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Development and Validation of Innovative Weighing in Motion Systems

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The development of an efficient *Weigh-In-Motion* (WIM) system, with the aim of estimating the axle loads of railway vehicles in motion, is quite interesting from both an industrial and academic point of view. Such systems, with which the loading conditions of a wide population of running vehicles can be verified, are very important from a safety and maintenance perspective. The evaluation of the axle load conditions is fundamental especially for freight wagons, more likely to be subjected at risk of unbalanced loads that may be extremely dangerous both for the vehicle running safety and the infrastructure integrity.
In this way, potentially dangerous overloads or defect of rolling surfaces could be easily identified: in case of measured overloads, the axle could be identified and monitored with non-destructive controls to prevent the propagation of potentially dangerous fatigue cracks. Also peaks on the measured contact forces could be caused by wheel flats or other kinds of damages of the rolling surfaces which could be early identified saving both vehicle and railway line from the dangerous consequence of a prolonged exposure to irregular loads. As a consequence the WIM system could be used both as Prognostic and Diagnostic tool thanks to its capability of early identifying a minor fault condition which could cause, if ignored, potentially catastrophic events.
The development, the simulation and the validation of the innovative WIM algorithm aimed at estimating the axle loads of railway vehicles will be presented in this paper. The innovative algorithm have been preliminary validated using experimental data provided by Ansaldo STS and further trained on FEM simulation results.
Obtained results are quite encouraging considering that experimental results have been optained with an experimental layout optimized for a different WIM algorithm previously developed by Ansaldo STS which, after the comparison, turned out to be inferior both in terms of performances and reliability.

1. Introduction

The development of efficient WIM (*Weigh In Motion*) systems capable of estimating the axle loads of railway vehicles in motion is an interesting topic from both an industrial and academic point of view. The importance of this kind of systems lies in the safety and the maintenance of track since it allows the verification of the loading conditions of a wide population of vehicles through a limited number of WIM devices placed along the railway network. The evaluation of the axle load conditions is fundamental especially for freight wagons, more subjected at risk of unbalanced loads which may be extremely dangerous both for the vehicle safety and the infrastructure maintenance.
In particular unbalanced loads could cause structural overloads which could drastically reduce the expected life of safety related components like the axles and the programmed maintenance and inspection cycles of both vehicle and infrastructure. Moreover, measuring the contact forces, the tool could be able to identify potentially dangerous defects of rolling surfaces which usually produces spiky or irregular measurements of the contact forces that can be easily recognized both in time and frequency domain.
In this way the WIM system could be considered both a diagnostic and prognostic tool (able to identify minor o tolerable fault conditions which could cause catastrophic events such as axle failures if not properly detected) very useful for predictive maintenance of the structural components of the vehicle.
In literature some WIM applications, based on different measurements of physical quantities (such as rail shear, rail bending, sleeper forces etc.) are present (Bracciali et. al. 2001a, Pretedel et. al. 2009,

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Kolakowski et. al. 2010). Also known manufacturer of sensor and diagnostic systems for railway applications, such as Cardinal, Stock, Kistler, Tagmaster (Cardinal 2012, Stock 2012, Kistler 2012, Tagmaster 2012) have produced their own WIM system based on different measurement layouts and identification algorithms.
Figure *1*, some examples concerning different sensors proposed on the cited commercial applications are shown.

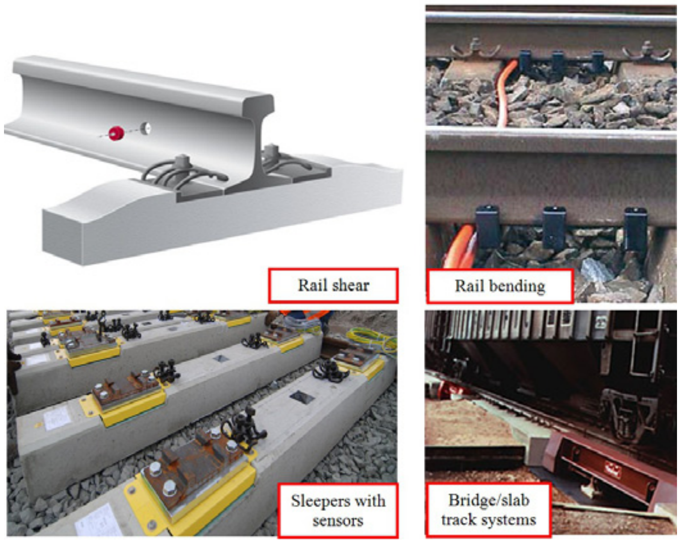

Figure 1: different kind of strain measurement used for WIM application ranging from rail shear and bending measurements to instrumented sleepers (with integrated load cells-strain gauges) or slab track

In this work a general purpose WIM algorithm is proposed, able to be adapted to almost every sensor layout and to measure rail contact forces starting from different measurements (strain, stress, forces on the sleepers, etc.).
The algorithm is tested considering as input bending strain measured on rail foot This choice was decided in order to make easier the comparison with the experimental data and the benchmark algorithm proposed by Ansaldo STS. It is a quite demanding benchmark, since shear measurement are usually less affected by measurement disturbances as also stated by (Bracciali 2001/a) .

2. The WIM algorithm

Principle of operation of the proposed algorithm is quite simple: to estimate the axle loads, the algorithm approximates the measured physical input through a set of elementary functions calculated by means of a single fictitious load moving on the track. Starting from the set of elementary functions, the measured signal is then reproduced through Least Square Optimization (LSO) techniques (Shampine et. al. 1997 Kelley 1995, Nocedal et. al. 1999): in more detail, the measured signal is considered as a linear combination of the elementary functions, the coefficients of which are the axle loads to be estimated.
The function $f(x,t,v)$ is the elementary solution (by example the bending strain on the rail foot along the longitudinal dimension *x* at the time *t*) due to an unitary load traveling on the railway line with speed *v.* In the proposed approach authors suppose that the solution $f_{tot}(x,t,v)$ corresponding to the passing of *n* axle over the line could be approximated/calculated by considering the superposition of effects principle and by using the weighted sum of the *n* elementary solutions, each shifted of a time delay t_{di} :

$$f_{tot}(x,t) \simeq \sum_{i=1}^{n} a_i f(x,t-t_{di},v) . \quad (1)$$

If relation (1) is valid (the system is approximately linear) coefficients a_i are the loads of corresponding axles. For the proposed WIM algorithm authors calculated the function $f(x,t,v)$ by using an approximate FEM model of the railway track (see the next chapter).
As a consequence the proposed approach manages the estimation of the vertical axle loads as a the solution of a best fit problem which can be solved by inverting relation (1) in the sense of a least square

approximation. The values of delays t_{di} and the train traveling speed *v* are supposed to be known through a dedicated measurement system, as for example a very precise axle counter. Since f_{tot} *(t,x)* is a generic output of the system (by example a set of strain or inertial measurements) the proposed approach is quite general and can be adapted to different sensor layouts.

3. Calculation of *f(x,t,v)*.

The proposed WIM method is based on the idea of using calculated elementary solutions $f(x,t,v)$ to fit the measured response of the railway line $f_{tot}(x,t,v)$; as a consequence a simplified model of the railway line has to be developed to calculate $f(x,t,v)$.

Rails and underlying infrastructures are modeled as a continuous beam representing the rails supported by an elastic foundation which simulates sleepers and ballast. For the rail, both the Euler-Bernoulli and the Rayleigh-Timoshenko models can be used (Iwnicki 2006). In particular, the Euler-Bernoulli beam model neglects the shear deformability considering only the contribution of the bending (Figure 2):

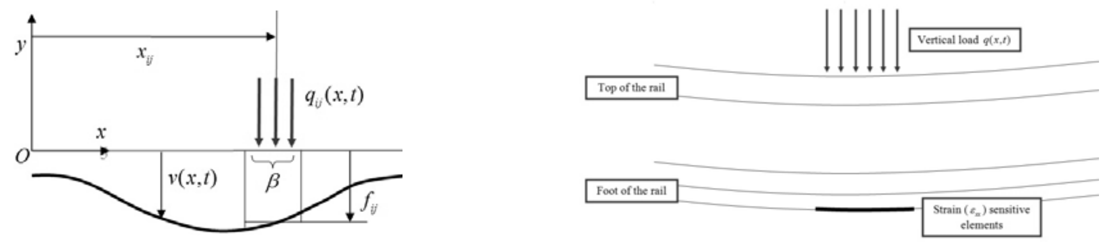

Figure 2: beam model of the track (left); measurement of the longitudinal deformations on the rail foot between two adjacent sleepers (right).

To take into account the contribution of the deformability of sleepers and ballast, different models of increasing complexity may be adopted (Esveld 2001, Iwnicki 2006, Dahlberg 2001). Authors have chosen a simplified, planar model proposed by Kisilowski (Kisilowski et al. 1991), often used for the simulation and the development of this kind of applications (Bracciali et al. 2001a-2001b, Pretedel et. al. 1999). In the considered model, visible in Figure 3, sleepers and ballast are modeled by means of single degree of freedom systems, with a consequent good compromise between accuracy and efficiency. The main parameters of the simplified railway line are visible in Table 1.

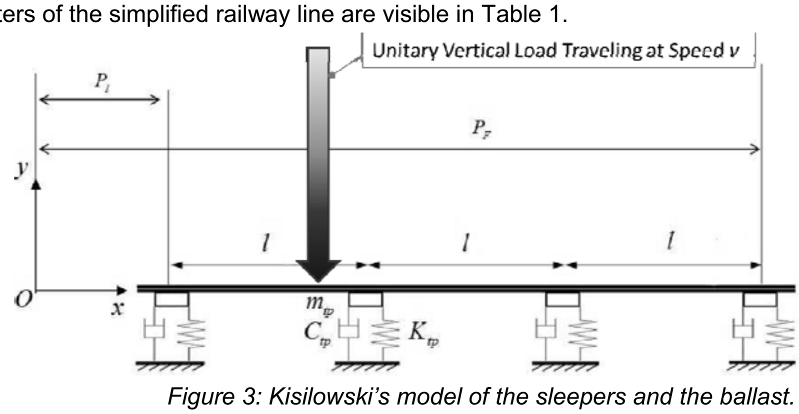

Figure 3: Kisilowski's model of the sleepers and the ballast.

Table 1: Main parameters used for the railway line model

Parameter	Units	Value
Sleepers-ballast mass m_{tp}	kg	10
Sleepers-ballast mass K_{tp}	N/m	$5*10^7$
Sleepers-ballast mass C_{tp}	Ns/m	$2.5*10^5$
Sleepers distance *l*	m	0.6
Sleepers total number N_t	-	201
Beginning of the track P_I	m	0
Beginning of the track P_F	m	120
Beam Properties	UIC 60 rail section	

The simulated load is an unitary vertical force traveling at speed *v*.
As regards of the longitudinal deformations on the rail foot, which are the physical inputs of the WIM algorithm for the proposed benchmark, they are measured at various points (few if possible to reduce both the measurement station dimensions and the economic costs) distributed along the railway track and placed between two contiguous sleepers to amplify the longitudinal deformations. On both the sides of the track, measurement points are present to reject the effect of spurious signals and load transfers produced by the lateral dynamics. A more detailed description of the proposed simulation model have been the object of previous publication of authors (Pugi et. al.,2012).

4. The Ansaldo STS Benchmark

Considering preliminary results on simulation models (Pugi et al. 2012), Ansaldo STS agreed to share with University of Florence some data in order to verify the performances of the proposed WIM algorithm.
Experimental data of Ansaldo STS were referred to the sensor layout visible in Figure 4: bending deformations on rail foot are measured in two different section of the line at a relative distance of 4.8 meters. Strain deformations measured on the two instrumented sections are used as input from the proposed WIM algorithm. The same inputs are also used by a benchmark WIM algorithm developed and calibrated by Ansaldo STS. It is interesting to notice that the characteristics of the algorithm used by Ansaldo STS was not known by authors.

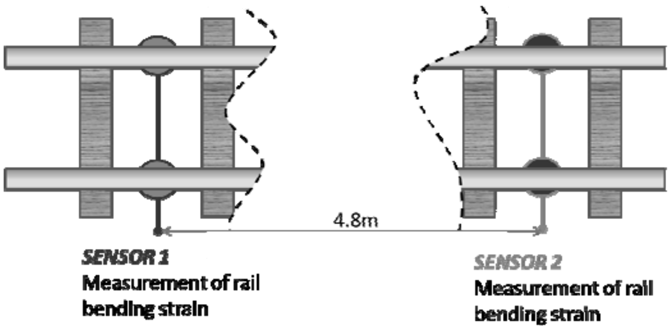

Figure 4: sensor layout proposed by Ansaldo STS as benchmark for the proposed WIM algorithm (Mazzino et al ,2012)

The proposed measurement layout is used to measure the axle loads of a benchmark train composed by three vehicles: a six axle locomotive and two different wagons with different wheelsets as visibile in Figure 5. The traveling speed of the benchmark train composition in the proposed test case is about 15.4km/h . Main features of the benchmark composition are shown in Table 2; it is interesting to notice that all the parameters of the suspension systems of the benchmark vehicles are not known

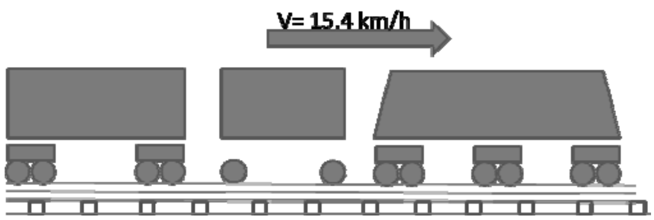

Figure 5: sensor layout proposed by Ansaldo STS as benchmark for the proposed WIM algorithm

Table 2: main known parameters of the benchmark composition

Vehicle	Wheelset (UIC desc.)	Prim. Sup. Stage	Sec. Susp Stage	Axle load [t]
Locomotive	b-b-b	Yes	Yes	17.7
Second Wagon	1-1	Yes	No	8.0
Third Wagon	2-2	Yes	Yes	7.8

As visible in Figure 6 the WIM algorithm proposed by authors is able to correctly identify the loads on all the axles of the proposed benchmark train: in particular the relative estimation errors of the proposed algorithm are lower if compared to the ones of the algorithm proposed by Ansaldo which has been calibrated on the chosen sensor layout (as visible in Table 3). As further result, in Figure 7 the strain $f_{tot}(x_1,t,v)$ measured on the sensor 1 section is compared with the FEM solution reconstructed by UNIFI WIM algorithm to identify the axle loads: experimental results and corresponding simulated response of the identified loads are quite similar.

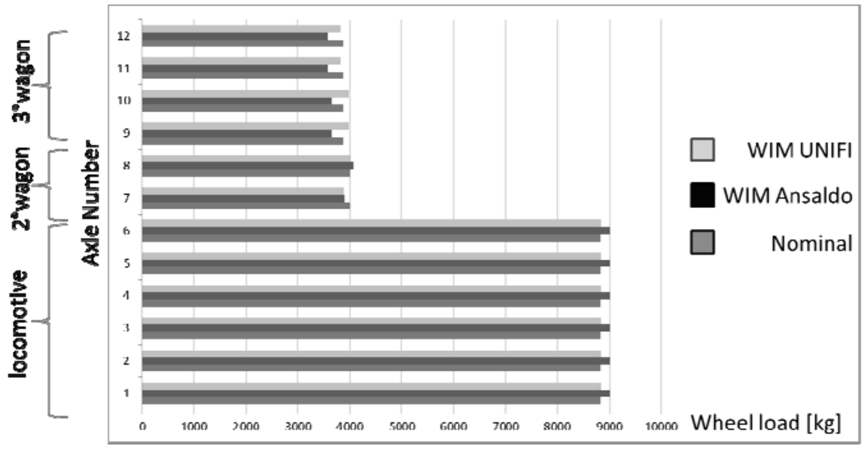

Figure 6: estimation results for algorithm proposed by Ansaldo STS and for the WIM algorithm proposed by the authors

Table 3: relative errors on axle load estimation for the proposed WIM algorithm and for the benchmark one proposed by Ansaldo

Axle n.	1	2	3	4	5	6	7	8	9	10	11	12
UNIFI WIM ALG. % error	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	-2.9%	+0.4%	2.7%	2.7%	-1.3%	-1.3%
ANSALDO WIM ALG. % error	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	-2.5%	+1.7%	-5.7%	-5.7%	-7.7%	-7.7%

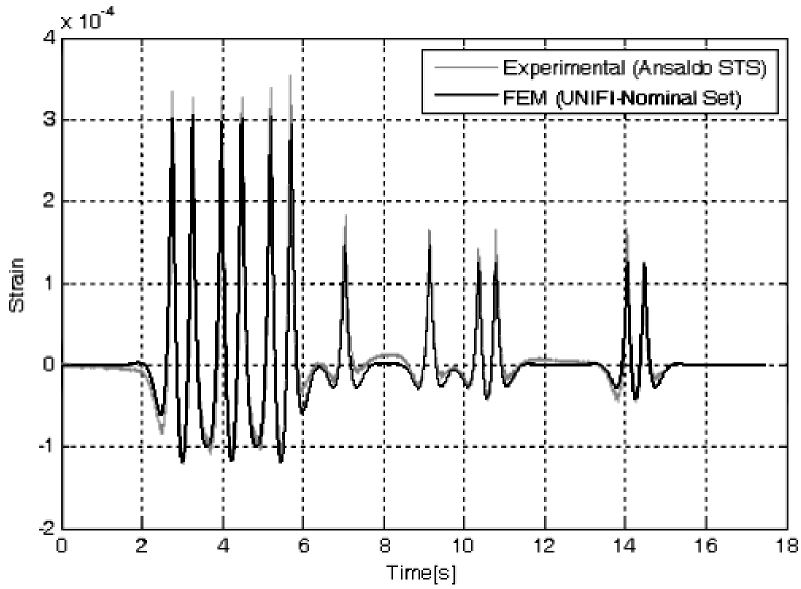

Figure 7: comparison between the experimental strain measured on the first measurement sections and the corresponding approximated FEM solution calculated by the WIM algorithm to identify axle loads

Conclusions

In this paper the authors presented an innovative WIM algorithm aimed at estimating the vertical axle loads of railway vehicles in order to evaluate the risk of vehicle loading. The validation of the new WIM algorithm highlighted a good agreement between the estimated quantities and the experimental data, confirming the accuracy and the reliability of the procedure. The most interesting feature of the proposed approach is the possibility of an easy customization of the WIM algorithm to different measurements layouts.

Further experimental and simulation campaigns are scheduled for the future, also considering different train compositions and traveling speeds, since available experimental data were referred to a quite simple test performed in near to static conditions.

Currently authors are also working to develop smart filtering and estimation techniques to estimate and/or identify potentially dangerous defects of rolling surfaces such as wheel flat, using the same input data employed for the weighing application.

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