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# Instrumented Roadway Characterized through an Optimized Indicators Method

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## Abstract

In recent years, pavement instrumentation became a common practice for structural monitoring. Instrumented roadway includes different type of sensors such as strain gauges, accelerometers or geophones. Data processing consists often in extracting different values such as extremum, number of positives or negatives peaks, calculate threshold, on so on. These values are generally representative of variations in the whole structure, but make it more difficult to follow a specific characteristic of the structure.

To overcome this limitation, an original method has been defined. It consists in finding weighting functions of the signal to calculate optimized indicators. As deduced, these indicators are particularly sensitive to a specific characteristic of the structure without being sensitive to the other characteristics. The application of these weighting functions to the measured signals makes it possible to deduce indicators specific to different characteristics of the structure and independently each other. This method has been applied during an experiment on an instrumented roadway with the fatigue carousel of the university Gustave Eiffel, campus of Nantes. The chosen equipment for the roadway are strain gauges embedded inside the bituminous layer of the roadway and allowing recording deformation signals as a function of applied loading cycles. A viscoelastic reference model for pavements defined for this study allowed calculating the structure's response under a simulated running load. The model also made possible the construction of optimized indicators, plotted with number of applied loads. The evolution of indicators are clearly representative of the damage of the different layers.

**Keywords:** pavement instrumentation, signal processing, indicators, weighting functions

## 1 Introduction

Roadways are world widely the most strategical infrastructures for the transport and communication, and their structural engineering evolves in each country to answer the needs due to the increase of heavy traffic. The mechanical and environmental solicitations lead to the merge of defects such as cracks, potholes and rutting, which decrease the service life of these infrastructures and affect the safety of users. Hence, the use and the development of Non Destructive (ND) methods and pavement's asset management systems know a strong interest [1-2]. The deflectometers are among the most current NDT method to characterize the structural state of pavements, therefore, it can be difficult to detect a defect that merges in the base layer to prevent its propagation through the bituminous layer, or vice versa. To overcome this limitation, the French "Laboratoire Auscultation, Modélisation et Expérimentation des infraStructures de transport" (LAMES) has developed an original method mentioned as Optimized Indicators Method (OIM) [3].

## 2 Theory of the Optimized Indicators Method

The OIM consists in searching for Weighting Functions, from a reference recorded signal. As constructed, these weighting functions are sensitive to the variation of a specific characteristic of the pavement structure (modules or thicknesses of the layers, interface status, etc.), as long

as it remains in the linear domain and without being sensitive to the others parameters [3]. So, in order to monitor the evolution of this characteristic during the pavement service life over time, a synthetic indicator that represents one of the pavement characteristics is calculated from a complete signal.

From a signal,  $\varepsilon(x, Y_l)$  which depends on an acquisition parameter  $x$  (time, distance...) and pavement characteristics  $Y_l$ , the problem consists for looking to an indicator  $I_j$ . This indicator takes the form of an integral characterized by the function,  $p_j(x)$ , designed as the weighting function, which is essentially sensitive to the value of the pavement characteristic  $Y_l$ , as indicated by the following equation:

$$I_j = \int_{-x}^{+x} p_j(x) \varepsilon(x, Y_l) dx \quad (1)$$

The determination of the function  $p_j(x)$  is done at the vicinity of a set of reference parameters  $Y_i$ . The partial derivative is calculated:

$$\delta I_j = \int_{-x}^{+x} p_j(x) \frac{\partial \varepsilon}{\partial Y_i}(x, Y_l) \delta Y_i dx \quad (2)$$

The weighting function,  $p_j(x)$ , can be associated with a coefficient,  $a_{jk}$ , as follows:

$$p_j(x) = a_{jk} \frac{\partial \varepsilon}{\partial Y_k}(x, Y_l) \quad (3)$$

So:

$$\delta I_j = \int_{-x}^{+x} a_{jk} \frac{\partial \varepsilon}{\partial Y_k}(x, Y_l) \frac{\partial \varepsilon}{\partial Y_i}(x, Y_l) \delta Y_i dx = \left( \int_{-x}^{+x} \frac{\partial \varepsilon}{\partial Y_i}(x, Y_l) \frac{\partial \varepsilon}{\partial Y_k}(x, Y_l) dx \right) a_{jk} \delta Y_i \quad (4)$$

Which finally leads to:

$$\delta I_j = b_{ik} a_{jk} \delta Y_i \quad (5)$$

With:

$$b_{ik} = \int_{-x}^{+x} \frac{\partial \varepsilon}{\partial Y_i}(x, Y_l) \frac{\partial \varepsilon}{\partial Y_k}(x, Y_l) dx \quad (6)$$

The orthogonality of  $p_j(x)$  is imposed with respect to the functions  $\frac{\partial \varepsilon}{\partial Y_i}(x, Y_l)$ , with  $i \neq j$  as:

$$a_{jk} b_{ik} = 1 \text{ for } j = k \quad (7)$$

$$a_{jk} b_{ik} = 0 \text{ for } j \neq k \quad (8)$$

The derivatives and integrals of the signal  $\varepsilon(x, Y_l)$  are calculated numerically, which allows determining  $p_j(x)$  and finally, the indicator  $I_j$ . After the calculation and the validation of calibrated weighting functions from a reference signal, obtained through a numerical modelling (or a real measurement) of the considered structure, the optimized indicator can be deduced. The OIM was applied for the data processing of real signals obtained during an experimental campaign [4] simulating high traffic running loads through an accelerated pavement testing facility (fatigue carousel) located at University Gustave Eiffel, campus of Nantes (Univ. Eiffel Nantes, previously known as IFSTTAR Nantes).

### 3 Experimental setup

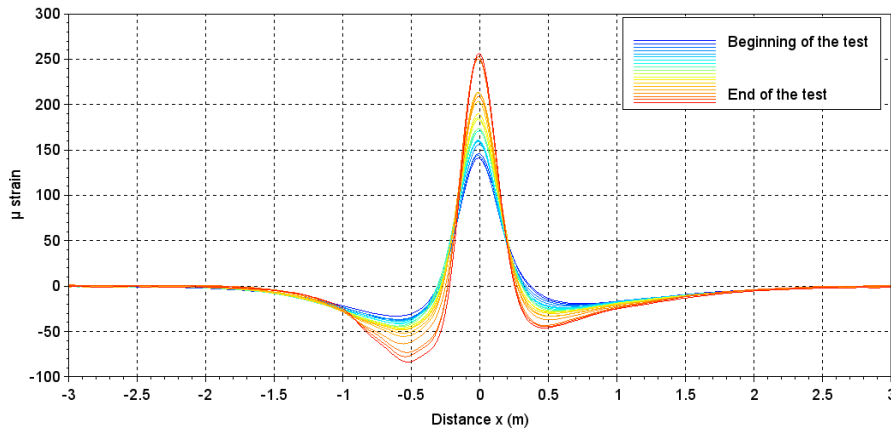
The fatigue carousel (Fig.1) at Univ. Eiffel Nantes is an outdoor road traffic simulator designed

to study the behaviour of real scale pavements under accelerated heavy traffic. It consists in 4 arms with dual-wheeled charges spinning around a circular pavement with a controlled velocity while applying loads up to 65 kN (more details in the following link : <https://lames.univ-gustave-eiffel.fr/en/equipments/the-pavement-fatigue-carrousel>).



**Figure 1:** The pavement fatigue carousel at university Gustave Eiffel (Nantes campus)

The studied pavement, specifically constructed for this study, consists in a surface bituminous layer and a base layer (Unbounded Granular Layer – UGM). The pavement is instrumented with longitudinal strain gauges (Dynatest PAST-IIA) implemented at the bottom of the bituminous layer, at 1 cm above the UGM, during the construction. After the construction of the pavement, a first batch of charging cycles is applied through the four dual-wheel arms as a consolidation step of the pavement. The number of cycles applied during this consolidation step is 37 800, which, considering the four arms of the carousel, corresponds to a total amount  $N$  of  $4 \times 37\,800 = 151\,200$  loadings. Then, a measurement of the longitudinal deformations at an estimated temperature of 9 °C and a loading speed of 72 km/h is recorded as a reference signal. This state is assumed as an initial state without damage to the structure. Next, an equivalent of a total traffic corresponding to one million heavy loads is applied over four months (from mid November 2017 to begin of February 2018), with regular recording of the longitudinal deformation. The figure 2 shows the evolution of the gauge signals shape from  $\pm 3$  m from the strain gauge in line with the number of loadings (from beginning of tests corresponding to  $N = 151\,200$  loads to end of test  $N = 881\,600$  loads).



**Figure 2:** Evolution of gauge signals with the loading.

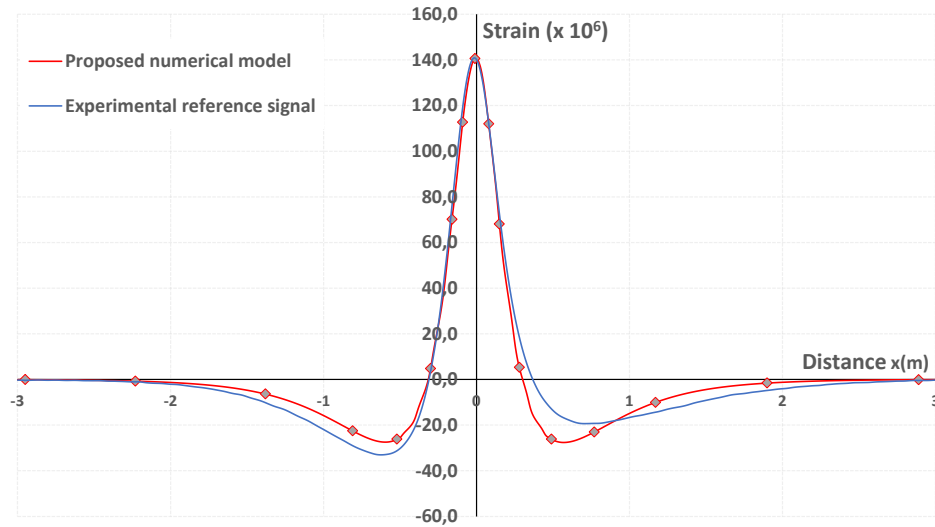
#### 4 Simulation step

The first step of the calibration of the OIM is to define a model allowing fitting the signal as a function of the physical parameters of the different layers of the structure. The Huet-Sayegh model is recognized to fit well the linear and viscoelastic behaviour of pavements [5]. This model is represented by a purely elastic spring ( $E_0$ ) (Branch I) connected in parallel to two parabolic dampers in series with an elastic spring ( $E_\infty - E_0$ ) (Branch II). In the frequency domain in which asphalt materials are characterized, the complex modulus of the Huet-Sayegh model reads:

$$E^*(\omega, \tau(\theta)) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(\theta))^{-k} + (i\omega\tau(\theta))^{-h}} \quad (9)$$

Where  $E_0$  is the static elastic modulus,  $E_\infty$  is the instantaneous elastic modulus,  $k$  and  $h$  are exponents of the parabolic dampers ( $1 > h > k > 0$ ), and  $\delta$  is a positive non-dimensional coefficient balancing the contribution of the first damper in the global behaviour. The parameter  $\theta$  denotes temperature and  $\tau$  is a response time parameter, which accounts for the equivalence principle between frequency and temperature.

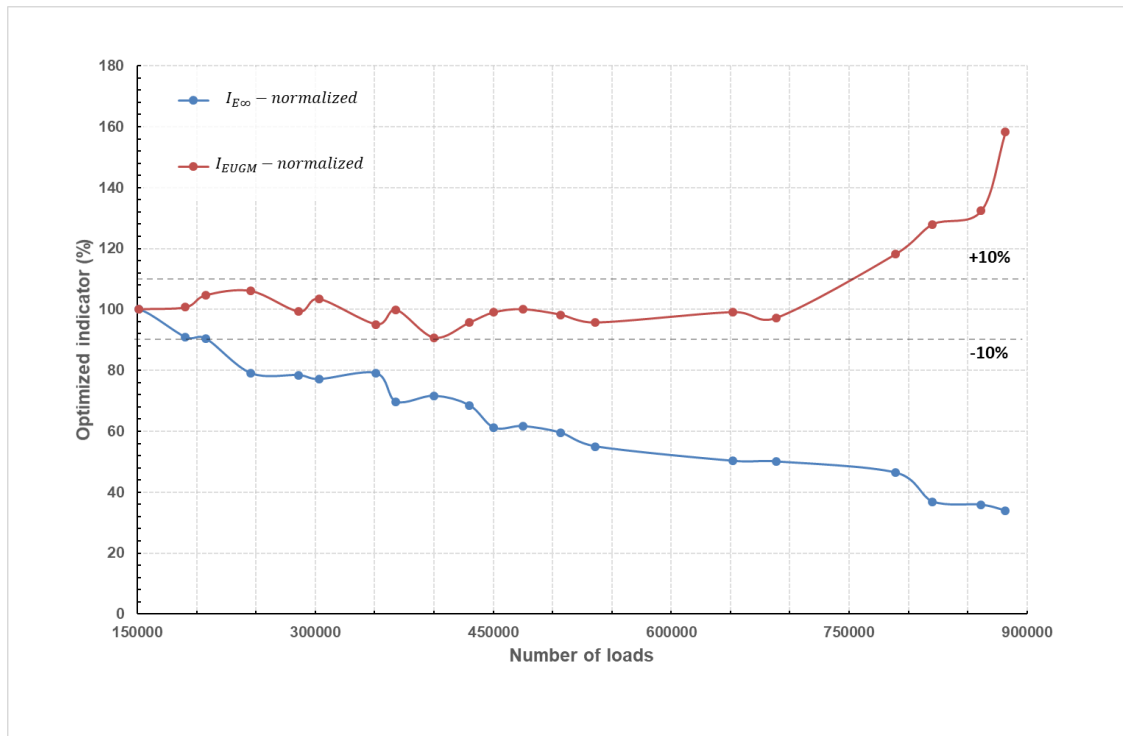
All model's parameters are calculated numerically with the use of Viscoroute® software [6], so that the simulated signal fits the reference experimental signal as perfectly as possible, by also taking in consideration the elastic modulus of the UGM ( $E_{UGM}$ ). The Figure 3 shows the shape of both reference and numerically modelled signals.



**Figure 3:** Adjustment of the proposed numerical model to the reference signal.

## 5 Application of the OIM

The determination of model's parameters showed that  $E_{\infty}$  and  $E_{UGM}$  are the most influent characteristics of the studied pavement. The weighting functions associated with each of these parameters are determined and calibrated through simulated signals obtained with  $\pm 10\%$ -variations of the considered parameter, while the second remains constant. The determined weighting functions are implemented on all recorded signals (plotted in Figure 2), which allowed extracting a value of the optimized indicator of the considered pavement's parameters (respectively labelled as  $I_{E_{\infty}}$  and  $I_{E_{UGM}}$ ) for each number of applied loads. The ratio between the reference ( $N = 151\ 200$  loading cycles) and the extracted optimized indicators (chosen this way due to the construction of the weighting functions) allows representing the evolution of normalized pavement's parameters with respect to the number of loads, as plotted in Figure 4, with relative variations in the range of  $\pm 10\%$  indicated by two lines.



**Figure 4:** Relative evolution of the optimized indicators with loading

The results plotted in figure 4 show that the optimized indicator associated with  $E_{\infty}$  ( $I_{E_{\infty}}$ ) follows a continuously decreasing tendency with the number of loads, which indicates that the bituminous layer starts being damaged with the repeated loadings, decreasing the bearing capacity of the structure, which is physically consistent. On the other side, the optimized indicator associated with  $E_{UGM}$  ( $I_{E_{UGM}}$ ) remains constant until  $N=700\,000$ . Above this number of loads, an exaggerated increase up to 160% is estimated for this parameter. As a variation greater than 10% is observed after 250 000 loadings for  $E_{\infty}$ , the current assumption is that the OIM is out of its linear domain. Indeed, as the calibration of the weighting functions was performed with one variable parameter while the other was set constant, a slight variation of  $E_{UGM}$  induces an overestimation as  $E_{\infty}$  is largely out of the linear domain. These results demonstrate anyway the interest of the OIM to evaluate the characteristics of a pavement's structure independently each other's, as the conventional methods cannot proceed this kind of evaluation. As it stands, a regular recalibration of the weighting functions seems required as long as at least one of the pavement characteristics reaches a threshold out of the linear domain.

## 6 Conclusion

The results presented in this paper show the OIM as a promising data processing tool. Used for the processing of strain gauge data embedded between two layers of a pavement, the OIM allows monitoring separately the characteristics of each layer, as the conventional processing of signals does not make it possible.

The determination of a threshold variation appears as a key parameter for the re-calibration of the weighting functions. A clear identification of the linearity domain of the OIM requires carrying out another parametric study consisting to evaluate the influence of the model's parameters with greater relative variations ( $\pm 30\%$  in example).





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