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# Inverse problems to monitor the railway system

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## Abstract

The present work proposes methods to monitor the railway system using dynamic reactions measured during commercial journeys. More precisely we propose to combine railway dynamic simulations and data models to detect damage of vehicle suspensions on one side and track geometry on the other side.

On a scientific point of view, the monitoring is based on the solving of a complex inverse problem. Indeed, the problem is non-linear (wheel/rail contact, suspensions, aerodynamics forces...) and contains many sources of uncertainties (wheel/rail friction coefficient, wind loads, …). The problem cannot therefore be posed in a deterministic way and a probabilistic framework must be adopted. The statistical dimension of the problem is moreover very large because it involves functional inputs and outputs (they depend on time and/or space). Dedicated methods have thus to be adopted.

The developments are first applied to the monitoring of high-speed train suspension elements over several years. The results obtained are encouraging and make it possible to monitor the various damage and maintenance. The second application concerns the monitoring of lateral offset defects. These are more difficult to reconstruct than the levelling defects due to the play in the track. A method for detecting large defects is proposed here.

**Keywords:** Track monitoring, Suspension diagnoses, Inverse problems.

# 1 Introduction

The railway system, which can be seen as a **system of systems** (train, track, power supply, etc.), is extremely complex as it presents many **physical interfaces** (wheel/rail, pantograph/catenary ...) but also **functional interfaces** between entities that do not always belong to the same companies. As a consequence, a global vision must be addressed on the whole system for the definition of the design, monitoring, maintenance, and certification criteria, but adaptations and translations of these different rules based on **direct and indirect approaches** must also be defined at the level of each **sub-system**.

Moreover, monitoring and maintaining the railway system is extremely challenging and very often rely on the solving of inverse problems. As an example, the track geometry is usually monitored by a train that measures chords in order to reconstruct in inverse an "image of the track geometry". In the same way, it is generally not possible to install reliable strain gauges at the wheel/rail contact to measure the contact forces. But estimations of these quantities of utmost importance for train stability can be deduced from measurements of the wheel deformation only at the cost of solving a **well-chosen inverse problem**.

The physical understanding and the numerical simulation of the dynamic evolution (at different time scales) of this system of systems are also made difficult by the presence of a many **non-linearities** (wheel/rail contact, suspensions, aerodynamics forces...) and many sources of **uncertainties** (*epistemic uncertainties:* masses, suspension characteristics, track irregularities… and *random uncertainties:* wheel/rail friction coefficient, wind loads, …). In this context, most of the problems of inferring the parameters on which the numerical models depend are often ill-posed in a deterministic framework and statistical reformulations are usually necessary to correctly identify these parameters from **indirect measurements** (on bench or on-line) while rigorously integrating the uncertainties. This is the case for instance for the identification of the friction coefficient at the wheel/rail contact, which has given rise to numerous experimental, analytical and numerical research works for the last decades, essentially based on inverse problems [1,2].

# 2 Methods

The present work focuses on the monitoring of the railway system using dynamic reactions of the system measured during commercial journeys. More precisely we show how the combined use of railway dynamic simulations and of data models enables the detections of damage of vehicle suspensions on one side and track geometry on the other side.

From an operational point of view commercial train equipment facilitates the monitoring. However, on the scientific point of view, it is complex since it is based on the solving of a complex inverse problem. Indeed, the problem is probabilistic because of the presence of uncertainties as discussed in introduction. Moreover, the statistical dimension of the problem is very large because it involves **functional inputs and outputs** (they depend on time and/or space).

Another challenge concerns the fact that the measured train dynamics depend on both infrastructure and rolling stock characteristics. Therefore, a clear distinction must be made between changes in dynamic behavior that must be attributed to damage to the infrastructure and changes in dynamic behavior that must be attributed to damage to the rolling stock. This will be done by comparing the behavior of several trains that have run in the same area or by comparing the trains behavior to a simulated response. A special effort was therefore made to synchronize the various measurements and to model the associated uncertainties. Similarly, the dynamic behavior of the trains considered was modelled in a multi-body code and the model errors were carefully integrated. Taking into account measurement and simulation uncertainties transforms the studied signals into probabilistic variables. Therefore, their comparison requires adapted tools. In the context of this work, the choice was made to use the likelihood function.

# 3 Results

**Suspension monitoring**

The first step of the work consisted in carrying out a qualitative sensitivity study in order to define the suspension elements (and more precisely the mechanical characteristics) that have a sufficient impact on the recorded accelerations. Only the health of this set of suspensions will be monitored by the device. To do this we implemented the one at a time Morris method on a railway dynamics model.

The evolution of the mechanical parameters selected was then studied by identifying, on a monthly basis, the parameters that best represent the measurement that was carried out. To do this, a Bayesian calibration of the dynamic model was carried out, based on the on-line dynamic measurements. The choice of the cost function, necessary for the comparison of the simulated and measured signals, was based on the likelihood of the measured spectral response to the simulated response.

The method has been applied to the monitoring of the suspensions of a high-speed train for several years. The results allow an interesting characterization of the damage and repairs.

**Track geometry monitoring**

A similar approach was applied to track geometry monitoring. Indeed, while vertical offset and cross-level can easily be reconstructed by double integration, the characterisation of gauge and lateral offset, due to the play in the track, is much more complex to monitor from dynamic signals.

Therefore, in this work, the dynamic signals that are most dependent on lateral track defects are determined through simulation. An analysis of the selected dynamic responses then allows the presence of large defects to be estimated. An update of a reference geometry through dynamic measurements also gives an indication of the evolution of major defects over time.

## 4 Conclusions and Contributions

Inverse problems are more and more used in railways dynamics whether to post-process complex measurements or to calibrate models. The applications are numerous: identification of model parameters, robust design, optimization under uncertainties and so on. However, inverse problems are complex to solve, often requiring a shift to a probabilistic framework and the use of specific methods. This work presents the resolution of two inverse problems under uncertainty for monitoring train suspensions and track geometry.

It presents several originalities. First of all, a special effort is made to ensure that the dynamic model is representative of the studied system. The errors are carefully modeled, and the parameters are identified thanks to Bayesian calibration with dynamic measurements on high-speed trains for the suspension diagnosis and on commuter trains for the track monitoring. This guarantees a good representation of the real system.
Second, the optimization problem has been set up in a probabilistic framework and adapted resolution method have been chosen.

The results obtained on both examples are encouraging and shows the efficiency of the method. The introduction to vehicle dynamics of these methods, which couple data and physical models, are however still in its infancy (particularly in industrial processes) but many new applications should continue to emerge in the coming years.

## References


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