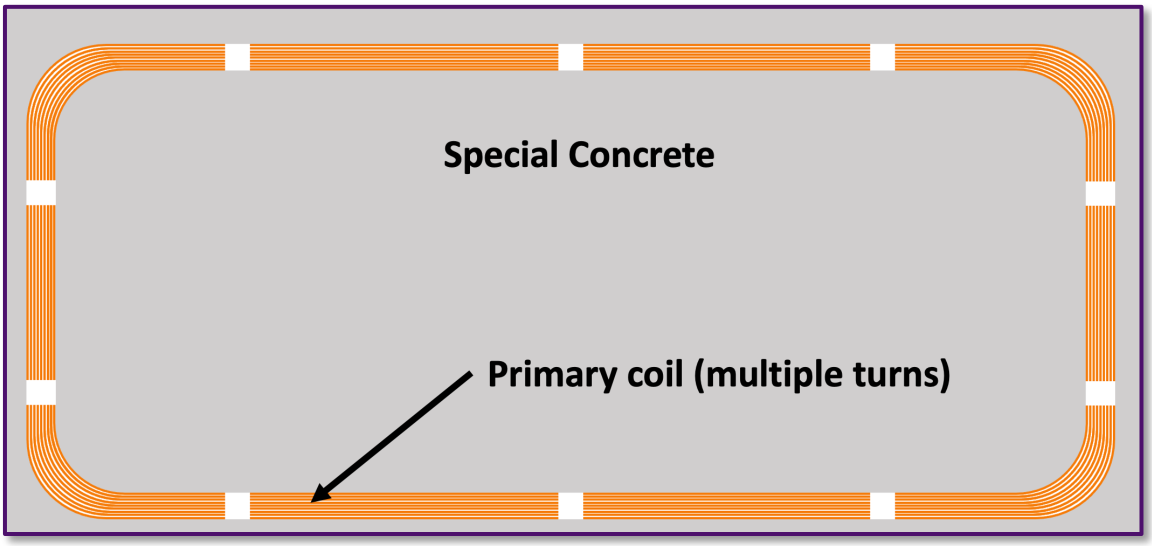

Figure 10. POLITO Primary Coil.

One of the most important parts of the electric circuit is the capacitor, which is a passive element that stores energy inside an electric field. The capacitor has two conductive walls and in between there is an insulating material. This element must hold a strong voltage stress. If this element loses its capacitance, that will lead to a huge variation on the equivalent response of the multiple winding coils.

For this reason, the POLITO University has developed and patented its own capacitor which meets the conditions above. Its name is “the RES power CAP”. This capacitor is also embedded on the ground with the multiple winding coils [23].

Coming back to the other Italian solution, the SAET Inductively Powered Vehicle has chosen a different type of coil for its primary setup.

In this case SAET developed a single coil (Figure 11) with only 22 turns and the length and width as it has been explained before (1’5x0’5 meters) [22].

On a first approach to the optimal measures for the coils, these were bigger but, finally, the current measures have been chosen in order to manufacture cheaper coils and improve their viability. These shorter coils have improved the efficiency of the energy transfer from this coil to the secondary one achieving the electromagnetic field conditions required.

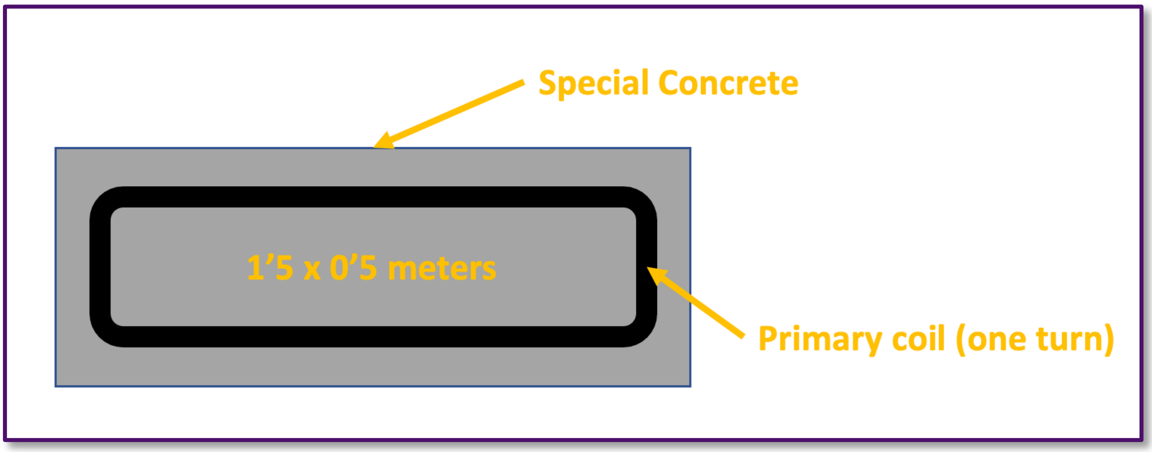

Figure 11. SAET Primary Coil.

Following the same setup for this coil as in the POLITO solution, it has not been assembled with any protection shield to the primary coil embedded on the e-road [20].

Apart from the coil form, there is another difference between the SAET and POLITO solutions. SAET has used his own developed voltage regulator which can decrease by 1:10 this property at the same time as the capacitors (this time buried with the DC/HF transmitter instead of with the coils) coincide with the impedance of the coil that is buried on the e-road (Figure 12).

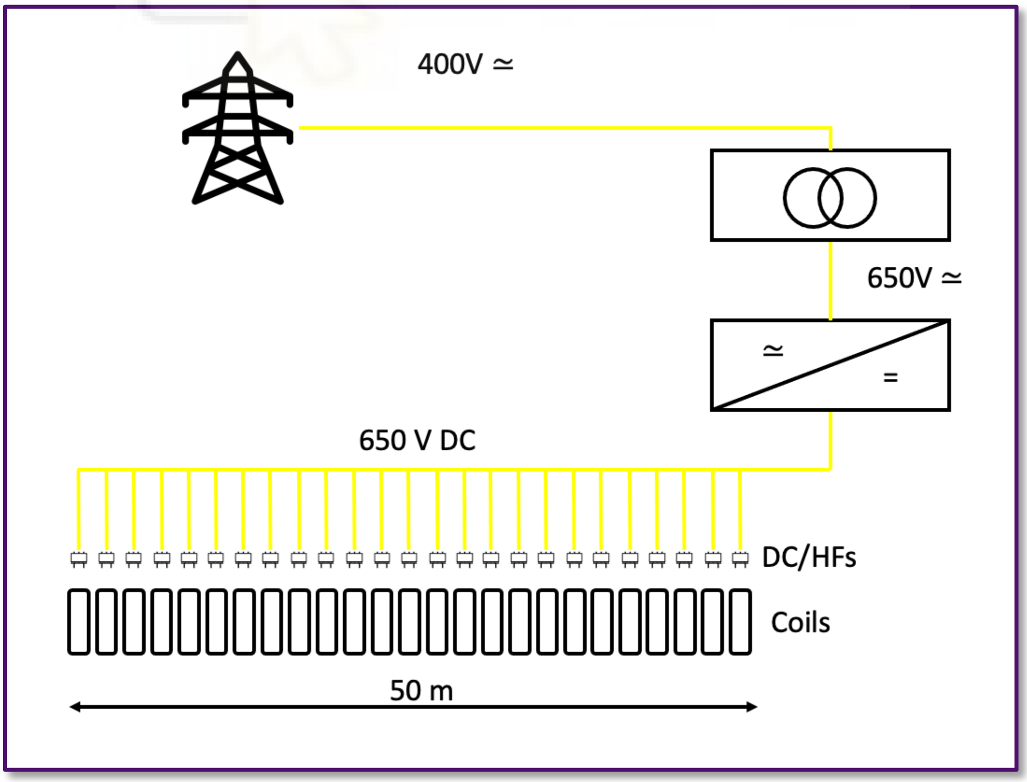

Figure 12. SAET architecture.

All these elements from the SAET wireless power transfer system have been embedded at only 40 millimetres of the ground surface [20].

With the aim of detecting the vehicle that will pass through the buried coil, SAET implemented an inductive system very similar to the traffic lights one. This system detects the position of the car when it is over the inductive and sends a signal to change the colour of the traffic light. If there is no car over the inductive, the light will not change staying in red while the light for the passengers is always in green avoiding interrupting the passenger if there are no vehicles waiting. The SAET system switches on a coil when the vehicle is over it. As every coil is 1’5 meters long, each car uses two or three primary coils at the same time [20].

However, the biggest problem that both solutions have faced respecting this primary coil was to embed it, as it has been explained before. When both partners have designed prototypes in the laboratory, the impedance amplitude (Ω) increased and the phase stayed at the same values (with a slight decrease after 700 kHz), both by increasing the frequency (kHz) [18].

After these laboratory tests, once they bury the coils in the ground, the resonance effect appears, reducing the impedance amplitude a little, and the phase to zero with 1000 kHz.

After many tests with different materials in which coils could be buried, it has been patented the best solution discovered which makes the resonance disappear.

After all the improvements in both solutions and, after overcoming many difficulties, many trials have been run on the e-road with different parameter selections to obtain the response of the dynamic wireless power transfer system analysing the most influent parameters and the different returns of the system. Once the results have been analysed, some conclusion can be drawn:

- POLITO Solution suffers a huge decrease in effectiveness with the misalignments of more than 300mm.

- SAET Solution is very sensitive to every misalignment of more than 300mm and also when the air gap between vehicle and road is higher than 200mm (Figure 13)[24].

- Both SAET and POLITO solutions transmit an electromagnetic field under the values specified (<27 µm) by the International Commission of Non-Ionized Radiation Protection (ICNIRP) [22].

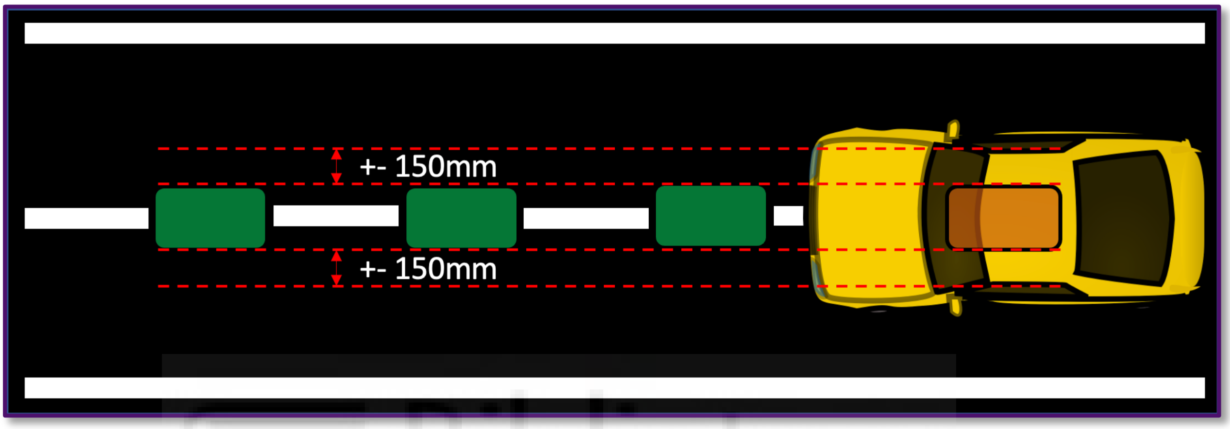

Figure 13. Coil alignment.

Other data and results are compiled in the following tables:

POLITO SOLUTION	
POWER TRANSFERED PER COIL	**20 kW**
E-ROAD LENGTH	**100 m**
MAXIMUM SPEED	**50 Km/h**
MISALIGNMENT PERMMITED	**300 mm**
AIR GAP PERMITED	**300 mm**
MAXIMUN POWER TRANSFERRED	**5'2 kW**
EFFICIENCY	**81%**

***Table 2**. POLITO results.*

SAET SOLUTION	
POWER TRANSFERED PER COIL	20 kW
E-ROAD LENGTH	50 m
MAXIMUM SPEED	30 Km/h
MISALIGNMENT PERMMITED	300 mm
AIR GAP PERMITED	300 mm
MAXIMUN POWER TRANSFERRED	9 kW
EFFICIENCY	66%

***Table 3**. SAET results.*

3.2. The French Test Site:

The European FABRIC project (**Fea**si**b**ility analysis and development of on-**r**oad charg**i**ng solutions for future electric vehi**c**les) has conducted another dynamic wireless power transfer experiment in France. More specifically in Satory, near Versailles (Figure 14) [25].

Figure 14. French test site.

This test has been developed by QUALCOMM and VEDECOM institute. The wireless transfer system is very similar to both Italian tests, but with important differences.

Figure 15. Test road and electrified sector.

This French test site has 100 meters of e-road (Figure 15) over a whole loop constructed with special pads which use the QUALCOMM HALO technology.

This technology is already used on the safety cars on the Formula E to recharge their batteries, but as Static wireless power transfer mode. This means that the car must be stopped to proceed with the charge.

The system is made of two pads, one on the ground connected to the electricity net and a second one installed on the bottom part of the car. These pads are composed of coils that transfer the electricity in the same way as in Italy, by induction [26].

When the vehicle needs to be charged, it must drive over the ground pad and control our alignment with a mobile app. The tolerance of misalignment that the pad accepts in the x and y axis is 300mm, similar to the e-roads in the Italian test site. Once we are in the right position, it is needed to turn off the vehicle. The wireless charge system begins automatically by itself (there is also the possibility to activate it manually). When the battery is fully charged, the system turns off by itself as well.

QUALCOMM has different pads (Figure 16) which transfer more or less power depending on the size [27]:

- 3’3 KW: Charge time 7-8h
- 6’6 KW: Charge time 2-3h
- 20 KW: Charge time 20 minutes

Figure 16. Qualcomm Halo. (Fabric Project - Dr. Angelos Amditis)

The challenge comes when we want to charge the vehicle while driving. In order to find a valid solution, QUALCOMM in collaboration with VEDECOM institute have developed a 100-meter e-road which is capable to charge two vehicles at the same time with a transmission power between primary and secondary pads of 20KW working with a frequency of 85 kHz [28].

The new solution is connected to the French grid network at 400V in tri-phase Alternating Current which passes through an AC/DC converter obtaining 1000V and 50 KW in Direct Current (DC).

The e-road is divided into four sectors. Each sector has 14 pads (segment of coils) and a length of 25 meters summing the 100 meters of the e-road. Each two sectors have a roadside cabinet in which there is an inverter providing the sectors 85 kHz in Alternating Current (AC) [29].

The vehicle used in these experiments was a Renault Kangoo II EV provided with two secondary (receiving) pads, one after the front wheel axle and the second after the rear wheel axle. Every pad can receive from the primary coil on the ground 10 KW, making the total charge 20 KW. This solution has been tested from stationary until 100Km/h with a good performance [30].

It has a maximum capacity of two vehicles at the same time because only one vehicle can be fed by each sector, so the minimum distance between cars must be 28 meters.

One big difference between this solution proposal and both Italian ones is that the QUALCOMM pads or BAN units (Base Area Network) are not buried or embedded on the concrete below the ground surface. In this case, it has been made a cavity of 0’45 meters on the centre of the road with the following dimension: 800x200 millimetres.

In this room was supposed to instal the primary pad and the controller. As it has been explained before, these pads don’t need any filling over them, just a non-ferrous cover to protect the system and avoid interferences on the power transmission to the secondary pads.

As cover, the investigators developed a reinforced protection of 30mm thick made of glass fibre capable of withstanding any applied force by the vehicle. All the cover protections use bolts to hold on to the ground allowing opening them quickly and without damaging any part of the e-road [20].

The system of these covers makes possible as well any change on the prototype or any adjustment necessary on the ground elements which make it a flexible system capable of adapting quickly to new tests.

The second big difference between QUALCOMM/VEDECOM and the Italian solutions can be found on the primary and secondary coils. As we have been seen before, for this

French solution, QUALCOMM has provided both primary and secondary pads while the Italian prototypes work with a simple (SAET) and multi winding coil (POLITO) solenoid which have a good coupling response but, in contrast, they produce higher emissions needing a shield to protect humans against them [31].

The QUALCOMM HALO solution provides coils inside the pads with a double D design with 8 turns for the secondary coils assembled on the vehicles and a bipolar coil with 7 turns for the primary coils that goes on the ground. Using this type of coils the results obtained shows higher coupling between primary and secondary coils with low electromagnetic field emissions and allows more tolerance for the air gap as well as with the misalignment produced in both as well as with the misalignment both X and Y axis [27].

Figure 17. Qualcomm Halo D coil.

(Fabric Project- Grzegorz Ombach, Qualcomm, "Magnetic solutions towards interoperability for stationary, semi-dynamic and dynamic charging" - 18.12.2014, IEEE- IEVC 2014 Conference, Florence)

As we have explained for the static wireless charge, the bigger the coil, the higher the power transferred. For the secondary coils:

The primary pads installed on the road have the following measures: 1'71m x 450mm end weight of 30kg.

This disposition of both primary and secondary coils makes it not necessary to provide the system any shielding protection in addition to the car shield due to the low level of electromagnetic field emitted by the pads [22].

This car shield consists of a 3 mm thick base made of aluminium which is assembled along almost the whole bottom of the vehicle protecting the inside of it and achieving the ICNIRP requirements for the passengers and possible effects on other elements.

The French charging test has four defined phases on a charging procedure.

At first (phase 1), the vehicle approaches the e-road without entering it.

On a second step (phase 2) the vehicle begins moving inside the e-road but more than 30 meters away from the first wireless charging module, until it enters on the 30 closer meters to the charging module (phase 3 - beacon mode). Once the vehicle is passing through the pads it begins to recharge the battery (phase 4 - charging mode). When the car has abandoned the charging area it is assumed that the process is over (phases 5 - post charge mode) [22].

One last system integrated on the vehicles of the French test site was the Lane Keeping Assistance (LKA). This tool was designed to avoid misalignments between the car and the pads on the road during the driving through the electric road [22].

This system is composed of a vision which recognizes the e-road width thanks to some marks on it and calculates the misalignment between vehicles and road. If this misalignment exceeds the specific limits, the interface provides a visual warning to correct the direction and continue charging on the better conditions as possible.

3.3. The Swedish Test Site:

Until this point, we have analysed different methods of vehicle recharging via wireless dynamic power transfer system but, the test scenario that Volvo and Alstom have developed in Hillered (Sweden) is completely different to the previous ones in France and Italy (Figure 18) [32].

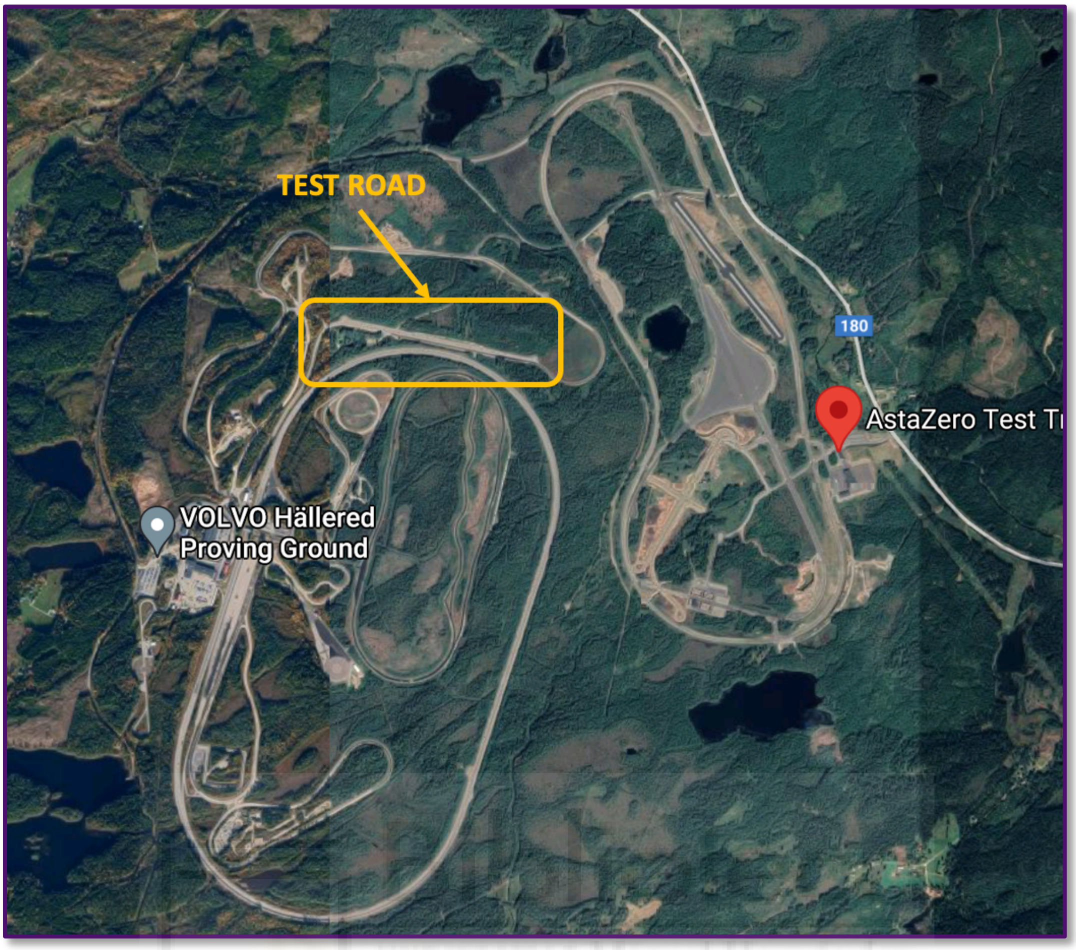

Figure 18. Hillered test road.

The technology developed by Volvo/Alston consists of a conductive dynamic power transfer system and it has been tested with trucks. This system is called Volvo ERS (Electric Road System). The e-road length is 264 meters (Figure 19) [20].

Figure 19. Volvo/Alston electrified sector.

Before entering deep on this technology description, it is needed to analyse the types of conductive dynamic power transfer and how they work for a better understanding of the Volvo Alstom system.

The conductive power transfer consists of a continuous flow of electricity due to the contact of a mechanical part of a vehicle with a rail that is connected to the electricity grid. There are two types of conductive power transfer: the overhead conductive road and the ground road [33]:

- **<u>Overhead conductive Road</u>**: In this specific case (Figure 20), the electricity flows from electrified rails to the vehicle across a pantograph which is an articulated mechanism that is situated on the top of the vehicle and touches the electrified rails to receive the electricity and recharge the battery. This system could be better used in trucks or buses due to their height making it easier to achieve the distance between the truck roof and the rails, and in vehicles which have predefined routes to keep plugged into the rails the whole time.

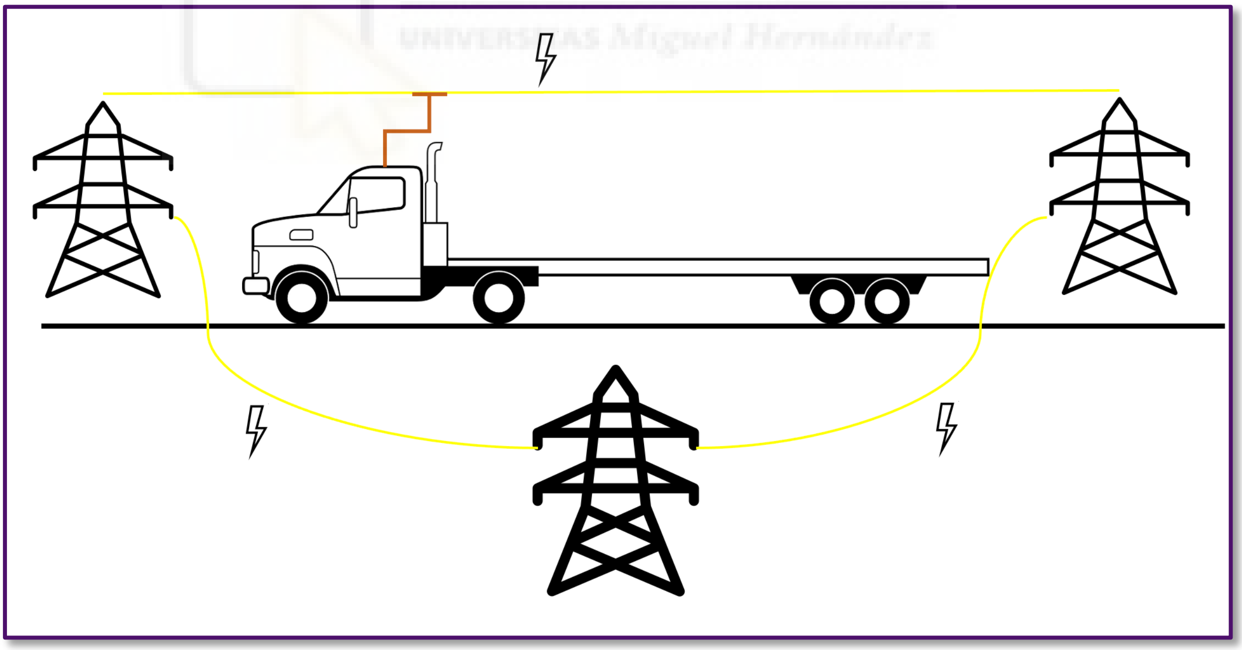

Figure 20. Overhead conductive road.

- **<u>Ground conductive Road</u>**: This is our case of study (Figure 21). The charging process is very similar to the previous one but, in this case the articulated mechanism is situated behind the car, and it gets in contact with a specific electrified rail which is situated on the road surface to obtain electricity from it and charge the battery

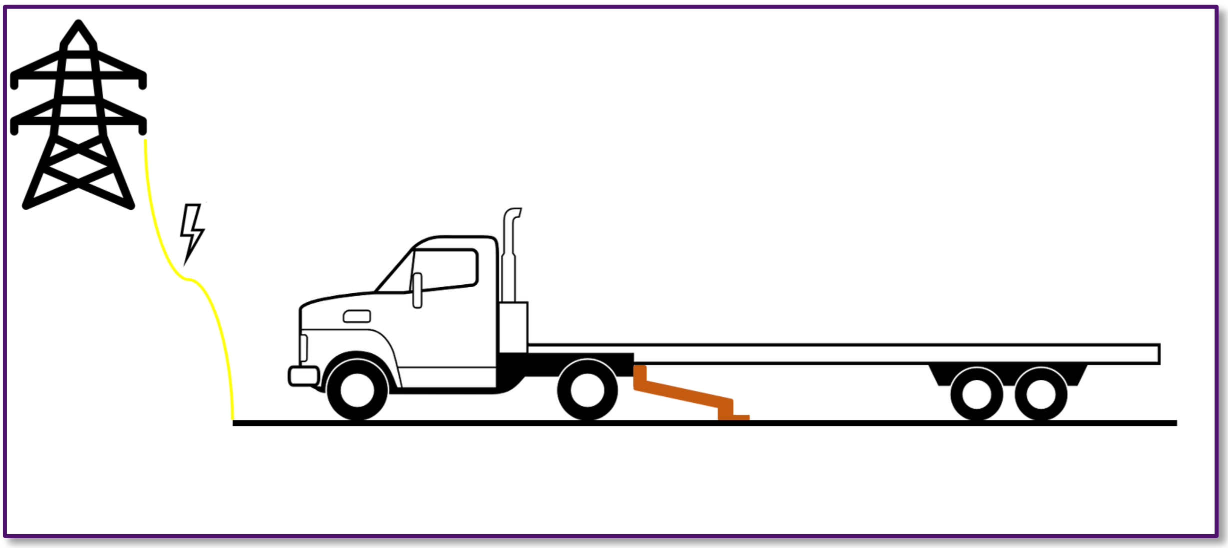

Figure 21. Ground conductive road.

As it has been explained in the paragraph below, the Volvo/Alstom ERS Uses a conductive road solution, this solution is based on the APS (Aesthetic Power Supplier) Technology that Alstom developed for tramways in certain cities. The difficulties in some places of having electrified rails above the tramways caused Alstom to develop the APS technology which has the electrified rail on the ground [34].

The APS system can be found operative in many French cities such as Bordeaux and in many others around the world such as Dubai or Rio de Janeiro. This system is completely safe. The tramway rails are divided in short sectors that are only activated when the tramway is going to pass through them. Once the tram has passed, the sector is deactivated avoiding any risks to other users.

This idea guided Alstom to develop a proper solution to the ground conducted road for vehicles. In this case, the proposal was to build a road with two electrified rails that go installed on the ground surface. The size of the element as the sector has been adapted to the requirements of vehicles smaller than tramways, this means a reduction on the size of the sectors installed on the ground surface but an increase on the number of switcher's needed in order to maintain safe conditions. This is a key point on this solution proposal that must be taken into consideration. We will come back through it after, explaining the current road distribution.

The e-road that has been raised by the Volvo/Alstom solution has a total length of 424 meters with only 264 of them electrified. It has 80 meters before the e-road and 80 meters after it [20].

The electrified road is divided into sectors (due to safety reasons), these sectors have an individual length of 22 meters. There are a total of 12 sectors. In order to activate or deactivate this sector there are installed power boxes (PB) that control two sectors each. These power boxes are connected to two detector loops (as we can see on the image) which are situated before the sectors that the PB can activate (Figure 22) [35].

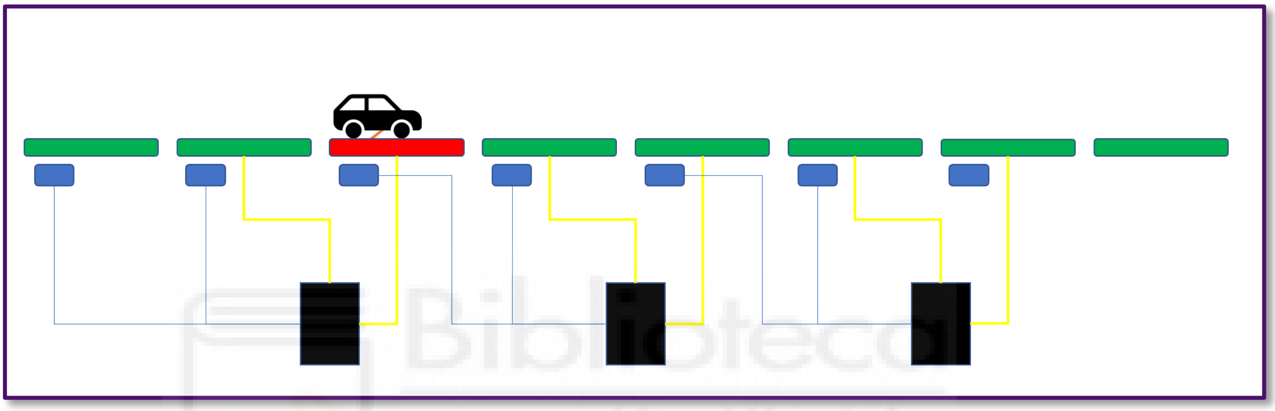

Figure 22. Volvo/Alstom architecture design.

Their mission consists of calculating the speed and the direction of the vehicle. If the speed is greater than the speed target, the PB will activate the first of his two sectors. Once the vehicle passes across the next detector loop the speed is calculated again and, depending on the value, the next sector will be activated or not.

Due to safety reasons and, because of the sector length (22m), vehicles must drive through the e-road with a speed between 60km/h and 100 km/h. This is because 60 km/h is approximately 17 m/s [36].

The logic is as follows: Even if it is very dangerous to be in front of a car in the middle of a road while this car is moving at 60km/h or higher, when the PB activates a sector, a person situated inside this sector can receive an electric shock but driving the car at 60km/h which is equivalent to 17 m/s means that this person is more or less 1 second away from the car. According to this premise, the level of risk electrifying the sector 1 second before the car passes through it, doesn't increase (Figure 23) [36].

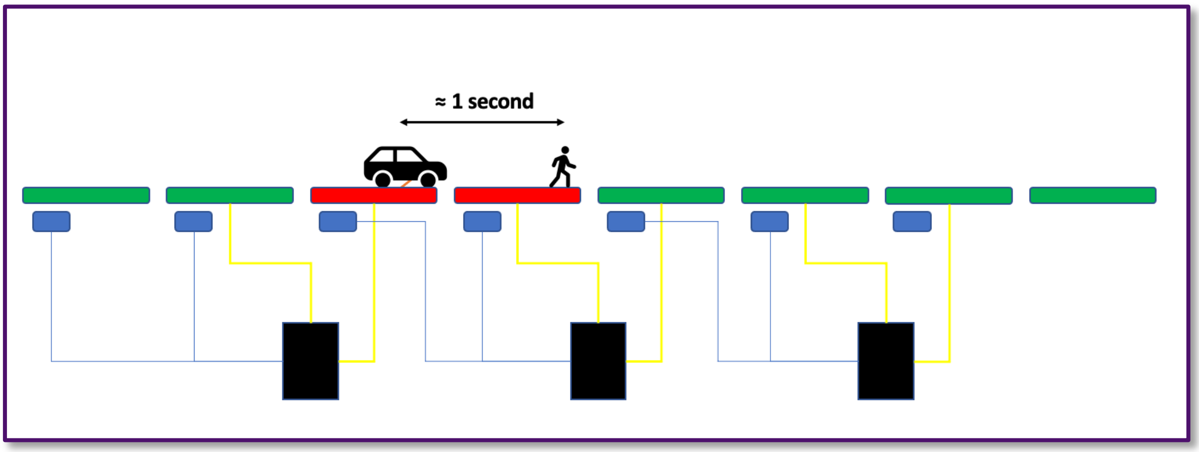

Figure 23. Electricity exposure (1).

Even so, there are situations that require to be evaluated and have not been tested at the moment. These situations could incur into unsafe situations in case this technology reaches our roads. These situations could be:

- A motorcycle rider who drives too close to the vehicle which has been charged by one sector. This rider could be inside the electrified sector, so he/she is exposed to the electricity current being able to suffer an electric shock (Figure 24).

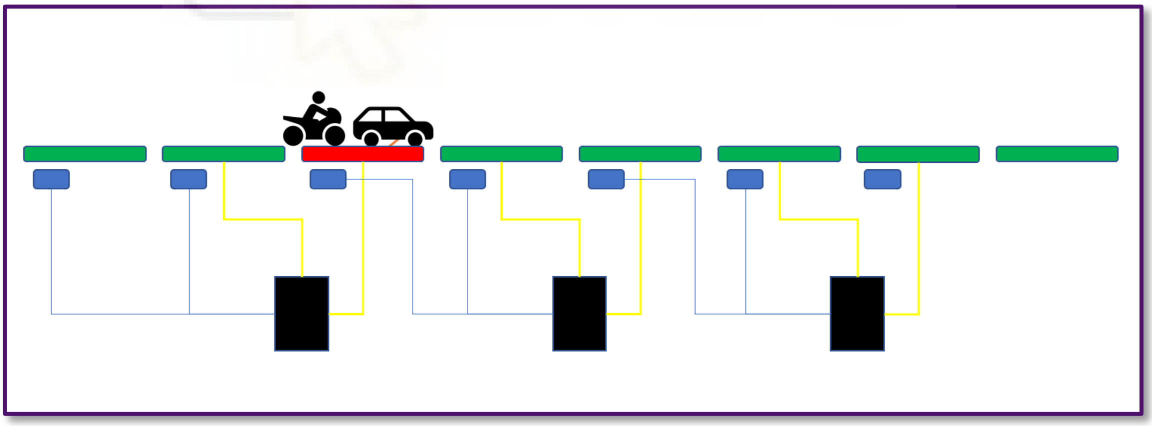

Figure 24. Electricity exposure (2).

- Some animals that cross the road and whose response time could be enough to run away from the car, may be affected by the electricity running through the activated sector. They could be paralysed, avoiding them from leaving the trajectory of the vehicle, causing a traffic accident.

Coming back to the conductive power transfer system, we have analysed the first part of the solution, the electrified road. Now, we are going to see how the power is transferred to the vehicle to achieve the connexion of it with the road.

Volvo, in collaboration with other partners, has designed two different prototypes which collect the energy from the road and charge the battery. These prototypes must be in contact with the road to do the proper connexion.

Both designs are composed of one mechanical arm with two collector endings (Figure 25). The reason for these two endlings it is to have at least one of them picking up power at every moment.

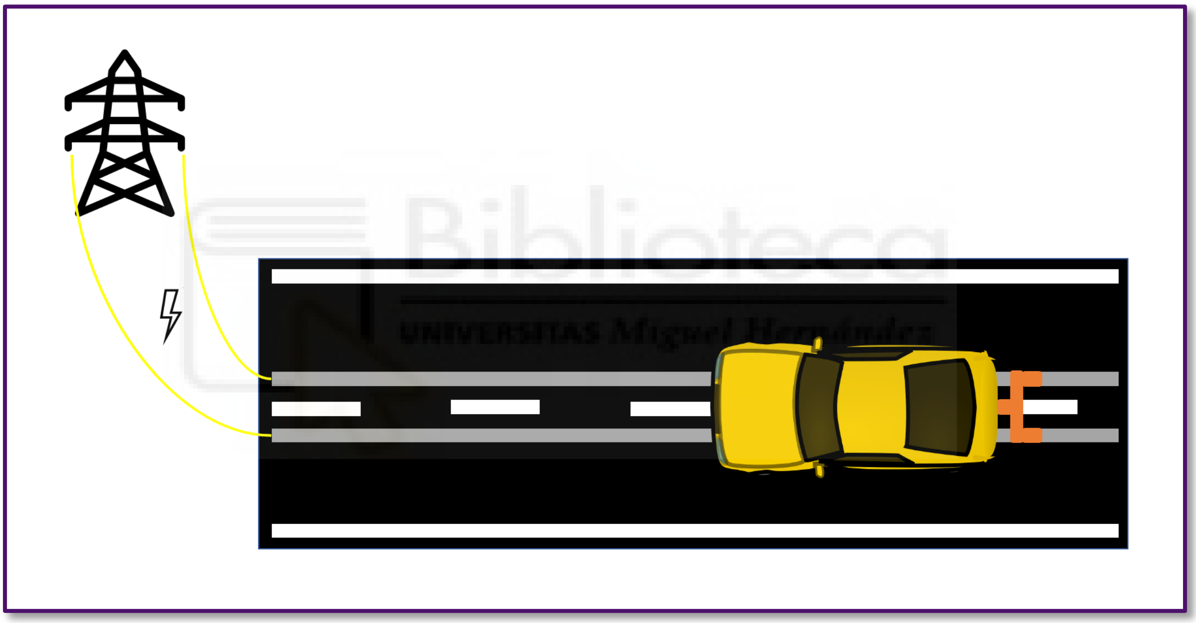

Figure 25. Volvo/Alstom conductive system.

The first prototype consists of a “turning pick up” mechanism which is capable of moving laterally thanks to a rotational movement provided by a pneumatic engine that goes assembled on the bottom part of the vehicle. It is possible to displace the mechanism on the vertical axis thanks to an electric engine [35].

On the other side, the second prototype is a “linear picking up” mechanism allowing the side-scrolling by a linear actuator. A pneumatic one is used to move the mechanism on the vertical axis, and it is fed by the vehicle pneumatic circuit.

As both pantographs allow the side-scrolling, the system can correct 500mm of misalignment between the vehicle and the electrified rail. These prototypes have a weight of 120kg and as dimensions 140x40x70 cm [36].

This solution presented by Volvo/Alstom is able to achieve a power between 3 and 200 kW with an overall efficiency of 97% [37].

4. OTHER DYNAMIC CHARGING SOLUTIONS:

After studying the solutions proposed inside the FABRIC project, we are going to analyse other charging solutions presented in different places in the world which use the dynamic charge or both static and dynamic:

4.1. VICTORIA Project:

The VICTORIA (Vehicle Initiative Consortium for Transport Operation & Road Inductive Applications) project was developed in Málaga (Spain), and it was a proposal to implement the charge of urban buses by using a combination of static and dynamic charge across a fixed path.

The partners that have developed this project are ENDESA and CIRCE with the help of Málaga council [38].

This project was developed on the line 16 (Figure 26) of the urban buses (total length 16 Km, 8 Km go, 8Km come back) in Málaga and it has three different charging methods [39]:

- The first one, produced inside the bus garage, is a conductive static charge. It means plugging the bus by a cable to an electrical recharge point. The bus does this charge after returning to the garage from its route.
- Along the bus path, there are distributed two static wireless panels which charge the bus every time it stops at the defined stops. These are two on the endings of the 100 meters e-road.
- The last method, installed 100 meters after the ending of the route, is a dynamic power transfer system.

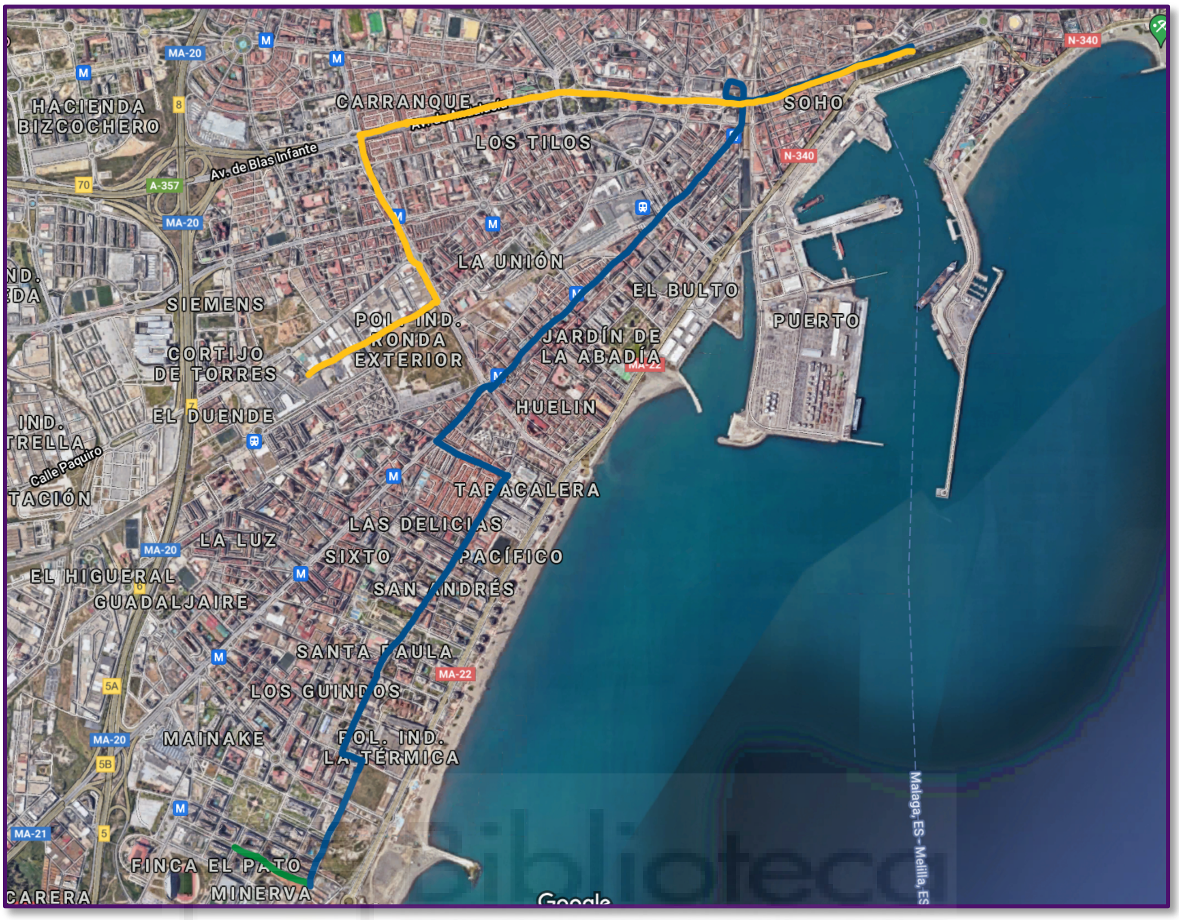

Figure 26. VICTORIA buses route.

The vehicle used in this e-road is the microbus Gulliver 250 ESP/LR which is 100% electric with a total length of 5’3 meters and an Ion-lithium battery of 30 kWh. It can support, as it has been explained, conductive static power transfer, wireless static power transfer and wireless dynamic power transfer [40].

In order to charge the battery inside the garage, it has been installed a charger CHAdeMO (Charge de Move) achieving 50KW of power transfer in DC. This system is used to charge the battery after the day’s driving, charging the battery at night. It also has fast charge mode [41].

After driving out the garage, the bus is not charged until it ends the first outward journey, where it is situated the wireless dynamic road and the two wireless static charging points. After the outward journey, the bus makes its first static charge in the first charging point. It has a duration of 11 minutes at 50 KW. After that, the bus begins driving across the e-road at 50 KW as well. Once the bus has driven out the e-road, it stops at the second static charging point, again 11 minutes at 50KW (Figure 27) [39].

At the end of this process, the bus can drive the way back where it started (8 Km).

Figure 27. VICTORIA e-road solution.

The e-road is composed of 8 primary coils which have a separation between centre points of 12’5 meters. The coils have the following dimensions: 800x600 millimetres and they are made of multiple winding turns.

The electrical power supplier system of these coils is very similar to the one installed in the French test side. It is composed of a transformer, which feeds the system with 700V in AC. After it, this voltage is inverted into DC. Once in DC, it feeds both static charging points through a DC/AC inverter, and also the inverters of the dynamic e-road. There is only one inverter every two coils (Figure 28) [38].

On the other side of the system, the secondary coil installed on the bottom of the bus is much bigger than its counterpart on the ground. This secondary coil has the following dimensions: 2500x600 millimetres. It also has a protection cover which isolates the cabin from the electromagnetic field.

The system allows a misalignment of 30% of the coil width. This means, 180mm of misalignment. Although this misalignment is permitted, the efficiency has been reduced almost 20% from more than 80% to a little more of 60% [39].

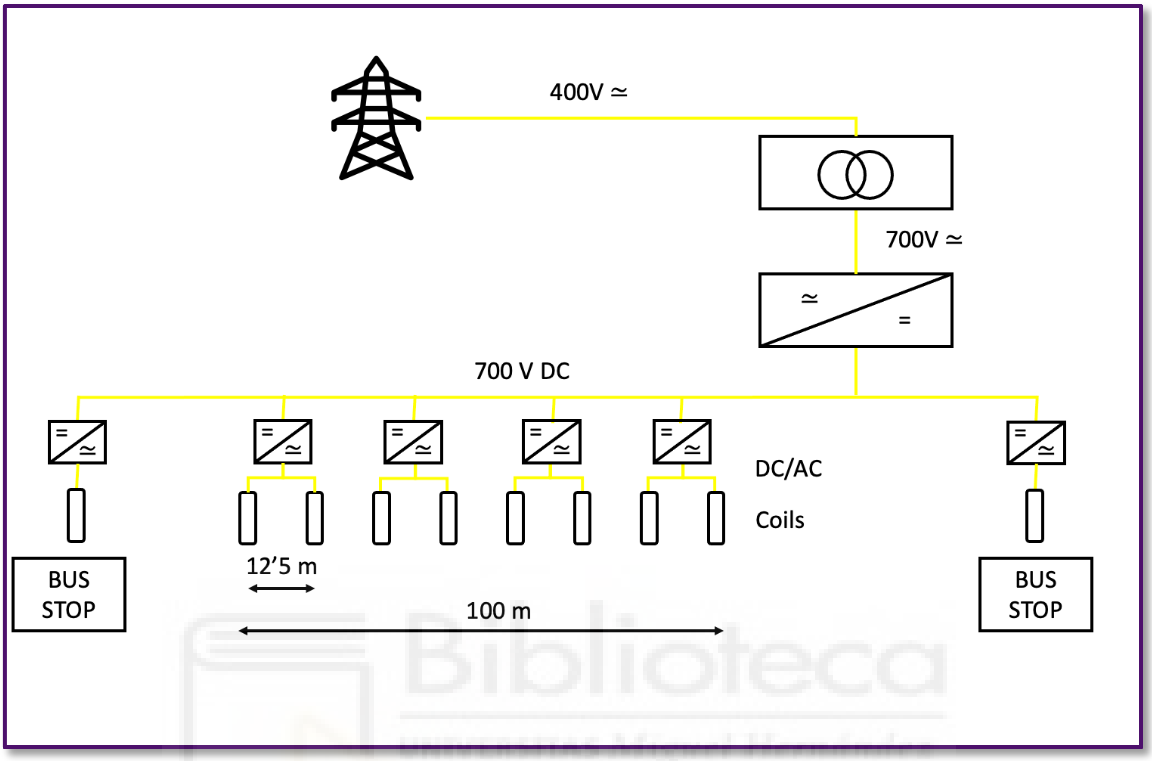

Figure 28. VICTORIA architecture.

In order to avoid misalignment and achieve the best efficiency possible, it has been developed an automatic control system which is capable to guide the bus inside the e-road without any human help [39].

The driver must drive the bus until the first static charging point on the e-road. There, the bus is detected, and the wireless static charge begins. After 11 minutes, the automatic system drives at 10Km/h by its own bus across the wireless dynamic e-road until the second wireless static charging point. The bus stops by its own as well over the charging point and begins its charge for another 11 minutes. At the end of this period of time the system is disconnected, and the driver takes control over the bus again to begin the route.

This autonomous guided system controls both the wheel and the speed to achieve the perfect alignment between coils, increasing the efficiency to 85% with an air gap between 150 and 250 millimetres.

4.2. KAIST OLEV Project:

The Korean Advanced Institute of technology (KAIST) has developed the first e-road with a dynamic wireless charging system which is currently working in South Korea. This project has been developed for buses which have a fixed route. It has created two scenarios with dynamic charge. The first one is a small e-road at KAIST campus with a total length of 3’4 Kilometres of circular route. It contains 8 stops (Figure 29). The shuttle bus used in this scenario consumes an average of 1’4 kWh/km and its battery has a capacity of 25kWh. This bus has 45 seats and 5 secondary coils which recharge the battery passing across the e-roads installed [42].

Figure 29. KAIST campus bus route.

The second scenario takes place in the South Korean city of Gumi. This project has been developed across one of the line buses of the city. This route is much bigger, covering an extension of 34’4 kilometres. This line has 48 stops distributed over the above-mentioned kilometres (Figure 30) [43].

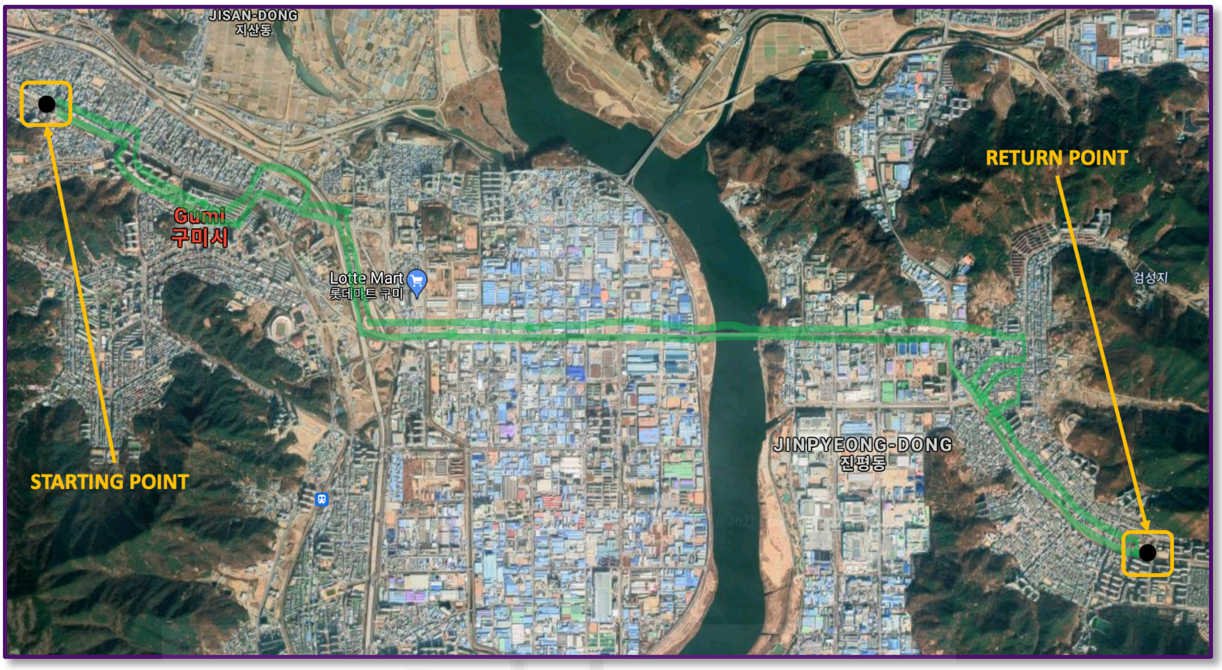

Figure 30. Gumi bus route.

This line is covered by two OLEV (**O**n**l**ine **E**lectric **V**ehicle) buses, which travel the route 10 times a day. Four of these ten times are made giving service and picking up passengers but the other 6 are made just for investigation reasons. These buses cover the whole route in almost two hours on average [44].

In these 34 kilometres there are five charging lines distributed where the buses can recharge their batteries (Figure31). Four of these charging lines coincide with bus stops. Doing this, the buses pass more time inside the recharging area, picking up more power as if the buses don’t stop and pass through the charging line in less time. Although the buses stop for picking up passengers while charging, it is considered dynamic charge because the buses don’t stop the engine.

In these 4 charging lines, the buses receive energy from the primary system at first moving slowly while they are approaching the bus stop and, finally, while the bus is stopped picking up passengers [45].

The fifth charging line has no bus stop, so the buses recharge their batteries by passing through it [45].

Every charging line has a length of 122 meters with primary coils made of a slim “W-Type” with less dick ferrite beads with the objective of reducing cost and achieving better power transfer.

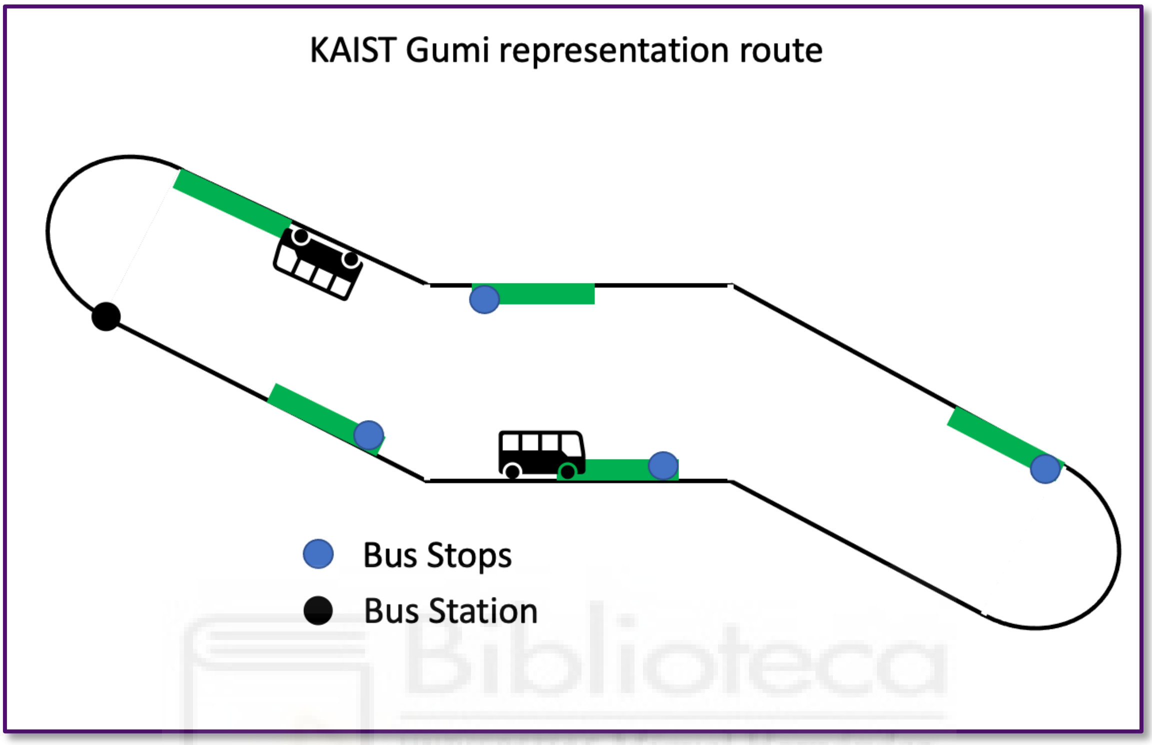

Figure 31. Gumi route architecture.

These five lines, with a length of 122.5 meters, are divided into small sectors. Each sector can have a length between 2’5 and 24 meters. The sectors are activated when the bus passes through them, and they are deactivated when the bus has completely passed the current sector [46].

As regards the secondary system, it has 5 coils located on the bottom of the bus. These coils (“pick-ups”) are capable of acquiring 20 kW each, with a total amount of 100 kW. After the coils, a rectifier is assembled and, before the battery, a regulator [47].

Here, the alignment between coils plays a very important role as in other solutions that have been explained. The primary and secondary coupling allows a misalignment of 20 centimetres with an air gap of 20 centimetres as well.

If the perfect alignment is achieved, the system will be able to transfer 20kW to every one of the 5 secondary coils with an average efficiency of 85%. Nevertheless, if the alignment is not perfect inside the specification limits, the efficiency can decrease to a little more than 60% [48].

This project developed by KAIST has the objective of increasing the bus fleet with these dynamic charging buses for the e-road already created and constructing other similar routes in different cities.

4.3. PRIMOVE Project:

PRIMOVE is currently a solution for the electromobility developed by BOMBARDIER in many different cities in Europe and around the world [49].

BOMBARDIER is a Canadian company which operates mainly on the railway and aerospace sectors [50].

The system used by the vehicles that BOMBARDIER has developed, is a dynamic wireless power transfer system. It consists of wireless charging on bus or tram stops. Once the bus arrives at a bus stop, it begins charging until the bus has picked up every passenger (Figure 32). As we have mentioned before, this type of charge is considered dynamic because the electric engine is working while the battery is being charged [51].

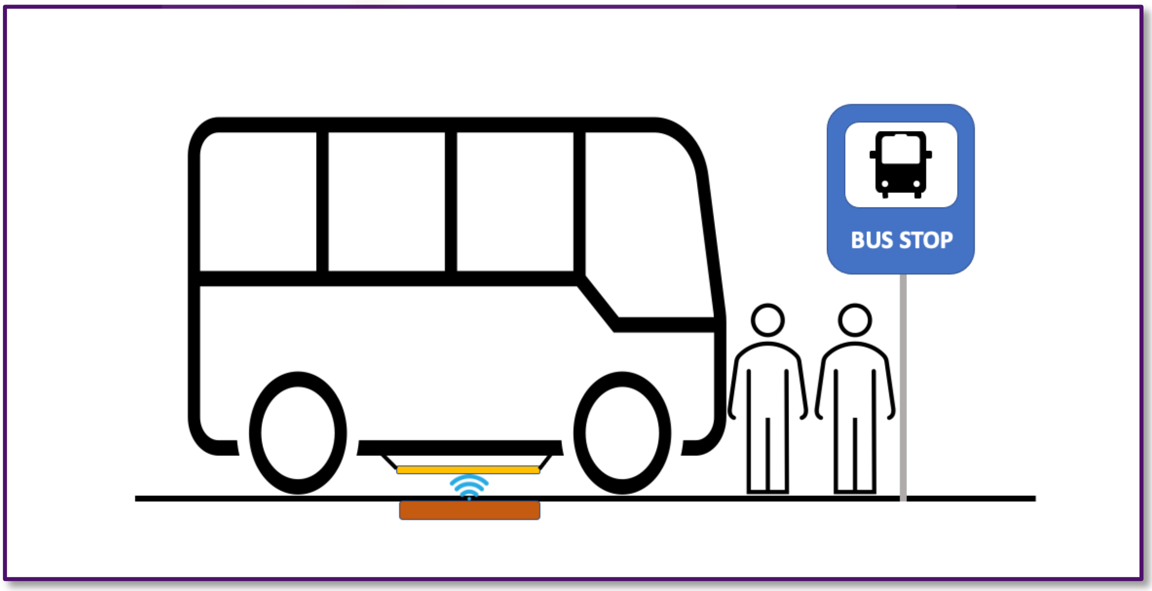

Figure 32. PRIMOVE power transfer system.

The PRIMOVE project has been developed not only for buses, but also for trains and vehicles. Nowadays, it is operative only in buses and tramways in cities like Berlin, Braunschweig, Mannheim, Augsburg, Bruges and Nanjing [52].

In order to explain this technology, it is going to be analysed the current situation in Mannheim (Germany). There, an e-road has been developed on the bus line number 63 from the Hauptbahnhof (train station) to the Waldpark (forest park) covering 9 km in route (Figure 33) [53].

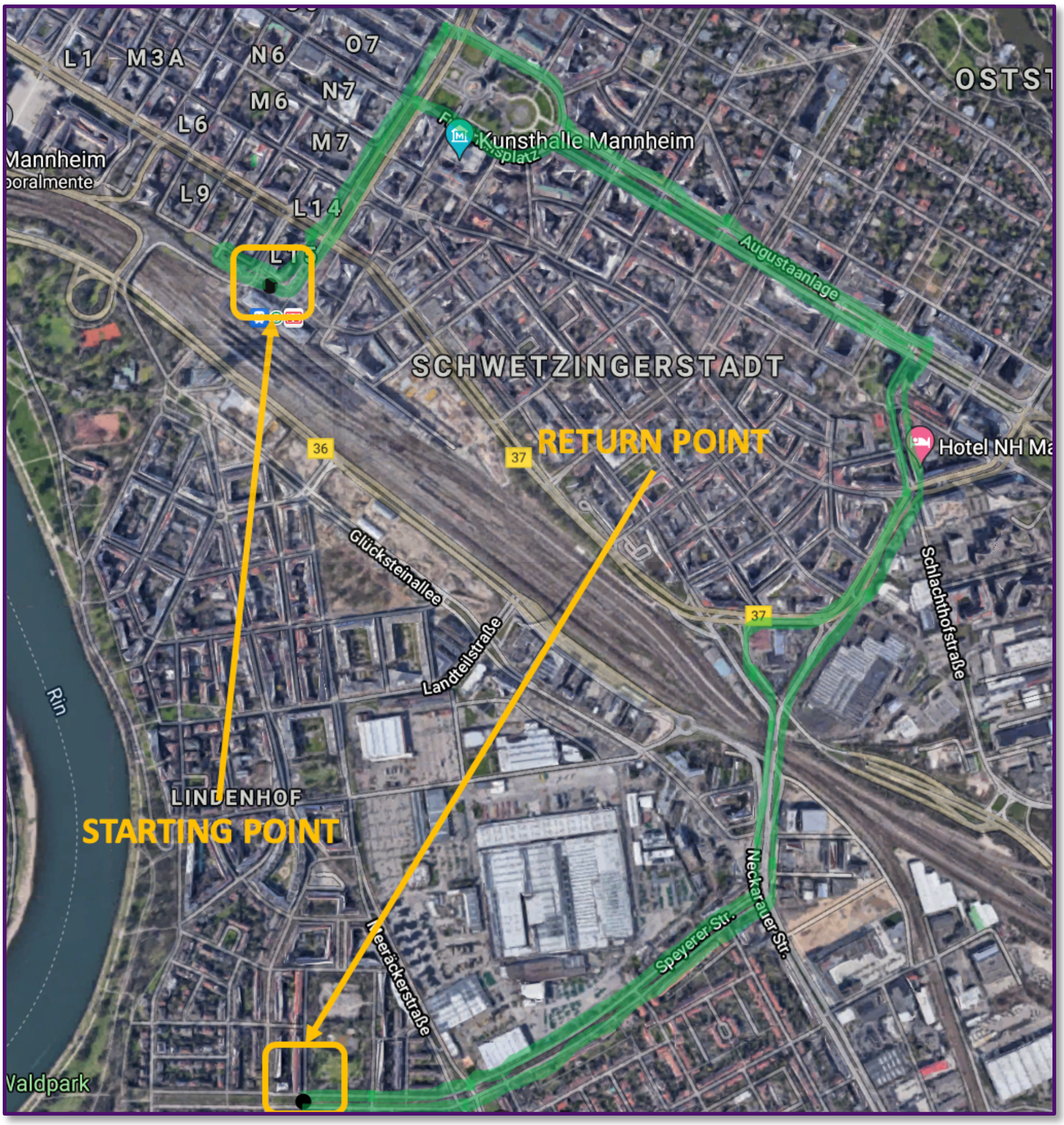

Figure 33. Mannheim e-bus route.

The route is covered by two e-buses. On the bottom of these buses, is located the receiving system (secondary system). In order to obtain a better efficiency on the dynamic wireless power transfer, this secondary system includes a mechanism which is capable of approaching the receiver to the sender on the ground [54].

This mechanism reduces the air gap between the primary system (sender) and the secondary system (receiver) achieving a higher power transfer efficiency. Once the bus is ready to continue its route, the mechanism rolls back the secondary system.

The primary system is embedded in each charging point of the route but accessible by a panel above the system, at the ground level.

The Mannheim route is composed of 4 in-route charging points (in 4 bus stops) distributed to recover the energy consumed in the in-between sectors. There are also two more charging points making them coincide with the ending points of the route, where the bus has more time to recharge the battery [55].

The average charging times obtained measuring it in the different charging points of the e-road are as follows [55]:

- Route Beginning Point: 2min30
- In-Between Stops: 18 seconds
- Route Terminus Point: 4 minutes

Every bus stop has two primary systems separated just in case two buses arrive at the same time to the same bus stop, so both buses can recharge their batteries.

It has been also thought to include a charging line while driving, but at this point it has not been implemented.

When the buses finish the day, they stay the night charging inside their garage to be the next day fully charged.

This PRIMOVE system is capable of transferring an average power between primary and secondary systems of 192 kW [55].

PRIMOVE has developed, as well, its own Ion-lithium battery which is capable of working with a high efficiency with a high useful life cycle. It also allows a high-speed charging mode.

5. CRITICAL ANALYSIS OF THE DIFFERENT SYSTEMS REVIEWED:

After the study of the state of the art made on the pages before, on the next ones it is going to be done a critical study of each technology described, analysing the pros and cons and making comparisons between them.

At this point, 7 similar technologies have been analysed in six different countries, each of them with their own peculiarities. To sum up, it has been described:

- Three wireless dynamic charge only charging while driving through a specific road (FABRIC project in Italy and France).
- One conductive dynamic charge (FABRIC project in Sweden)
- Two wireless dynamic charge combining the recharge while driving and at some stops in a defined path (VICTORIA project in Málaga and KAIST OLEV in South Korea)
- One wireless dynamic charge only charges when the vehicle arrives at different stops in a defined path.

After overviewing the different solutions, it can be observed at first, the differences between objectives and focuses of these projects.

5.1. FABRIC projects: Dynamic wireless charge:

In the case of the three FABRIC projects carried out in Italy (both POLITO and SAET solutions) and France (QUALCOMM/VEDECOM) the main objective was to create possible solutions for a wireless dynamic charge in order to implement it on utility vehicles to create highways with this technology. Achieving it, a road plan could be developed in Europe to increase the use of electric vehicles against intern combustion ones, helping the expansion of them.

As the main problem of electric vehicles is the short duration of their batteries and, in case of large duration, these batteries are big and very expensive, if these three solutions could be implemented in the European roads, cheaper electric vehicles could be developed and they would be able to reach big distances without the need to stop to recharge the batteries. This is the strongest point of these solutions proposed. Even if it is recommended in every European country to stop after a few hours driving (Spain – 2 hours or 150/200 Km, Germany – 2/3 hours or France – 2 hours), it is not mandatory so, with this technology, long distances could be achieved. This is also very important from an infrastructure point of view.

In the event that most vehicles are electric, it would be necessary to install a huge number of chargers distributed along the highways to feed all the batteries of the electric vehicles. As a fast charge could be done in 30 minutes, there must be lots of charging points to cover the alleged demand at certain points in the calendar such as long weekends and holidays, where many vehicles would need to recharge their batteries at the same time.

By installing these e-lanes inside the highways net, it is needed only a few stretches every hundreds of kilometres to feed and recharge the batteries providing another solution of battery charging and venting a little the static recharge points.

These solutions can be added to the static charging points to encourage the use and progression of electric vehicles. Both solutions together could be a proper combination to push back internal combustion vehicles, in the struggle to reduce greenhouse gases to the atmosphere.

The establishment of these e-roads could also do “useful” traffic jams, mainly near big cities, where vehicles could recharge their batteries by staying or moving slowly through the e-lane during the traffic jam. Instead of making a stop of 20-30 minutes out of the highway to recharge the battery of the electric vehicle, this time could be used during the traffic jam to advance and recharge the battery.

In addition, batteries would be smaller due to the instant recharge while driving. Nowadays, bigger batteries are being developed to achieve larger distances without the necessity to stop every few kilometres.

However, developing a wireless dynamic solution, a vehicle doesn't need a big battery because, when this battery is getting empty, the car could go inside the recharge lane, which would be inside the highway itself (Figure 34).

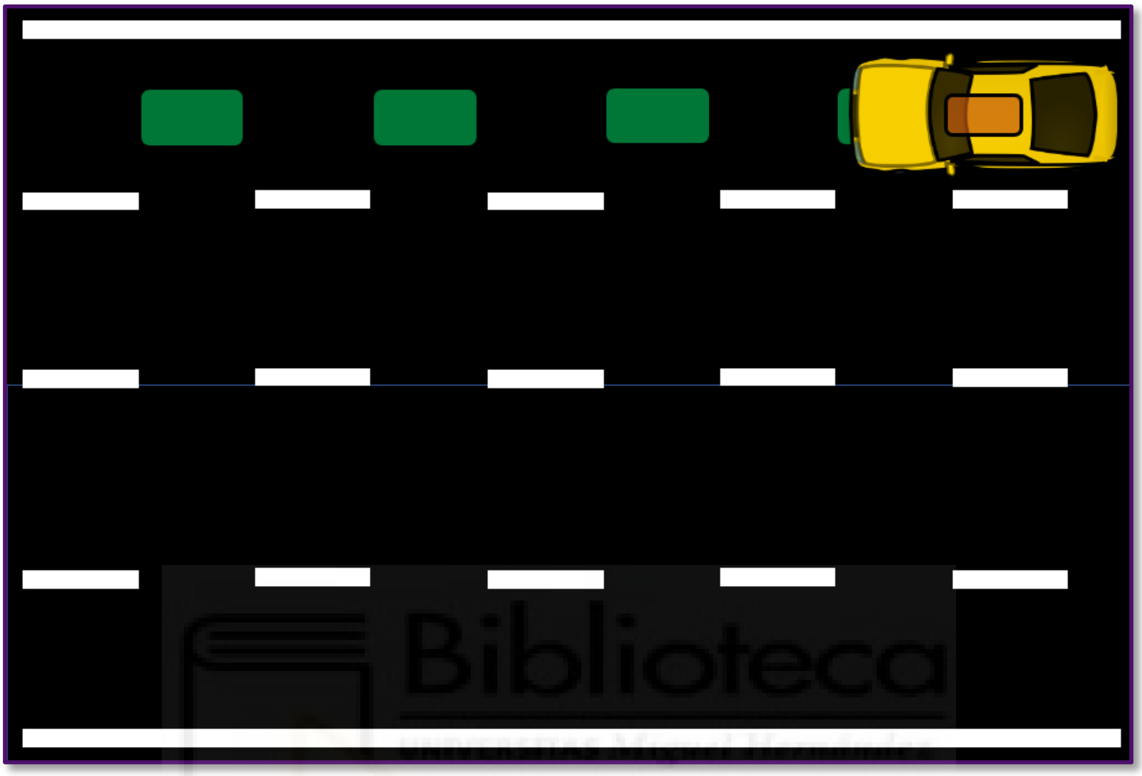

Figure 34. E-Lane inside a highway.

By doing this, the idea is that the e-road itself detects the vehicle and begins transmitting power. Nevertheless, there are many challenges to face here. As it has been seen on the solutions proposed in Italy and France, there were similar recognition systems. The vehicle approaches the e-lane, the system recognizes it and begins transmitting power.

Assuming the highest power transferred in these tests was the solution in France with 20 Kw transferred with the best efficiency achieved of 70%, it makes a power of 14 Kw received by the battery in an hour. If this efficiency has been achieved at 30 Km/h, in order to recharge a full battery of 20 Kw with 25% - 5 Kw remaining, it needs an e-lane of 30 Km long.

Therefore, what happens if the e-lane has a length higher than 30 Km? Should the vehicle begin its recharge at the beginning of the lane? Or, could it be able to enter on the lane at different points?

At this moment, with the systems of recognition developed, this is not possible. The vehicle must be at the beginning of it. Thus, it is important to have control over the e-lanes available in the route and the battery status at every moment.

To do so, it would be a good idea to create a system in the vehicle navigation which could relate the vehicle battery remaining with the distance to the different charging e-lanes indicating where and when the vehicle should begin with the charging process entering an e-lane.

Comparing both Italian solutions and the French one, it will be analysed the feasibility of these solutions in the near future (Table 4).

- The SAET solution has a power transfer of 9 kW at 30 Km/h. This means that, having a 25 % remaining battery of 20 Kw, a vehicle would need almost two hours driving through an e-lane. This e-lane would have a length higher than 50Km. Apart from that, the average efficiency achieved after all the trials has been 66%.
- The POLITO solution, on the other hand, has a power transfer of 5’2 kW/h but going faster, 50 km/h. In this case, to recharge a 20 kW battery having a 25 % remaining, a vehicle would need three hours and a large e-lane with minimum 150 Km long. In this case, the average efficiency achieved after all the trials has been 81%.
- The last one, the QUALCOMM solution, has been able to transfer 14 Kw between primary and secondary coils, at an average speed of 30 Km/h but achieving power transferred at 100 Km/h with less efficiency. In this case it only needs 30 Km of e-lane and one hour driving through it.

It is clear that at this point it is not possible to implement these solutions at any highway in Europe but, this is a very first approach inside a very interesting project.

As the higher power transferred is transmitted by the French proposal, it is going to be taken as reference.

	SAET	POLITO	QUALCOMM
Power Transfer	13'6 kW	6'3 kW	20 kW
Efficiency	66%	82%	70%
Power Achieved	9 kW	5'2 kW	14 kW
E-Road Length	> 50 km	150 km	30 km
Speed	30 km/h	50 km/h	30 km/h
Time Through E-lane	2 hours	3 hours	1 Hours

***Table 4**. FABRIC wireless projects comparison.*

In order to make possible the development of these projects on highways it is needed to improve the quantity of power transferred and the speed while driving. Both are related, the faster the vehicle drives, the higher power transferred needed, because driving faster means less time on the e-road unless the e-lanes were larger.

5.2. FABRIC projects: Dynamic conductive vs wireless charge:

As it can be seen before in the Swedish solution, the higher power transferred on average was 200 Kw. If this power would be achieved at an average speed of 100 Km/h, it would need only an e-lane of 10 Km long with a duration of 6 minutes driving through it (Table 5).

	QUALCOMM	VOLVO/ALSTOM
Power Transfer	20 kW	200 kW
Efficiency	70%	97%
Power Achieved	14 kW	194 kW
E-Road Length	30 km	10 km
Speed	30 km/h	100 km/h
Time Through E-lane	1 Hours	6 Minutes

***Table 5**. QUALCOMM vs VOLVO/ALSTOM.*

Achieving this 200 Kw is not possible right now due to the technical limitations that have been seen, but it would be possible to reach 50Kw, which would be almost 20 minutes and an e-lane of 33 Km.

Analysing the speed, it is also a very important point. Taking as reference the French solution again, it has been seen that it is needed an hour driving at 30 Km/h to recharge a 75% of a 20Kw battery. This means that a vehicle drives 30 Km in an hour to recharge the battery.

On the other hand, if that vehicle instead of charging its battery with this solution, it stops to charge on a static point with fast charge mode, in 30 minutes the battery is fully charged and the vehicle can continue driving on the highway at 120 Km/hour. This means that in 15 minutes driving, the vehicle travels 30 Kilometres.

Comparing both recharges, with the wireless dynamic solution the vehicle travels 30 Km in one hour charging the whole battery. However, charging on the static point, the vehicle stops for 30 minutes and in 15 minutes travels for 30 Km. In the end, the vehicle that has stopped to charge the battery, in one hour has travelled 30 Km more than the vehicle which has used the e-lane. In addition, the pilot of the static charge vehicle has been able to rest for half an hour (Table 6).

	STATIC CHARNGE	D. WIRELESS CHARGE
Time Stopped	**30 minutes**	**0 minutes**
Speed while driving	**120 km/h**	**30 km/h**
Time driving	**15 minutes**	**1 hour**
Kilometres made	**30 km**	**30 km**
Total Time	**45 minutes**	**1 hour**

***Table 6**. Static vs dynamic charge simulation.*

An additional appointment comparing these three solutions between them is the way the primary coil is embedded on the ground. Both Italian solutions are embedded in concrete but, on the other hand, the French primary coil is assembled under a screwable surface.

From a maintenance point of view, the French scenario is much better, where any damaged electrical part could be fixed or changed in a quick and easy way. In the Italian e-road, if there is any breakdown, it is necessary to bite the concrete to remove the damaged parts, fix it and rebuild it into the special concrete.

It is also important to note the differences between the shape of the coils (Table 7). We have seen two different coils in Italy, the simple turn coil and the multiple turn coil. The first one was capable of transferring more power (9 Kw) but with less efficiency (66%) driving slowly (30 Km/h). On the other hand, the multiple coils transferred less power (5’2 Kw) but with higher efficiency (81%) and driving faster (50 Km/h). These systems, the faster the vehicle drives through it, the lower the efficiency is. This means that the simple coil doesn’t have good behaviour. It transfers more power because of the system designed so, the same system with multiple turn coils would be a better solution with higher power transfer, higher efficiency and higher speed. The French solution has modules (pads) with multiple winding coils and this solution has the higher power transferred with very good efficiency (70 %) at high speeds.

PROJECT	SHAPE	EFFICIENCY	POWER TRANFER
SAET	**Simple turn coils**	**66%**	**9 kW**
POLITO	**Multiple turn coils**	**81%**	**5'2 kW**
QUALCOMM	**Qualcomm Pads**	**70%**	**14 kW**

Table 7*. Shape comparison.*

As a conclusion, solutions such as the one developed in France or Italy by the University of Torino (POLITO) may be viable in the near future. Nevertheless, there are still many aspects to improve to make this possible.

The QUALCOMM Halo solution applied for the dynamic charge has demonstrated promising results, but it is key to transfer more power while driving faster as they did on the assays.

The Italian solution developed by POLITO is also a good approach but there are some aspects to improve. It would be better to use an embedding system similar to the QUALCOMM one, making possible quicker interventions in the system. The efficiency is the higher of the three, but the power transferred is very low so, by using this system with the pads designed by QUALCOMM could be a good beginning point in order to achieve the best solution possible for the feasibility of the technology.

Apart from these wireless dynamic charge solutions, the FABRIC project developed by VOLVO in Sweden was a conductive dynamic solution. This solution was thought to be implemented on trucks and vehicles with a fixed route. That is a good approach. It is possible to create conductive lanes on points of transport trucks concurrence to recharge the trucks batteries and give an option to introduce electric trucks which can achieve long distances without stops.

This could be a good solution for trucks and for long distance buses. Buses have also defined routes, so they could recharge the battery by installing conductive lanes in strategic points of the route.

In the case of utility vehicles, this solution is not applicable from a mechanical point of view because it would be needed to provide every car with a conductive system in order to connect it with the grid. This means an increase in the weight of the vehicle and, as it consists of a new mechanical part, it would need maintenance and could lead to mechanical failures due to the contact between the picking-up system and the road. In addition, the road must be in perfect conditions to avoid bumps which can damage the mechanical pick-up system.

The weight in this system plays a very important role. If one of the objectives of the dynamic charge (wireless or conductive) is reducing the weight of batteries, it makes no sense to increase the vehicle weight with a mechanical tool.

In addition, even if it could be a good solution for trucks, this additional weight for the truck could be a deterrent. Trucks must not exceed certain weight specifications so, an increase on the weight of the truck can suppose a reduction on the transport charge.

On the other hand, this weight doesn’t penalize buses, so it is still a good solution for these vehicles which can have the pick-up system assembled without a reduction in the bus capacity. Moreover, by using this kind of technology, it would not need any shield on the bottom of the bus to avoid the interaction of the electromagnetic field with the passengers as occurs with the wireless dynamic charge. For this reason, the secondary system (pick-up system) is much simpler than the wireless ones.

It is also challenging referring to the implementation of the system on utility vehicles, the way the vehicle identification system recognises them. As the system reads the speed of the vehicle and the direction, it could be a problem to install these e-lanes on concurrency highways because, in case of traffic jams or slow traffic, the system may not get activated.

With heavy traffic across an e-lane, even driving over the target speed, another problem could be the synchronization between power boxes to activate and deactivate road stretches.

As it can be observed, this kind of charge is not the best solution for utility vehicles at this moment.

Analysing the power transfers and efficiency, as this is a system that has direct connection to the electrical network due to the contact between the pick-up mechanism and the grid, this efficiency is very high, there are almost any losses. Obviously, by contact the efficiency is much better as by wireless charge (97 % efficiency conductive against 85% maximum in wireless transfer).

Furthermore, the power transferred by the VOLVO system is much higher as with the wireless systems (between 3 and 200 Kw). This means that with very short e-lanes, the battery would recharge in a very short time. Driving at 100 Km/h assuming 100 Kw transferred (half of the maximum) means that, a battery of 20 Kw with 25% remaining, is charged in 8’4 minutes inside an e-lane of 14 kilometres (Table 8).

VOLVO PROJECT SIMULATION	
Speed	**100 km/h**
Power Transfer	**100 kW**
E-lane length	**14 km**
Time through e-lane	**8'4 minutes**

Table 8. *VICTORIA project simulation.*

This length is something achievable, as the trial one in Sweden was almost 300 meters (2 %).

As it has been explained, this solution is not suitable for utility vehicles as there are more disadvantages than advantages. On the other hand, developing a lightweight picking-up system, this solution could be feasible for trucks on key highways in road haulage. Finally, it is also feasible to introduce this system on bus routes, similar to trolleybus inside the cities but with a conductive system installed on the road.

5.3. VICTORIA, KAIST/OLEV & PRIMOVE:

All these previous analysed projects were solution proposals inside the FABRIC European project but, in the next paragraphs it is going to be analysed in different situations already implemented in some cities around the world.

The first project being analysed is the VICTORIA solution. This Spanish solution combines dynamic charge while driving and static charge after doing the whole route.

The power recovered while the vehicle is charging statically is at 50 Kw during 11 minutes, so 9,1 Kw recovered every pad, there are two static pads making a total power recovered of 18.2 Kw. Apart from that, the buses also recharge their batteries on a 100 meters stretch while driving at 10 Km/h at 50 Kw which makes a power recovered of 0’5 Kw (Table 9).

	VICTORIA PROJECT	
Methodology	**Static Charge**	**Dynamic Charge**
Power Transfer	**50 kW**	**50 kW**
Time Charging	**11 minutes**	**0'6 minutes**
Energy recovered	**9'1 kW**	**0'5 kW**
Points of charge	**2 pads**	**1 e-lane**

__Table 9__. VICTORIA summary.

Comparing the power obtained by the dynamic wireless lane and the static wireless pad, the power recovered while driving practically doesn’t represent anything.

The perspective changed if there were more e-lane distributed across the bus route but, anyway, at 10 Km/h as these buses passed through the e-lane is very slow. The speed would be improved, and the e-lanes distributed along the route.

On the other hand, as the whole route of the VICTORIA buses is not very long (8 Km round and 8 come back) assuming 1’5 kW used every Km more or less as KAIST buses, the total consumed by the bus considering the 16 km is 24 kW. Every time the buses complete the whole route consume 24 but recover 18’7, they lose almost 5 kW, which means that the buses could do 6 whole trips before running out of battery and coming back to the garage.

It would be a possible solution for these buses to increase a little the time charging on the pads before beginning the route again. Another possible solution could be adding some charging pads in some stops along the route as in PRIMOVE or KAIST / OLEV solutions.

However, in any case, the dynamic e-lane would be eliminated. It is not worth having an electrified stretch that needs to be maintained and only provides 0’5 kW of the 24 consumed. For this project, this e-lane is certainly not needed.

Additionally, as the buses have assembled the guidance system to avoid misalignment between bus and primary coils inside the wireless dynamic stretch, by eliminating this e-lane the bus would simplify its system on board. Buses maintenance would be easier.

The VICTORIA buses are currently not working and the e-lane was dismantled. Even if the results were not bad at all, they couldn’t find investors to keep on going with the proposal.

Another project that is still nowadays working, using the dynamic charge, is the KAIST / OLEV applied only for buses. In this case, as we have seen it is a combination of dynamic charge while driving and dynamic charge once the buses stand at different route stops.

This proposal is quite similar to the VICTORIA one, but with a very important difference. As in the VICTORIA solution the buses only recharge their batteries at the end of the round road, here the charger pads are distributed across the whole route. On the VICTORIA project there was only one electrified stretch but, in this case, there are 5. Therefore, the power received by the batteries due to the wireless dynamic stretches is now more significant.

Anyway, e-lane stretches have a length of 122’5 metres. As the route has 5 stretches, the total distance where the buses recover battery while driving is 612’5 metres. Assuming that the buses pass through it at an average of 20 Km/h because the bus is decelerating to stop and pick-up customers or accelerating after picking-up them, the total time buses are recharging their batteries is 1’8 minutes in the whole route of 33 Km (Table 10).

	KAIST/OLEV PROJECT	
Methodology	**Dynamic Stopped**	**Dynamic Driving**
Power Transfer	**100 kW**	**100 kW**
Time Charging	**8 minutes**	**1'8 minutes**
Energy recovered	**4'8 kW**	**1'08 kW**
Points of charge	**4 point**	**5 e-lanes**

***Table 10**. KAIST/OLEV summary.*

On the other hand, the total time that the buses recharge their batteries while they are stopped picking-up people (which they make it in 4 different points of the route) is on average 8 minutes (2 minutes each). In this case, the dynamic charge while driving suppose a 22’5% of the total energy obtained by the battery.

However, the resources used to construct the e-lanes along the route, their maintenance and the implementations needed on the buses may not be enough to justify only a charge of 22’5% of the battery.

Adding only one more pad in another stop of the route would be enough to charge this 22’5 % of the batteries so, it would be possible to avoid constructing more than 600 metres of electrified road saving time and money.

Moreover, if at any moment it is decided to reduce the battery size, it would be much simpler and faster to accommodate the route to new needs by installing new pads in different stops of the defined road.

For sure, these e-lanes are also developed to investigate the possibility of expanding these technologies but, at this moment, as we have said before, the power transferred while driving is not high enough to be feasible.

For the completion of the critical analysis, it is going to analyse other solutions that are currently running in some cities of Germany and around the world. This is the PRIMOVE project, which is applicable again only for buses.

The reason that has led this project to be a success has been simplicity. The road is composed only of dynamic charging pads that transfer energy while the buses stop to pick-up passengers. There are no e-lane to obtain energy while driving (Table 11).

	PRIMOVE
Methodology	**Dynamic Stopped**
Power Transfer	**192 kW**
Time Charging	**-> Begining: 2min30** **-> In between stops: 18 seconds** **-> Terminus: 4 minutes**
Energy recovered	**Minimum of 32kW**

Table 11. PRIMOVE summary.

On this project the focus was to recover all the battery consumed before starting again the route. The route length here is similar to the VICTORIA one but, the solution is much better because the buses get almost the energy consumed. They can achieve driving the whole day with the simplest system of the three analysed.

This is the perfect example of a sustainable transport within cities, it can cover the necessities of the customers without affecting the time used to complete the route. On the other hand, this solution is not extrapolatable to long-distance transport because the bus stops are far apart from each other. It could be also possible to introduce this solution to medium distances maybe assembling a big battery and making a bit longer the stops and charging fully the battery at terminus.

6. ECONOMIC STUDY:

As the PRIMOVE solution for buses is already running as a feasible solution for this kind of vehicle, it is going to be studied a future state for utility vehicles following the FABRIC projects architecture developed on a busy motorway with the aim of analysing the costs of the infrastructure and the costs associated to the electricity consumption.

The economic study will be done over a dynamic wireless road implemented for vehicles based on the French test site (QUALCOMM).

To do so, it is needed to make some assumptions regarding the future state of this technology in case of its future feasibility. It is going to be used the proposal made in the critical analysis (Table 12):

- 50 kW of power transmission
- 100 Km/h
- 35 Km (needed to recharge 15 kW)
- 85% of efficiency
- Batteries of 20 kW (150 km autonomy)

As it is not possible to know the prices of the pads used by QUALCOMM, it is going to be assumed the infrastructure price per Km noted on the FABRIC project for 2030 [56].

Infrastructure cost per Km per year → 3.000.000 €

Apart from the installation, kilometres of connexion cables and workforce, the elements included on the infrastructure are:

- 560 QUALCOMM pads per km. TOTAL: 19.600 pads
- 20 Inverters per km. TOTAL: 700 inverters
- 20 cabinets per km. TOTAL: 700 cabinets
- 1 AC/DC converter per Km. TOTAL: 35 converters

The next step is to analyse how many vehicles would use the e-lane throughout the year. To do so, it is going to be calculated the maximum number of vehicles that would be able to use the e-lane in a day according to the safety rules.

When a vehicle drives at 100 km/h, it must keep a security distance with the vehicle in front equivalent to 2 seconds. According to this rule, a day means 86.400 seconds, a maximum of 43.200 vehicles per day.

It is going to be assumed a little less than a half of the e-lane utilization, taking in consideration that at night, roads are almost empty and during the day the highway utilization doesn't achieve 100%.

Vehicles per day → 20.000 units

ASSUMPTIONS	
No. of Vehices/day	**20.000 units**
Power Transferred	**50 kW**
Efficiency	**85%**
Speed	**100 Km/h**
E-lane Length	**35 Km**
Battery Capacity	**20 kW**
Infrastructure costs per km & year	**3.000.000 €**

***Table 12**. Assumptions for the economic calculation.*

Relating this amount of cars this the costs of the infrastructure in a year, it can be reached the associated cost of the infrastructure to each vehicle:

Total infrastructure costs per year → 105.000.000 €

Total vehicles per year → 7.300.000 units

Total infrastructure costs per vehicle → 14'38 €

An average price for kWh for industrial consumption in Spain is variable but it is around 0'08 €/kW.

As every vehicle drives through the e-lain during 21 minutes to cover the 35 Km, the hours of electricity consumption of these 20.000 vehicles are 7.000 hours.

According to the assumption made before, every pad inside the system would be able to transmit 50 kWh. The total amount of Kw consumed per day are:

Kw consumed in a day → 350.000 kW

With all this data, it can be calculated the total costs of the electricity consumption in a day across the 35 km e-lane:

Total Electricity Costs in a Day → 28.000 €

As we considered 20.000 vehicles using this e-lane a day means that every vehicle recharges the battery spending less than two euros.

Electricity Cost per Vehicle → 1’4 €

Calculating the total electricity costs in a year:

Total Electricity Costs in a Year → 10.220.000 €

Finally, the total costs of the e-lane and the costs associated to each vehicle are as follows:

E-lane Costs per Year → 115.220.000 €

Total Costs per Vehicle → 15’78 €

ECONOMIC SUMMARY	
Infrastructure costs per km & year	**3.000.000 €**
Kw consumed in a day	**350.000 kW**
Average price for kWh	**0'08 €/kWh**
Electricity costs per day	**28.000 €**
Electricity costs per year	**10.220.000 €**
E-lane costs per year	**115.220.000 €**
Infrastructure costs per vehicle	**14'38 €**
Electricity costs per vehicle	**1'4 €**
Total costs per recharge	**15'78 €**

Table 13. Economic summary.

As it can be observed (Table 13), the main cost is the infrastructure. By implementing pads able to transfer more power than the 50 kW assumed, the e-lane would be much shorter and cheaper, reducing the total costs per vehicle and making it interesting for drivers.

7. CONCLUSIONS:

After reviewing many different proposals of vehicle dynamic charging for a green and sustainable mobility, the key points of the study are summarized below:

- Wireless dynamic e-lanes are mainly aimed at utility vehicles due to a lower energy consumption. However, it is also not disposable for trucks and buses with bigger batteries.

- These dynamic wireless e-roads designed are a very first step in the search for a viable solution to the low range of electric vehicles. Some key point are described below (Table 14):

SOLUTION	Efficiency	KEY POINTS TO IMPROVE
SAET	**66%**	**Efficiency (66%)**
POLITO	**82%**	**Power Transfer (5'2 kW)**
QUALCOMM	**70%**	**Efficiency (70%)**
VOLVO/ALSTOM	**97% (conductive)**	**Pick-up System**
VICTORIA	**80% - 85%**	**Charging points in bus stops instead of e-lane**
KAIST/OLEV	**85%**	**Power Transfer or no. of charging points**
PRIMOVE	**>90%**	**NA**

***Table 14**. Efficiency & Key points of each project.*

- At the moment, the power transmission on wireless dynamic e-lanes is very low and cannot be feasible solutions (maximum 20 kW). These e-lanes need to increase the power transferred to the vehicle(minimum 50 kW). As more energy is transmitted, shorter e-lanes would be needed.

- Even if the power transmission is not high on these wireless dynamic e-lanes, the efficiency does, mainly the POLITO and PRIMOVE solutions (Table 14).

- The key point of the wireless dynamic charge is the relationship between power transferred and time. Each e-lane should have the best combination between distance and power transmitted to fulfil the vehicle’s batteries.

- Conductive dynamic lanes don’t fit at all with utility vehicles due to the installation of the pick-up system. However, it could be a good proposal for trucks or long-route buses with predefined routes. These e-lanes could be constructed at major freight and passenger transport points.

- Solutions such as VICTORIA for buses would get better results by focusing the dynamic recharge only on bus stops instead of creating small wireless e-roads where the bus doesn’t stay much time.

- The KAIST solution for buses, which combines wireless charge while driving and also stopped, would be a feasible solution by increasing the power transferred by the pads on the e-lanes or increasing the number of bus stops with wireless charging pads. Comparing the power transferred with the PRIMOVE solution, KAIST systems are able to transfer 100 kWh, which is a good performance. However, PRIMOVE buses are able to feel their batteries with 190 kWh.

- The PRIMOVE solution for electric buses is already today a feasible solution in process of expansion using only wireless dynamic charging pads situated in different bus stops along the route.

- As dynamic wireless e-lane infrastructures have huge costs compared to electricity, by increasing the power transferred by the pads, the cost of these e-lanes would be greatly reduced.

- Regarding the dynamic wireless power transfer, a critical aspect is the protection of passengers from the electromagnetic field generated between primary and secondary systems.

- Finally, the best solutions proposed for to implement the dynamic recharge are (Table 15):

VEHICLES	BEST SOLUTION	STRENGTHS			WEAKNESS
Utility vehicle	**QUALCOMM**	**Speed (until 100 km/h)**	**Power transferred 20 kW**	**Primary Coil Burying**	**Efficiency (70%)**
Trucks	**VOLVO**	**Efficiency (97%)**	**Power transferred 126 kW**	**NA**	**Mechanical pick up system (weight & maintenance)**
Buses	**PRIMOVE**	**Efficiency (>90%)**	**Power transferred 190 kW**	**Two buses at the same time**	**NA**

***Table 15**. Best solutions depending on the vehicle.*

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