Analysis of effects and consequences of constructing Inductive Power Transfer Systems in road infrastructure

A case study for the Stockholm Region (Sweden)

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Abstract

The continuous growth in road transportation demand requires the development towards sustainable strategies. The concept of Smart Roads is arising as a convergence of technologies that will lead the mobility by road into a more efficient and interactive system between infrastructure, environment and vehicles. Within this context, e-mobility appears as one of the key components.

The implementation of e-mobility based on Electric Vehicles (EVs) has been restricted by numerous shortcomings such as their driving range, the battery size, the dependence on charging stations and the time required for its charging. However, the electrification of the road infrastructure, which will enable a dynamic charging of the EVs while driving, is becoming a potential solution to overcome these deficiencies.

This study aims to contribute for the future introduction of electrified roads (eRoads) into the current network, by focusing on the effects and consequences of embedding Inductive Power Transfer (IPT) systems in the road infrastructure. A structural design of an eRoad is conducted through a Finite Elements Analysis (FEA) by analysing the behaviour of a pavement structure based on Swedish conditions subjected to traffic loading. Valuable conclusions can be displayed from this analysis and thus, a summary concerning considerations and effects over the design, construction and maintenance of eRoads can be built. Nevertheless, this analysis must be complemented and coordinated from a lifetime perspective to reach the social, environmental and economic requirements related to the development of road infrastructure nowadays. Hence, a guideline from a life cycle approach is stated over the integration of eRoads in order to enable the assessment of the infrastructure during its different phases.

To be sustainable, the development of road infrastructure must reach not just structural and appropriate performance requirements, but also preserve the environmental and economic impact. This thesis pretends to combine all these aspects as a state of the art, providing a basis that stands out the most relevant issues related to the feasible implementation of eRoads in the mid-long term.

Keywords: eRoad, Inductive Power Transfer (IPT), Finite Elements Method (FEM), Structural Pavement Design, Considerations and Effects, Life Cycle Analysis
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Stockholm, August 2015
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Abbreviations

BC ................................................................. Boundary Condition
CPT ............................................................. Conductive Power Transfer
DERS ........................................................ Dynamic Electrified Road System
EMF ............................................................. Electromagnetic Fields
eRoad ........................................................ Electrified Road
ESAL .......................................................... Equivalent Single Axle Load
EV ............................................................... Electric Vehicle
FE ................................................................. Finite Elements
FEA ............................................................. Finite Elements Analysis
FEM ............................................................. Finite Elements Method
FU ................................................................. Functional Unit
GWP ............................................................ Global Warning Potential
HMA ............................................................. Hot Mix Asphalt
ICE ............................................................. Internal Combustion Engine
IPT ............................................................... Inductive Power Transfer
LCA ............................................................. Life Cycle Assessment
LCCA ........................................................... Life Cycle Cost Analysis
PCC ............................................................. Portland Cement Concrete
PMS ............................................................. Pavement Management System
PTE ............................................................. Power Transfer Efficiency
STA ........................................................... Swedish Transport Administration
WPT ........................................................... Wireless Power Transfer
1. Introduction

1.1. Background and motivation

Facing climate change and the environmental degradation, arises the necessity of reducing the use of fossil fuels, the primary energy source at the present and responsible of a non-recoverable damage to the environment.

Currently the role of the automotive sector is crucial in the sphere of mobility due to the importance of the transport of people and goods by road. As reported by the European Environment Agency, road transport accounted for 82% of total energy consumption in transportation in 2012, a figure which represent almost 22% higher than in 1990 (European Commission, 2014). In fact, being road transport the principal means of transport in the European Union, contributes about one-fifth of the EU’s total emissions of carbon dioxide (CO2), and is the only major sector in the EU where greenhouse gas (GHG) emissions are still rising (European Commission, 2015). Also disconcerting is the subservience to fuel supply, a finite resource with increasing prices and a strong dependence on imports from other countries.

According to the facts stated before, the pursuit of a higher energy efficiency and the use of renewable energy sources lead to the development of new ways of mobility where e-mobility has emerged as a solid alternative. The multiple energy sources able to produce electricity, the pre-existing distribution grid in most developed countries and the fact that contributes to an increase in energy efficiency are some of the reason towards its introduction in road transportation. However, the introduction of the Electric Vehicle (EV) in the market has been restraint by its several shortcomings. For instance, the EV driving range, the battery size and cost, the dependence on charging stations infrastructure besides their limited availability and finally the required time to recharge the batteries among others. Within this context, the electrification of the road infrastructure also known as eRoad is becoming a potential solution that enables a dynamic charge of the vehicles while driving along the road.

The concept of the eRoad is based on the in-motion charging solutions, which consists on the electrification of the road infrastructure that would allow the energy transfer from the pavement to the EVs to overwhelm the limitations of the current batteries. Besides, the emissions to the atmosphere would be enormously reduced as well as the dependence on fossil fuels, promoting therefore sustainable road transportation. Although there are several alternatives for the implementation of eRoads, the Wireless Power Transfer (WPT) solutions seem to be the most appropriate due to their advantages over other conductive solutions such as the overhead lines or the railroad. Specially, Inductive Power Transfer (IPT) systems are a way of wireless transmission with better qualities among the others by being more powerful, tolerant to misalignment, safer and more efficient (Covic & Boys, 2013).
These systems are based on a magnetic coupling flux between the charging system embedded in the pavement and the pick-up system installed in the EV that will provide energy to the vehicle.

Having this in mind, currently the challenge resides on how integrate the eRoad based on IPT systems in the current road network and how to reach the structural, operational and performance requirements in coherence with the sustainability of the road infrastructure system. Moreover, the effects and consequences of constructing these systems into the road remain unknown. The studies regarding this topic are limited and most of them have been focused on the development of better technologies for the power transmission with the vehicles but not on the structural and sustainable integrity of the electrified infrastructure. However, some pilot projects have been developed in the last years related to these issues. For instance, in California, during the decade of the 90s a track construction and testing project was developed based on Inductive Coupling Systems (ICS) (PATH & UC Berkeley, 1994). Besides, from 2009, in Korea has been promoted an initiative of e-mobility called the “Online Electric Vehicle” (OLEV), also based on IPT Systems (KAIST OLEV, 2015). Also in Europe some projects have been conducted such as the "Slide-in Electric Road System” in Sweden (Viktoria Swedish ICT, 2013) or the FABRIC project for the development of on-road charging solutions in the European Union (FABRIC- project, 2015). Nevertheless these projects were developed mainly in a feasibility level without analysing the pavement.

Transport infrastructures have an enormous influence from an economic, environmental and social perspective. The high cost and environmental impact associated with road construction and maintenance makes the pavement a decisive issue for any highway project and thus, it is important to assure its adequate performance during its lifetime. Likewise, the assessment of the related input and output flows of the systems over the different phases forming the implementation process is essential to identify and evaluate the issues, shortcomings and future challenges that will enable the introduction of a feasible and sustainable electrified infrastructure.

On the other hand, the integration of eRoad infrastructure within the current road network will have a great impact in the transport system. The long haulage transportation can be highly beneficiated by the introduction of this new concept, reducing the costs and increasing the efficiency in transportation. Besides, the promotion of public road transportation is the other main expected affection to the transport sector after eRoad’s implementation. According to this, most of the projects and stakeholders involved in the electrification process are focused in heavy vehicles such as trucks or buses, since the establishment of long-regular distance routes between important locations to favour the flow of goods and people, is currently the more accepted alternative.

In this study the convergence of the effects and consequences related with the integration of sustainable and structurally stable eRoad infrastructure based on IPT systems is analysed. As an outline of the state-of-the-art in this field, this work will provide a basis to stand out the considerations over the process of electrifying road infrastructure and the aspects where further focus is required.

Motivation

There are several reasons to develop a study such as the one in this thesis. Giving the relevance of road transportation as a basic activity from a social-economic point of view, the development of the infrastructure that enables this mobility within an environmentally
friendly approach should be of great importance. Moreover, the opportunity of approaching such an innovative topic as the electrification of the road infrastructure has been an incentive for the conduction of this thesis as a pioneering study.

Most of the studies regarding this topic have been mainly focused in the development of the EVs but not in the infrastructure for them. In addition, since the development of pavement engineering, a large number of researchers have analysed the mechanical behaviour of conventional pavement structures but in this case, the introduction of IPT systems supposed a challenge due to the several uncertainties regarding pavement composition, geometry and disposition of the technologies, besides the non-existence of methods were these IPT systems could be embedded directly into the structure.

On the other hand, this thesis has given the chance to present a global outline of the effects and considerations of implementing this infrastructure. The life cycle concept is becoming popular and seems the best way to assess the future eRoad. This perspective enables the possibility of analysing the economic and environmental aspects for the integration of the infrastructure over its whole lifetime and thus, the connection with the mechanical behaviour of the eRoad pavement that will be required for the performance of the road during its life cycle. Hence, having an overview of the process will ease the achievement of a feasible and sustainable introduction of the IPT systems into the road infrastructure.

1.2. Aim and objectives. Boundaries of the study

The research question behind this study is the pursuit of potential effects and consequences of introducing IPT systems in pavements for the sustainability of the road infrastructure system.

According to this, the aim of developing this study is to gather the requirements needed to integrate the eRoads in the current infrastructure, by emphasizing its feasibility and sustainability over the whole implementation process. In order to accomplish it, this objective can be divided into the following sub-objectives:

- Introduce the concept of eRoad and IPT systems
- Analyse the requirements to integrate IPT systems in a flexible pavement under Swedish conditions.
- Build a FE model to compare the mechanical behaviour between an eRoad and a conventional pavement.
- Summarize the considerations and effects of such implementation over the life cycle stages of the infrastructure
- Develop a standard life cycle framework for eRoads

Boundaries

An overview of the main boundaries assumed for this work is presented in this section. Nevertheless, some of them are exposed more explicitly during the course of this study in the corresponding parts. The overall boundaries of the study are as follows:

- The only Wireless Power Transfer (WPT) solution considered for analysis is the Inductive Power Transfer (IPT).
The study focuses on the lane of the road, excluding the description or evaluation of the wayside.

Finite Element Analysis (FEA) is only subjected to static traffic loading being the climate effects not considered. The model assumes linear-elastic behaviour for the pavement.

Material Properties only based on Swedish regulations, specifically for the Stockholm region.

Life Cycle perspective evaluated from a descriptive approach.

1.3. Methodology. Report outline

This thesis will be divided in 3 main sections:

a) Literature Review: the first step for starting this study was reading up some literature related with eRoads and its integration in the infrastructure. Several meetings with the supervisors and other experts of the field were also conducted to determine the scope and establish the boundaries of the work. Bringing together these contributions, an overview of the purpose of the study could be created. Once the purpose was established, the next step was to meet the necessities and considerations for implementing eRoads that would lead to a model and the way that this model should be configured.

b) Modelling (Figure 1): based on the previous step, the next procedure was to develop a modelling work were the integration of IPT systems in the pavement could be achievable. The Finite Elements Analysis (FEA) is a method appeared from progressive contributions in discretization of continuum problems from engineers and mathematicians and is able to provide the tools required for simulate the embedment of IPT systems in the pavement cross section. Thus, the FE software ABAQUS 6.11 was used with this aim. However, in order to verify the reliability of the model built with ABAQUS, another software (specific for pavement design) was used. This computer program is based on layered elastic models and it is called KENLAYER. The outputs obtained from this analysis were the response of the pavement by introducing IPT systems into the cross section. With this information, several conclusions could be obtained to determinate further consequences and effects of this implementation that should be considered in the next steps of the cycle.
b) Modelling: Mechanistic Pavement Design

Design Factors & 
Response Model
- Linear Elastic Behaviour and Loading Conditions
- Structure Geometry and Material Properties
- eRoad Features

Model Assemble
- Model Validation: KENLAYER
- Model Calibration and Application to eRoad: ABAQUS

Pavement 
Response
- Stresses (σ)
- Strains (ε)

Figure 1 Development scheme of for the pavement modelling

c) Life Cycle Approach: this section is deeply related with the previous, flowing the information in both directions. In other terms, this section establishes several considerations for the configuration of the pavement structure that must be taken into account for the modelling. On the other hand, at the same time the results displayed from the modelling design allowed the establishment of certain conclusions over the other phases of the implementation process (construction and maintenance). Having this in mind, a further discussion about the effects and consequences is conducted through a life cycle approach methodology. The creation of an eRoad’s framework over its life cycle stages it is of great importance to assess the environmental and economic requirements that will lead to a sustainable implementation of electrified roads.

<table>
<thead>
<tr>
<th>a) Literature Review</th>
<th>b) Modelling</th>
<th>c) Life Cycle Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective: get knowledge about the topic</td>
<td>Objective: analyse the pavement’s structural behaviour</td>
<td>Objective: summarize the considerations for future eRoad LC performance</td>
</tr>
<tr>
<td>Tools: books, academic articles, reports, web</td>
<td>Tools: ABAQUS 6.11, KENLAYER</td>
<td>Tools: current LC tools</td>
</tr>
</tbody>
</table>

Writing Report

Figure 2 Scheme over the methodology followed during the development of the study
Report outline

Chapter 2: Literature review → Literature related to the aim of the thesis:
- **General Literature:** Introduction to the concept of Smart Roads focusing on eRoads.
- **Inductive Power Transfer (IPT) systems:** wireless solutions. Operation of the technologies and acquiring knowledge related to Power Transfer Efficiency (PTE).
- **Pavement Structural Design:** types of pavement and distress modes. Methodology for the design.
- **Life Cycle Analysis methodology:** concept and requirements for framework development.

Chapter 3: FE Modelling
- **Conventional Pavement Modelling:** input data collection for the configuration of a pavement structure model based on Swedish conditions. Verification of such model by comparing results from both computer programs on the conventional pavement configured.
- **eRoad Pavement Modelling:** adaptation of the previous model for its application to eRoad infrastructure.
- **Analysis of the results:** analysis of the structure’s response in vertical and transversal direction. Sensitivity analysis of thickness-stiffness on the overlay. Improvement of the model by using an expansive joint.

Chapter 4: Life Cycle Approach
- **Considerations and effects:** summary of contributions that need to meet the procedures for implementing IPT systems in road infrastructure over the project stages (design & construction, maintenance).
- **Life Cycle Perspective:** creation of a Life Cycle framework based on the available tools (LCA and LCCA) for approaching the introduction of eRoads.

Chapter 5: Conclusions and Future Work
Summary of the results observed and statements concluded. Perspectives for further investigations related with FEA and Life Cycle Analysis tools.
2. Literature review

This chapter summarizes the notions for comprehending the development of electrified roads (eRoads) based on Inductive Power Transfer (IPT) systems and its integration on the existing infrastructure. Firstly, an overview of Smart Roads is exposed to focus later on the Dynamic Electrified Road Systems (DERs), especially IPT systems, as an emerging alternative for future mobility. Secondly, there is a review of the types of pavements and their failure mechanisms. Finally, to understand the effects and consequences of implementing eRoad infrastructure in a feasible and sustainable way during the whole process, an explanation of the structural pavement design and Life Cycle methodologies used during this study is displayed.

2.1. Smart Roads

Since the beginning of modern road infrastructure, two main objectives have been the centre of attention of researchers and specialists in the subject; - the aim of achieving the most flow mobility and, - the pursuit of the most economic infrastructure that enabled an appropriate performance. Nevertheless, recently other approaches are gaining interest for experts and society. For instance, energy efficiency, environment, security, traveling conditions or user comfort are some of the issues concerning the current studies. Unifying all these ideas appears the concept of Smart Roads.

The name of Smart Road is given to define the convergence of different innovative technologies that enable an intelligent and sustainable interaction between users, vehicles, the infrastructure and its surroundings. In essence, the aim of this kind of project is to improve the mobility by road as a whole, using means provided by current technologies. As stated by Studio Roosegaarde: “sustainability, safety and perception are the key to this concept” (Hejmans and Roosegaarde Studio, 2015). In order to achieve that purpose, some of the aspects that are being object of further research are (Chen et al., 2015 a):

- Road perception and management: with the aim of emphasizing the pavement markings and lighting in order to improve the perception of the roadway and the correct operation. Different technologies can be used to achieve this. For instance, the idea of smart highway in the Netherlands (Hejmans and Roosegaarde Studio, 2015)
has developed an intelligent light system controlled by sensors which turns on just when the vehicles are approaching, increasing thus the safety of the path and saving unnecessary energy consuming. Besides, a dynamic lines system which can be adjusted to show a continuous or dotted line in order to distribute the capacity of the lanes.

- **Interactive communication**: combination of sensing, computation and communication technologies to establish an efficient interaction between user, vehicle and infrastructure. Features such as those used in Virginia (Virginia Tech Transportation Institute, 2014) in-pavement sensors (for temperature, moisture or pavement physical condition), dynamic marking lights which intensity varies with the temperature to warn road users, or sensor networks to collect data on the move and therefore improve traffic congestion, pavement performance and safety conditions.

- **Automated driving**: vehicles prepared to drive without human control, by having installed sensing technologies that allow them to sense the environment and the interaction along the road. Different initiatives have been initiated in many European countries like Spain, France, Germany, The Netherlands, United Kingdom or Sweden which project is known as “Drive Me- Self Driving cars for sustainable mobility” (EPoSS, 2015).

- **Energy harvesting**: consisting in energy collecting devices in the road pavement (embedded, on the surface or situated in the waysides) to use it later as a resource to execute different functions such as lighting up roadway marks in the dark, frost protection and melting snow and feed other smart components.

- **In-motion vehicle charging (eRoads)**: new infrastructure devices to stimulate sustainable transportation by establishing an electric power transfer between road and vehicle in order to reduce the fossil fuel dependency and look forward to breaking out with the shortcomings offered by the rechargeable batteries. Known as DERS, some potential solutions are the focus of transportation scientists and practitioners studies.

The attainment of *Smart Roads* is a great challenge for road infrastructure and transportation due to the complexity of its integration. Within this convergence of different technologies, the electrification of roads seems to be one of the distinguished systems liable to development due to the economic, environmental and social impacts involved in energy usage for road transportation. This thesis will get in depth in the development of DERS, in particular, in the implementation of IPT systems as potential and feasible alternative for modern road infrastructure in mid-long term.

### 2.2. Dynamic Electrified Road Systems (DERs)

Having in mind the previous section, within all the potential developments involved in the creation of the future Smart Roads, one of the most emerging characteristics is the creation of a road transport network based on the electrification of the system that would promote the use of electric vehicles (EVs) by charging them while driving along the road infrastructure. This concept is known as Dynamic Electric Road System (DERs), since differs from the current static solutions for EVs where the vehicle must be charged before its use, and the infrastructure that enables this power transmission is called eRoad.
Many alternatives are under active investigation with the purpose of creating these DERSs. These systems can be elaborated based mainly on two concepts: the conductive and the wireless power transfer solutions (Chen et al., 2015a). Even though currently most of the projects developed until today are mostly based on stationary charging solutions for EVs, these solutions do not imply the electrification of the infrastructure and then are not within the scope of the eRoad concept.

For the configuration of these DERSs, either considering one concept or the other, there are three basic components that must be present (Andersson & Edfeldt, 2013):

- An EV with the devices and the technology required to turn the external electricity supply into mechanical energy for driving.
- The electrified infrastructure to allow an uninterrupted power transfer (the eRoad).
- The equipment to achieve the power transfer from the eRoad to the vehicle and to stop this transmission if necessary.

### 2.2.1. **Conductive Power Transfer (CPT) solutions**

**a) Overhead lines**

This solution is similar to the traditional contact line systems that are present in the rail transportation nowadays (trains, trams and trolleybuses for instance). Besides, this solution is adequate for heavy vehicles such as trucks or buses and not for regular vehicles due to the difficulties to connect the vehicle with the hanging catenary. The power transfer is done through a pantograph located in the top of the vehicle, which can be removed from the wire if necessary to ease overtaking other vehicles or change the direction (Viktoria Swedish ICT, 2013).

Currently, Siemens is developing a project called eHighway based in this system for its implementation in road freight traffic (SIEMENS, 2015) that could be an alternative as a CPT solution.

**b) Rail embedded into the road**

In this case, the energy is transferred to the vehicles from a continuous rail embedded in the pavement through a pickup system installed in the vehicles that enables the electricity collection. There is an initiative in Sweden that is currently being developed known as the Elways project with the aim of introducing this system as a feasible DERS solution (Andersson & Edfeldt, 2013) and (ELWAYS, 2015). However, some issues concerning human safety and driving under bad weather conditions have questioned the viability of these solutions.

### 2.2.2. **Wireless Power Transfer (WPT) solutions**

It seems quite clear that the final alternative for DERS is going to imply the use of a WPT in one way or another, since these solutions have the benefits of the CPT solutions but at the same time are able to solve the problems presented before by being safer, giving an inherent electrical isolation and reducing aspects such as the weight and the volume of the vehicles (F. Musavi, 2012).
Nikola Tesla, also known as “the father of wireless”, defined the concept of Wireless power transmission as “the transmission of electrical energy from one point to another through the vacuum of space without wires” (Mohammed, Ramasamy, & Shanmuganantham, 2010). In (F. Musavi, 2012) a survey of the different WPT technologies was conducted in order to review the available alternatives and their potential application to eRoads:

- **Capacitive Power Transfer (CPT):** the advantage present in this solution is its cost and the reduced size of the system. Nevertheless, for high power requirements is not an appropriate alternative.

- **Permanent Magnet Coupling Transfer (PMPT):** this system combines elements of magnetic gears and electric machines. Even though the fact that a prototype was created at the University of British Columbia with a good power efficiency, the mechanical components presented problems such as noise, vibration and lifetime.

- **Resonant Inductive Power Transfer (RIPT):** initially promoted by Nikola Tesla, with the new electronic devices has become into an approved WPT technology proving efficiency at distances up to 40 cm.

- **On-line Power Transfer (OLPT):** similar to RIP, presents a short range of EVs and an important cost of infrastructure but due to the good charging the vehicles could be constructed with a small battery achieving then a reduction in the weight and the cost of the vehicle.

- **Resonant Antennae Power Transfer (RAPT):** also promoted by Nikola Tesla and currently updated by MIT and Intel, these systems have shown an efficient power transfer for distances until 10 m. However, the basic limits on human exposure to radio frequency radiation are much higher than the allowed.

- **Inductive Power Transfer (IPT):** this technology seems to be the most suitable solution for its application in the DERS due to the advantages over the other options by being more powerful, more tolerant to misalignment, safer and more efficient (Covic & Boys, 2013). Chen et al. (2015 a) explained the functioning of IPT systems for DERS as the system composed by two ensemble technologies: i) the on-board, which is included at the EV; and ii) the off-board, which is embedded into the road pavement. The off-board technology is made up by rectifier substations connected to the electric grid at regular intervals, where a DC voltage is distributed to a converter. This converter will generate high frequencies AC in order to energise a transmitter coupled with the pick-up device installed in the EV. Then, a magnetic coupling flux between the transmitter and the pick-up on-board technology will occur. This pick-up system which can only receive high frequency AC, will change it into DC in order to charge the battery installed on the vehicle.

### 2.2.2.1. Wireless Power Transfer Efficiency (WPTE)

Together with the mechanical integrity of the pavement structure, the WPTE is the key issue where further investigation is needed in order to achieve a feasible implementation of eRoads based on WPT solutions such as IPT systems. The achievement of a powerful and efficient energy transmission between vehicle and infrastructure is mandatory for the establishment of these systems.
Even though this matter concerns other disciplines such as, for instance, the electromagnetic engineering and thus, is beyond the aim of this thesis, it is necessary to introduce an overview of some of the concepts related and the studies already developed regarding this issue.

Wireless power transfer has been tested in free space in many studies. However, the interaction of magnetic fields through materials (road materials for eRoad’s application) is a recent challenge for approaching certain applications of this technology. Chen & Kringos (2014) stand out the importance of the electromagnetic loss (dissipation of electromagnetic energy) that might affect the PTE between vehicle and transmitter due to the presence of the pavement while the magnetic field pass through. This electromagnetic loss is related to the dielectric properties of the materials because is the media through which the waves of the electromagnetic field are propagated. Likewise, these dielectric properties can be characterized by the relative permittivity ($\varepsilon_r$) of the material, where materials with small $\varepsilon_r$ favour the magnetic flux. Moreover, the dielectric loss of the materials is normally parameterized in terms of loss tangent ($\tan \delta$) of the magnetic field or also called Dissipation factor $D$, as for instance in the test performed by Chen et al. (2015 b) to study the dielectric response of bitumen doing dielectric spectroscopy measurements.

Some studies have conducted experimental applications regarding this issue. For instance, in Austin, the University of Texas tested the PTE between a transmit (T) and a receive (R) antennas, being the first one enclosed by a material shell. The results showed a degradation in the PTE comparing to the situation in free space due to the high relative permittivity ($\varepsilon_r$) and dielectric loss of the material (Yoon & Ling, 2012).

Finally, the disposition of the devices is also important for establish an adequate PTE. A project developed by the Stanford University in collaboration with the centre for automotive research (Yu et al., 2011) measured the PTE to a receiver situated next to a metallic ground plane. By testing different structure combinations and analysing the PTE some conclusions were displayed: i) As the distance between the source and the receiver increases, the decrease in the PTE is highly significant. ii) Keeping the symmetry between the source and the receiver shown advantageous results in terms of efficiency. . iii) The orientations of the IPT facilities are also important; in a previous study (Yu et al., 2011) was proven that the capacitor and coils orientation had a significant effect over the PTE, especially the coils.

2.3. Pavement engineering

Pavement is an essential element in any road construction. Two fundamental functions are provided by the pavement; firstly it is used as a reference for the driver to delineate the roadway by giving a visual perspective of the horizontal and vertical alignment of the travelled path. Secondly, and directly related with the focus of this thesis, is the responsible of receive the traffic loads and transmit them through the structure ensuring a mechanical integrity (Mannering et al., 2000). Besides, with the higher cost related to construction and maintenance for highways settlement, pavement design is directly related to the implementation of a new road project.

The road pavement consists of superimposed layers creating a structure from the composition of certain selected and processed materials placed on the basement soil or subgrade (C.A.O’Flaherty, 2002). The structural function of the pavement is to support the wheel loads applied to the carriageway and distribute them to the underlying subgrade, and thus an
adequate design must consider the effect of these actions to assure the performance of the infrastructure.

2.3.1. Types of pavements

Flexible pavements

A flexible pavement is constructed with asphaltic cement or also called “hot mix asphalt” (HMA) and aggregates forming unbound and/or bituminous-bound granular layered systems (Mannerling et al., 2000). This procedure of locating a layer of HMA at the top has been lately the most common in developed countries, including Sweden, and thus will be included in the analysis developed in this study.

As shown in Figure 3, the cross section of a conventional flexible pavement is formed by the following layers (H.Huang, 2004):

![Figure 3 Typical cross section of a conventional flexible pavement (H.Huang, 2004)](image)

- **Surface course:** also called wearing course, is the uppermost layer of an asphalt pavement. It is usually made of dense graded HMA. Being the layer in direct contact with the traffic and the environment, its primary function is to provide a safe, smooth and stable riding surface for the vehicles. Moreover, is also essential its contribution to protect the pavement from natural elements, waterproof for instance, which will provide structural stability. In case of not accomplishing the above requirements, the use of a seal coat is recommended. The Seal coat is a thin asphalt surface treatment utilized to provide skid resistance and waterproof.

- **Binder course:** sometimes also called asphalt base course. Due to the thickness of the HMA, normally it cannot be compacted in one layer, reason for using a binder course in addition to the surface course. This structural platform ensures the good riding quality of the wearing course and helps to distribute the applied traffic loads. Usually is prepared with larger aggregates and less asphalt providing an inferior quality than the surface with the purpose of achieving a more economical design. If the binder course is more than 76 mm, it is generally placed in two layers.

- **Base course:** is the main structural layer which provides the composite system with the platform for the surfacing. Generally, is made of crushed aggregates which are
either unstabilized or stabilized with a cementing material. The main function of the roadbase is to distribute the loads transmitted by the traffic and consequently prevent the mechanical surplus of underneath layers. (Marnering et al., 2000)

- **Subbase course**: is very often to present a separate layer from the base course, made likewise of granular materials but of lesser quality. Economic reasons justify this fact, although it must be able to resist the stresses transmitted via the base course, the same resistance is not required.

- **Subgrade**: is the lower layer, the soil itself, but normally the top (around 150 mm) should be scarified and compacted to provide a uniform material with good density and therefore prevent the upward infiltration of fine-grained subgrade soil into the subbase layer. A layer of selected material can be used or the in-situ soil as well.

**Rigid pavements**

Rigid pavements are characterized by laying the pavement directly over a prepared subgrade or on a single layer of granular or stabilized material. This pavement is normally composed of a cement concrete slab, receiving the name of rigid pavement due to the much stiffer behaviour of the concrete than the iMA, that makes the distribution of the load influencing over a wider area (H.Huang, 2004).

![Typical cross section of a rigid pavement](Figure 4)

*Figure 4 Typical cross section of a rigid pavement (Texas Department of Transportation TxDot, 2011)*

In Figure 4, an overview of a rigid pavement cross section can be observed. However, a base course and/or a subbase course may or may not be used depending on the specific circumstances of the road, designer preferences and construction procedures. The first pavements of this type were built without using a base course but some problems appeared in early stages due to the lack of this layer such as pumping, frost action and drainage. By getting more experience in these constructions, the use of a granular base or subbase course became a regular practice since contributed with a more uniform, stable and permanent support for the slab and improvements in the previous shortcomings were observed (C.A.G‘Flaherty, 2002).

Taking in consideration the different interpretations and practices related to rigid pavement types developed in every country, in general terms, concrete slabs in this pavements are either
jointed unreinforced or reinforced. Having this in mind and, considering the disposition of longitudinal and transverse joints, mainly four types of concrete pavements are presented in (H.Huang, 2004): jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), continuous reinforced concrete pavement (CRCP), and pretressed concrete pavement (PCP).

**Composite pavements**

A composite pavement is the result of the combination between a flexible and a rigid pavement structure. This is the use of a rigid concrete or cement slab as a bottom layer to provide a solid base, and HMA as a top layer procureing a smooth and comfortable surface for the pavement composition.

![Figure 5 Example of cross section of a composite pavement (Flintsch et al., 2008)](image)

Figure 5 shows an example of a composite pavement structure with a Portland cement concrete (PCC) slab as a rigid slab. Although more compositions could be considered for the rigid layer, such as cement treated or stabilized base, a lean mix concrete or a rolled-compacted concrete, this type of pavement has shown better characteristics than traditional pavements. In Flintsch et al. (2008) some of the benefits provided by these pavements were displayed: i) better levels of structural and functional performance; ii) solid base and support provided for the rigid layer; iii) improvements provided by the use of a flexible layer as a surface: smooth and rideable surface with adequate friction features, the fact that the surface overlay can be periodically replaced, protection and insulation of the rigid layer from climate effects thanks to the use of the flexible overlay. Even though these type of pavements have become more common and popular, the economic increase makes the implementation of it for mostly rehabilitations of concrete pavements and not as a new construction (H.Huang, 2004).

### 2.3.2. Failure mechanisms: Pavement distress modes

Due to the combination of traffic loads and environmental conditions, distresses are developed in the pavement giving place to the beginning of a deterioration process. The failure/fracture of the pavements does not occur immediately after the service entering because of the strength of the materials, but an infinitesimal amount of deterioration is gradually increasing and accumulating until a failure condition is reached. Thus, a distress is an important consideration in pavement design. Nevertheless, frequently the distresses are occasioned through deficiencies in construction, materials, and maintenance and not merely by an inadequate design. (H.Huang, 2004)
Considering the eRoad nature as a non-pure flexible pavement because of the introduction of a charging-unit in the asphalt layers, the most representative distresses in flexible and composite pavements might be exposed and classified as follows (Sharad & Gupta, 2009):

- Cracking
- Surface deformation
- Disintegration
- Surface defects

a) **Cracking:** continuous traffic loads producing an accumulation of fatigue damage lead to string of interconnected polygonal pattern in different forms:

**Alligator or Fatigue Cracking:** in thin pavements the initiation of the cracking occurs at the bottom of the asphalt layer, where the tensile stress or strain is higher, to be propagated afterwards to the surface shaped like longitudinal parallel cracks. However, in thick structures, normally the cracking is started on upper regions. After constant traffic loading, the cracks connect forming a representative pattern similar to the skin of an alligator.

**Longitudinal Cracking:** cracks parallel to the road center line mainly produced due to low temperatures or resulted from reflective cracks from underneath the asphalt surface.

**Transverse Cracking:** cracks orthogonal to the center line of the pavement, with similar causes as longitudinal cracks, being mainly thermal fluctuations in aged pavements.

**Block Cracking:** cracks dividing the surface into rectangular blocks with an approximate size of 0.1 and 9 m² produced by temperature cycling and the shrinkage of asphalt.

![Figure 6 Main cracking mechanisms in pavements (Svensson, 2013)](image)

**Reflective Cracking:** cracks produced on asphalt surface overlay that covers a jointed concrete slab. Therefore, is produced principally by the movement of concrete slab under the asphalt layer as a consequence of thermal and moisture changes.

![Figure 7 Reflective Cracking (Strategic Highway Research Program, National Research Council, 1993)](image)
b) **Surface deformation:** induced by the fact that volume ratios are different in each asphalt mixture, as a consequence of not having equal viscoelastic properties in permanent deformation. (Svensson, 2013)

*Rutting:* consists on surface depressions in the wheel paths, creating a lift up adjacent to the sides of the rut. This phenomenon is normally caused by the permanent deformation on the pavement layers or subgrade, due to the consolidation process or lateral movements of the materials induced by traffic loading. When this deformation occurs in the pavement, usually the wheel paths remain filled with water after a rainfall.

*Depressions:* small bowl-shaped regions on the surface that might involve cracking. Commonly produced by deficiencies in construction, materials, or maintenance. Similarly to rutting, depressions cause roughness and after or even during a rainfall, could cause hydroplaning of vehicles as a consequence of containing water.

*Corrugation and Shoving:* consist on a plastic movement typified by ripples (corrugation) or an abrupt wave (shoving) across the pavement surface. The deformation is orthogonal to the vehicle’s way and it is a typical phenomenon in areas where the vehicles start and stop with frequency or where the asphalt adjoins a rigid object.

![Figure 8 Main Surface Deformations in pavements (Svensson, 2013)](image)

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c) **Disintegrations:** it is a gradual deterioration of the pavement into small loose pieces because of traffic loading, temperature changes, material behaviour or poor construction practices. Specially in countries with hard winter conditions, as Sweden for instance, the high variations of temperature induces stress intensity concentrations given place to this phenomenon. The most common types of disintegrations are known as potholes and patches.
d) **Surface defects**: basically caused by asphalt concrete surface fatigue. The most two common types of these distresses are:

Raveling: caused by an inefficient adhesion of the aggregate and the asphalt cement, producing an absence of material in the surface.

Bleeding: produced by high asphalt content or low air void content that creates a film of bituminous material on the surface with lower skid-resistance which could be potentially slippery.

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### 2.4. Structural pavement design methodology

#### 2.4.1. Mechanistic design methods

Mechanistic structural pavement design methods are based on the mechanics of materials that relates inputs, such as the wheel load, the geometry or the BCs, to an output or pavement response, such as displacements, stress or strain (H.Huang, 2004). To obtain a realistic and accurate response of the pavement the construction of an appropriate model is essential.

In order to develop an adequate mechanistic design method, some steps must be followed: i) state the input parameters such as traffic and environmental conditioning and material
properties for instance; ii) Assume a certain structure, establishing the geometry, thickness and type of material of each layer; iii) Conduct a pavement analysis based on the critical response, which currently is done by using specific software; iv) Compare critical responses with the standard boundaries of performance models such as fatigue or permanent deformation; v) In case of not satisfying the requirements, the conditions should be adjusted in order to conduct a new analysis; vi) evaluate the economic feasibility of the results (Nilsson, 1999).

Within this context, an analytical design model normally is composed by two parts: a) the design of the mix and b) the pavement structural design which includes the response and the prediction performance models. The first part is not heeded in this study since is usually considered separately.

2.4.1.1. Layer elastic models

Following the previous introduction to analytical methods and being the layer elastic models within this approach, the aim of these techniques is to obtain the responses of a pavement structure subjected to a load. As stated before, these models are based, firstly, on the Boussinesq (1885) studies and later on the contributions of Burminster (1942), and thus some assumptions are considered for its development (H. Huang, 2004):

- The materials composing each layer are considered homogeneous, isotropic and linearly elastic.
- The material is weightless and infinite in areal extent.
- The thickness of each layer is previously defined except for the subgrade which is infinite in thickness.
- The layer interfaces are ruled by continuity conditions, this is, they are frictionless and the responses are the same at the immediate points mass from this interface.

The inputs required for the characterization of the composite layered system are the elastic modulus and the Poisson ratio regarding the materials properties of each layer, the thickness of every layer and the description of the load (magnitude, area of contact with the surface, wheel axle configuration and number of applications).

On the other hand, the outputs obtained by running the pavement configuration established previously, are the response of the pavement, this is, the displacements, the stresses and strains in critical locations. Usually the critical locations in the pavement cross section for design are: the bottom of the asphalt layer, the top of the subgrade and is common as well to analyse the displacement in the road surface (Kooehmishi, 2013).

Some of the computer programs created with the purpose of such an analysis that are available in the market are: KENLAYER (software used for develop this study), DEPAV, BISAR, ELSYM5 or ALIZE (Rondón & Reyes, 2007).

2.4.1.2. Finite Elements Methods (FEM)

Even though the fact that the layered systems models have been further developed over time, new improved methodologies have emerged for conducting more accurate analytical pavement designs.
The finite elements methodology is based on the use of constitutive equations for the calculation of strains and stresses assuming that the material is continuous. In this technique, the individual components of the material are homogenized in a global macroscopic behaviour.

The application of this method to pavements brought some benefits for the analysis since allowed the introduction of non-linearity for the granular materials and visco-elastic behaviour for the asphalt layers, which indeed, is a great step towards simulating the real state of the pavement. Moreover, regarding the inputs for the analysis: the geometry can be further specified regarding dimensions and mesh construction, as well as the boundary conditions, the material properties and the possibility of simulate a cyclic or dynamic load (Rondón & Reyes, 2007). Thus, this data is much specific than for layered systems, giving the option of implementing a wide range of constitutive behaviours and offering as a consequence, the option of obtaining accurate outputs regarding not just the pavement response but also damage and failure criterions.

There are currently some general computer programs where any analysis can be conducted such as ABAQUS (the one used for the analysis in this study), ANSYS or PLAXYS. However, some other finite element programs have been developed specifically for pavement analysis such as ILLI-PAVE, MICHPAVE, FENLAP or DIANA (H.Huang, 2004).

2.4.1.3. Response model: Constitutive behaviour

The determination of the pavement response by creating a structural model requires a correspondence between the mechanical attributes of the pavement materials inputted and the theoretic constitutive behaviour used to the representation of this response.

Many pavement design methods have been developed during the consolidation of pavement engineering with the aim of obtaining the most veracious approach. Nevertheless, due to the wide different factors that can affect the response, pavement structure analysis has become a truly complex discipline.

Different components have to be considered in order to perform a pavement analysis. For instance, besides elastic deformations, road materials can behave with a viscous, viscoelastic and plastic response and with a non-linear function of the stress condition. In addition, these materials are usually anisotropic, particulate and no homogeneous (Nilsson, 1999). By the same token, the interaction between tire and pavement, the affection of the traffic loads, the time dependence, and the affections produced by environmental fluctuations can be interpreted in many different manners. Hence, the integration of all these constituents in the same model is difficult to achieve and hereby, simplifications in pavement modelling are an unavoidably reality.

According to the purpose of this thesis, the aim of analysing the structural response of the pavement is to exhibit the different behaviour between a conventional pavement and the one adapted for eRoads. Due to the relatively recent development of IPT solutions in pavement structures, studies and projects within this field are mostly elaborated on a feasibility analysis level and thus neither previous experience nor specific design tools have been elaborated. Given this, the development of the structural response of the pavement in this work will follow the theory of linear-elasticity.
Linear-elasticity is a simple way to characterize the behaviour of a flexible pavement under traffic loads, but also a useful procedure which has been often utilized as a tool design. One of the first researchers in introducing such theory was Boussinesq (1885), enabling the determination of the stresses, strains, and deflections for single-layer isotropic pavement. However, flexible pavement cannot be represented by a homogeneous mass because is constituted by different layers and materials. In 1942, Burmister proposed a solution for double-layer structures considering homogeneity in the layers, and then improve it in 1945 to a triple-layer system. After the development of technology, the use of computers allowed the application to a multi-layered system with any number of layers and following a linear-elastic behaviour, which in fact is the procedure that has been used for this study (H.Huang, 2004).

Since the decade of the 60s the computational improvement enabled the accurate determination of responses (displacements, stresses and strains) by introducing the inputs that configure the pavement composition (loading, material properties, layer thickness, etc.), that have driven to good quality approaches (Rondón & Reyes, 2007). For the case of flexible pavements, two of the most used approaches are the layer elastic models and the finite elements methods, which both have been used for conducting this study and where an overview is presented in the following section.

2.5. **Life Cycle Analysis methodology**

Approaching infrastructure projects from a life cycle perspective is becoming a common procedure in order to obtain a feasible implementation and an improved performance during the different stages composing the life span of these constructions. Moreover, the aim of creating sustainable and economic high quality road infrastructures that assure the empowerment of mobility and society requires the use of tools able to complement the design and construction of the same (Azhar Butt, 2014). The Life Cycle of a product can be analysed from both an economic and environmental perspective with the use of the two following techniques: Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) respectively.

According to the Federal Highway Administration, “Life Cycle Cost Analysis (LCCA) is a technique based on economic analysis to evaluate the long-term economic efficiency between competing alternative investment options” (FHWA, 1998). This tool is becoming crucial for providing cost estimation over the lifetime of a road and creating a framework for identify and evaluate key factors that will guide designers, road administrators and contractors during the development of a project. For instance, in Sweden the transport administration has demanded the elaboration of LCCA for all the investments related with road projects since 2012 (Mirzadeh et al., 2013).

On the other hand, Baumann & Tillman (2004) defined Life Cycle Assessment (LCA) as a technique to evaluate the environmental behaviour of a product, a service or an activity through characterizing and quantifying the flows of the system during its life cycle. While there is a standardized LCCA framework for pavement development, the LCA tool has not been standardized for road infrastructure analysis yet (Santero et al., 2011). Nevertheless, from the end of 1990s the International Organization for Standardization (ISO) began with the development of a general framework, goal, scope and inventory assessment for a general approach (Azhar Butt, 2014) and with the increased interest in this field due to its proved
value, the performance of such methodology is suggested for the coming road infrastructure projects such as the eRoad implementation.
3. Finite Element modelling: eRoad
Case study for the Stockholm region

In this chapter a FEA is conducted to evaluate the structural integrity of an eRoad. First, the FE model is developed for a conventional pavement featured according to a typical road in the region of Stockholm. Once this model is built and verified through the use of a complementary software, an application for the eRoad will be developed by embedding a charging unit module into the pavement that will allow the evaluation of its behaviour. In addition, a sensitivity analysis of the mesh is conducted to improve the accuracy of the results. The responses obtained for both analyses are displayed in the vertical and transversal direction of the cross section.

3.1. FE modelling of conventional pavement

During the structural design of the pavement, the inputs of the model have been modified and adjusted with the aim of achieving a coherent configuration. Over the years, mechanistic methods have been used to characterize the pavement structure based on the response’s analysis of a particular road construction subjected to a load. Nevertheless, these methods can provide different response predictions attending to their specific approaches: i) accuracy in the constitutive behaviour of the materials; ii) input data characterization; iii) domain regions and boundary conditions imposed; iv) interaction between layers; v) loading conditions (Calderón & Munoz, 2005). The preciseness on the combination of these elements will display the level of reliability of the model response and its analogy to a real situation.

3.1.1. Linear-Elastic behaviour

Due to the complexity of the pavement structure and its response in the road, different approaches can be applied for the characterization of this ensemble. Particularly, the linear-elastic approach has been used for characterize the response of a flexible pavement under wheel loads. Thus, this model is built based on the following features:

- All the materials properties are assumed to be time-independent and have a linear-elastic behaviour.
- The pavement layers composing the cross section have a homogeneous and isotropic mass.
- Load is considered stationary and uniformly distributed over the contact area between pavement surface and tire.

An elastic behaviour of the materials is representative of a loading during low temperature and short time scale, which will experience a fully recover upon unloading. For the characterization of this constitutive behaviour, and thus for the model developed in this study, each layer of the pavement structure is described by its Elastic Modulus (E) and its Poisson’s ratio (ν). The aim of this analysis is not to predict the long-term behaviour of the eRoad and thus, elastic material properties are enough accurate in this work. Other characteristics related to advanced materials properties (e.g. viscoelastic, plastic or non-linear) and loading (e.g. cyclic or dynamic), are beyond the scope of this research.

3.1.2. Model verification

In order to obtain a suitable model with adequate dimensions and structural response, a multi-layer analysis using a pavement software is applied and compared with the FE model developed in ABAQUS/Standard.

The KENLAYER computer program has been used to evaluate a conventional flexible pavement. This software among others is an example of the layer elastic models explained in the previous section. Developed by Dr. Yang H. Huang, it is based on Burminster’s layered theory for the analysis of the pavement. Specifically, it is applied for an elastic multi-layer system under a single circular loaded area (H. Huang, 2004), and is used in this study to compare its theoretical solution with the response given by the FEM. The purpose is to improve the construction of the model in ABAQUS and build a domain size able to provide the most accurate response from the FEA. The following pavement characteristics are representative of Swedish conditions for pavement design, specially featuring the Stockholm region, and are considered in the study:

a) Cross section and material composition

With the goal of contributing to the feasibility of eRoads in the region of Stockholm, a typical Swedish cross section is proposed to the attainment of this work. Figure 11 shows an example of a standard cross section composition presented in the Slide-In project in 2013 for an Electric Road System (Viktoria Swedish ICT, 2013):
Therefore, with this pavement structure as basis, other considerations have been taken into account for the establishment of the materials composition. Regarding climate conditions, there are established five different climate zones in Sweden (Vägverket, 2008). According to Figure 12, the region of Stockholm is situated in the zone number two and thus, the conditions proposed for that zone are followed.

Following the guidelines established by the Swedish Transport Administration (Trafikverket), further information has been obtained related to the region of Stockholm; Table 1 summarizes the number of days given in each climate zone under different weather conditions. According
to this, the area of Stockholm is subjected to summer conditions during 153 days per year, almost duplicating the period under winter conditions (80 days per year). Besides, Table 2 shows the average temperature in the surface layer for every climate zone. The difference of 20-Celsius degrees in temperature between winter and summer conditions should be the cause of great variations on the values for material properties. However, the consideration of the temperature has not been sought for the development of this analysis and then, as established by table 1, seems reasonable to set summer conditions as a predominant situation during the year.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>49</td>
<td>80</td>
<td>121</td>
<td>151</td>
<td>166</td>
</tr>
<tr>
<td>Winter thaw</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring thaw</td>
<td>15</td>
<td>31</td>
<td>45</td>
<td>61</td>
<td>91</td>
</tr>
<tr>
<td>Late Spring</td>
<td>46</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>153</td>
<td>153</td>
<td>123</td>
<td>77</td>
<td>47</td>
</tr>
<tr>
<td>Autumn</td>
<td>92</td>
<td>76</td>
<td>76</td>
<td>76</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 1 Climate duration (number of days during the year) (Vägverket, 2008)

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>-1,9</td>
<td>-1,9</td>
<td>-3,6</td>
<td>-5,1</td>
<td>-7</td>
</tr>
<tr>
<td>Winter thaw</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring thaw</td>
<td>1</td>
<td>2,3</td>
<td>4,5</td>
<td>6,5</td>
<td>7,5</td>
</tr>
<tr>
<td>Late Spring</td>
<td>4</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>19,8</td>
<td>18,1</td>
<td>17,2</td>
<td>18,1</td>
<td>16,4</td>
</tr>
<tr>
<td>Autumn</td>
<td>6,9</td>
<td>3,8</td>
<td>3,8</td>
<td>3,8</td>
<td>3,2</td>
</tr>
</tbody>
</table>

Table 2 Temperature of road surface for the different climate zones (Vägverket, 2008)

Following the same guidelines, the material properties for the pavement structure have been obtained. These properties are implemented in the pavement management systems (PMS) database commonly used by the Swedish administration. Currently, the design is conducted using a computer program known as PMS Objekt 2000 (NordFoUProject, 2010), which is an analytical design method based on linear-elastic theory, reason for considering the data appropriate for the requirements of this study. Accordingly, values regarding the Elastic Modulus (MPa) from the following tables can be used as a reference for asphalt layers, unbound layers and subgrade materials in new road constructions for climate zone 2. In agreement with this source, all values are related to undamaged coating at the specified thicknesses in the tables. The use of the asphalt concrete AB over and asphalt-bound base layer AG is normally used in Sweden for high traffic levels, which, indeed, agrees on eRoads’ idea of high capacity route connections. Thus AB 160/220 bitumen-bound was used in the surface course and AG 160/220 in the base course (Vägverket, 2008).
For the asphalt layer in climate zone 2 under summer conditions the values for the E Modulus are:

- For thickness < 50 mm: 4000 MPa
- Thickness 50-100 mm: 3000 MPa
- Thickness ≥ 100 mm: 2500 MPa

For unbound layers in new constructions the values are:

- For unbound base materials: 450 MPa
- For subbase crushed materials: 240 MPa
- For subbase uncrushed materials: 450 MPa

For the subgrade, the reference value used for the E Modulus is 100 MPa.

Regarding the Poisson’s ratio, as stated in chapter 3 on (Vägverket, 2008), a value of 0.35 is assumed for every layer. This parameter is normally a required input for analytic methods in structural pavement design, especially in a linear-elastic analysis. Indeed, common figures of Poisson’s ratio for materials constituting flexible pavements normally have fluctuations approximately between 0.3 and 0.45, which justifies the utilization of 0.35 as a good figure (H. Huang, 2004).

Table 3 summarizes the pavement configuration utilized for the 3-D model composition:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>E Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wearing Course (AB)</td>
<td>40</td>
<td>4000</td>
<td>0.35</td>
</tr>
<tr>
<td>Base Course (AG)</td>
<td>150</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Unbound Base</td>
<td>80</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Subbase Layer</td>
<td>480</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Subgrade</td>
<td>Infinite</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Layer thickness and material properties for the 3-D modelling

b) Geometry and boundary conditions

The selection of an appropriate geometry has a significant influence over the model performance. With the aim of obtaining a proper accuracy in the response but also utilizing an efficient demand of computer resources, a validation process has been conducted between ABAQUS and KENLAYER to configure the dimensions of the model.

Some studies such as the ones developed by Hjelmstad (1997) and Kim, J. (2000), reported the importance of the distance from the load to the boundaries in order to avoid the errors produced by effect of the edge proximity. According to them, the influence of the boundary conditions could be neglected for domains larger than about 150 times the radius of the load R in a vertical direction (Chen-Ming & Fang, 2011). Nevertheless, Duncan, J.M. (1968), stated that reliable data was obtained for boundaries situated to 40 times R in vertical direction and 12 times R in the horizontal direction (Koohmishi, 2013).
The Swedish design guidelines (Vägverket, 2008) have established a 100 kN Equivalent Single Axle Load (ESAL). Due to symmetry this represents 50 kN in the section represented by the model and thus a tyre pressure of 800 kPa and a radius of 14 cm is assumed for configuring the load. Besides, a depth of 5.6 m is considered acceptable for avoiding errors in vertical direction. Moreover, also because of symmetry simplifications it has not been feasible to avoid the edge effect in transversal direction and, keep both the reality of the model and the restriction of computer resources. Despite this fact, to correct this deficiency, infinite elements type CIN3D8 are used for the boundary conditions along transversal direction as a simulation of the wayside of the road and along the longitudinal direction. These elements are not supported by ABAQUS/CAE and then have been generated outside the graphic environment with a text editor (Abaqus/CAE, 2012). Regarding boundary conditions, the vertical plane passing through the longitudinal direction (driving direction) and the one passing between the two wheels, are considered a plane of symmetry and thus the orthogonal displacements to these planes are prevented. Moreover, the vertical displacements at the bottom plane of the composition are also restricted.

![Characteristics of the conventional pavement model to enable its application for eRoad modelling](image)

**Figure 13** Characteristics of the conventional pavement model to enable its application for eRoad modelling

To develop this verification, the Swedish road cross section is modelled both in ABAQUS and KENLAYER. Once coherence between the results from both computer programs is achieved, the dimensions of the model can be verified and the model ready to its application for eRoads, this is, ready to introduce the charging unit module of the IPT Systems. In the following graphics the outputs from different model configurations are shown. For the ones where infinite elements have been used as a boundary condition (BC), considering the radius of 14 cm, the extension of the infinite elements is \( \frac{25}{14} r = 25 \text{ cm} \) and \( \frac{5}{7} r = 10 \text{ cm} \) respectively.
Figure 14 Vertical displacements comparison

Figure 15 Tensile strain comparison
As shown in Figs. 14 to 17, different configurations of the FE model are disposed to obtain the best and most reliable response. Fifteen different location in the cross section have been chosen from the surface to downwards (Y direction) under the centre of the load application to analyse the pavement response, always having the consideration that results displayed by KENLAYER in middle of a pavement layer corresponds to the bottom of the upper layer (H.Huang, 2004).

In general, the analysed stress and strain responses are similar between ABAQUS and the theoretical solution, but an important gap is noticeable in the displacements (Figure 14). For this reason, the use of infinite elements is necessary, obtaining a significant improvement in all parameters but especially in displacements. Hence, the suggested geometry seems to be reliable and further applications with this model ready to be developed. In order to have a
better visualization of this comparison, table 4 shows the main design outputs by considering the elastic behaviour for the asphalt concrete layer from both approaches:

<table>
<thead>
<tr>
<th>Response</th>
<th>Location</th>
<th>Unit</th>
<th>ABAQUS</th>
<th>KENLAYER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection</td>
<td>Surface</td>
<td>mm</td>
<td>0.359</td>
<td>0.364</td>
</tr>
<tr>
<td>Horizontal Tensile Strain</td>
<td>Bottom of HMA layer</td>
<td>[]</td>
<td>0.00016</td>
<td>0.00017</td>
</tr>
<tr>
<td>Vertical Stress</td>
<td>Bottom of HMA layer</td>
<td>KPa</td>
<td>-173,739</td>
<td>-165,511</td>
</tr>
<tr>
<td>Vertical Strain</td>
<td>Top of Subgrade</td>
<td>[]</td>
<td>-0,00012</td>
<td>-0,00013</td>
</tr>
<tr>
<td>Vertical Stress</td>
<td>Top of Subgrade</td>
<td>KPa</td>
<td>-19,544</td>
<td>-18,06</td>
</tr>
</tbody>
</table>

Table 4 Outputs comparison between ABAQUS and KENLAYER modelling for model verification

3.2. FE modelling of eRoads with IPT systems

Once all the requirements for constructing a reliable model were configured (geometry and disposition of the cross section, BCs, constitutive behaviour and properties of the materials) and after its verification, this configuration can be applied for the simulation of the eRoads based on IPT Systems. However, some modifications must be done to ease the introduction of the charging unit module in the cross section. The characteristics of the model for representing the eRoad, are the following:

a) Load contact area

As stated before, for the model verification, a circular load with a radius of 14 cm has been applied to obtain the structural response of the pavement. This is justified due to the inability of KENLAYER to apply other shapes for the contact area between tire and pavement, since circular tire imprint area was considered as a good simplification in the first mechanistic approaches. Although some studies have demonstrated that the most appropriate area consist of a rectangle with two semicircles at both sides (Rahman et al., 2011), most of researchers have recourse to circular or rectangular contact areas for simplicity, since the error incurred is believed to be small (H.Huang, 2004). Thus, with the purpose of ease the model construction, the loading area for the eRoad simulation will be selected rectangular, instead of circular, with 0.2 m in width and 0.3 m in length for a single tire. This will facilitate the creation of a fine mesh over the charging unit module to obtain a more accurate response in this area, a fact that was not necessary for modelling a conventional road.

Besides, in structural pavement design, tire pressure and contact pressure is commonly assumed to be equal and therefore, again according to Swedish regulations (Vägverket, 2008), the pressure representing the wheel load is assumed of 800 kPa. Considering this pressure uniformly distributed over the rectangular contact area established, the ESAL imposed by the Swedish guidelines for a single tire can be obtained ($F = Pressure \times Area \approx 50 \text{ kN}$). However, in order to optimizing the use of computer resources and given the symmetry conditions, the analysis will consider the pavement under a half wheel load ($F = Pressure \times 0.5Area \approx 25 \text{ kN}$).
b) Mesh calibration and elements type

Another key issue in a 3D finite elements model is the construction of the mesh. An inappropriate distorted mesh with important extension might produce an incorrect output response in addition to an unnecessary use of computer resources (Chen-Ming & Fang, 2011). Figure 18 shows the mesh sensitivity analysis conducted to achieve a good precision, based on the accuracy of the outputs for different mesh sizes. From this figure, it can be observed the results from the FE simulation carried out with different coarse and fine meshes. During the first simulations, the mesh diverged to finally converge from 40 thousand nodes.

![Sensitivity Analysis Mesh](image)

Figure 18 Mesh sensitivity analysis at surface under load centre.

An example of a proper mesh composition of the model is displayed in Figure 19 from different isometric perspectives. The stress gradient is normally bigger in the region of the loading area because of proportionately thickness of layers in comparison with the load contact area (Chen-Ming & Fang, 2011). For this reason, smaller elements are required in the loading area to achieve an accurate result. Besides, in the model designed to introduce the charging-unit module, meticulous and fine mesh composition is developed along the extension of this entity (specially focusing in weak points such as module corners or border interfaces).

![Mesh Model Composition](image)

Figure 19 Mesh Model Composition from different isometric perspectives
This pavement composition has been elaborated by the use of 8-node continuum linear brick reduced integration elements (C3D8R elements), which are adequate for modelling under a linear-elastic domain (Abaqus/CAE, 2012).

c) IPT systems characteristics

Once all the features regarding domain size, loading and boundary conditions, material properties and mesh density are calibrated, the next procedure is to characterize the items for the representation of Inductive Power Transfer (IPT) Systems into the road pavement.

Due to uncertainties at the moment, different ways to approach the location of the charging devices into the pavement structure have been suggested (see considerations in chapter 4), but seems that the most appropriate manner of simulate the presence of a charging-unit module in the pavement is as follows; the specific components of IPT have not been specified inside the pavement structure, rather a prefabricated module embedded as an entity is taking into account for IPT devices simulation (Chen et al., 2015 a).

Assuming a rectangular shape located between asphalt layers, the analysis of the response over this entity is conducted. Figure 20 shows the standard dimensions and the location considered for the charging-unit module. Given the uncertainties related with the material composition of such a module, an Elastic Modulus of 30000 MPa and a Poisson ratio of 0.2 are assumed for representing it. On the other hand, considering the recommendations that will be exposed in chapter 4, an asphalt mixture overlay between 20 and 50 mm will be disposed for the wearing course. The location of the charging-unit module immediately under this overlay into an asphalt mixture base course, seems better than positioning it into a deeper location due to several reasons; i) the distance between the IPT charging unit and the pick-up systems of the vehicles should be as short as possible to improve the power transfer efficiency (PTE). ii) in case of a deeper embedment, for instance; in the base or subbase layers, a possible failure would imply important structural deficiencies affecting the whole pavement composition and thus an exhaustive reparation on the road would be needed to perform the rehabilitation.

In order to perform the response analysis of the eRoad cross section, the same configuration used for a typical Swedish pavement composition is used but with the addition of the charging-unit module embedded and the corresponding modifications to enable it. Given the fact that there is not any previous study that considers the embedment of a module in the pavement, there are no standard laws to analyse the damage caused by the traffic loading. However, a comparison of the main outputs in critical locations of the cross section can be done between eRoad and conventional pavement with the aim of creating an overview of the key issues that should be considered in future works.
In addition to this configuration, other assumptions and dispositions have been considered for the development of a model including the main aspects of an eRoad system:

a) Wearing Course (Overlay): being one of the main elements for the structural integrity of the charging-unit as a stress relief layer and as a distance barrier for the power transmission, a sensitivity analysis of the thickness and stiffness will be carried out to observe the relevance of both aspects that could lead into a more efficient integration in future designs.

b) Interface module-pavement: considering fully bonded interfaces between layers (no gaps), the same criteria is used for the interface between the charging-unit module and the pavement. This is a common procedure for soil composition using FEM. Moreover, the consideration of an interaction between materials such as friction or cohesiveness would involve different constitutive behaviours like non-linearity or plasticity.

c) Part of the analysis is developed with the inclusion of a silicone expansion rubber joint (E=1 MPa ν=0.47) between the interfaces of charging-units to observe the stress response. Being the analysis of the reflective cracking beyond the scope of this study, at least with these solutions, the visualization of stress relief in certain locations is possible and a pathway for further improvements will be open.
3.3. **Conventional road vs eRoad. Analysis of results**

3.3.1. **Analysis in vertical direction**

An analysis along the vertical direction of the cross section ($\tilde{Y}$ direction) has been conducted in order to observe the response along the different layers. Previous observations showed that under the load centre, the influence of the charging-unit module is alleviated and thus a section crossing the module has been selected for the analysis.

Figs. 21 and 22, show the von Mises stress distribution in the two study cases described: a conventional flexible pavement and its equal eRoad approximation. As stated before, both alternatives are based on Swedish conditions.

Von Mises stresses are used to compare critical stress between these pavement constructions. Being proportional to materials energy distortion, this magnitude is often used to describe the stress state of structural compositions; the contour lines give a visual perception of the internal stress distribution (Wu et al., 2011). Hence, it has been used to determine critical
areas of the cross section after introducing the charging facilities into the asphalt rather than as a pavement fracture criterion.

Figure 23 stands out the stress concentration present along the base course layer in the eRoad solution (between 40 and 190 mm depth). Obviously, these concentrations are produced by the presence of the unit-charging module, explaining the difference with a conventional road. At the top and the bottom of the module, stress peaks are emphasized due to the interface with the wearing course (top) and the unbound base (bottom). However, the rest of the structure has a similar behaviour, being the difference between both models negligible.

![Figure 23 Von Mises stress distribution in vertical direction $\tilde{Y}$ (mm)](image)

![Figure 24 Longitudinal stress distribution (S33) in vertical direction $\tilde{Y}$ (mm)](image)
Figs. 24 and 25 show the graphs regarding the longitudinal (33) and horizontal stresses (11). In the case of a conventional road, it is observable that stresses, especially the horizontal, are not really significant, remaining close to zero along the section. Besides, from the outputs for horizontal stresses can be appreciated that the overlay in the eRoad solution is subjected to significantly higher stresses. In fact, the conventional road remains under a compressive stress along the structure whereas in the eRoad case the stress over the wearing course has a tensile behaviour, which shifts progressively into compression along the charging module to reach the critical stress at the bottom of the asphalt layer. On the other hand, longitudinal stresses presents a similar behaviour during most of the pavement layers in both solutions; but again, the stress concentration along the module in the eRoad case presents a much higher intensity expressed in the graphic as a ramp that shifts from compression to tension [-800, + 800] KPa along the charging-unit module. Besides, it is noticeable a higher magnitude in the longitudinal component than in the horizontal, and therefore has more influence over von Mises stresses distribution.

Regarding the horizontal strains shown in Figure 26, it is distinguished how, in contrast with the stress distribution, the eRoad solution displays lower values over the charging-unit. Nevertheless, the overlay seems to be more affected by these tensile strains in the eRoad case.
3.3.2. Analysis in transversal direction

After the observations from the previous analysis, it seems interesting to evaluate the bottom of the base course asphalt layer, due to the critical responses observed there. Being a key location for pavement design, further analysis along this area is developed.

Figs. 27 and 28 show the stress distribution in the cross section of a conventional pavement and the eRoad solution respectively, where critical areas due to high stresses concentrations are easily observable. For instance, the shape of the charging-unit module is clearly visible in this transverse direction ($X$ direction) due to the contrast along its base and especially next to the corners, indicating that these are locations that are more vulnerable.

Taking into consideration the area subjected to this transversal analysis, the addition of a new configuration to the eRoad model seems interesting. As stated before, another comparison is done for this analysis by including a silicone rubber joint in the interfaces between charging-unit slabs (see the material properties in the previous section 3.2.c). After observing in the vertical analysis the stress concentration generated by the integration of the charging-unit module into the pavement, this third configuration pretends to show a stress relief in critical areas.
areas under the same conditions than the previous solutions. This technique is commonly used for pavement construction and will provide information for future further approaches.

Figure 29 represents the stresses in the pavement along the transversal direction ($\bar{X}$ direction) for a depth of 190 mm, this is, at the bottom of the asphalt layer where is settled the charging-unit module. It shows a maximum stress of 1000 KPa, located at the border of the charging-unit bottom, next to the load. In general, there is a very significant increase of stress along the presence of the module ($\bar{X}$ between 0 and 600 mm) with strong fluctuations during the length of this entity. Especially there is a sudden decrease in the interface module-asphalt ($\bar{X} =$600 mm). These differences with a conventional flexible structure are a logical response due to the insertion of a module in the pavement.

However, special attention should be paid to the stresses peaks in this integrated device in order to reduce the high contrast created in the interface with the asphalt and also in the corners of the module because might be a probable cause of deterioration or failure in early operation stages. The role of a joint load transfer between modules seems to be a good solution for stress relief. In Figure 29 a big difference can be observed by the use of this joint in the pavement model. All along the extension of the module, the stress is reduced almost to the half achieving a great relief of the peak located in the corner and with a smoother decrease after this peak when its produced the change of material at the end of the module ($x=0.6m$).

**Horizontal Stresses and Strains**

Horizontal Stresses and Strains are key parameters in pavement design implementation for fatigue failure. Flexible pavement design has traditionally count upon the analysis of tensile strains at the bottom of the asphalt layer due to the importance of this stratum for improving structural capacity. Nevertheless, for composite pavements, crucial response location turns to tensile stress location at the bottom of the firm slabs (Flintsch et al., 2008). Taking into account the structural nature of this eRoad, with features from both pavement types, seems reasonable to obtain the two horizontal responses in this area to discuss the results. Figs. 30 and 31 reflect the results of the horizontal stress and strain outputs from the FE model at the bottom of the asphalt layer.
In first place, the stresses at the bottom of the base course layer for the conventional flexible pavement are much smaller due to its low stiffness modulus. For the eRoad case, the horizontal stress is featured by a strong compression component during the presence of the module. It is shown how is developed the transition to tensile behaviour as the stiffness of the base decreases because of the transition to asphalt and the load centre gets closer. On the other hand, the joint solution seems to have a worse response in terms of horizontal stresses. This is probably because of the insertion of this joint in the transversal direction, which adds another interface to the structure. However, the differences between both eRoad solutions are negligible in comparison with a conventional road. From these observations, it can be concluded that the horizontal stresses at the base of the charging-unit module is an essential output and should be taken into consideration for fatigue life prediction in eRoad structural pavement design.

Secondly, Figure 31 shows the output for horizontal strain response at the bottom of the asphalt layer. Tensile strain is one of the key parameters evaluated for fatigue failure in the design of common flexible pavements. However, in this case, it is noticeable that along the transversal direction, just the point corresponding to the corner of the module box (which is the interface with the asphalt) experiences a higher magnitude than conventional pavements.
For the rest of the extension, horizontal strains are lower in the eRoad solution, but still the difference seems to be small. Moreover, in terms of strains the role of the joint seems almost negligible with almost any difference with the original eRoad solution. In summary, with this analysis is proved the lower significance of horizontal strains in comparison with stresses for the eRoad models. Thus, it is suggested the fact that failure influenced by tensile strains at the bottom of the asphalt layer is relatively lower by the incorporation of the unit-charging module and more attention should be paid for the stress concentration in this area.

**Vertical Strains**

Finally, vertical strains along transversal direction at the top of the subgrade are analysed. This output has generally been used for pavement designers to predict rutting failure in the subgrade. Even though a linear-elastic domain is not able to provide permanent deformation due to the recovery after removing the load, is also interesting to observe the differences within another design parameter. Figure 32 shows the output for vertical strains at the top of subgrade for both pavement types. In a similar way to horizontal strains, there is a small reduction of the strains in the eRoad solution and the joint does not seems relevant as well. Therefore might be suggested that rutting failure could also be lower for this type of constructions.

![Figure 32 Vertical strains (E22) at the top of subgrade (Y=750 mm)](image)

**3.3.3. Thickness and stiffness influence**

A sensitivity analysis has been conducted with different eRoads models in order to see the influence of modifying the overlay thickness and stiffness in the pavement structure. As will be explained in chapter 4, the role of the overlay or wearing course is crucial in the development of IPT systems. The overlay should be as thin as possible in order to achieve a good power transfer efficiency (PTE), but also able to provide a good protection and performance for the structure and the IPT facilities. Having this on mind, variations in the overlay are developed using as a basis the original model for the eRoad, with the purpose of evaluating the relevance of these parameters correlated with pavement responses.

Figs. 33 to 35 display the response of different models by modifying either the thickness or the stiffness of the overlay. These modifications are realized using as a basis the original
model simulated for typical Swedish roads, which is, 40 mm overlay thickness and a Young Modulus of 4000 MPa.

Figure 33 Horizontal strains (E11) variations by modifying E modulus or thickness overlay

Figure 34 von Mises stresses variations by modifying E modulus or thickness overlay
The previous figures stand out the fact that modifying the thickness implies higher fluctuations in both strains and stresses. In addition, tables 5 and 6 show the differences between critical responses for the thresholds selected in order to provide a better visualization of these variations. In the case of the E Modulus seems reasonable to show the evolution between 3000 and 6000 MPa and in the case of the overlay thickness the values oscillate between 20 and 50 mm in order to achieve an appropriate PTE between vehicle and pavement.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>-389.6</td>
<td>1028.04</td>
<td>6.44E-05</td>
</tr>
<tr>
<td>4000</td>
<td>-363.878</td>
<td>1005.73</td>
<td>5.80E-05</td>
</tr>
<tr>
<td>5000</td>
<td>-344.608</td>
<td>988.771</td>
<td>5.34E-05</td>
</tr>
<tr>
<td>6000</td>
<td>-329.733</td>
<td>975.519</td>
<td>5.00E-05</td>
</tr>
<tr>
<td>Maximum Difference</td>
<td></td>
<td></td>
<td>1.44E-05</td>
</tr>
</tbody>
</table>

Table 5 Critical responses for the models with variations in the E modulus of the overlay

<table>
<thead>
<tr>
<th>Overlay Thickness (mm)</th>
<th>Critical H.Stress (KPa)</th>
<th>Critical von M.Stress (KPa)</th>
<th>Critical H.Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-464.05</td>
<td>1094.79</td>
<td>7.25E-05</td>
</tr>
<tr>
<td>30</td>
<td>-411.083</td>
<td>1048.37</td>
<td>6.47E-05</td>
</tr>
<tr>
<td>40</td>
<td>-363.878</td>
<td>1005.73</td>
<td>5.80E-05</td>
</tr>
<tr>
<td>50</td>
<td>-321.443</td>
<td>966.284</td>
<td>5.25E-05</td>
</tr>
<tr>
<td>Maximum Difference</td>
<td></td>
<td></td>
<td>2.00E-05</td>
</tr>
</tbody>
</table>

Table 6 Critical responses for the models with variations in the thickness of the overlay

From these tables is observable that between using an overlay of 20 mm or another of 50 mm the difference in stress values is significant (between 128 and 142 KPa). However, in the case of modifying the E modulus, the difference between applying an E modulus of 3000 MPa or
another of 6000 MPa just supposes stress fluctuations between 52 and around 60 KPa, which is less than the half difference induced by thicknesses variations. In the case of the strains, it is also noticeable that the influence of the thickness is higher than the E modulus. Again, the overlay thickness modification presents a higher oscillation, which proves the higher relevance of this input over the improvement of the asphalt quality.

3.4. Summary

This chapter shows the modelling work developed for simulate the integration of IPT systems into the road pavement. Mechanistic methods are a tool to characterize the pavement structure under loading conditions by evaluating the responses displayed. However, depending on the configuration of the model different results can be obtained. Hence, according to the experience observed in previous studies of pavement design from a literature review, the configuration of the FEA performed with ABAQUS has been realized considering the following assumptions:

- Response model: linear-elastic behaviour and time-independent.
- Layers have a homogeneous and isotropic material.
- Load is considered stationary and uniformly distributed.

The inputs related to cross section composition, material properties and geometry are selected based on literature review and following the Swedish guidelines for pavement design (Vägverket, 2008).

A verification and calibration to obtain a reliable response of the multilayer FE model with different materials in each layer was necessary. A multi-layer system software (KENLAYER) is used with this purpose. Based also in linear-elastic and time-independent behaviour, a conventional flexible pavement with the characteristics shown above is analysed with this software, in order to compare the results with the ones provided by ABAQUS. Once the response is approximately the same for both approaches, the model created can be verified to be applied for the simulation of an eRoad construction.

For the applicability of the 3D FE model to eRoads, basic assumptions are considered due to the current uncertainties related to the geometry and composition of IPT items. Fundamentally, a prefabricated module simulating an IPT charging-unit is assumed to be embedded into the base course asphalt layer in order to evaluate the response of the same after the traffic load application. The pavement composition is the same than the used previously for the verification of the model. In addition, some modifications, such as including an expansion joint or variating the stiffness and thickness of the overlay layer, are realized to observe the different responses on the model. The main results displayed from the analysis are summarized as follows:

- The interface between the asphalt and the charging-unit module presents stresses concentrations, especially at the bottom and corners, which should be considered as concerning in future designs. Besides, in general the stresses over the whole area of the charging-unit module are much higher than in the conventional pavement solution.
- The analysis in vertical direction has shown lower horizontal strains values over the charging-unit module for the eRoad solution. However, the values are higher in the overlay and the unbound base. The analysis in transversal direction has not displayed
significant differences in strains except for the interface between charging-unit and asphalt.
- The introduction of the joint causes a stress relief as expected.
- After conducting a sensitivity analysis for different compositions, it is outlined a higher influence of the thickness of the overlay than of the stiffness, providing softer responses for the charging-unit.
4. Considerations and effects for implementing IPT Systems in road infrastructure

The integration of eRoads to road transportation is a progressive and slow process. Moreover, regarding economic issues, every step towards these systems requires more resources than a conventional road; for example the development of adequate innovative structural designs to ensure its performance, the complex construction practices with their corresponding future maintenance activities considering the lack of previous experience and the use of new unknown materials and components among others. Nevertheless, this integration would also produce potential benefits in energy and environmental terms such as: breaking up with fossil fuel consumption and its strong dependence, notable reductions of the emissions to the atmosphere and also reductions in total energy consumed due to the higher energy efficiency related with electric devices.

Most of the research works aiming the successful incorporation of e-mobility solutions in road transportation have been focused on improving vehicles and technology devices to contribute in the industry’s objective of creating new products for the consumers. In contrast, the investigations related to the integration of these technologies into the road infrastructure have been barely developed. Thus, from a highway engineering point of view, is imperative to emphasise the design, construction and maintenance/rehabilitation stages since the adequate performance of future eRoads will depend on these stages.

The purpose of this chapter is to build and overview of potential considerations for the introduction of dynamic IPT systems in road infrastructure, and then to evaluate its effects along some stages of the eRoad life cycle. The development of a system modelling Life Cycle Analysis is beyond the scope of this study. At the moment, there are no inputs related to the eRoad pavement and thus, it is not possible to evaluate aspects such as consumption of resources, quantities of waste flows, emissions or costs attributable to this new infrastructure. However, this study should be useful to improve the ability on Life Cycle Analysis ensemble concerning eRoads implementation and could be used as a guideline for future applications. Besides, contributing with good-practice concepts for the inclusion of these technologies in eRoads might be interesting for future decision support within industry sectors and project developers.
4.1. **eRoad Design and Construction**

The failure of a road pavement is not immediate but after entering service, the deterioration grade can vary significantly if the design is inadequate. Although recent pavement design is focused on creating the most economical combinations of pavement materials, the pavement performance during the life span of the road is as well a main issue to take into consideration. Especially for eRoads implementation, being the constructive experience almost non-existent, the quality of the design should strictly meet the requirements to avoid future inconveniences. In the same way the construction procedures are essential for a good structural integrity and the long term performance. Inappropriate construction practices can cause important deteriorations in early stages, having important consequences in the pavement integrity and even causing unexpected rehabilitations. Therefore, increasing the knowledge regarding eRoads during these phases is necessary for the inclusion of IPT Systems in order to avoid premature reconstructions as a consequence of pavement failures.

From the eRoad 3D FEA conducted in chapter 3, four main conclusions were displayed from the pavement behavior:

- Stress concentrations in the area along the interface between asphalt-charging module (specially at the bottom). Alarming peak stresses at the corners of the charging-unit module entity.
- Generalized strain increase in most layers for the eRoad solution. In contrast, over the charging-unit a decrease was noticeable.
- Stress relief by the incorporation of certain mechanisms into the cross section. In this case, the use of an expansion joint between slabs shown an important reduction in critical stresses.
- The stress magnitude over the charging-unit module was much more dependent on the thickness of the overlay (wearing course) than on its stiffness, fact that should have consequences regarding the protection of the IPT facilities.

4.1.1. **Design and Construction considerations for eRoads**

Having on mind the observations presented above and after the experience of modelling a hypothetic eRoad pavement cross section, a better understanding of the composition was achieved. Thus, some considerations for future design of this type of roads could be exposed:

**a) IPT facilities integration**

Although the configuration of IPT facilities inside the pavement still remains ambiguous, the inclusion of IPT systems into the road could be performed in some different ways. However, in general, two basic approaches might prevail among others:

- The IPT components are installed directly in the pavement as a skeleton structure in the corresponding location which will be replenish afterwards with pavement materials for its sealing and protection (Chen et al., 2015). This configuration consists
on excavating the current pavement in order to install in situ the IPT components such as conductors and ferrite cores. After that, as was done in the OLEV project in Korea (KAIST OLEV, 2015), the trench is filled up with pavement materials (concrete in that case) to protect the facilities.

- The IPT facilities are integrated in a prefabricated unit, as a solid entity or slab, and embedded as one piece into the pavement (Chen, Taylor, & Kringos, Electrification of Roads: Opportunities and Challenges, 2015). Different approaches can be adopted for this solution. For instance, a metallic box made of materials such as aluminium, titanium or other metallic alloy and filled up with a softer filler material containing the electric devices. Other option is a pavement block or slab, similar to composite pavements with concrete slabs and a HMA layer over it. Due to the relatively ease of this second option for its installation and analysis, the FE 3D structural analysis was performed assuming the embedment on this way. Even though the composition of the block remains an uncertainty, previous experience with concrete slabs suggests a coil pad block as a potential solution.

Notwithstanding, regardless of whether the first approach or the second is developed, the charging facilities should always be installed in a way to allow paving over top and previous to the final paving step, in similarity to the methodologies used for the inclusion of snow melting cables (Viktoria Swedish ICT, 2013).

b) IPT systems charging-units geometry and location

Some considerations have to be taken into account for the disposition of the IPT charging-units when developing eRoads by using this solution. In first place, the more reasonable solution for the disposition of the facilities might consider every lane as a singular unit for its integration. This fact will allow the possibility of combining different traffic flows in the short term, this is; combine internal combustion engine (ICE) vehicles with EVs adapted to inductive solutions. Secondly, the concept of eRoads is conceived for regular routes, mainly highways with high traffic demands, and thus the distribution of the IPT systems should be done assembling groups or sections of charging units to ease an intervention in case of an incident and not interrupting the traffic flow. Third, another important consideration is the spacing technology distribution; since the vehicles have incorporated a battery that is charged while they are driving through the IPT facilities, there is no necessity of a constant coverage along the entire route with this technology to make it fully inductive. The issue is the location of these systems at strategic areas to keep the batteries energy reserve during the route, with a full charge by the time the route finishes. Further study regarding this topic could significantly save the total costs and time construction spent.

Having on mind the previous considerations regarding IPT systems distribution, it is possible to suggest some configurations for their colocation in the road. The IPT facilities should be placed symmetrically respect the centre of the lane to obtain a good power transmission with less misalignment. Therefore, the width of the unit charging module should be similar to a standard wheel separation for EVs. Due to the different axle configurations, for instance, in the 3D FE model a width of 1.2 meters was chosen for the representation of IPT facilities. In addition, the longitudinal dimension of the slab or unit charging module should be at least a distance close to the separation between the main axels. Again, even though there are different axle configurations for heavy and regular vehicles (NVF, 2008), a longitude of
around 1.75-2 meters is reasonable in order to establish consistency between the vehicle’s wheel separation and the module longitude.

Regarding the location of the IPT facilities in depth along the cross section, several reasons lead to their location under the protective overlay or wearing course (road surface layer). Firstly, due to the need of achieve a good Power Transfer Efficiency (PTE), the distance between vehicles and charging unit should be as short as possible. Secondly, it is not recommended to locate the IPT facilities in layers with a significant structural weight. For instance, the roadbase, which is the main structural layer and provides the platform for the surfacing (C.A.O’Flaherty, 2002). Thus the inclusion of the charging facilities in this layer could cause a bad mechanical integrity in the whole structure, giving place to exhaustive and expensive reparation works. Besides, subbase and subgrade are weaker structural layers situated considerably far from the surface. Hence, an adequate location for these technologies should be somewhere between the roadbase and the surface course. However, this is not a definitive statement and all the possible configurations should be considered given a certain eRoad development.

c) Protective Overlay

The wearing course plays a fundamental role in every pavement type. Being part of the road surface, it is the layer in direct contact with the environment and the one where the interaction with the vehicles takes place. Likewise, in the case of an eRoad, this layer is even more important. Even though there is no consensus about the specific characteristics of the overlay, it is clear that it has to meet certain features simultaneously; this is, the optimum thickness to provide structural performance and protection to the IPT facilities but at the same time being as thin as possible to allow a good PTE.

The 3D FEA concluded that the thickness’ increase of this surface course has much more influence for stresses relief than increasing the stiffness. Of course, this seems logical since the stresses induced in the pavement by the applied wheel loads decrease with depth, and thus higher thickness provides more resistance. But some limitations have to be imposed regarding this thickness. In a previous study regarding mechanical integrity for eRoad implementation Chen et al. (2015) suggested that the overlay should increase the energy transfer distance by 20 to 50 mm, which indicates an overlay thickness with similar dimensions. In addition to stress relief, this layer should gather other features such as good skid resistance, allow a fast drainage, minimize traffic noise, protect the underlying road structure and require minimal maintenance providing good behavior for the long term performance (C.A.O’Flaherty, 2002). Special attention should be paid to IPT facilities protection since water ingress could cause safety problems due to the electrification of certain devices. Moreover, this layer should be capable of being recycled or overlaid, especially considering the fact that maintenance and rehabilitation might be conducted only to this layer (Chen et al., 2015).

For the moment, a great challenge remains in the configuration of the protective overlay. As will explained in the following section, further research is required to find the balance between mechanical and magnetic properties of the overlay. To do so, it is necessary to achieve an adequate thickness to reduce the gap distance but at the same time, a material composition able to protect the IPT technologies and ease the transmission of the magnetic field.
d) Inductive Power Transfer Efficiency (IPTE)

Considerations regarding the Inductive PTE are crucial to enable the implementation of the eRoads based on IPT systems. An adequate infrastructure adapted for the eRoad requires a coherence between the pavement and the technology embedded in it to achieve the optimal operation of the whole system. Thus, it is necessary to be aware of the aspects related to this during the pavement design and apply them when constructing in order to guarantee the adequate energy transmission between vehicle and road.

Fundamentally, three factors are influencing the PTE: the dielectric response of the materials composing the pavement overlay, the gap distance and the misalignments between vehicles and IPT technologies.

As explained in chapter 2, the PTE is dependent on the electromagnetic loss, which represents the dissipation of electromagnetic energy. Taking into account the presence of the road surface layer between vehicle and IPT technologies, the PTE will be reduced in this environment. Moreover, being the energy loss related to the characteristics of the materials, the properties of the materials composing the overlay is fundamental to ease the efficiency. For instance, a reduced relative permittivity $\varepsilon_r$ is favourable for the magnetic flux and that fact will establish boundaries for the use of certain materials. Moreover, the presence of water adversely affects the PTE since causes an increase in the relative permittivity $\varepsilon_r$, so the pavement structure for eRoad should improve drainage properties comparing with conventional roads.

The air gap between road surface and vehicle is normally between 150 and 300 mm (Covic & Boys, 2013). In addition, as stated before, the fraction of pavement between the surface and the charging unit should normally oscillate between 20 and 50 mm or even more, depending of the pavement configuration. Considering these notions, the gap distance between vehicles and IPT technologies would be somewhere between 170 and 350 mm. Having this on mind, the PTE is degraded as the distance between the pick-up system in the vehicle and the IPT facilities increases. Hence, the challenge for the eRoad is the reduction of this distance but simultaneously to assure the protection and structural integrity of the pavement.

While the transfer distance remains almost constant along the lane, misalignments during driving are inevitable, reason why further investigation must be conducted to improve the system’s tolerance. First, an active coordination between constructors and vehicle manufacturers should be necessary to maintain the symmetry between the source and the receiver and therefore reduce the misalignments. Besides, the orientation of some of the IPT facilities such as the capacitor and coils has an influence over the PTE and therefore should be considered during the design and construction of eRoads.

Having this on mind, the adequate performance of an eRoad’s structural design based on IPT systems has no sense without the achievement of an efficient power transmission. Thus, further research in terms of electromagnetism and its coordination with infrastructural developments is necessary to reach the rigorous energy levels, distance gaps and misalignments that a feasible eRoad will require.

e) eRoad pavement distress modes

The accommodation of IPT technologies into the pavement represents a challenge for the mechanical stability of the future eRoad pavements. Moreover, reaching a good performance of the road for the long term is another obstacle that needs to be overcome.
The required technologies to embed into the road consist of fragile ferrite components that may have an unexpected behaviour once installed due to the unfavourable environment for such devices (Chen et al., 2015). Despite this fact, it is necessary for these components to bear the actions induced by traffic loading and the fluctuations of the weather conditions.

The stress induced in a conventional flexible pavement decreases progressively with depth. The upper layers distribute the loads transmitted to them until the weaker layers like the subbase or subgrade. However, the charging technologies embedded in the base course (asphalt) or in the proximities to the roadbase (normally unbound materials) are responsible of peak stresses along these strata that might drive the structure to a critical response. The previous FEA showed the predominance of high stresses along the interfaces between the asphalt and the IPT facilities. Specifically, after entering service, during the first stages of the constructed infrastructure, premature instability might be induced in the weak locations of the technologies, such as the corners of the unit charging module.

Traditional flexible pavements rely principally on the asphalt layer because it is in the upper one and therefore is submitted to bigger loads, requiring better stress endurance. This makes tensile strains at the bottom of the asphalt layer a key issue for the design due to the risk of fatigue failure that could be initiated in this location (Flintsch et al., 2008). Nevertheless, the modification of the cross section to enable the introduction of IPT technologies suggests that the bottom of the charging block in this case might be the critical area and thus attention should be paid to the stresses induced here due to the concentrations observed.

In addition, the weakness observed in the interfaces of the blocks containing IPT technologies should also be considered as a main issue for future structural development. These areas have a propensity to deteriorations and failures by being inflection zones. Reflective cracking is a potential distress mode in pavements composed by slabs or blocks due to their movements because of vehicles’ actions and temperature cycles. This could generate high stress concentrations in the interfaces of the charging units causing a crack in the overlay, especially in the areas located above the joints (Flintsch et al., 2008). These cracks may lead to water filtrations that in the case of eRoads would be very alarming for the charging facilities, the human safety and more generally for the PTE (causing an increase of loss). Moreover, a lack of awareness on these distress modes would be the cause of extra maintenance activities due to the additional resources required, which goes against the principle of sustainability (economic, environmental and social efficiency) related to eRoads.

4.2. Maintenance

Road maintenance is essential for guarantee an appropriate performance of the network. There are several reasons why good maintenance practices must be realized during the life span of the roads. Being in general the principal way of transport, our social and economic development depends partly on the condition of the road, and thus it is necessary to provide a safe and efficient transport infrastructure. Besides, quotidian activities and goods provisioning in developed countries are often done via the road network.

Pavement maintenance and rehabilitation is some sort of empirical discipline emerged from previous road evolution and performance observations. Even though there are no observable effects on eRoads due to the fact that they have not been constructed yet, the experience on conventional roads can be used as a reference for these future works. Hence, with the
introduction of IPT systems in road transportation the concept remains the same, this is; deal periodically with pavement defects in order to maintain an adequate pavement condition as well as reduce the future rate of deterioration, and therefore extend the road lifetime. Nevertheless, the construction of a different pavement structure might modify some of the deterioration processes and some of the procedures for the maintenance and rehabilitation. Furthermore, new design standards for eRoads should also be based on the expectation of future maintenance, which makes a growing interest in the conservation of this future infrastructure.

![Graph showing Pavement Condition over Service Time](image)

Figure 3.6 Evolution of the pavement condition with time under maintenance activities

Figure 3.6 shows a general overview regarding the principle of conducting regular maintenance and rehabilitations. The blue line is representing the hypothetical evolution of the road condition over time if any maintenance activity would be done during the life span. On the other hand, the red line shows a typical evolution of the pavement condition under a planned maintenance management. Number 1 represents the application of a regular maintenance. Foreseeing small defects in the pavement by applying a preventive maintenance is used to avoid worsening deterioration that could drive to serious damage to the road structure. However, there is a point when, even having conducted strict maintenance works, it is necessary to realize some rehabilitations to return the quality of the pavement to a similar state as the one in the origin (number 2 in the image). Future rehabilitations will be necessary over time (number 3 for example) to restore pavement conditions until the end of its performance.

Being a detailed description of maintenance activities beyond the scope of this section, a general visualization of the main types of pavement maintenance could be identified as follows (AASHTO, NDOR, 2002):

- **Preventive Maintenance**: previously strategically planned, the objective is to realize the treatment before the moment the deterioration happens in order to improve pavement condition, this is, improve the functional condition but not the structural resistance. Within this maintenance type, some of the activities realized are: crack filling and sealing, joint rescaling in rigid and composite pavements, micro surfacing or seal coats such as fog seals, scrub seals or slurry seals.
- **Corrective maintenance**: this maintenance is conducted when the pavement suffers deteriorations such as rutting, ravelling or extensive cracking. Sometimes there are confusions between preventive and corrective, and some processes may be difficult to differentiate but corrective maintenance is a reactive activity, which is done after deterioration when the pavement needs reparation.

- **Emergency maintenance**: this type of maintenance is carried out in critical circumstances, where severe deterioration on the pavement has occurred, such as a blow-up or a severe pothole. Sometimes, these activities are realized as a short-term solution until better treatments can be realized.

### 4.2.1. Maintenance considerations for eRoads

Even though maintenance activities have mainly a practical character established from previous observations, some considerations can be done for maintenance practices in future eRoads as a basis of further development.

In first place, as shown above, different maintenance strategies are developed depending on the given circumstances of the road, being all of them necessary to ensure a safe and long-lasting pavement condition. However in the case of eRoad performance, the role of preventive maintenance seems to be essential. Due to the complexity of the pavement compositions with IPT solutions embedded into the infrastructure, the purpose is to postpone as much as possible the activities involving structural interventions. The initial investment would be much higher than for conventional roads, and as a consequence, any repairing work would imply the use of more sources. Hence, the performance of the surface layer is much more important in this case to delay these kinds of activities. Moreover, based on experience, this stage of maintenance has been shown as the most cost-effective (AASHTO, NDOR, 2002), and therefore a good preventive maintenance might mean a cost and intervention reduction during the life span of the eRoad infrastructure.

According with the stated before, the introduction of eRoads should imply the update of current Pavement Management Systems (PMSs). Having in consideration the strong investment related to eRoads implementation, the specialization of these systems might be necessary to maximize the use of resources, preserve the high investment and increase maintenance effectivity. Even though the experience on conventional roads, it is a challenge to introduce an efficient PMS responsive to the effects of roads electrification. To assure the appropriate inclusion of the new infrastructure, it is necessary an assistance for the engineers using data collection and management, performance prediction models, economic analysis and, prioritization and optimization of resources (Kulkarni & Miller, 2014).

In general terms, the introduction of new technologies in the pavement should allow the regular procedures for road maintenance. Normally, the asphalt surface is periodically replaced every few years, depending on the road composition. With the implementation of IPT facilities should be possible to keep doing these interventions and thus the technology embedded must allow these activities. In the case of using new materials or mixtures for the wearing course special attention should be paid for not modifying functional properties of the surface such as the skid resistance or the impermeability.
Regarding the affection of weather conditions, some aspects have to be considered. Exceptional surface deteriorations normally occur due to weather conditions. Because of the embedment of IPT facilities special attention should be paid in areas next to electric devices. Potential damage near to these technologies could cause a breech in the cables or other conduction devices, creating an exposure to external conditions. This could compromise interferences in the electric supply or in the energy transmission and the safety for humans. Moreover, being leakage of water a problem in current conventional roads, the insulation and sealed of the charging facilities must be a priority issue. Additionally, in the case of areas subjected to strong winter conditions, like the north of Sweden, the maintenance activities would be more complex. The possible creation of a layer due to snow or ice accumulation could be a barrier to the energy transfer distance between vehicles and pavement. Besides, the intrusion of salt used for winter maintenance or the accumulation of water within the joints between slabs or modules could cause frost damage.

For the access to the IPT systems into the pavement, seems reasonable the necessity of providing every entity or group of IPT technologies (maybe organized by slabs or blocks) with an access chamber. Having a specific location, it would allow the entrance of the power cables and ease the manipulation of the electrical devices, achieving a quick and effective maintenance and/or reparation without altering the pavement structure. Thus, the integration of the IPT facilities in prefabricated modules, which would be embedded afterwards into the pavement structure, seems better than installing these technologies in situ since their replacement could be easier and the protection over the electric components better.

Another issue to consider is the rutting caused by many vehicles driving through the electrified lanes. Due to the necessity of an accurate alignment for achieving a good power transmission and the specialization of the lane for this specific type of EVs, the depressions in the surface along the wheel path would appear sooner than in conventional roads (Viktoria Swedish ICT, 2013). This problem could also be present in other applications of the Smart Roads, such as, for instance in the autonomous driving, and thus more frequent maintenance would be necessary to avoid it. Ruts normally tend to be filled up with water, and in case of being in an advanced phase the water could penetrate into the pavement giving place to a deterioration of the structure and a possible affection to the electric technologies installed.

Finally, the detection of the damage evolution in the road structure could be improved by the use of sensor systems for continuous active monitoring procedures. New devices has been developed lately regarding this issue, for instances, the ones developed by the Federal Highway Administration (FHWA, 2013) or by the Road Research Institute in Vilnius (Cygas et al., 2014) where smart pavement monitoring systems are capable of monitoring and storing the dynamic strain and stress levels in pavement structure. These sensors can provide many benefits to highway experts by analysing the fluctuations in stresses, strains, deflections, accelerations and temperature or/and moisture. Besides, the data collected periodically by these systems could ease the development of a PMS database for the future eRoad network. By using these systems, an optimization on pavement interventions decision making, predicting pavement fatigue life, and more efficient management of future budgets could be achieved.
4.3. Effects for a Life Cycle approach

The purpose behind the implementation of eRoads is to develop a sustainable road infrastructure based on e-mobility that will be environmentally friendly, economically feasible and will strengthen the society. Thus, additionally to a solid design and construction that contemplates the considerations stated until now, a method able to provide an assessment of the whole system during its lifetime performance is essential to identify and evaluate the aspects that could guide the decision-making towards a sustainable way. Within this context, tools such as Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) are becoming popular for road projects development. By using these methods, better long term quality performance, reduced environmental and economic impacts and advances in new materials and construction types can be achieved (Azhar Butt, 2014). Hence, the development of a Life Cycle framework applied to eRoad projects is essential to accomplish this purpose. However, different approaches can be given to these methods depending on the scope of the analysis (Chen et al., 2015 a):

a) **Energy life cycle performance**: related to energy production and consumption. The flows of energy consumption would be deeply modified. Regarding fuel, the incorporation of eRoad mobility solutions will cause a significant reduction in its use, which currently represents the 82% of total energy consumption in transportation (European Commission, 2014). On the other hand, in a scenario where electricity would be the primary vehicle fuel, new markets and opportunities will be open for the state and agencies towards the reduction of environmental impacts, oil imports and increase energy efficiency (Tongur, 2013). Most of the studies regarding this concern are focused in the comparison between ICE vehicles and hybrid or battery EVs, but not much attention have been paid on analysing energy life cycle flows for dynamic electrified road systems (DERS). However, in general terms, it is clear that EVs are more energy efficient and less polluting and could bring substantial improvements and costs reductions in long term, but still the integration of DERS should be accompanied of new policies related to global life cycle management.

b) **Vehicle life cycle performance**: related to manufacture, use and end of life assessment. Concerning economic terms, a priori the production of EVs will be more expensive. A pilot project in Sweden deployed an eRoad connecting Stockholm and Gothenburg suggesting the use of heavier and more expensive vehicles. This is due to the transfer technologies incorporated such as the pick-up equipment or the batteries, and the shielding required to minimize the impact of the magnetic fields associated with these devices (Viktoria Swedish ICT, 2013). Nevertheless, other studies have proven the financial savings with time, as for instance in (Aguirre et al., 2012) where a comparison between ICE vehicles and EVs over the lifetime showed a period of 13 years to pay off the extra initial cost of the EVs. On the other hand, some other studies have been conducted analysing the environmental impact between producing EVs and conventional vehicles. In Hawkins et al. (2012) an increase of almost the double in global warming potential (GWP) is shown with respect ICE vehicles during the production. Moreover, increases in human toxicity, freshwater eco-toxicity and eutrophication and metal depletion impacts are displayed from the EVs coming from the vehicle supply chain. Even though these statements show an economic and
environmental increase during production, the reality is a global reduction compensate during the use phase.

c) **Energy supply infrastructure life cycle performance:** the presence of devices to provide energy supply to the infrastructure in eRoads will also increment the environmental and the economic costs. IPT Systems integrated into the eRoad infrastructure would consist mainly in three components: energy storage system, power conversion system and balance of plant (Gill et al., 2014) which will imply extra costs during the infrastructure construction, maintenance and operation. In addition, extra costs for power companies for the expansion or reinforcement of the power grid distribution should be required. From an environmental point of view, these issues might not be that relevant, even though the fact that would mean an increase in the energy usage and the emissions and thus should be considered as well.

d) **Road Infrastructure life cycle performance:** considering the fact that the eRoad would be constructed by modifying the current network, this process involves similar steps to a new conventional road construction. The development of a road infrastructure system requires an important demand of energy, economic and environmental resources and thus has an important impact over society. In most of developed countries, road materials supply represents a whole sector as for instance in the Swedish economy (Azhar Butt, 2014). Thus, the creation of a framework managing an adequate use of energy and materials for the roads could lead to reductions on the resources used. Life Cycle Analysis tools have proven to be a method that can evaluate the impacts of a road during the different stages of its lifetime. In addition, the utilization of these techniques can improve the quantification of the pavement performance, driving to a more efficient ways on future infrastructure developments. The following section is focused on providing a life cycle approach that could be used as a reference for the development of future eRoad infrastructure projects.

### 4.3.1. eRoad Infrastructure Life Cycle Approach

As stated above, the development of an integrated life cycle analysis from an economic (LCCA) and environmental (LCA) perspective is necessary for stimulate and make feasible the introduction of DERS within the road infrastructure. In the case of LCCA, there is a road framework established by the FHWA with a detailed scheme of inputs and outputs for conducting such analysis. However, there are some shortcomings on the application of LCA tools since the pavement framework is standardized only on general levels such as the ISO (Santero et al., 2011).

Having this in mind, for the successful implementation of a new way of mobility by road as the eRoads, it seems necessary to create a standardized pavement Life Cycle framework to assess the economic and environmental flows. Even though that the elaboration of a quantitative analysis of future related inputs and outputs is beyond the scope of this study, the purpose is to present a guidance for future developments regarding this topic by outlining the main effects and consequences that involve the inclusion of IPT Systems into the road. Certainly, in this work a global approach is conducted with some environmental and
economic aspects rather than a specialized distinction between both techniques (LCCA and LCA). Since these are emerging tools for pavement analysis, considering the aspects related with the adaptation of eRoads is the first step towards the creation and standardization of electrified pavement Life Cycle Analysis structure that, in fact, will be necessary to evaluate the feasibility of the inductive dynamic charging alternative.

Figure 37 Suggested road Life Cycle system

Figure 37 represents the principal stages during the life cycle of a conventional road. Apparently, the process for a conventional road and an eRoad could be similar since both solutions are based on the same principles. However, the existence of many differences involved during the whole process for the formulation of the eRoad is obvious and some variations must be done to properly apply life cycle analysis tools.

4.3.2. eRoad Life Cycle approach framework

The following contents are attempting to develop the main procedural steps in conducting a typical life cycle approach but including some of the issues introduced by a possible integration of eRoad infrastructure. Figure 38 suggests a general life cycle analysis framework for its application to eRoads based on the established by the International Organization for Standardization (ISO 14040:2006).
Based on this general framework, an analysis could be further developed. As stated before, since there are not specific standards or experiences in the application of this tools to eRoads, the assembly of such an analysis is highly subjected to the authors perspective and thus the whole process is under their interpretation. The first step regarding goal and scope definition should expose the purpose, the audience of the study, establish the system boundaries and settle an analysis period and a maintenance activity timing. The inventory analysis corresponds to the part where the data for the analysis is collected and a product system model elaborated. Finally, the environmental and economic impact analysis should evaluate the outputs of the road life cycle and obtain conclusions for decision support.

1. **Goal and Scope Definition**

   a) **Purpose and Audience of the Study**

As a part of the whole implementation eRoad process, the creation of a standard framework should have the aim of developing a life cycle analysis methodology for eRoad pavements. In addition, elaborate a quantification of the energy consumption, the emissions and the costs related to this implementation in order to expose the feasibility and future strategies to the stakeholders involved (Figure 39).

The transition towards eRoads presents different roles for the stakeholders in contrast with traditional roads: i) Automotive firms might adopt new competencies in producing vehicles for the DERS; ii) The importance of petroleum firms would change due to the fluctuations on the demand, but probably even in a minor role, they might also be significant in this new scenario and new businesses will challenge these companies; iii) Construction companies will be the responsible of developing the infrastructure and therefore an effort in innovative practices must be done to the success of the eRoad; iv) State and agencies would have a key role as coordinators for the investment in infrastructure and mediators for the establishment of new policies; v) Power companies have to change their conventional perspective to incorporate the system into new business opportunities with the potential emergence of new
eRoad companies pioneering in the field. Finally, vi) the approach to the users is fundamental to guarantee their conviction to eRoad’s inclusion in the infrastructure.

![Diagram of eRoad Stakeholders]

Figure 39 Main stakeholders involved in the transition towards eRoads

b) System Boundaries

System boundaries are established by the goal and scope and should provide a description of the eRoad system (Rebitzer et al., 2003). This section determines the set of life cycle phases and their components considered during the analysis. Figure 40 at the end of this section, shows an example of a characteristic flow chart illustrating the phases included within the system boundaries (Santero et al., 2011).

Fig 25 showed the main phases present during the life cycle of a common road. At this stage of development within eRoads implementation and, having into account the considerations stated in the previous section, the most reasonable should be to establish as main phases for the analysis the design, the construction, and the maintenance/rehabilitation. The operation phase is normally not considered during the development of Life Cycle analysis in pavements due to the following reason: if the fuel and electricity consumption as well as the emissions from the vehicles are considered in a life cycle analysis, this would make the values displayed from other phases negligible (Azhar Butt, 2014). Thus, is better considered within a network level evaluation and of course it is taken into account for decision-making during implementation processes. However, in the case of an eRoad the balance between stages would be different (fuel and electricity consumptions), providing more weight to the other stages in terms of energy consumption. For instance, the Power Transfer Efficiency (PTE) would be a key parameter during the operation phase, influencing enormously the consumption levels during the operation phase, but at the same deeply related with the procedures conducted during the other phases. Hence, in this case cannot be stated that the operation phase should be analysed individually, and a previous balance between stages should be developed. Moreover, other phases such as demolition, recycling and waste treatment could be considered at a project level but not within the Life Cycle Analysis considering the early development stage of eRoads. Nevertheless, these considerations are under the perspective of the analyst and then different approaches could be developed.
Other boundary of the system is the traffic. The traffic is normally incorporated to the system in terms of equivalent single axle loads (ESALs), to represent the traffic loading and frequency (Azhar Butt, 2014). In addition, can be represented in terms of user delay during the stages of construction and maintenance. Having into account the fact that the traffic flows will be influenced by the integration of eRoads, these modifications should be considered for the balance and comparison with conventional roads and standardize the terms in order to allow that comparison.

It is also necessary to define the materials considered during the phases of construction and maintenance for their quantification. From here, different perspectives can be adopted depending on the purpose, for example, a quantification of energy, emissions or economic terms. Besides, new items would appear from the inclusion of IPT facilities into the road and should be quantified as well.

Finally, either in economic or environmental terms, the inputs for the analysis have to be presented in the same units in order to allow an equitable comparison between alternatives. Different economic indicators are normally used for the analysis, such as benefit/cost ratios (B/C), internal rate of return (IRR), net present value (NPV) or the equivalent uniform annual cost (EUAC) outlined in (FHWA, 1998). In terms of energy or emissions, conversion factors must be used to set certain measures. For instance, as stated in (Azhar Butt, 2014), if fuel energy and electricity are considered combined in the analysis to obtain equivalent thermal energy (ETE), conversion factors are required.

Having this on mind, the next step should be to establish the functional unit (FU). The functional unit is the basis which all inputs and outputs are normalized against to enable their comparison and analysis (Rebitzer et al., 2003). A suggested FU for the analysis over an eRoad could be for instance, one km of eRoad pavement along the main lane for the pre-established design life, or other relevant dimension as the lane width or the entirety of the lanes. Besides, typical FU also include traffic volumes.
Figure 40 Example of flow chart for a possible eRoad Life Cycle approach. Identification of the phases considered in the analysis within the system boundaries.

c) Establish Design Alternatives

The design phase normally is not considered of having a notable contribution to the process of assembling a life cycle analysis and for that reason is often not taken into consideration. Nevertheless, in this case, the configuration developed during the design will be the one subjected to the life cycle analysis and therefore will have effects over the following stages. Hence, despite the fact of not being significant for the quantitative analysis, at least should be considered from a global level.

The structural eRoad design developed in chapter 3 could be a potential alternative for the analysis. From here the materials composing the cross section can be quantified and analysed. For instance, the integration of the charging-unit module or the expansion joint would add different materials, giving place to changes during the analysis. However, in order to establish a comparison between different alternatives for presenting the most adequate, more eRoad configurations could be done based on the considerations stated at the beginning of the chapter. In addition, a conventional pavement alternative (like the one presented under Swedish conditions) should be required for this comparison in order to evaluate the feasibility of eRoads against current constructions. Finally seems appropriate as well to try different configurations in order to test the PTE of the different solutions, since this parameter will be crucial for the operation and maintenance phases.

d) Analysis Period

Road infrastructure is designed to provide a proper level service during decades. Even though the alternatives considered for the comparison might have a different service life, the conduction of an adequate life cycle analysis should apply the same analysis period for all of them and always be longer than the pavement design period (FHWA, 2002). According to the FHWA’s September 1996 Final LCCA Policy statement, an analysis period of at least 35
years for all pavement projects is recommended (FHWA, 1998). In the case of eRoads design, as stated in (Chen, Taylor, & Kringos, Electrification of Roads: Opportunities and Challenges, 2015) and in coherence with the considerations suggested previously in this chapter, the analysis period should be even longer due to the pursuit of delaying the modification of the original eRoad's structure with interventions as much as possible due to its complex composition.

e) Determine Performance Periods and Activity Timing

Once all the boundaries, components and alternatives have been identified, the next step is planning the maintenance and rehabilitation activities over the analysis period. Being eRoads a new development, there are not maintenance and rehabilitations practices established or previous experiences conducting these tasks. However, via analytical methods, performance models can be built to forecast these activity timing. Currently two approaches could be applied to the establishment of performance periods: i) a mechanistic-empirical approach. Based on transference formulas for the calculation of approximate failure cycles, has been commonly used in pavement design. Nevertheless, in this case might not be the best option considering the fact that these formulas are based on previous experiences and for the moment this data is not available for eRoads. ii) a pure mechanistic approach in order to running a distress simulation.

The first part of this thesis is based on the concept of a pure mechanistic approach by conducting a FEA for the integration of eRoads (chapter 3). At the present this solutions seems the most suitable given the lack of data from real projects in electrified infrastructure. Besides, with the use of advanced material properties supported by experimental observations, the long term performance of the pavements can be obtained enabling the establishment of future maintenance activities.

With this information obtained from the modelling, scheduled future maintenance and rehabilitation activities should be programmed in order to make the agencies aware about the periods when funds will be expended because these activities represent a significant portion over the total Life Cycle Analysis of a project (FHWA, 2002).

2. Inventory Analysis

During the inventory analysis, a data collection process is conducted. This stage is normally the most work and time consuming during the construction of a life cycle analysis (Rebitzer et al., 2003). Likewise, an estimation of agency and users costs must be done to quantify the economic part.

This data is normally obtained from different sources as literature, inventory databases, historical records, current bids and from the interpretation of professionals when dealing with new materials or methods, as in the case of eRoads. All the inventory data should be related to the FU (Rebitzer et al., 2003). Besides, the data values normally differ between studies and its selection should be adapted to the geographical location of the construction and be as much updated as possible.

These inventory data quantifies parameters such as the energy used and the emissions produced during every phase considered within the boundaries of the analysis. For instance, (Azhar Butt, 2014) on a life cycle inventory conducted in a typical Swedish asphalt pavement of the Norra Länken project in Stockholm, the energy, fuel and electricity was calculated as MJ/FU and the emissions and materials as tonne/FU, being the FU a 1 km section of the road.
Here the calculations were realized using data from different sources, such as the provided by the study elaborated in the IVL Swedish Environmental Research Institute (Stripple, 2001). This data was reported for procedures such as material production, mixing processes, vehicles transportations, and equipment paving and compacting. In the case of introducing IPT systems into the pavement, probably new data inventory should be constitute including data related to components such as ferrite or copper, and materials associated with the skeleton of the charging-unit or the expansion joints for example.

Likewise, agency and users costs are quantified for its estimation and following evaluation within the different alternatives. For agency costs are included things like preliminary engineering, contract administration, construction supervision and costs, routine and preventive maintenance, resurfacing, rehabilitation and associated administrative costs. On the other hand, users costs are related to the costs incurred by the highway user over the life of the project, such as time delays, vehicle operating or crash costs (FHWA, 1998). Mirzadeh et al. (2013) conducted a LCCA over the same section on the Norra Länken in Stockholm. In this case, the framework quantified the costs in terms of energy and time related with the different processes. Here the agency costs were composed mainly by the material production, the labour and equipment, and the transportation. Regarding users costs, work zone delay and vehicle operation were the basic parameters considered. Besides, some of the databases consulted for costs estimation coincided with the ones used for the LCA over the same road section. Applying this to eRoad solutions, there are some studies that have been focused in infrastructure costs related to IPT systems integration with the aim of creating business models for this process. For example, in (Gill et al., 2014) was outlined a cost that at first sight could result unperceived. During the maintenance phase, one of the most cost and time-consuming procedures would be the training of employees in combining the management database systems used to monitor the pavement and the understanding of IPT facilities at the same time.

Once all the parameters are identified and enabled to their quantification, the next steps is the development of a methodology to create a system model to evaluate the attributes of interest for the study. Nowadays the common procedures are based on computing the life cycle environmental and economic costs and create a model with the inputs and assumptions defined during the goal and scope, in order to realize the calculations that will provide the desired outputs. Some of the available tools for conducting LCA are PaLATE, asPect, PE-2, GreenDOT, BenReMod and CHANGER. On the other hand, for LCCA development some of the available softwares are STAMP, VTISM, BridgeLCC or Real Cost by the FHWA.

### 3. Economic and Environmental Impact Analysis

The objective of this third stage on the life cycle analysis is to comprehend the economic and environmental meaning of the previous inventory analysis carried out. This is, to interpret the flows obtained in terms of human, ecosystem and consumption of resources that might help for decision-making between the different alternatives presented. Of course, this does not mean that the development of such studies are always conducted to make decisions, but to amplify the knowledge of the different options that could drive to improvements during the development of the project. Normally, a selection of impact categories is established, depending on the project’s circumstances, to evaluate the relevance of the results. In case of environmental impact for example, the most generally used selection of impact categories is the CML methodology (FHWA, 2014), being some of the impact groups considered the energy and resources use, the emissions, the toxicity, the water or the waste, for instance.
Even though the fact that a quantitative analysis has not been carried out in this study and thus there no interpretation of the economic and environmental impact can be done, certain conclusions can be considered. In the case of eRoads, the balance between the phases of the cycle system might change (Figure 39), especially the weight of the different stages for conducting a life cycle analysis could be modified. A decrease in the fuel consumption would be obvious with the electrification of the roads, but at the same time, an increase in the electricity consumption would take place. As well, the fact that the use of the ICEs will be reduced implies the reduction of the emissions to the atmosphere. However, the role of the PTE for this balance is going to be crucial, since the consumption and emissions are going to be dependent on this efficiency. Thus, in eRoad systems with a reduced PTE, the waste outputs would be higher, so this fact would change the whole balance of the system in terms of environmental and economic impact, reason why a deep comparison with conventional pavement should be necessary. Having this in mind, the structural design will be decisive, since the disposition of the IPT systems and the composition of the pavement will affect to the magnetic loss and therefore to this PTE. Finally, the origin of the electricity generated to supply the road infrastructure can also be critical; in case of not coming from renewable sources the consumption levels would be modified as well and probably being unfavourable for the eRoad solution.

4.4. Summary

This chapter summarizes the considerations and effects of implementing eRoads based on IPT systems in road infrastructure. A review over the main stages of an eRoad project development is conducted in order to appreciate the following considerations:

a) Design and construction:
   - The IPT facilities can be integrated directly into the pavement as a skeleton structure or embedded in a prefabricated unit, being this last option the adopted for the FEM and thus the one used as a basis for following considerations.
   - The IPT systems should be placed symmetrically in the centre of the lane and the dimension of the charging module would be similar to the ones between wheels in a regular vehicle.
   - The adequate protective overlay should meet the appropriate balance between dimensions and materials composition in order to allow a good PTE.
   - The PTE is mainly influenced the dielectric response of the overlay´s materials, the gap distance and the misalignments between vehicles and IPT solutions.
   - eRoads designs will be probably more influenced for stress than for strains requirements.

b) Maintenance: the role of the preventive maintenance would be essential for the integration of the eRoads since the main purpose is to delay as much as possible the intervention of the structure. Besides, the access to the IPT technologies is suggested for realize their adequate maintenance. Pavement monitoring and management systems are suggested to improve the maintenance.
The second section of the chapter constitutes a first approach for future Life Cycle analysis applied to eRoad infrastructure. The aim is to stand out the value of conducting an assessment during the lifetime of the eRoad infrastructure in order to achieve its feasible and sustainable implementation. Having this on mind, the main conclusions displayed are:

- Create a framework applied to eRoads is necessary for future development of Life Cycle analysis over this infrastructure.
- The environmental and economic impact would be highly dependent on the operation phase and therefore, this stage should be included in future analysis.
- Different design alternatives of eRoads must be included in the analysis in addition to a conventional pavement alternative in order to do a comparison between solutions.
- The PTE will be influential for the balance of the system and thus special attention should be pay in further developments.
5. Conclusions and Future Work

The development of eRoads within the context of Smart Roads, is currently under active investigation. At the present, the road infrastructure studies related with DERS have mostly been performed on a feasibility analysis level or as a pilot projects. Thus, there are still a large number of remaining gaps and uncertainties regarding the implementation of IPT Systems in road transportation.

By the use of mechanistic structural pavement design methods, such as the multi-layered systems or FEM, the pavement structure subjected to traffic loading can be characterized by its response (stresses, strains and displacements). This study aimed to create a model using a FE tool, where IPT systems are integrated into the pavement to simulate the mechanical behaviour of an eRoad. The pavement is configured according to Swedish conditions, focusing on the region of Stockholm, and thus a first layer of HMA is placed over the IPT technologies to follow the structure of most Swedish pavements. Fundamentally the conclusions displayed were:

- Significant stress concentration over the charging-unit is noticeable and then is suggested that the failure criteria will turn to critical stress at the bottom of the charging-unit module instead of tensile strains as typically demonstrated in conventional flexible pavements (similarity with composite pavements)
- The use of a silicone expansive rubber joint in the interfaces between the charging-units produced a stress relief in this area as expected. These observations suggest the investment in further research for the integration of mechanisms that could release the pressure applied to the IPT facilities and thus achieve a better mechanical integrity.
- Finally, the sensitivity analysis conducted to evaluate the relevance of the thickness and stiffness in the overlay showed the thickness as essential parameter. Obviously, for better improvement the use of better quality materials in the overlay will be necessary. On the other hand, definitely, the reduction of the thickness with the aim of decreasing the gap distance between IPT technologies and vehicles seems remote and thus, distances of 40 or 50 mm for the surface layer will be required as well as has been until the present.

The second extract of this study (chapter 4) is divided by two main parts:

a) The first part stands out the considerations and effects that should be considered during the main stages of an eRoad infrastructure project development (design, construction and maintenance/rehabilitation) and which thus were considered over the
structural FEA developed in chapter 3. The main conclusions obtained during this compilation are:

- During the design and construction of eRoad based on IPT systems, the main aspects to take into consideration were the way of integrating the IPT facilities into the pavement, the geometry and location of the same, the characteristics of the protective overlay and considerations over the PTE that are required for the proper operation of the system.

- Regarding the maintenance: preventive maintenance would probably acquire an important role to delay future interventions in the pavement. In addition, some fundamental aspects that need to be taken into account are: potential damage next to electrical components, interferences in electric supply, human safety, intensification of maintenance activities under winter conditions, frost damage within joints and pronounced rutting effect. Finally, can be outlined as well, the necessity of easing the access to IPT facilities and the use of some systems such as monitoring procedures or PMS to improve the efficiency in those activities.

b) On the other hand, a Life Cycle perspective over the eRoad infrastructure is essential for concluding the implementation process. The electrification of road infrastructure is the expression of renovated and sustainable road transportation, where the assessment during its lifetime must complement the design in order to accomplish this purpose of sustainability. Even if a design reaches all the structural requirements, within this new idea of e-mobility, the realization of such projects would make no sense if the environmental, social and economic goals are not accomplished. Hence, the purpose is to create a guideline as a first approximation for future Life Cycle analysis applications over eRoad infrastructure. To do so, a review over the framework of a road project is conducted through adding some of the considerations imposed by the integration of electrified roads into the network. The main conclusions obtained from that review are:

- The necessity of creating an appropriate framework specialized and standardized for the elaboration of Life Cycle analysis of eRoads.
- The modifications on the waste flows and the economic and environmental impact suggest the inclusion of the operation phase for future analyses.
- Several eRoad design configurations are required to achieve the balance between structural performance and PTE.
- The role of the PTE is essential because will affect the balance of the system and therefore should be considered as a key issue in further development.

Having concluded all this considerations that will lead to a feasible integration of the eRoads in the current infrastructure, which are the consequences of this implementation over the road transport system? There are different scales for the implementation of this concept: i) the creation of a network within the city to promote the city logistics and public transportation: short routes adapted for light trucks, vans, buses and regular vehicles; and ii) the creation of a network between main cities or nodes: long distance routes created for the regular long haulage transportation of goods and people. This means the creation of a new concept for the road transportation where new policies and regulations, new road classifications and new standardizations (traffic signals, especial lanes, etc.) would need to be developed. Besides, the
role of the stakeholders will be modified, reducing the prominence of certain sectors and
given the chance of promotion to other areas. Being the industry sector the highest beneficiary
of the electrification of roads due to the costs reduction and the increase on efficiency, the
option of establishing long-regular distance routes seems currently the more realistic.
However, despite the fact that once the infrastructure is constructed the cost of transportation
would be relatively low (in similarity with the railway), the initial investment will be really
high and thus, industry and governments will play a fundamental role for its promotion by
taking certain risks and start introducing it in the markets. Nowadays, the option of
electrifying the entire road network seems not viable and the solution may involve a
combination of the two alternatives with the use of hybrid vehicles using electricity in
combination with other fuels. The investment in studies like the developed in this thesis
where, the sustainability and feasibility of the infrastructure can be evaluated, in combination
with further research in terms of transportation and logistics, is the first step to ease the
adaptation process that could lead to the full electrification of the road infrastructure in the
long term, revolutionizing thus the road transportation.

Finally, presented the main conclusions of the study, some perspectives are open for future
studies. The inclusion of advanced material properties into the FEA, such as viscoelasticity or
non-linear stress conditions, and a dynamic or cyclic load could lead to a much more realistic
analysis. The development of a mechanistic model based on this new conditions, could
provide not just outputs related to the response (stresses, strains and displacements) but also
damage, cracking, fatigue and cycles to failure that would contribute to the determination of
long term performance periods and thus activity timing. Within this modelling, sensitivity
analyses could be realized between different configuration to evaluate the relevance of aspects
such as the material composition or dimensions (e.g. thickness and E). Moreover, another
contribution should be an empirical approach by conducting tests with IPT systems integrated
in the pavement that would also display valuable data. Likewise, electro-magnetic simulations
of the whole systems should be a good practice to evaluate and improve the PTE of the IPT
systems in the infrastructure.

On the other hand, all the results and conclusions obtained from this progress during the
structural analysis should be integrated into a Life Cycle Analysis. Given the improvement
regarding knowledge and quality data, the design alternatives and the analysis and
performance periods could be more accurately established. This together with the
coordination with transport research concerning e-mobility, could enormously contribute to
the standardization of a Life Cycle perspective for eRoad infrastructure as for instance,
settling the system boundaries. Besides, initiate a collection data process to create a database
or inventory for eRoads components quantification seems as well a future requirement.
Having this on mind, the creation of a standard and elaborated framework would be possible
and thus the development of Life Cycle Analysis would guarantee a sustainable and feasible
eRoad implementation.
References


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