FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

Integrated LCA/LCCA system for evaluation of E-roads

Deliverable No.		D5.3.1	
Workpackage No.	WP5.3	Workpackage Title	Road Infrastructure Impact & Solutions
Authors		KTH, QiE, POLITO	
Status		Final	
Dissemination level		Public	
Project start date and duration		01 January 2014, 48 Months	
Revision date		2016- 10 - 08	
Submission date		2016- 10 - 13	

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 605405

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
CAM	Cement Asphalt Mortar
CU	Charging Unit
DWPT	Dynamic Wireless Power Transfer
EF	Environmental Factor
EOL	End of the Life
E-road	Electrified Road
EV	Electric Vehicle
FU	Functional Unit
HMA	Hot Mix Asphalt
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
MTS	Material Testing System

REVISION CHART AND HISTORY LOG

REV	DATE	REASON
1st revision	2016-10-08	Revision made according to the comments from peer review

EXECUTIVE SUMMARY

This document is deliverable D5.3.1 'Integrated LCA/LCCA system for evaluation of E-roads', which is to summarize the first tasks in WP53 i.e. Tasks 5.3.1 Sustainability of the E-road at a system's scale (LCA/LCCA component integration and development) and long term performance prediction framework for the E-road (Task 5.3.2).

The aim of this WP is to assess the life cycle environmental and economic impacts of the E-road infrastructure, while the work plan is made as follows:

1) *Step 1:* To develop the life cycle assessment and costs tools (Task 5.3.1), as well as a long term performance prediction framework for the E-road (Task 5.3.2);
2) *Step 2:* To make an comprehensive evaluation of the E-road construction procedures (5.3.3) and long term performance predictions (Task 5.3.4), as well as strategies for monitoring, maintaining & operating of E-road (Task 5.3.6).
3) *Step 3:* To perform case studies regarding the detailed LCA/LCCA assessment of E-roads (Task 5.3.7), based on the methodology developed in Task 5.3.1 and the procedures and strategies identified in Tasks 5.3.2-5.

In this deliverable D5.3.1, the work in step 1 has been completed. Specifically,

i. an integrated LCA and LCCA system has been defined, in which the important system boundaries to enable meaningful comparisons between the E-road solutions as well as with non-electrified roads have been established carefully.
ii. Some important aspects regarding the framework have been detailed for further explanations and clarifications, such as methodological theories and data collection.
iii. A comprehensive evaluation framework for E-road long term service performance predictions has been created, which can provide an important methodological basis for the later work in Step 2 of the WP regarding the E-road structural design and optimizations, as well as the time planning strategies in the various phases of an E-road life cycle.

As such, this deliverable has established a comprehensively integrated LCA/LCCA system for assessing the E-road sustainability, which can serve as a first step for the future detailed LCA/LCCA assessment in D5.3.4. Some limitations of this deliverable should be noted: the detailed information regarding the geometry and material properties of the assumed functional unit have not been specified in this deliverable, which are indeed important for a complete framework development. The on-going research work in the next deliverables D5.3.2 'Technical specifications of construction of E-roads (TRL)' and D5.3.3 'Technical specifications of maintenance & operations of E-roads (POLITO)', which are under development in parallel with D5.3.1, will provide more reliable assumptions/recommendations regarding the details of the E-road structure. It is thereby advised to leave this information to be specified and included in the actual case studies of LCA/LCCA in D5.3.4.

1 INTRODUCTION

Supposing that all technical limitations can ultimately be removed for E-road solutions, there is still a great need to reflect upon the original aim of pursuing the EV technology to effectively reduce the life cycle impacts produced by the road transportation sector. It is therefore important that appropriate system boundaries in the life cycle analysis are chosen and that the integrated system is considered from a holistic point of view, especially in context of enabling the E-road charging infrastructure. Several aspects can be included in such an analysis:

- *Fuel.* This includes phases of upstream production and downstream in-use.
- *Vehicle life cycle.* This includes phases of vehicle production, use and end of life.
- *Energy supply infrastructure.* The energy supply infrastructure (including power plant, grid and distribution) has performed as an indirect role in the EVs' life cycle environmental performance (Nansai, Tohno et al. 2001, Lucas, Neto et al. 2012, Lucas, Silva et al. 2012, Meinrenken and Lackner 2015).
- *Road infrastructure.* Provided that the E-road is built based on upgrading the existing road infrastructure, the road pavement will be excavated and reconstructed. Likewise, regular operational maintenance actions will be performed throughout the use phase to ensure the good conditions of the E-road. In these stages, new infrastructural materials, new on-site processes and extra waste disposals can be involved but the consequential impacts are unclear. Therefore, for the case of E-road infrastructure, the impacts of the changed road construction and maintenance also need to be included in EV's total life cycle analysis. In other words, the benefits of the electrified road transportation should not be overshadowed by the added environmental burdens associated with the inclusion of IPT charging technology in the road infrastructure.

To answer the above concerns over the life cycle performances of the E-road infrastructure, a systematic LCA/LCCA evaluation will be performed in this WP53 of FABRIC project. As such, it should also be noted that this 'systemic' evaluation is referring only to the infrastructure part at project level and is not including the vehicle or energy parts. In fact, approaching road infrastructure from a life cycle point of view is becoming a common procedure to implement feasible and efficient pavement projects as well as to improve their performance during the different stages of the lifespan in these constructions. In order to create sustainable and economic road infrastructures, it is necessary to use tools that complement the design and construction (Butt 2014). The Life Cycle of a road pavement can be analysed from both economic and environmental perspectives by using the two following techniques respectively: Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA).

- LCA can be defined as a technique to evaluate the environmental behaviour of a product, service or an activity through characterizing and quantifying the flows of the system during its cycle of life (Baumann and Tillman 2004). The use of LCA tools in pavements started in the 1990's and has been much more developed since then (Butt 2014). It is a powerful tool largely used by industry and

researchers, while the most common type consists of a comparison of alternatives or materials and even though there is not a specific standard for it and therefore the outputs from study to study vary.

- LCCA, according to the definition by U.S. Federal Highway Administration, is a technique based on economic analysis to evaluate the long-term economic efficiency between alternative investment options' (Smith 1998). This tool is of great importance for providing cost estimation over the lifetime of a road and creating a framework to identify and evaluate key factors for designers, road administrators and contractors prior and during the development of a project. Many transport administrations have integrated the elaboration of this type of analysis to the investments related to normal road projects in the last years, as for instance in Sweden (Mirzadeh, Butt et al. 2014).

This deliverable is the first part of a complete life cycle assessment in environmental and economic terms of WP5.3. Thus, the aim of this deliverable D5.3.1 is to establish a general framework and its boundaries that will be considered for the evaluation of E-road pavement and its comparison with a conventional pavement. Specifically, the first section of this document displays the system boundaries of the analysis that are common for both LCA and LCCA approaches. This is essentially the goal and scope definition, where the phases over the lifetime, the analysis period, the functional unit (FU), the pavement alternatives and the scheduled activity timing are stated. Thereafter, the methodology and more specific system boundaries are particularly shown for the LCA and the LCCA. Afterwards, a comprehensive evaluation framework for E-road long term service performance predictions has also been created, which can provide an important methodological basis for the later work in Step 2 and thus the boundary inputs in the detailed LCA/LCCA analyses in Step 3.

2 METHODOLOGY FRAMEWORK DEVELOPMENT OF LIFE CYCLE ANALYSIS OF E-ROAD

2.1 Goal

The aim of this WP53 work, as already mentioned above, is to make a systematic evaluation over the life cycle performances of E-road infrastructure, in terms of environmental impacts and economic costs. The conclusions from these analyses will provide important insight into where the impacts and costs are occurring in the E-road life cycle, as well as help to develop the strategies that can reduce these impacts and costs. In this regard, this work would help decision-makers in industry organizations and governmental agencies adopt more sustainable E-road design practices, contributing thus to the improved sustainability of our road transport sector through electrification as a whole. The objectives of this work have therefore been identified as follows:

1. Develop a common LCC/LCCA framework as a methodological base to coordinate the detailed life cycle performance analyses of E-roads (D5.3.1).
2. Establish a comprehensive evaluation framework for E-road structural design and long term service performance of the E-roads (D5.3.1).
3. Make an comprehensive evaluation of the E-road construction, monitoring and maintenance procedures (D5.3.2 & D5.3.3).
4. Quantify the life cycle environmental impacts and economic costs of E-roads, based on D5.3.1, D5.3.2 and D5.3.3 (D5.3.4).

Within this deliverable D5.3.1, the system boundaries for the development of a tool capable of assessing the long-term environmental and economic impact of the E-road infrastructure will be established. With this purpose, as a first step towards a more detailed study in D.5.3.4, it is necessary to build individual LCA and LCCA frameworks where the components of the E-road infrastructure over its lifetime are defined. In fact, there is not a specific LCA framework elaborated for pavements and currently has been just standardized on general levels according to the ISO guidelines (ISO 14040:2006 and ISO 14044:2006), whilst a framework for developing a LCCA for pavement projects has been established by the U.S. Federal Highway Administration (FHWA)(Smith 1998). Nevertheless, in order to perform a meaningful analysis, both LCA and LCCA tools must be connected and developed with the same approach and therefore the methodology followed in this document tries to develop both tools in parallel.

2.2 Scope

This section goes through the common aspects of the E-road pavement that are considered for both LCA and LCCA over their different stages from a framework approach. In this regard, the scope of this analysis is to include important processes that might be relevant for E-road pavements, which must be outlined in order to have a better understanding on how to develop a tool able to assess the environmental and cost impacts of E-road pavements, as well as the comparison with reference pavements. The focus is placed on specific impacts for the pavement and broader evaluations to address the implementation of E-roads as a whole, which will be further developed in

coming deliverables. Larger issues related to road transportation are beyond the scope of this deliverable.

2.2.1 Phases included in the study and analysis period

The analysis period should be chosen to cover the important environmental and economic costs that involved in different life stages of the pavement alternatives. In this, typical design lifetime for new/reconstructed highway pavements surfaces ranges from 10 to 20 years for asphalt structures and 20 to 30 years for concrete structures. And there should be at least one future rehabilitation activity included in this period.

It is noteworthy to mention that depending on the construction method used for the alternatives, it might be appropriate to vary this analysis period. For instance, full-lane new constructions are encouraged to have longer analysis periods than reconstructions or modification projects. However, it is required to be consistent and apply the same analysis period to all the pavement alternatives considered in the analysis and therefore, an analysis period of 25 years is established for both E-road and conventional pavements. Therefore, the study mainly includes the construction of the E-road pavement with its multiple components and the operation and maintenance events over 20~25 years, including as well rehabilitation activities (shown in Figure 1).

Moreover, the energy and resources consumptions by the traffic during the operation phase are not included in this study, since it is limited to the project level; WP5.5 is specially focusing on this issue and afterwards both studies will be exposed in a network level. Depending on the research question and how the system boundaries are defined, the End of Life (EOL) can vary its relevance within the life cycle of the pavement. Considering the infrastructures are rarely completely demolished and disposed after the end of their life (Miliutenko 2012), this phase is thus not considered in this analysis.

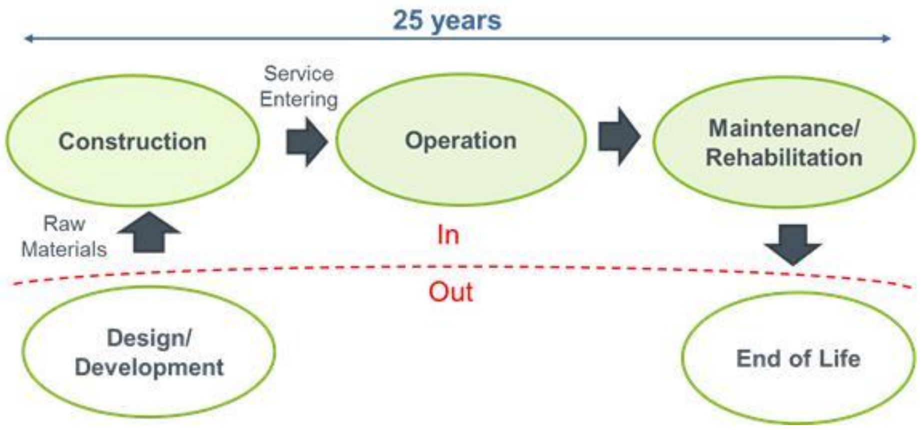

Figure 1 Phases considered in the framework for E-roads

2.2.2 Functional Unit

The functional unit (FU) is the basis for which all inputs and outputs are normalized against to enable their comparison and analysis (Rebitzer, Ekvall et al. 2004). The FU

can be common for both LCA and LCCA, with a premise that the different pavements are evaluated and compared with equivalent parameters. For this analysis, it seems adequate to consider a functional unit of 1 km-long pavement, following many authors in previous studies made in Europe (Carlson 2011).

At least two feasible pavement alternatives need to be identified for the LCA/LCCA evaluation i.e. an E-road and a conventional road. Therefore, the chosen representative structures are based on the assessment of a single highway lane, where the E-road pavement is compared with a conventional pavement with the same material and structural compositions. A generic illustration of a potential E-road cross-sectional geometry is illustrated in the following Figure 2, which is based on modifications of a traditional road. Starting from the top, the E-road pavement structure consists of an asphalt layer, granular base, subbase and subgrade layers. The charging unit (CU) is embedded within the asphalt layer in the middle of the lane, within a few centimetres to the pavement surface. The detailed E-road pavement structural information, such as material properties and thicknesses of individual layers, will be identified in the final D54.3. This is because the on-going research work in D5.3.2 and D5.3.3, in terms of such an E-road construction and long term performance predictions, will provide more reliable assumptions regarding these details of the E-road structure. Moreover, the structure of a traditional road can be the same as the E-road, except for that without the embedment of the CU.

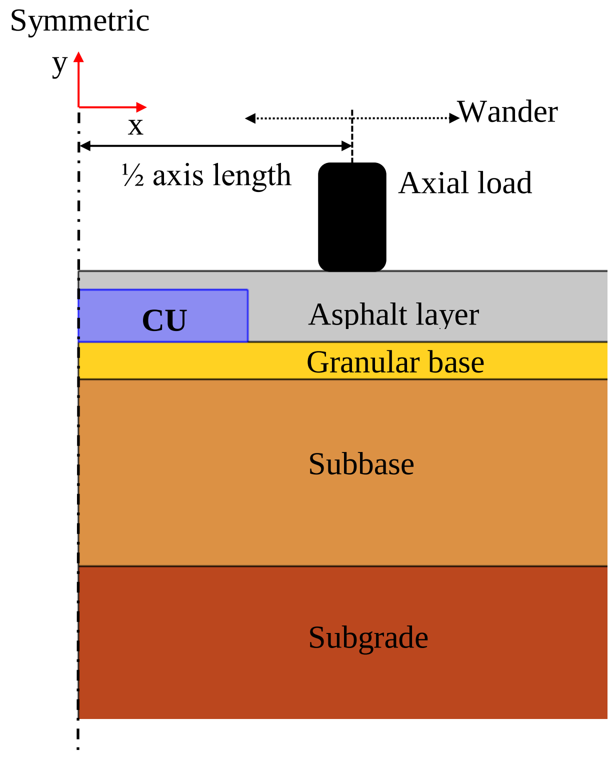

Figure 2 Example of cross section of a E-road lane (2D symmetric plane)

An important component in the E-road is the Charging Unit (CU), which is normally composed by induction coils, magnetic shaping materials (Ferrites), and other ICT facilities, as well as the module matrix for holding these components firmly and safely under traffic and environmental loading. There are three main construction methods for the installation of a Dynamic Wireless Power Transfer (DWPT) system: trench based construction, full lane construction and full lane prefabricated construction. These three construction technologies are described and compared in Table 1. At least one (the most representative) solution should be considered in the detailed LCC/LCCA assessment studies of the next stage.

For the same reason explained above, the details of geometry and material properties of the CU for LCC/LCCA will be decided later upon, based on the outcomes of D5.3.2 & D5.3.3, which will be incorporated into the D5.3.4. For illustration purpose, a possible CU case can be found in the following Figure 3, which is based on a testing prototype developed at the Italian test site (D5.3.3). In this, the module of the charging unit, which could influence the structural performance of the whole system, can be fabricated by either asphalt material or high stiffness Cement Asphalt Mortar (CAM) (Wang, Yan et al. 2011), and without any covering overlay i.e. the CU top surface is being flush with the pavement surface as a whole. However, the final decisions on this case, for instance regarding whether asphalt or CAM will be used for the CU module or whether it is necessary to use an extra overlay for protection purpose, should be decided according to further investigations in D5.3.2 & D5.3.3.

Table 1 E-lane construction methods

Construction methods	Description	Features
Trench based construction	Creating a trench in the existing highway, installation of the system (whether in situ or pre-cast), backfilling and layer an asphalt surfacing layer	Quickest and cheapest option, potential reflective cracking at the surface and transverse joints. Need to customise a machine for specific width and depth requirements
Full lane reconstruction	Removing the full depth of bound layers from lane, and either constructing in-situ or using pre-cast units, followed by construction of a concrete pavement around the units and then by asphalt surfacing	More time consuming and expensive but with the advantage of locating longitudinal construction joints at the edge of the lane. DWPT units and associated connection pipework would be delivered to the site in precast form and the pavement constructed around them
Full lane prefabricated construction	Replace with a full lane width prefabricated section containing the entire system. This could possibly be finished with a asphalt surfacing as above, or by having a porous concrete surfacing already placed on the prefabricated sections	An accelerated construction period and factory construction quality. Whilst prefabrication is likely to be the highest capital cost option, there would be significant savings in traffic management costs with the only major concern being the potential disruption caused by the transport of these systems to site

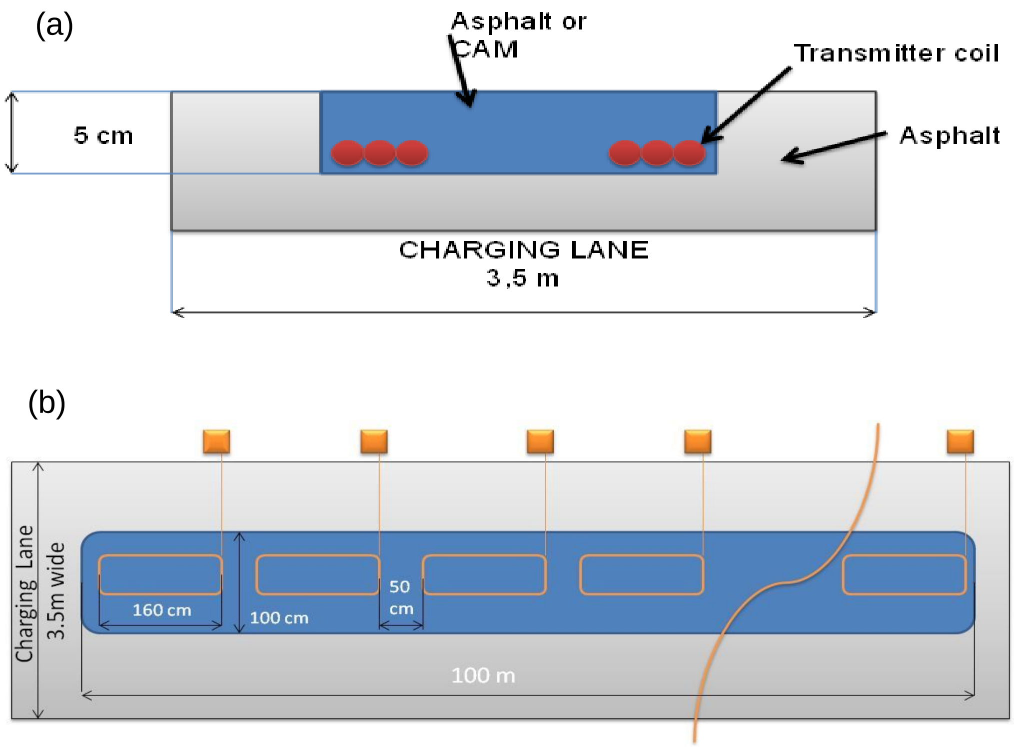

Figure 3 An alternative solution for E-road structure: (a) cross-sectional view (b) Top view.

2.2.3 System Boundaries

It is of great importance to define the system boundaries and attributes constituting the life cycle stages to further develop a detailed study that will reinforce the decision-making and recommendations in the coming implementation of E-roads.

Figure 4 presents an illustration of the stages and components included in the system boundaries for the future life cycle analysis. As stated before, the phases (construction, maintenance and operation) of the life cycle considered for the analysis are represented with their multiple components. The definition of system boundaries is based on where the system needs further development in order to provide a better decision support. Therefore, this definition will exclude some processes that are beyond the scope of the analysis or with less influence. For instance, during the construction phase the subgrade preparation, road markings, fences and railings, road signs, lightning and traffic lights are excluded since the impact derived from them would be the same for the E-road as for a conventional road (used as reference alternative). The same applies for maintenance and operation of the above named elements, given the fact that the electrical components are the most significant entities when comparing the E-road with the traditional road. These exclusions are specified and justified in the corresponding sections.

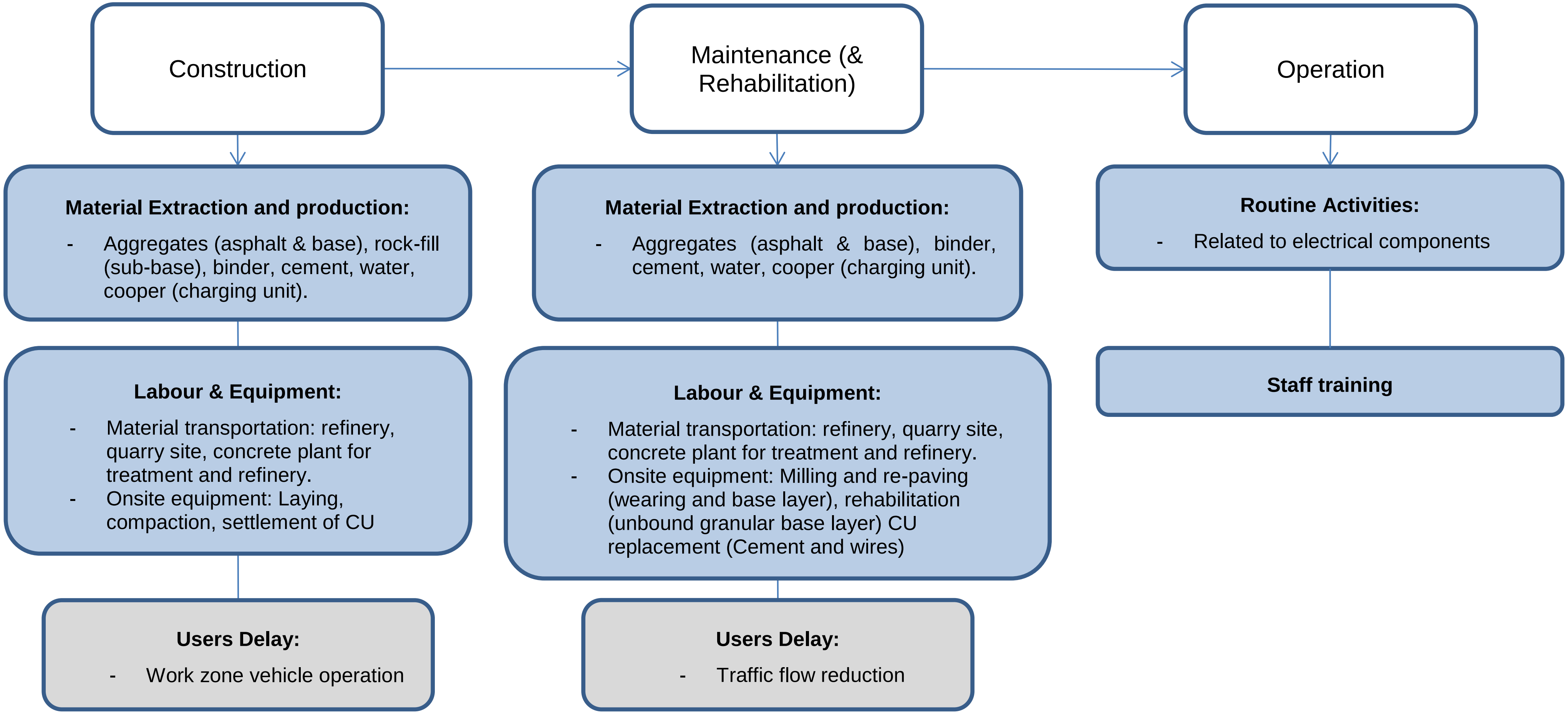

Figure 4 Life cycle system boundaries (phases and components) considered in the LCA & type of costs in the LCCA (Agency costs (blue), users costs (grey))

3 SOME IMPORTANT ASPECTS FOR LCA/LCCA

3.1 Important aspects for LCA

3.1.1 Data collection

Once the phases and components considered in the LCA are stated, it is necessary to establish the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) methodology in the framework, to further develop a detailed environmental analysis of the pavement alternatives.

Before moving to the second phase, i.e. the LCI, a number of technical items are to be considered in order to comply with the ISO guidelines (ISO 14044:2006). In the previous paragraphs functional unit and system boundaries have already been defined. However, other aspects need clarification:

- *Allocation factors*: in the present case there is no evidence of co-products or by-products of economic relevance, therefore there should be no need to introduce allocation factors; in any case, this point has to be explicitly discussed when full LCA will be performed in the next deliverables.

- *Data quality requirements*: geographical coverage need explicit discussion because country energy mix will play a fundamental role in the environmental performance assessment; instead, time-related coverage is less vital for E-roads which are still on a project scale (laboratory and industrial pilots), however for the selection of average technologies to be used in the road infrastructure construction a time reference is to be chosen.

- *Cut-off criteria*: in principle all material and energy flows are to be included in the LCA analysis, but this is not always possible or feasible or reasonable; there are flows whose amount and relevance to the analysis are absolutely negligible and their collection is not worth the effort; however, criteria to decide which flows to exclude from the analysis have to be clearly stated before starting data collection. Generally, for materials in inputs a mass criterion is a good choice (for instance, all flows lower than 1% of the total input masses as long as their sum does not exceed 5%); a similar criterion can be adopted for input energy flows and output waste flows.

- *Critical review*: an independent critical review is generally optional in LCA, but it becomes mandatory in the case of comparative assessment as it is here the case; so, it should be discussed among the stakeholders of the project which policy to adopt.

Once these preliminary, but necessary, items have been assessed, the second phase, can be tackled.

3.1.1.1 Product system

In order to carry out consistent and comparable LCA studies of the two product systems discussed previusly, i.e. E-road and conventional road, a simple roadmap can be skecthed out before starting data collection.

- Give a preliminary description of the system.
- Make a list of the unit processes that compose the product system; the choice of unit processes is to a certain extent arbitrary and depends on the level of accuracy of the analysis that one wants to perform; of course, it is fundamental to adopt the same level of accuracy in both analyses, i.e. E-road or conventional road.
- Sketch in the product system under analysis, i.e. E-road or conventional road, using a process flow diagram, where unit processes and their inter-relationships are clearly drawn.
- Give a detailed description of each unit process listing all the input and output flows, classifying them in terms of elementary flows (raw materials, emissions to air, water and soil), product flows, and wastes.

3.1.1.2 Data quality and requirements

These activities are preliminary to data collection. Generally, data can be of three types:

- *Measured or primary data*: these data are directly measured in the specific system under study or in equivalent representative systems; clearly, in the case of E-roads they are to be supplied by partners thanks to pilot activities.
- *Calculated data or secondary data*: these data are usually taken from databases or other official sources that have calculated them on systems that can be considered equivalent to the unit process present in the product system to be analysed. For instance, in the E-road construction, cement is an input product; obviously, the direct emissions from the cement production plant supplying the cement for the E-road need not be directly measured, but one can admit that the average emission factor of the European cement production industry can be safely used; clearly, this value has been calculated by averaging on a number of primary data and listed in a database.
- *Estimated data or tertiary data*: generally these data are deduced from literature works or other sources that are not directly related to the system under study or to equivalent systems; the model system can be loosely compared or linked to the system being investigated, but it might be preferable to have an estimated value of a relevant flow instead of no value at all.

The three kinds of data are admitted by the ISO standard and it is likely that they all will be used in the following deliverables. Once all the data have been collected and

elaborated so that the flows are referred to the functional unit, they can be converted into environmental impacts following the guidelines of ISO 140444.

3.1.2 Life Cycle Impact Assessment (LCIA)

Each material or energy flow calculated in the LCI phase (input data in the LCIA phase) can be connected to an environmental burden (output of the LCIA phase) through the Enviromental Factors (often called Characterization Factors). The EF units depend on the input and output that are being linked: for the example of a CO_2 output, materials EFs might be in kg CO_2/kg material, or transportation EFs in kg CO_2/kg-km traveled (Santero, Loijos et al. 2011). EFs are found in a number of primary sources, such as journals, reports, LCI databases, process-specific models, and other sources. Usually, professional softwares adopted to carry out the LCA offer a full range of EFs for a large number of impact assessment methods. The software used in the present project is Simapro by PRé (https://www.pre-sustainability.com/simapro).

In this way, LCI results are converted to one or more midpoint impact categories (e.g., climate change) through characterization factors (e.g., global warming potential), which normalize similar pollutants (CO_2, CH_4, N_2O, etc.) to a single metric.

3.1.2.1 Impact categories

Before calculating the impacts it is necessary to choose the impact categories to be used in the study. Typical impact categories for LCA of road pavements are:

- Cumulative Energy Demand (CED) or Total Energy Demand
- Green House Gas (GHG/CO_2) emissions (Global Warming Potential)
- SO_2 emissions (if necessary)

For a larger choice of the impact categories that might be relevant in the transport sector, the outcomes of the European project LCE4ROADS (http://ecolabelproject.eu/) can be considered (Díez 2015).

As for the LCIA methods listed above, they are well known and details can be easily found in the current literature (e.g Frischknecht, Wyss et al. 2015); GHG characterization factors are published by the IPCC in their most recent report (Change 2013). In case additional impact categories, such as acidification, eutrophication, photochemical ozone creation potential, etc., are considered, characterization factors can be easily recovered, being embedded in most technical softwares used to assess environmental LCA.

3.2 Important aspects for LCCA

3.2.1 System boundaries

As described above, LCCA is an engineering economic analysis tool that allows to quantify the differential costs of alternative investment options for a given project. In our specific case, LCCA can be used to study new E-roads projects and to examine

roadmaps and strategies for the upcoming years. LCCA considers all agency and user costs throughout the life of an alternative, (not only the initial investments). More than a simple cost comparison, LCCA offers sophisticated methods to determine and demonstrate the economic merits of the selected alternative in an analytical and fact-based manner.

In order to clarify the system boundaries, it is important to appropriately define the following concepts:

1) **Agency costs**. Agency costs are the ones incurred by contractors and owners for the construction, maintenance, rehabilitation and operation activities. Critical to an insightful LCCA are good estimates of the various agency cost items associated with initial construction and periodic maintenance, rehabilitation and operation activities.
   - *Construction expenditure.* Data on construction costs are obtained from historical records, current bids, and engineering judgment (particularly when new materials and techniques are employed as in the FABRIC project).

   - *Maintenance and rehabilitation expenditure.* Similarly, costs must be attached to the maintenance and rehabilitation activities identified in the previous steps to maintain the asset above some predetermined condition, performance, and safety levels. These costs include those for preventive activities that are planned to extend the life of the asset, day-to-day routine maintenance intended to address safety and operational concerns, and rehabilitation or restoration activities

   - *Operation expenditure.* It includes those costs related to electrical components operation in a daily routine (charging and payment supervision, flow control, etc). We also consider here the staff training process.

   Neither the "salvage value," usually the net value from the recycling of materials at the end of a project's life nor the "remaining service life" (RSL), value of an alternative (the residual value of an improvement when its service life extends beyond the end of the analysis period), will be considered in our calculations, as defined in Figure 1.

2) **Users costs**. Users costs are the costs incurred by the public (drivers, residents, etcetera) and in this case referred to travel time delays and crash costs. We can consider two types of user costs.
   - Users travel delays during the e-corridor construction due to traffic restrictions and users delays during the maintenance and rehabilitation operations by the same reasons.

   - Crash costs differential increase over a conventional road, due to the specific E-roads layout and the successive maintenance and rehabilitation operations. Depending on the safety conditions of the final design, we will appreciate statistical differences in terms of crash costs between a conventional lane and the e-corridors.

A summary of the main expenditure to be considered in the LCCA is depicted in Figure 4 (agency costs in blue and users costs in grey).

3.2.2 Data collection

The main advantage of the FABRIC project is the possibility for the first time, to compute real costs for the DWPT technologies. Three demonstration sites will generate a set of cost data as a base for a further analysis allowing real market projections overtime. The general exercise to be done by all the stakeholders involved includes three main phases:

3.2.2.1 Identification of main expenditure items at the demo sites.

This information does not reflect the potential market prices but provides an order of magnitude as a base for the roadmap calculations. Of course, the manufacturing processes for the equipments are not optimised at this stage and maybe some machinery to improve the e-lane construction need to be adapted and so on. The application of lean management techniques will allow moving to the next step in the process. Within this deliverable 5.3.1. the cost analysis will be focused exclusively in the E-roads.

3.2.2.2 Estimation of first entry market prices.

This is a very complex process requiring to match offer and demand, show in Figure 5. At one side, there will be equipment suppliers, contractors (owners or leaseholders of the installations) and the public administration (owner of roads) and public or private utilities (energy suppliers). In addition, from the demand side, a calculation about the number of users, and the corresponding energy demand must be foreseen. To that end, an estimation of the type and number of vehicles using the E-roads will be needed to calculate earnings within the system. For sure, at the very beginning some kind of subsidies will be assumed by the administrations. A set of contracts with public entities and/or environmental aware commercial companies will be needed to ensure the continuous flow of vehicles through the e-corridors. In this complex ecosystem all participating actors shall balance their economies.

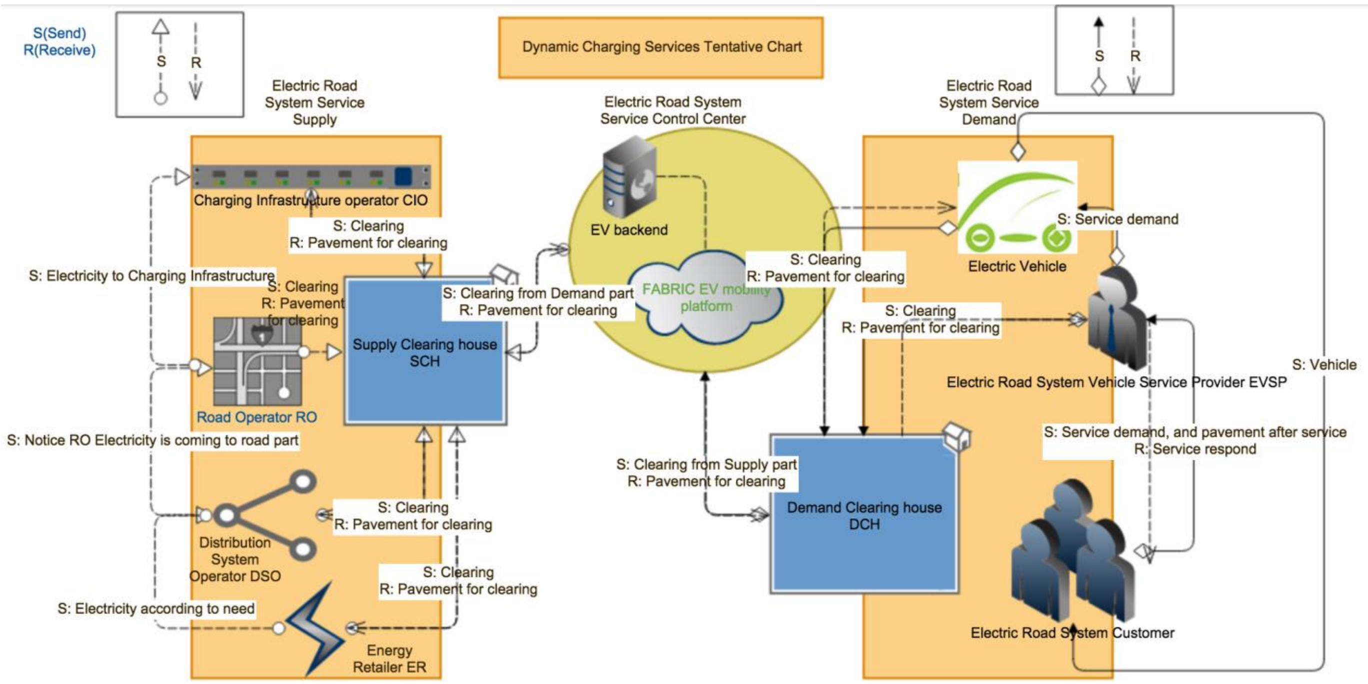

Figure 5 E-road ecosystem

To appropriately understand this concept, some formulas reflecting the interconnections among different stakeholders are deployed below in Figure 6.

FOR ADMINISTRATIONS

(Total Energy Consumed BEV/year + Infrastructure e-roads/Nº years depreciation)

<=

(Total Energy consumed ICE/y+ Infrastructure conv. roads/years depreciation+ Environmental Costs/year)

FOR INVESTORS

(Incomes sales electricity e-road + Incomes Services e-road)

>=

(Cost of e-infrastructure)

FOR DC-BEV USERS

(DC-BEV Costs + Static Recharging Costs + Dynamic Recharging Costs - Extra Advantages (externalities) [1] +Extra variable of range and outage anxiety) **<=** (ICE Costs +Fuel Costs)

[1] Extra advantages converted in economical value includes concepts as less noisy vehicles, environmental advantages, healthy aspects. Outage range operates in the opposite sense (reduce economic value)

Figure 6 Interrelation between different stakeholders and minimum conditions of the business model.

In the next chart in Figure 7, the equilibrium between costs and incomes is reflected including the expected industrial margin.

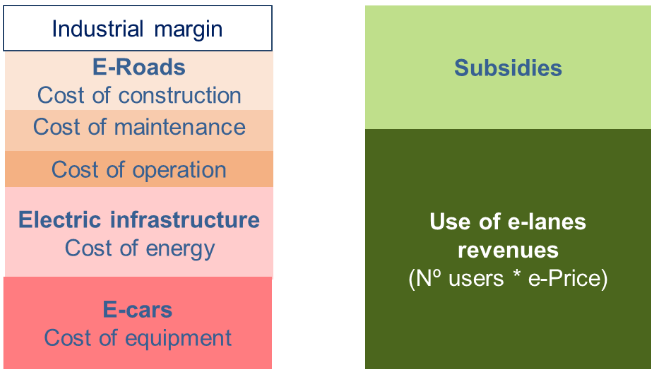

Figure 7 Balance between incomes and costs in the E-road business model

So, there will be a first calculation of the costs of all the stakeholders providing goods or services (offer). Then, an estimation of the E-roads deployment process will be included in the calculation. In parallel, and according to such deployment, the number of E-cars coupled with the dynamic system will be estimated without considering any incentive policies from the administrations. Finally, the single price of the service by type of vehicle will be calculated, using the pricing construction method established in two pending Tasks i.e. 5.5.2. business models and market ordering and 5.5.3 social cost benefit analysis. If that price is too high (comparing with alternatives), some incentives (subsidies) may be proposed for the take-up process. First cost data (from the offer) will be derived from the demo sites but eliminating the effects of the initial R&D extra expenditure. All manufacturers will be inquired to calculate that these possible optimised costs in three years' time when reaching the initial maturity of the technologies (2020).

Within this deliverable D5.3.1 only the E-road costs are considered, but it is important to understand the whole picture and perceive the relation between the different cost items.

3.2.2.3 Roadmap for the cost and charging price estimation till 2050.

The overall economic ecosystem will not be stable and reasonable from the offer and demand viewpoints until time has passed. The fitting of the economic situation will not be satisfied as long as certain market conditions are not fulfilled (i.e. sufficient number e-vehicles carrying the DWPT system in the roads, optimization of the manufacturing processes for equipment and tools, enough support from administrations, costs reductions due to economies of scale, public mobilization toward the electric mobility, etc.). Hence, an exercise will finally be implemented to figure out the future through a sensibility analysis considering variation of major parameters. From this exercise some practical lessons and recommendations will arise. The equilibrium point will be defined for the future business model.

3.2.3 Specific analysis for the E-roads

The current deliverable D5.3.1 only contemplates costs associated to the E-road construction, maintenance and operation. So, hereinafter an exercise has been done to determine the following aspects:

1) Construction
   - What technologies will be reviewed?
   - Who will provide the cost estimations?
   - Which are the main cost items in the construction phase?

2) Maintenance
   - What kind of elements will be maintained?
   - Who will provide such information?
   - Which are the main cost items in the maintenance phase?

3) Operation
   - What type of activities are considered in the operation phase?
   - Who will provide such information?
   - Which are the main cost items in the operation phase?

Below in Figure 8, the depicted charts answer those questions and describe the type of information that will be required for the analyses in the next stage of work.

E-road Construction methodology
Trench based
Full lane
Full lane prefabricated

Who provides information	
On e-road	Polito, Tecnositaf, Cemex
On technology	Vedecom, Fiat, Polito, Volvo, Qualcomm
Cost calculation	TRL

Cost items	Today (2020)[1]	Future (2050)	Events to reduce costs	Prob
Materials costs (asphalt)				
Man power				
Heavy movement Equip (renting, hours of use)				
Dynamic power system (coils, wiring,etc)				
Others (only extra costs deriving from the DPS)				

[1] €/km (determined width)

E-road Maintenance
Surface layer
Binder layer
Base course layer and granular base (?)
Charging units maintenance
Other costs (energy consumed in maintenance)

Who provides information	
e-road Mainten.	TecnoSitaf, Cemex
Charging unit maint.	Polito, Qualcomm, Volvo
Other	TRL

Cost items	Today (2020)	Future (2050)	Events to reduce costs	Prob
Materials costs (asphalt)/layer				
Man power				
Equipment (renting, hours of use)				
Dynamic Power System (consumable, replacement)				
Others (only extra costs deriving from the DPS)				

E-road Operation
Dedicated activities during operation (?)
Energy consumption of ICT system during operation
Other

Who provides information	
e-road operation	TecnoSitaf

Cost items	Today (2020)	Future (2050)	Events to reduce costs	Prob
Man power				
Energy consumed in ICT system				
Other				

Figure 8 Costs associated to E-road construction, maintenance and operation (an example)[1].

[1] This is just an example to understand the future procedure to take out the information. In later practical analyses, the Italian and French entities (and probably more) will be considered.

4 E-ROAD PERFORMANCE PREDICTION FRAMEWORK

From a life cycle point of view, for implementing electrified roads successfully, the pavement infrastructure must satisfactorily meet the structural requirements to assure an adequate long-term performance that guarantees a safe operation and minimizes the maintenance and rehabilitation during its lifetime. In order to incorporate all the important activities in different phases of the E-road life cycle into the LCC/LCCA assessment of the next stage, it is of essential importance to have a comprehensive framework for evaluation of the E-roads service performance in the long term run. To be able to make accurate predictions of the E-roads behaviour over their life-time (i.e. 20~30 years), a combined experimental-computational analysis framework is developed and detailed in this section. Specifically, two individual frameworks have been designed, which are suitable for predicting the premature damage/cracking potential (short term) and fatigue life (long term) respectively. In this, the first framework for premature damage analysis is to ensure that the optimized E-road structural solutions are chosen, while the second long term fatigue life prediction framework will guarantee the safety of the integrated structure in the designed lifetime. In this regard, the E-road structural optimization analysis framework will provide support for E-road structural design and practical constructions while the fatigue life prediction framework will be more significant for making the time planning for E-road maintenance & operations, both of which could influence the outcomes of the later LCA/LCCA assessment studies.

4.1 Structural optimization analysis framework for E-road

This framework is a continuation of the E-road structural analysis that based on the work have been documented in D4.5.2. Specifically, a combined computational and experimental approach has been developed in the established E-road structural optimization analysis framework, which is schematically shown in Figure 9. This analysis framework includes two essential evaluations:

- Computational evaluation: An advanced constitutive model for a typical asphalt material has been developed and calibrated (Chen et al. 2016). This model could reproduce sophisticated mechanistic responses of asphalt material (both recoverable and irrecoverable deformations), taking as well the time and temperature dependencies into account. This model is further implemented into a Finite Element code and by using this computational tool, the potential effects on E-road structural performance under continuous traffic loading conditions can be well predicted, in terms of such as magnitudes and distributions of critical stresses, permanent (plastic) deformations and damages.

- Experimental evaluation: MTS loading tests are conducted through applying different loading conditions over the small-scale E-road samples compacted in the laboratory, the effects of which can be further understood through internal structure characterizations based on X-Ray scanning test in 3D.

From the combined computational and experimental evaluations, a comparison between E-road and traditional road regarding their structural performances under

different loading conditions can thus be made. Meanwhile, different E-road structural optimization solutions, in terms of geometry and material properties of the CU, covering overlay, as well as different interfaces, can be further selected and evaluated using this combined approach again. If it turns out that E-road performs better than or at least close to that of the traditional road in their service life, guidelines regarding practical structural design and construction procedures can be finally made.

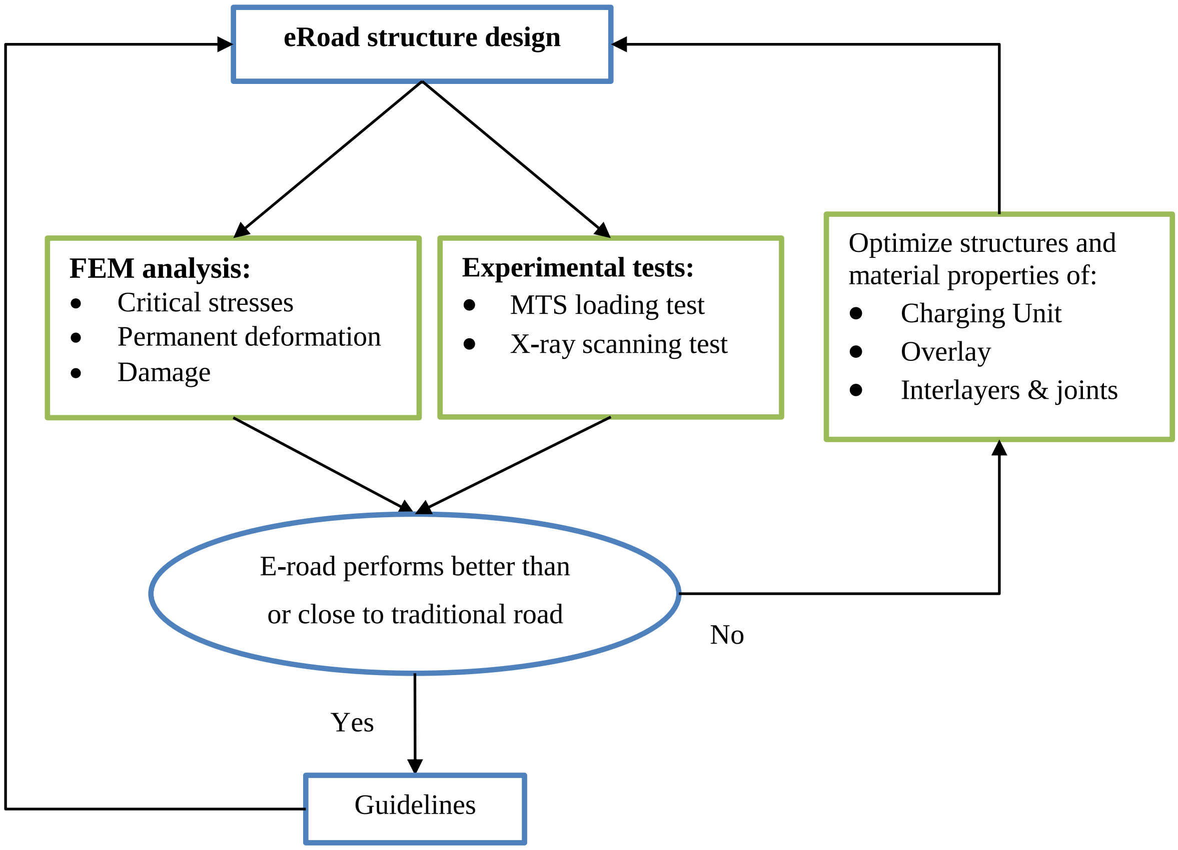

Figure 9 Schematic of E-road structural optimization analysis framework

4.2 Fatigue life prediction framework for E-road

The evaluation of the fatigue endurance of the pavement structure has been the object of a considerable amount of research in the past. In this context, there are two principal types of approaches: (i) dynamic cyclic analysis; (ii) equivalent load approaches. Although the first approach is the most realistic one, its use is limited to a small number of cycles due to its high computational demand. The equivalent load approach, instead, consists in defining the time of application of an equivalent load as the product between the single load duration and the number of load cycles.

A large number of methods, some of which imply the use of empirical laws for the asphalt layer of pavement, can be used to calculate the lifetime of a road structure. Such laws typically correlate the number of load cycles to failure, N_f, to the value of

tensile transverse strain at the bottom of the surface layer of pavement (Zhou, Hu et al. 2007, Pais, Pereira et al. 2009, Ren, Tang et al. 2012).

With regards to the vehicle load and its distribution, it must be considered that heavy vehicles are responsible of a high percentage of damage. Accordingly, the computational methodology followed for the structural assessment of E-roads must take into account the effects of both standard and heavy vehicles. Moreover, the peculiar design of E-roads calls for proper assumptions about the transverse load distribution.

The computational procedure that has been adopted for the estimation of the lifetime of E-roads is summarised in Figure 10. The procedure starts with the definition of some statistical laws and parameter initialization (STEP 1 - 2), e.g. about: vehicles load, vehicles inter-arrival time, and transverse distribution of the vehicles inter-arrival time, etc. Based on the assumed, or calculated, probabilistic laws, the vehicle load and inter-arrival time associated to a percentile value can be estimated for both standard and heavy vehicles (STEP 3). The inter-arrival time is then modified to account for the transverse distribution of loads on the E-road section (STEP 4 - 5). In order to apply the equivalent approach, a correction of the material viscosity (STEP 6), η, must be applied based on the calculated distributed inter-arrival time, $T_a(x)$, and on the time duration of the single load cycle, τ_a. This is necessary because the visco-response of road materials depends on the cyclic characteristic of the vehicle load, which would be lost with the equivalent approach. In fact, the corrected or equivalent viscosity, $\eta_{eq}(x)$, represents the viscosity that in a static analysis would provide the same visco-strain that would be obtained with a cyclic analysis. Accordingly, this parameter is defined as:

$$\eta_{eq}(x) = \eta \cdot C(x) \tag{1}$$

where *C*(*x*) is a correction function depending on the relative duration of the load cycle:

$$C(x) = T_a(x)/\tau_a \tag{2}$$

Knowing the equivalent material parameters, and the percentile of vehicle load, standard static equivalent structural analysis methodologies can be applied (STEP 7 – 8).

The results of the analysis combined with damage accumulation laws (STEP 9) are used to calculate the number of cycles to failure (STEP 10) and, based on $T_a(x)$, the corresponding lifetime of the E-road structure (STEP 11). The calculated lifetime is compared to the previous value and a recursive procedure starts, up to convergence.

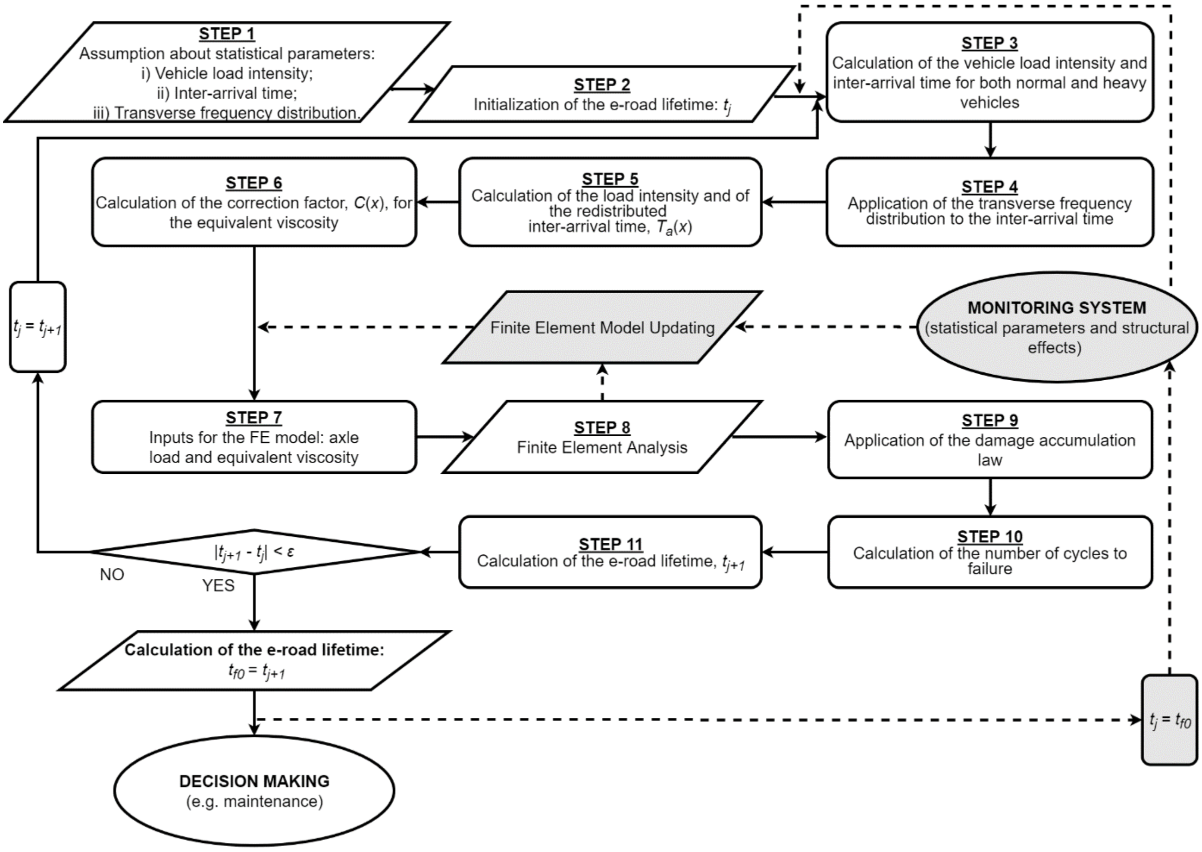

Figure 10 Layout of the computational procedure used to evaluate the E-road lifetime prediction.

4.3 Next steps

Based on the established E-road performance prediction framework shown above, in the following D5.3.2 & D5.3.3, the actual performance analyses (both experimentally and computationally) will be detailed, from where conclusions will be made towards the improved E-road structural design, suitable construction procedures, as well as proper decision-makings regarding the monitoring and maintenance procedures. These information will serve as essential inputs for the final practical LCA/LCCA analyses for quantifying and reducing the life cycle environmental impacts and economic costs of E-roads (D5.3.4), which have already been explained in the system boundaries of framework that defined in Figure 4.

5 CONCLUSIONS AND NEXT STEPS

The aim of this WP53 work is to make a systematic evaluation over the life cycle performances of E-road infrastructure, in terms of environmental impacts and economic costs. The conclusions will provide important insight into where the impacts and costs are occurring in the E-road life cycle, as well as help to develop the strategies that can reduce these impacts and costs. The objectives of this WP are presented as follows:

- Develop a common LCC/LCCA framework as a methodological base to coordinate the detailed life cycle performance analyses of E-roads (D5.3.1).
- Establish a comprehensive evaluation framework for E-road structural design and long term service performance of the E-roads (D5.3.1).
- Make an comprehensive evaluation of the E-road construction, monitoring and maintenance procedures (D5.3.2 & D5.3.3).
- Quantify the life cycle environmental impacts and economic costs of E-roads, based on D5.3.1, D52.2 and D5.3.3 (D5.3.4).

This first deliverable in the WP (i.e. D5.3.1) has established a comprehensively integrated LCA/LCCA framework for assessing the sustainability of the E-road infrastructure, which can serve as a first framework for the detailed LCA/LCCA assessment studies of the next stage. Specifically, in this deliverable:

1) An integrated LCA and LCCA system has been defined, in which the important system boundaries to enable meaningful comparisons between the E-road solutions as well as with non-electrified roads have been established carefully.
2) The important aspects of the LCC/LCCA framework has been outlined for further explanations and clarifications, in terms of both methodological theories and data collections, which can be significant for the next stage of analysis work as well.
3) A comprehensive analysis framework for evaluating E-road long term service performances has been created, using a combined computational and experimental approach. This framework can provide important basis for the work in D5.3.2 &D5.3.3, regarding the action and time planning strategies in different phases of E-road life cycle.

The next step for this WP is to make the detailed LCA/LCCA assessment, following the integrated LCA/LCCA assessment framework that has been established in this deliverable D5.3.1 and the actual activities included in different phases of the life cycle (D5.3.2 & D5.3.3). Moreover, the missing information regarding the geometry and material properties of the assumed functional unit will be collected based on the outcomes of D5.3.2 & D5.3.3, which will be documented in the final deliverable D5.3.4 as well.

Overall, the final outcomes of these analysis work in WP53 will help decision-makers in industry organizations and governmental agencies adopt more sustainable E-road design practices, contributing thus to the improved sustainability of our road transport sector through electrification as a whole.

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