STRATEGIES FOR ASSESSING THE STRUCTURAL PERFORMANCE OF ELECTRIC ROAD INFRASTRUCTURES

Invited presentation:

ISHMII WORKSHOP

ISHMII

Workshop on Civil Structural Health Monitoring

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QUEEN'S UNIVERSITY
Belfast, Ireland

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INTRODUCTION

Electric roads (E-roads)

E-roads are special infrastructures allowing for recharging of electric vehicles (Evs) via Wireless Power Transfer (WPT).

The vehicle is recharged during travelling, without need to stop (dynamic process). The dynamic WPT that uses an inductive process is often referred to as dynamic inductive recharging

INTRODUCTION

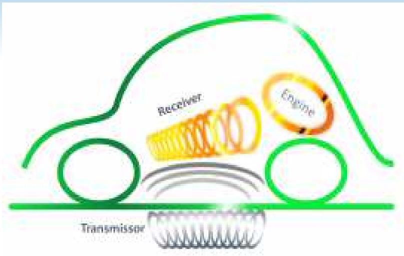
Benefits of the dynamic inductive recharging

Frequent charging of car's battery **prevents its depletion** and longer life

Car's battery would need to have approximately 1/5 of capacity than a traditional EV's battery, **reducing the weight** and the price of EVs

Electric vehicles are **recharged while travelling** without the need to stop for short or long periods

INTRODUCTION



EU projects on smart mobility and e-roads

Unplugged

FP7-SST-2012-RTD-1 Smart infrastructures and innovative services for electric vehicles in the urban grid and road environment

UNPLUGGED – "Wireless charging for electric vehicles project" aims to investigate how the use of inductive charging of Electric Vehicles (EV) in urban environments improves the convenience and sustainability of car-based mobility. (www.unplugged-project.eu)

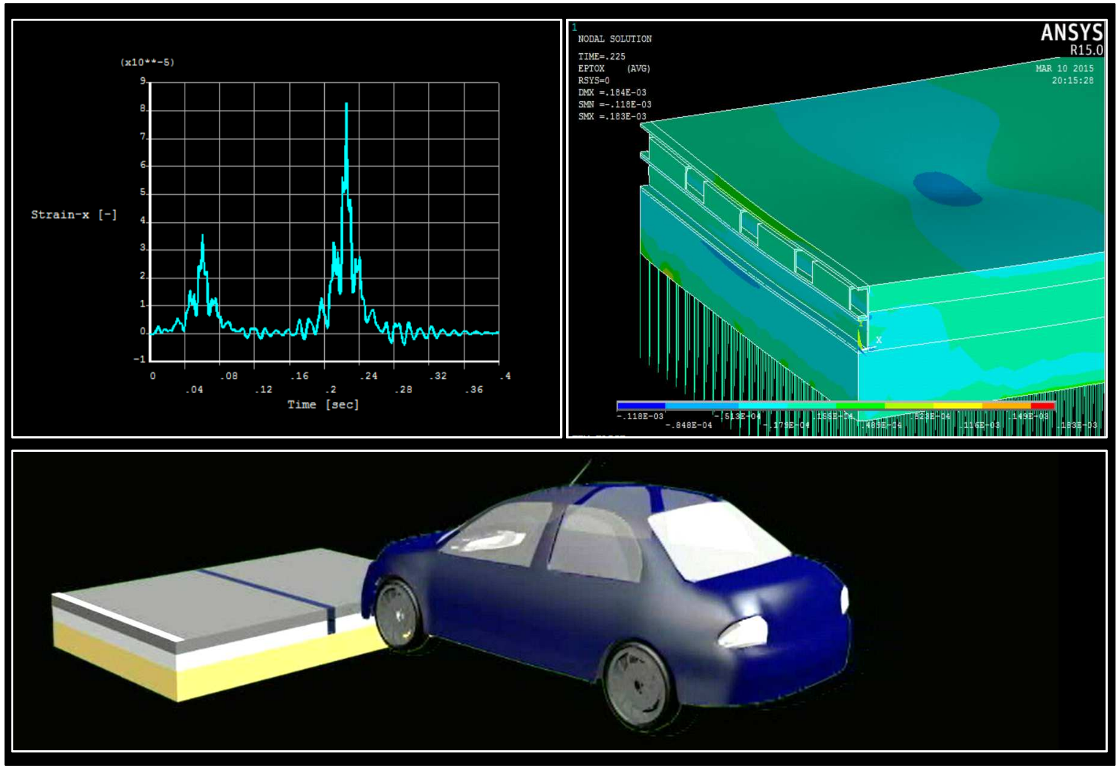
FABRIC

FP7-SST-2013-RTD-1 Smart infrastructures and innovative services for electric vehicles in the urban grid and road environment

FABRIC - FeAsiBility analysis and development of on-Road chargIng solutions for future electric vehiCles. Paving the way for large scale deployment of electromobility (http://www.fabric-project.eu/)

INTRODUCTION

Dynamic modelling of e-roads



Average values of transverse strain at the bottom of wear layer:

30 – 80 μstrain

Comparable with the experimental data on traditional road (t-roads)

(50 – 150 μstrain)

ISSUES ON STRUCTURAL ASSESSMENT OF E-ROAD

E-road system technologies

Computational strategies needed for lifetime assessment of e-roads

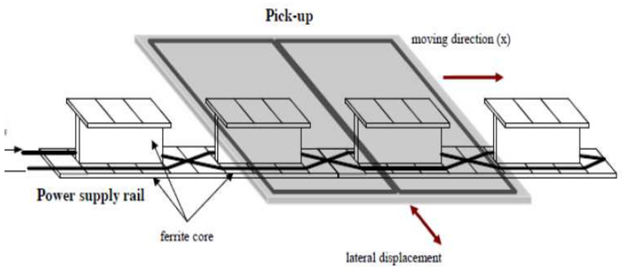
Time-dependent structural performance of e-roads

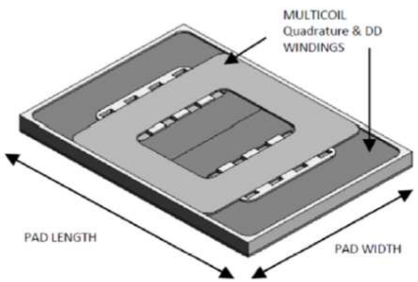
Structural analysis of e-roads: examples

Monitoring and maintenance of e-roads: perspectives

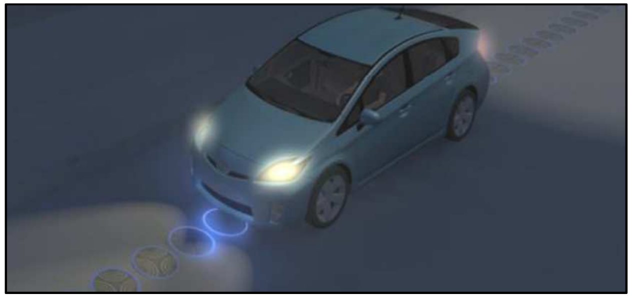
E-ROAD SYSTEM TECHNOLOGIES

KAIST | **QUALCOMM** | **PRIMOVE**





KAIST 4G
(Chun, 2013)



QUALCOMM
(Boys and Covic, 2012)

SCANIA&BOMBARIDER -
Primove
(Viktoria Swedish ICT, 2013)

E-ROAD SYSTEM TECHNOLOGIES

Threshold values for some technology parameters

Electromagnetic field < 6.25 μT

Vertical air-gap > 0.2 - 0.3 m

Horizontal misalignment > 0.2 - 0.3 m

Power transferred > 20 - 30 kW

A COMPUTATIONAL STRATEGY FOR LIFETIME ASSESSMENT OF E-ROADS

Structural problems arising in e-roads

- Transverse distribution of loads depending on the recharging technology ⇒ Higher vertical visco-deformations
- Transverse distribution of loads depending on the recharging technology ⇒ Spatial concentration of load cycles
- Presence of high-tech technological components ⇒ Possible influence on stress and strain distributions

A COMPUTATIONAL STRATEGY FOR LIFETIME ASSESSMENT OF E-ROADS

Long term effects

Spatial concentration of load cycles ⇒ Lower lifetime and increased maintenance operations

Higher vertical visco-deformations ⇒ Drivability and recharging problems

Influence on stress and strain distributions ⇒ Settlements and fatigue on the recharging components

A COMPUTATIONAL STRATEGY FOR LIFETIME ASSESSMENT OF E-ROADS

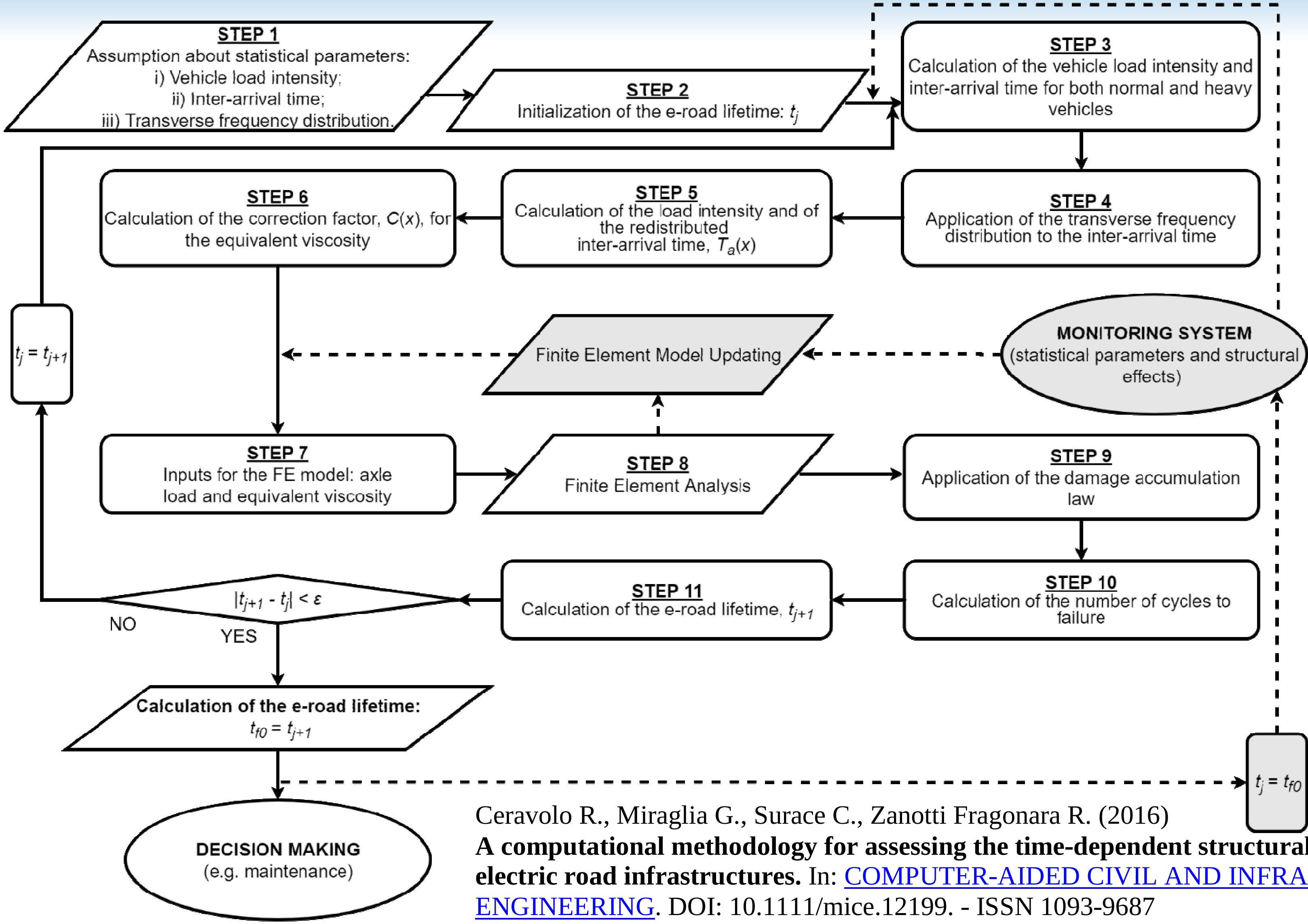
Long term structural assessment of e-roads and residual life

Finite Elements (FE) analysis accounting for contact behaviour

Fatigue estimation with a recursive probabilistic approach, corroborated by data from monitoring systems

Viscodeformation estimation, with a recursive probabilistic approach, corroborated by data from monitoring systems

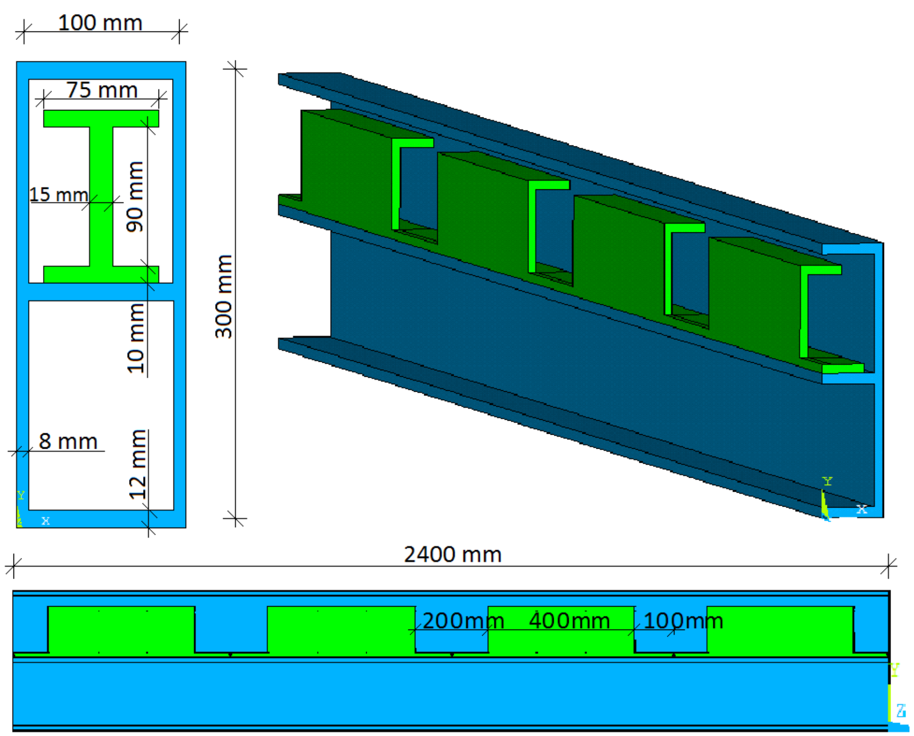
A COMPUTATIONAL STRATEGY FOR LIFETIME ASSESSMENT OF E-ROADS



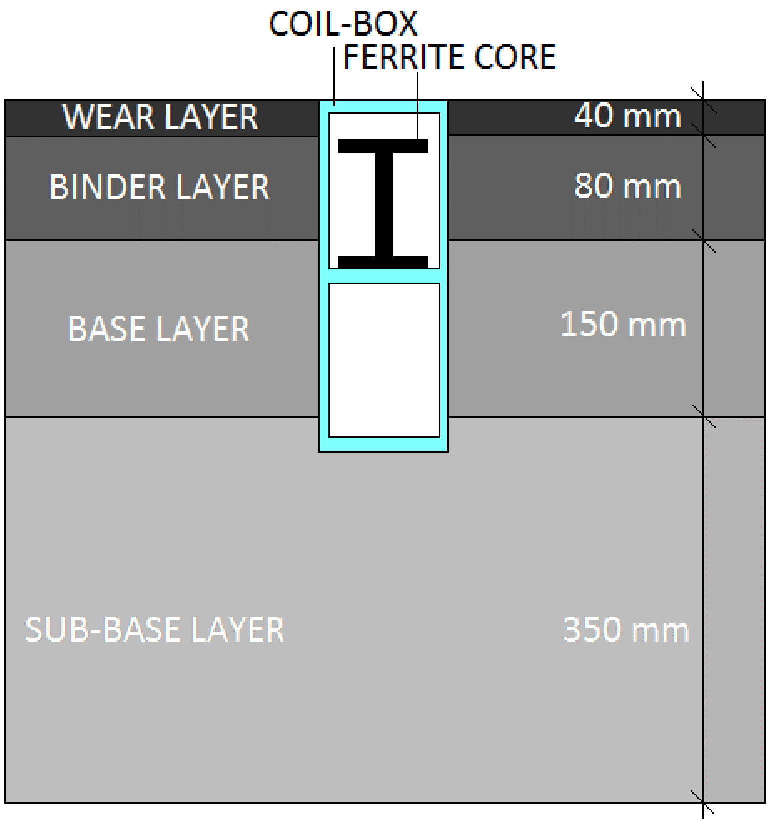
Ceravolo R., Miraglia G., Surace C., Zanotti Fragonara R. (2016)
A computational methodology for assessing the time-dependent structural performance of electric road infrastructures. In: COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING. DOI: 10.1111/mice.12199. - ISSN 1093-9687

STRUCTURAL ASSESSMENT OF E-ROADS: THE CASE OF A "RAIL" SOLUTION

Geometric model for the "rail" solution



Recharging Unit



Road stratigraphy

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

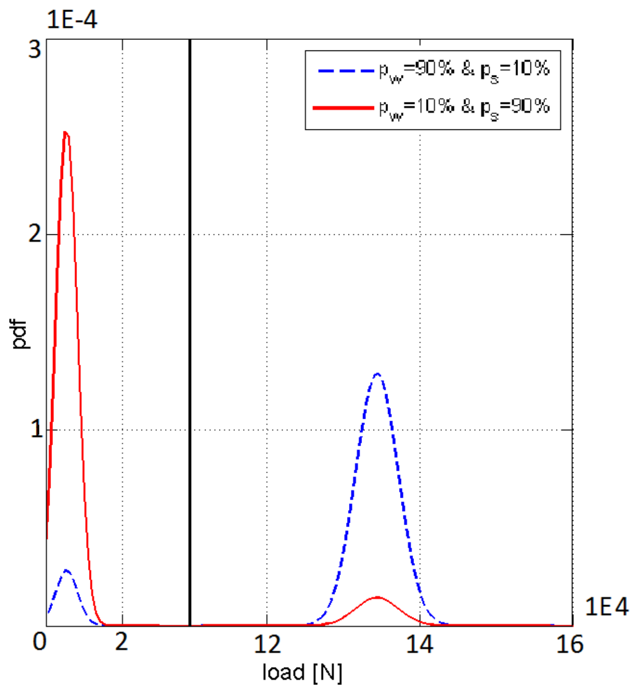
STEP 1
Assumption about statistical parameters:
i) Vehicle load intensity;
ii) Inter-arrival time;
iii) Transverse frequency distribution.

i) Vehicle load: Bimodal distribution

$$\hat{B}(q) = p_s \cdot \phi_s(q, \mu_s, \sigma_s) + p_w \cdot \phi_w\,(q, \mu_w, \sigma_w)$$

ii) Inter arrival time: Poisson process on the number of arriving vehicles

$$P(n_{vehicles})$$



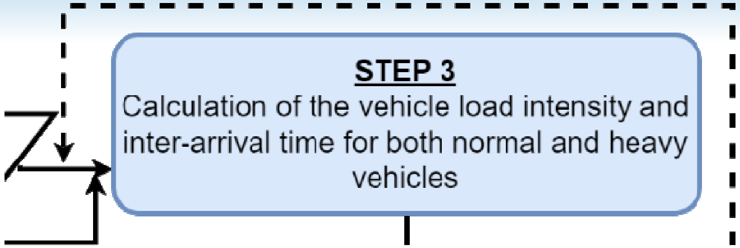
iii) Transverse frequency distribution: Normal distribution for standard vehicles and Laplace distribution for heavy vehicles:

$$F_s(x) = \int \frac{1}{\sqrt{2\pi}\sigma_G} e^{-\left(\frac{x-\mu_G}{2\sigma_G{}^2}\right)} dx\,;\; F_w(x) = \int \frac{\sqrt{2}}{2\sigma_G} e^{-\sqrt{2}\left(\frac{|x-\mu_G|}{\sigma_G}\right)} dx$$

STEP 2
Initialization of the e-road lifetime: t_j

t_j

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION



τ_a= 0.015 s (vehicle speed 70 km/h);
$\mu_s = 12{,}705\ N$ (mean for normal vehicles);
$\sigma_s = 1{,}407\ N$ (standard deviation for normal vehicles);
$\mu_w = 134{,}424\ N$ (mean for heavy vehicles);
$\sigma_w = 2{,}784\ N$ (standard deviation for heavy vehicles);
p_s and p_w: values from 0 to 1 with 0.1 increment;
$\mu_G = 1$ m;
$\sigma_G = 0.19799$ m;
$\lambda = 0.02385$;

Probability distribution for standard vehicles load intensity:

$$Q_s(q) = e^{-\lambda\, p_s t_f [1-\phi_s(q)]} = 95\% \rightarrow q_{95s}$$

Probability distribution for heavy vehicles load intensity:

$$Q_w(q) = e^{-\lambda\, p_w t_f [1-\phi_w(q)]} = 95\% \rightarrow q_{95w}$$

Probability distribution for the number of standard vehicles in the lifetime:

$$P_s(n_{vehicles}) = 95\% \rightarrow n_{95s} \rightarrow T_{95s}$$

Probability distribution for the number of heavy vehicles in the life time:

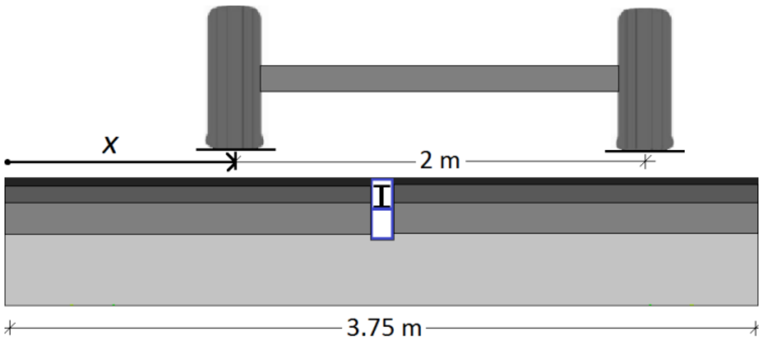
$$P_w(n_{vehicles}) = 95\% \rightarrow n_{95w} \rightarrow T_{95w}$$

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

STEP 4
Application of the transverse frequency distribution to the inter-arrival time

Redistributed inter arrival time for standard vehicles:
$$T_s(x) = T_{95s}/F_s(x)$$

Redistributed inter arrival time for heavy vehicles:
$$T_w(x) = T_{95w}/F_w(x)$$



E-road lane with loading axle

STEP 5
Calculation of the load intensity and of the redistributed inter-arrival time, $T_a(x)$

Standard vehicles load intensity: q_{95s}

Axle load intensity: q_a

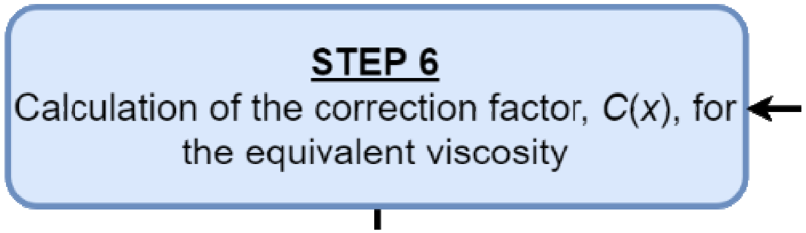
Heavy vehicles load intensity: q_{95w}

Standard vehicles inter arrival time: $T_s(x)$

Axle inter arrival time: $T_a(x)$

Heavy vehicles inter arrival time: $T_w(x)$

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION



Correction function for viscous effects:

$$C(x) = T_a(x)/\tau_a$$

Equivalent viscosity parameters:

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

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

STEP 7
Inputs for the FE model: axle load and equivalent viscosity

Mat. ID	Structural Element	E [MPa]	v	ρ [kg/m³]
1	**Surface layer**	6,500	0.3	2,500
2	Base layer	130	0.35	2,200
3	Sub-base layer	90	0.4	1,200
4	Polymer coil-box	2,200	0.35	1,150
5	Sub-grade layer	3,000	0.4	2,000
6	Ferrite core	180,000	0.28	5,000

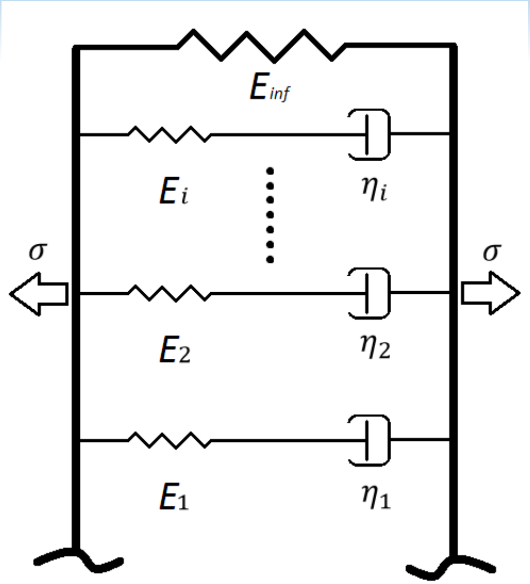
Axle load:
q_a

Equivalent viscosity parameters:
$\eta_{eq}(x)$

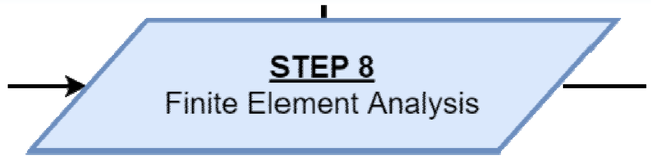
Equivalent relaxation time:
$\tau_{eq,i} = \eta_{eq,i}(x)/E_i$

Equivalent relaxation law:
$$E(t_r) = E_\infty + \sum_{i=1}^{N} E_i e^{-\frac{t_r}{\tau_{eq,i}}}$$

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION



Viscoelastic chain model

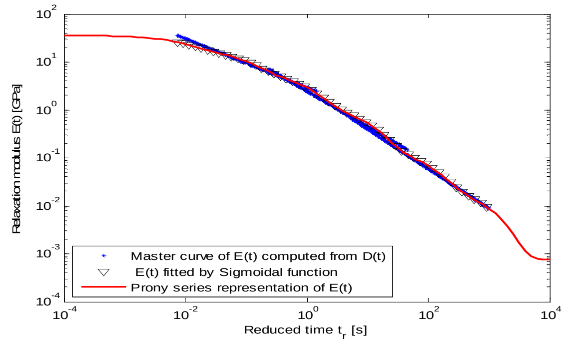


Generalized Maxwell viscoelastic model

Equivalent relaxation law:

$$E(t_r) = E_\infty + \sum_{i=1}^{N+1} E_i e^{-\frac{t_r}{\tau_{eq,i}}}$$

A function of: the inter arrival time, $T_a(x)$; transverse distribution; load duration, τ_a



11(1)			11(2)			11(3)			11(4)		
i	E_i [GPa]	τ_i [s]	**i**	E_i [GPa]	τ_i [s]	**i**	E_i[GPa]	τ_i [s]	**i**	E_i [GPa]	τ_i [s]
1	9.1825	1.00E-02	**1**	7.7954	1.00E-02	**1**	18.153	1.00E-02	**1**	17.218	1.00E-02
2	6.4356	1.00E-01	**2**	6.0582	1.00E-01	**2**	15.191	1.00E-01	**2**	24.971	1.00E-01
3	3.3676	1.00E+00	**3**	3.1833	1.00E+00	**3**	9.277	1.00E+00	**3**	17.7	1.00E+00
4	1.1274	1.00E+01	**4**	1.0256	1.00E+01	**4**	4.0715	1.00E+01	**4**	3.8847	1.00E+01
5	0.2086	1.00E+02	**5**	0.16914	1.00E+02	**5**	1.0385	1.00E+02	**5**	0.44153	1.00E+02
6	0.024434	1.00E+03	**6**	0.015804	1.00E+03	**6**	0.20039	1.00E+03	**6**	0.0736	1.00E+03
Einf	0.001		**Einf**	0.001		**Einf**	0.001		**Einf**	0.021574	

Calibration of Prony's constants: **elastic moduli** and **equivalent relaxation times**.

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

STEP 9
Application of the damage accumulation law

$$N_f(x) = k_1\left(\frac{1}{\varepsilon(x)}\right)^{k_2} \rightarrow D_s = \frac{\ln(2N_i-1)}{\ln(2N_f-1)};\ D_o = \frac{\ln(2N_e-1)-\ln(2N_f-1)}{\ln(2N_e-1)-\ln(2N_i-1)} \rightarrow D_{so} = D_s \cdot D_o$$

(Ben-Amoz, 2009)

STEP 10
Calculation of the number of cycles to failure

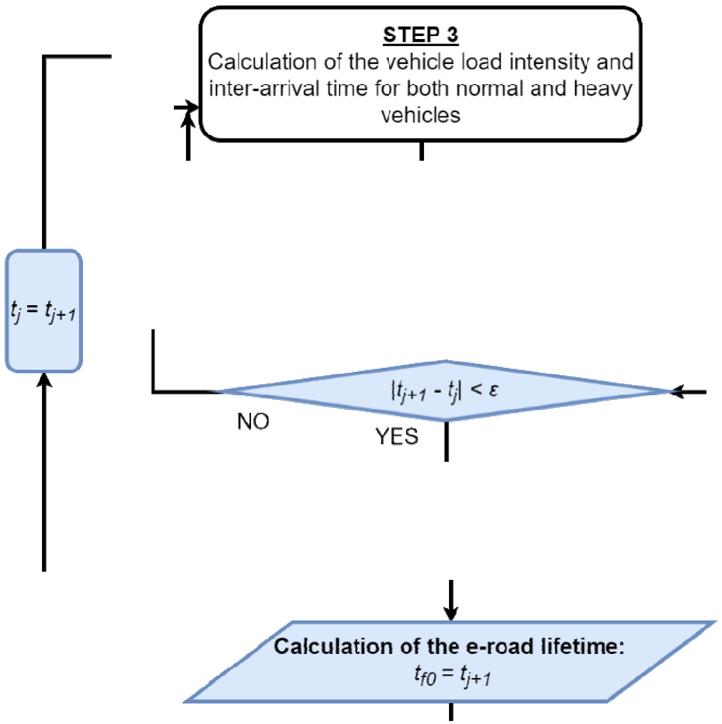
$$N_{f0}(x)$$

STEP 11
Calculation of the e-road lifetime, t_{j+1}

$$t_{j+1} = min_x\,\{\,N_{f0}(x)\cdot T_a(x)\,\}$$

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

Lifetime calculation



The recursive procedure lasts when the estimate for lifetime converges to a value

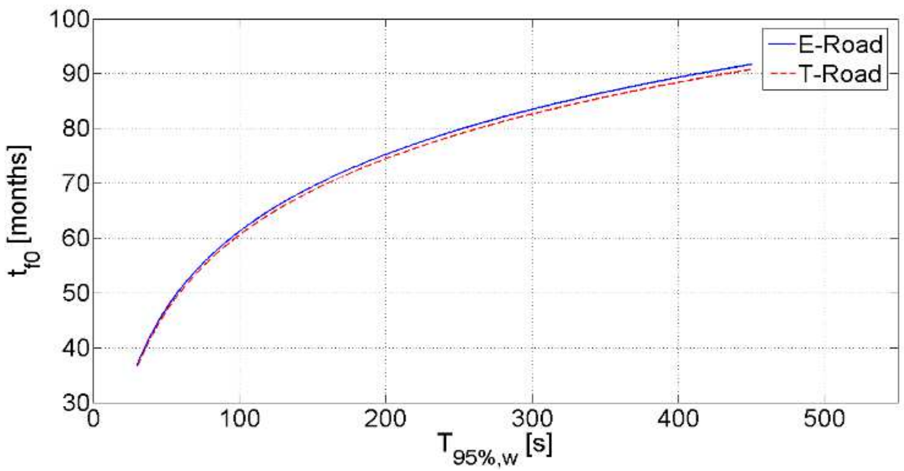
$$t_{f0} = t_{j+1} = min_x \{ N_{f0}(x) \cdot T_a(x) \}$$

TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

Results: Fatigue

The lifetime of both e-road and t-road decreases with decreasing the inter arrival time, resulting to be slightly higher for the e-road than the t-road.

For low values of the inter arrival time of the heavy vehicles (under 150 s), assuming a mean load of 134,424 N, the lifetime decreases rapidly for both e-road and t-road.



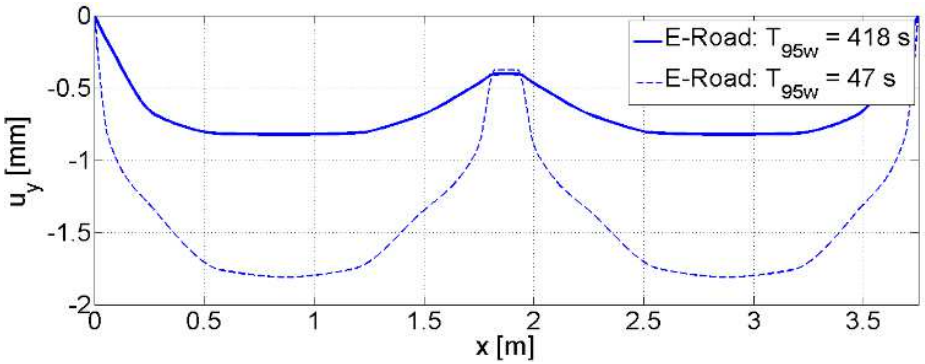
Lifetime of both e-raod and t-road as a function of the inter-arrival time of heavy vehicles

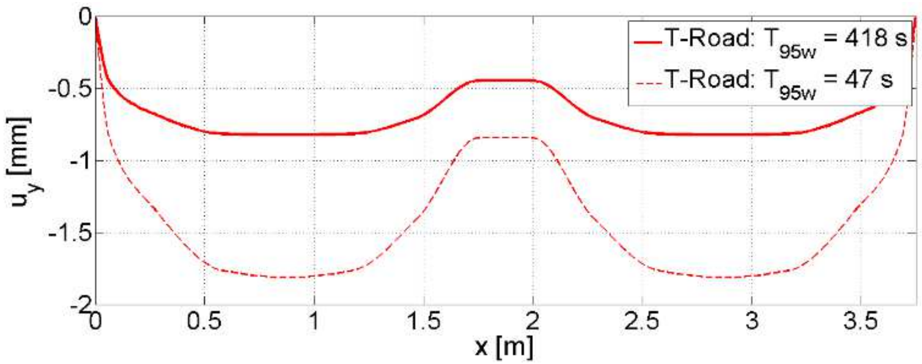
TIME-DEPENDENT STRUCTURAL PERFORMANCE OF E-ROADS: "RAIL" SOLUTION

Results: Visco-deformations

Passing from T_{95w}=418 s, to T_{95w}=47 s results in a **non-uniform increase** of the vertical displacements.

The main differences between e-roads and t-roads concerns the central part of the lane, where the presence of the coil-box limits visco-deformations.



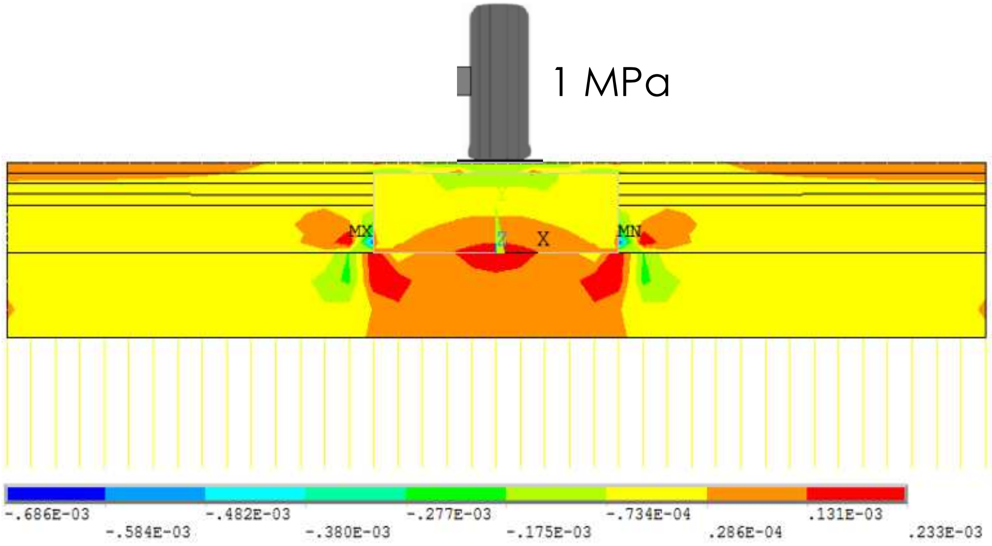


Vertical visco-displacements after 6.25E6 cycles, Uy [mm], of the entire lane, in the e-roads (left) and t-roads (right)

STRUCTURAL ANALYSIS OF E-ROADS: "BURIED" SOLUTION

Strain analysis with resilient modulus: comparing stress and strain distribution at two different temperatures (-10 °C and +20 °C)

A transition temperature from -10 to +20 may lead to changes of strain from 20 up to 100 µstrain.



Transverse strain – E-road

“BURIED” SOLUTION: LIFETIME PREDICTION

Number of load cycles to failure for the “buried” solution

$$N_f(x) = k_1 \left(\frac{1}{\varepsilon(x)}\right)^{k_2} \quad \text{(Yeo et al., 2008) with accelerated pavement testing (APT)}$$

- “buried” e-road: **Nf = 1,353,954** (in the assumption of εt=104.6 μstrain)
- t-road: **Nf = 7,862,400**
- “rail” e-road: **Nf = 7,948,800**

The initial solution developed within FP7 FABRIC project had to be modified.

CONCLUSIONS

Conclusions

Specialized mathematical models (non linear, contact, etc.) are to be used to obtain a realistic representation of the stress in the pavement of e-roads.

Due to visco-deformations, long term gaps between surface and coil-box may reach values in the order of a few mm. Verifications needed for possible misalignment and additional damage in the charging device.

Possible fatigue problems envisaged in the wear layer for buried solutions. Special materials should be evaluated and tested for incorporating technological components. Maintenance evaluations and lifecycle analysis to be performed.

The longitudinal stress induced by the braking force strongly depends on friction coefficient between the wear layer and coil-box (buried solution).

No significant structural problems were observed in electric components, e.g. copper cables or aluminium box (buried solution), however specific verifications and lifecycle analysis are in general needed for high-tech components

THANK YOU FOR THE KIND ATTENTION

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