Fatigue damage assessment of electric roads based on probabilistic load models

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Abstract. The electro-mobility is becoming an increasingly present reality in recent years. The most important drawback of this technology is known to be limited battery autonomy. In an attempt to overcome this problem, for specific studies and testing, a number of roads have been implemented with coil systems in order to transfer power to electric vehicles, as described in this article. While on the one hand this could solve the problem of charging, on the other hand the introduction of a technology within an existing infrastructure could result in further structural issues. Since little or no information on the possible structural effect of the introduction of a charging system in the road is currently available, this study has focused on the long-term fatigue analysis of an electric road infrastructure in which an inductive wireless charging system has been introduced into the road structure. To perform the fatigue analysis, a recursive procedure defined within a probabilistic framework was developed and applied to a benchmark case study. The results obtained from the analysis represent an initial database for the definition of strategies and protocols for the monitoring, maintenance and operations of future electric roads infrastructures.

1. Introduction
The electric road (termed ‘e-road’), an infrastructure able to provide power to vehicles, is potentially one of the key components of future smart cities. Electric power can be transferred to the vehicles operating on the e-road using a Wireless Power Transmission (WPT), a system that transmits electric power through an air-gap between vehicle and road without direct contact. In particular, the Inductive Power Transfer (IPT) technology is a near-field WPT technology suited for the contactless charging solution of electric vehicles in e-roads, [1]. In order to optimise the WPT between the e-road and the vehicle, the wear layer of the pavement needs to be very thin. Typical reference values of its thickness are 40-50 mm, [2].

The use of e-road would result in several advantages including the possibility of realising lighter and cheaper electric vehicles through the use of smaller batteries which, being recharged continually, need to store a reduced amount of energy, [3]. In addition, in a wider vision for the future, electric vehicles could store energy and return it to the grid (vehicle to e-road energy transfer phase) in times of greatest need. Furthermore, the energy could be transferred to the network even with the use of innovative solutions applied to the field of renewable resources. Although the benefits of such an infrastructure are very attractive, their development depends on the actual feasibility and viability of realisation. In this sense, a technical feasibility study (http://www.fabric-project.eu/), represents the first step towards the definition and development of a suitable technology which is at the same time accessible and reasonably easy to use. The technical feasibility and sustainability of e-roads touches...
many themes and research fields, such as Power Engineering, Telecommunications Engineering, Structural Engineering. As concerns structural feasibility, the lack of information regarding the long-terms structural response of e-roads is a major issue due to its impact on maintenance and the potentially high related costs. An estimate of the fatigue endurance of e-roads infrastructure is thus needed.

This consideration has led the authors to investigate ways for predicting the long-term effects that the introduction of recharging devices within the e-road pavement can cause. Correspondingly, this article presents a methodology for the fatigue damage assessment of e-roads based on data from numerical models to simulate the existence of a monitoring system typical for e-roads.

The numerical models take into account some specific features of e-roads such as, for example, a small misalignment of the vehicle during travel. For recharging reasons, in fact, the maximum allowed misalignment for power transfer is about 20 cm, \cite{4}. This means that the vehicle is forced to follow a specific trajectory, determining a possible acceleration of the damage evolution as well as premature rutting formation, leading to high driveability problems that could potentially compromise also the recharging phase. The methodology was applied for two solution of e-road: one that uses Cement Asphalt Mortar (CAM) to fill the Charging Unit (CU), and one that uses asphalt (see Figure 1).

To evaluate the long-term effects (such as damage evolution and fatigue resistance) within a numerical framework, the choice of the appropriate damage law is of paramount importance. One useful method to identify the life of a road pavement is the definition of the number of load cycles to failure. There are different ways to evaluate the number of load cycle of an asphalt layer based on strains, stresses, temperatures or on the dissipated energy, \cite{5}. The strain-based models are most general models to assess the fatigue damage accumulated by the pavement which are related to the tensile strain at the bottom of the asphalt layer. In the present study, a generalised Maxwell constitutive model was used to represent the road materials and the damage evolution law chosen, \cite{6} taking into account the generalised Maxwell type on several terms with inclusion of a viscous strain. The damage is then related to the energy density release rate considering both the elastic and viscous effects.

In this paper, Section 2 contains a description of the case study analysed. Section 3 reports the definition of the simulated monitoring system to provide the input data for the analysis. In Section 4, the probabilistic methodology used to evaluate the lifetime of e-roads is briefly presented before the damage evolution law applied to the methodology is deeply analysed. Finally, Section 5 reports the entire recursive procedure followed by the simulation results.

2. Benchmark case study description

The e-road solution analysed involves the use of a coil box which contains the recharging technology. The coil-box is covered with a bituminous material (CAM or Asphalt) in the first layer of the e-road. Figure 1 shows the layout of the case study investigated.

![Figure 1. Layout of the charging solution installed in the first layer of the e-road in the middle of the lane.](image)

The recharging equipment is directly inserted under the surface of the road in a hole cut with a depth of 60-70 cm. The power electronics and control equipment are placed in manholes at the track sides,
optimising the installation of the Charging Unit (CU). Successively the wires are embedded and the hole is covered with asphalt or Cement Asphalt Mortar (CAM). The use of CAM as an alternative to the asphalt is due mainly to its impact load absorption properties, [7]. In addition, CAM does not need to be compacted, an action that could potentially affect the technology.

3. Monitoring System

3.1. Traffic data simulation
In the present study, the variation ranges for the simulation of the time series are imposed as follows. The speed is assumed to vary between a minimum of 50 km/h (below which the charging system is switched off for safety reasons) and a maximum of 130 km/h. At the same time, the footprint area is assumed to vary from 0.1 m to 0.6 m. As regards the vehicle load and number of vehicle axles, it is assumed that between 8 kN and 35 kN the vehicle has 2 axles and can be considered as a ‘light’. Above 35 kN the vehicle is classified as ‘heavy’ with 2 axles up to 180 kN, 3 axles between 180 kN and 260 kN, 4 axles between 260 kN and 400 kN and 5 axles over 400 kN, the upper boundary being set at 440 kN. As regards the axle width, for light vehicles the boundary conditions were set between 1.2 m and 1.9 m, while for heavy vehicles, the random generation of the axle width has affected values from 1.9 up to 2.6 m.

The transverse misalignment of the vehicle was simulated, as described in, [8]. Assuming a Poisson process, [9] to simulate the number of axles in a reference period (set equal to 20 years in this analysis), the distribution parameter was calibrated so as to obtain values of the inter-arrival time of the axles within a reasonable range (e.g. 0.8-12 s). The dynamic amplification of the gross weight load is assumed to be 1.4. Finally, the lane width is assumed to be 3.75 m.

Figure 2 shows the simulated axle load series, while in Figure 3 the generated transverse position of the vehicle axle is shown for both e- and t-road infrastructure.

![Figure 2. Simulated axle load (left) and fitting with bimodal distribution (right).](image)

![Figure 3. Simulated vehicle misalignment for both traditional (left) and e-road (right) infrastructures.](image)
4. Basic theory

4.1. The probabilistic methodology

In order to evaluate the lifetime of the e-road infrastructure, a strategy that takes into account four elements has been followed. These elements can be summarised as:

- The equivalent static load approaches, expressed by the generalised Maxwell model modified with an equivalent viscosity, [4];
- The statistical evaluation of the load intensity, \( q \), and the inter-arrival time between two axles \( T_a(x) \);
- The fatigue damage law, [6];
- Finite Element Model.

For the recursive procedure, reference was made to, [8], which is based on the following assumption: starting from a reference value of lifetime, \( t_j \), the axle load intensity \( q_a \) and the redistributed inter-arrival time \( T_a(x) \) is calculated. Then it is possible to calculate the correction factor for the viscous effect \( C(x) \) that takes into account the actual cyclic nature of the vehicle loads, [10].

\[
C(x) = \frac{T_a(x)}{\tau_a}
\]  

(1)

where \( \tau_a \) is the impulse duration of the load.

Successively, the Finite Elements (FEs) analysis can be performed with the load intensity, \( q_a \), and equivalent viscosity, obtained by multiply the actual viscosity for the correction factor of Equation (1). From the analysis, the horizontal tensile strains at the bottom of the asphalt layers (commonly related to the failure of the surface layers), is considered in order to calculate the number of cycle to failure at constant strain by following Equation (2):

\[
N_f = k_A \left( \frac{1}{\varepsilon_t} \right)^k_B
\]  

(2)

with, \( k_A=1.29 e^{-6} \), and \( k_B=3.02 \), experimental parameters that were set to the values obtained in, [11], with Accelerated Pavement Testing (APT), which simulate the road conditions as closely as possible by considering vehicle ‘wandering’, resulting in a longer life estimation.

\( \varepsilon_t \) is the transverse strain at the bottom of the asphalt layers.

Finally, the damage accumulation law can be applied. This study assumed the law identified by the Equation (14). When the damage, \( D \), reaches the value of 1, the number of applied load cycles, \( N \) (corresponding to the ratio between the equivalent time used in the generalised Maxwell model and the inter-arrival time \( T_a \), is assumed to have reached the number of fatigue cycles to failure, \( N_f \). The new reference time, \( t_{j+1} \), can be thus updated within all related probabilistic models (i.e. load, inter arrival time, vehicle misalignment). The recursive procedure continues until the estimate for the lifetime converges to a value \( |t_{j+1} - t_j| < \varepsilon \).

In the present study, the residual \( \varepsilon \), is assumed to be \( \varepsilon=604,800 \) s (1 week).

4.2. Damage law description

A framework based on the continuum damage mechanics and thermodynamics of irreversible processes with internal state variables is used to characterize the distributed damage in viscoelastic asphalt materials. This is obtained by simulating damage in the form of micro-crack initiation and accumulation. A model based on a non-associated damage evolution law is capable to describe the temperature-
dependent processes of micro-crack initiation, evolution and macro-crack formation, respectively, in good agreement with the material response in the Superpave Indirect Tensile (IDT) strength test, [12]. With this type of model, the energy density release rate, \( Y \), can be written, without loss of generality, in terms of the characteristic relaxation function and the total strain as, [6]:

\[
Y(t) = - \frac{\partial \psi}{\partial D} = \frac{1}{2} E(t) \varepsilon_t^2
\]

(3)

where, \( \varepsilon_t \), is the transverse strain field, and \( \psi \) represents the Helmholtz free energy, which, for the described generalized Maxwell model, can be expressed as:

\[
\psi = (1 - D)(\psi_\infty + \sum_{i=1}^{n} \psi_{\text{neq}}^i)
\]

(4)

with \( \psi_\infty \) and \( \psi_{\text{neq}}^i \) representing the free energy functions of the long-term equilibrium (time independent) and the non-equilibrium (time dependent) parts respectively, \( D \) the value of damage, and \( E(t) \) the relaxation modulus of Maxwell model at reduced time \( t \).

The energy-based damage law unifies many particular damage modes such as ductile, creep, fatigue, quasi-brittle damage with the critical damage densities related to mesocrack initiation. The energy-based damage model in, [13][14][15], is adapted and further extended for the damage characterization in viscoelastic asphalt concrete material. The micro-crack initiation criterion can be expressed in the form:

\[
f^d = q_1^*(Y) - q_{1,c}^*(S_0) - R(r) = 0
\]

(5)

where \( q_1^*(Y) \) is the micro-crack initiation potential function, \( q_{1,c}^*(S_0) \) is the critical micro-crack damage threshold and \( R(r) \) is the isotropic damage hardening function. The micro-crack initiation potential function \( q_1^*(Y) \), which is used to obtain the point at which micro-crack initiates, is a function of the linear viscoelastic energy \( Y \), and can be expressed as:

\[
q_1^*(Y) = \frac{S_0}{k_2 + 1} \left( \frac{Y}{S_0} \right)^{k_2+1} \frac{1}{1 - D}
\]

(6)

where \( k_2, S_0 \) are material parameters. The parameter \( S_0 \) is the critical energy when the micro-crack initiates.

When \( Y=S_0 \), the linear viscoelastic energy reaches the value for which the damage mechanism starts to evolve. In this situation, the value of damage is supposed to be \( D = 0 \). Incorporating these assumptions in Equation (6), it is possible to get the value of the potential function corresponding to the damage activation mechanism, expressed as:

\[
q_{1,c}^*(S_0) = \frac{S_0}{k_2 + 1}
\]

(7)

Using a non-associated micro-crack evolution rule, a micro-crack propagation criterion is introduced and expressed as:
\[ F_D = \varphi^*_2(Y) - \frac{k_1}{k_2} \varphi_{1,c}^*(S_0) - R(r) = 0 \]  
\[ \text{(8)} \]

where \( \varphi^*_2(Y) \) is the micro-crack propagation potential, expressed in the form:

\[ \varphi^*_2(Y) = \frac{k_1}{k_2} S_0 \frac{Y}{S_0}^{k_2+1} \]  
\[ \text{(9)} \]

The evolution of micro-crack, can be obtained with respect to the dissipative micro-crack potential \( F_D \) by taking the derivative of the dissipation potential, which reads [6]:

\[ \dot{D} = \lambda \frac{\partial F_D}{\partial Y} = \frac{k_1}{k_2} \left( \frac{Y}{S_0} \right)^{k_2} \dot{\lambda} \]  
\[ \text{(10)} \]

The damage (micro-crack) hardening variable, \( r \), can be obtained as a function of the Lagrange multiplier \( \lambda \) and expressed as:

\[ \dot{r} = -\lambda \frac{\partial F_D}{\partial R} = \dot{\lambda} \]  
\[ \text{(11)} \]

With, \( r = \dot{p}(1 - D) \), where \( \dot{p} \) denotes the cumulative plastic strain, [14]. The resulting damage evolution law is given as:

\[ \dot{D} = \frac{k_1}{k_2} \left( \frac{Y}{S_0} \right)^{k_2} \dot{p}(1 - D) \]  
\[ \text{(12)} \]

Finally, the damage law results from the solution of the following differential equation:

\[ \frac{dD}{dt} = \frac{k_1}{k_2} \left( \frac{Y}{S_0} \right)^{k_2} \frac{d\varepsilon_t}{dt} (1 - D) \]  
\[ \text{(13)} \]

For simplicity, \( Y \) was assumed as constant within each interval \( \Delta \varepsilon \)

\[ D = 1 - \exp\left( - \frac{k_1}{k_2} \left( \frac{Y}{S_0} \right)^{k_2} \Delta \varepsilon_t + \frac{k_1}{k_2} \Delta \varepsilon_t \right) \]  
\[ \text{(14)} \]

The damage model coefficients used to model the damage evolution in the asphalt mixtures are listed hereinafter, [6]:

- \( k_1 = 27.43 \)
- \( k_2 = 0.29 \)
- \( S_0 = 0.437 \) \( \frac{kf}{m^3} \)

Finally, the full damage constitutive equation, which was implemented successively in the algorithm for evaluating the time life of e-roads, can be summarised as:
\[
\begin{aligned}
&\text{if } q_1^* < q_{1,C}^* \quad \text{no microcrack initiation} \\
&\text{if } q_1^* = q_{1,C}^* \quad \text{microcrack initiation} \\
&\text{if } q_2^* > k_1 q_{1,C}^* \quad \text{microcrack evolution}
\end{aligned}
\]

(15)

5. Recursive procedure for e-road lifetime estimation

5.1. Algorithm description

In order to calculate the lifetime, an algorithm was specifically created in the Matlab environment to implement a recursive procedure. The possibility of working in batch mode optimises the calculation process and allows to calculate the infrastructure’s lifetime by exploiting the potential of FE analysis. In more detail, the Matlab ‘script’ generates input data for the FE model, as shown previously. Having defined the load intensity and the correction factor of Prony’s serie, the algorithm starts the batch mode analysis of the FE model, which produces a time history of parameters such as strain and energy. These values are used as data input for the cumulative damage law. The final outcome is an estimate for the lifetime, which corresponds to the attainment of \(D=1\). If the damage does not reach its maximum value, the lifetime is set \(>20\) years.

The algorithm can take into account different aspects.

- Transverse position of vehicles loads. In this case 2 critical positions for the load are considered (see Figure 5), but the analysis can be virtually conducted for any position of load in the transverse direction;
- Any type of cumulative damage law can be assumed;
- For the CU, the fatigue damage is supposed to be reached when the asphalt under it reaches its \(t_f\).

The cycle of Figure 4 evaluates the lifetime of e-roads referring to a single coupled of \(p_s\) and \(p_w\), which characterise the percentage of passage of standard and heavy vehicles, respectively.
5.2. Results

With the aim to assess both the fatigue endurance of e-roads and the use of CAM as alternative material to fill the Charging Unit (CU), two load conditions were defined. The first one, for the estimation of the e-road lifetime, with centred load, and a second one for the estimation of the damage in the CU, with a load placed on it. These load conditions are represented in Figures 5.

![Figure 5](image)

**Figure 5.** Load conditions for the estimation of the lifetime of e-roads (left), and the damage in the CU (right).

The results show that the fatigue life increases with increasing inter-arrival time of heavy vehicles, following a power law. Negligible differences were found between CAM or asphalt filling solutions in terms of fatigue endurance of the entire e-road. Consequently, outside the CU, the material used to fill the coils does not affect significantly the fatigue life. In the analysis, the average value of the characteristic load at 95% is found to be, for standard and heavy vehicles respectively, equal to 25 kN and 150 kN.

![Figure 6](image)

**Figure 6.** E-roads lifetime function of $T_{95\%_w}$.

The lifetime decreases with decreasing inter-arrival time (95 percentile) of heavy vehicles, $T_{95\%_w}$, accelerating for small values. Figure 6 shows the trend of the fatigue life, $t_{f0}$, as approximated by Equation (16).

$$t_{f0} = 14.26 \cdot T_{95\%_w}^{0.6209}$$ (16)
In the absence of heavy vehicles, it would be sufficient to particularise the analysis by referring to a $t_{95\%}$ associated to high values of $T_{95\%,w}$. Accordingly, the lifetime associated with the highest $T_{95\%,w}$ would correspond to the value searched. In this case, with a characteristic load of standard vehicles of 25 kN, the fatigue in presence of a lowest number of heavy vehicles ($T_{95\%,w} = 75$ min) is equal to about 17 years.

![Transverse distribution of loads](image1)

**Figure 7.** Transverse distribution of loads.

To estimate the damage near the CU, a local assessment was also performed on the endurance of the portion of infrastructure closed to it. The CU’s fatigue endurance is supposed to be reached when the asphalt under it reaches its $t_{95\%}$. In fact, once the link between the CU and infrastructure fails, any further transit of vehicles could irreparably damage the CU and the whole e-road infrastructure.

![Damage function of $T_{95\%,w}$](image2)

**Figure 8.** Damage function of $T_{95\%,w}$.

Accordingly, the CU’s endurance was estimated to exceed 20 years in both CAM and asphalt solutions. Figure 8 reports the damage value rated to 20 years, in the case of both asphalt- and CAM-CU. The damage is less than 40% in both solutions, which ensures a considerable safety margin from the limit condition. However, it can be seen for $T_{95\%,w}$ exceeding 52 minutes that the damage is greater in an asphalt-CU. Under this value, there is a reversal of the behaviour. More specifically, for a CAM-CU the damage increases with decreasing inter-arrival time of heavy vehicles. By contrast, under
95%w = 52 min, the asphalt-CU solution damage decreases with decreasing of $T_{95\%w}$. This is due to the greater importance that takes the Laplace distribution with respect to the Gauss one. In fact, when the number of heavy vehicles increases, the transverse distribution tends to a Laplace [8], which has a smaller second order moment (see Figure 7), this limiting the damage to the CU.

6. Conclusions
The results of the analysis can be summarised as follows.

- The fatigue analysis revealed a high dependence of the lifetime on the inter-arrival time of heavy vehicles, being the characteristic load assumed in this study equal to 25 kN and 150 kN, for standard and heavy vehicles respectively.
- The fatigue endurance of the CU can be set greater of 20 years for both asphalt or CAM-filling solutions. However, when the inter-arrival time of heavy vehicles is less than 52 min, better results in terms of damage are found with asphalt. For longer inter-arrival times the CAM gives a better performance (less damage).

The overall procedure can be easily applied to any configuration of different e-road solutions, providing indications to define an optimal maintenance plan for the entire lifetime of the e-road. During the service life, the procedure also allows for updating the maintenance plan, based on the observed levels of damage in the e-road structure, and for scheduling interventions.

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