**The homologation of low-flatcar wagons: instrumentation and on-track tests**

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**Abstract**

Low-flatcar wagons are designed to load entire articulated lorries instead of loading only the containers in order to make the loading and unloading stages easier and faster. This design implies a particular layout of the bogie and suspension system, aiming at minimizing the height of the flatcar with respect to the rail level. This solution influences the dynamic behavior of the wagons, reducing the steering capability and causing high lateral forces on the driving wheels when low-radius curves or turnouts are negotiated.

Aim of the work is the homologation of low-flatcar wagons on the Italian railways. Besides the classical homologation procedure prescribed by the EN14363 rule, a particular focus will be devoted to the running safety when negotiating turnouts. Indeed, it will be demonstrated that, under certain conditions, this is a very critical running condition for these vehicles. First, a numerical analysis is performed to identify the most critical condition. Then, this condition is reproduced experimentally, measuring the wheel-rail contact forces in order to assess the running safety of these wagons.

1. **Introduction**

Low-flatcar wagons represent an attempt to transfer part of the road traffic onto railroads. Indeed, they are designed to load entire articulated lorries instead of loading only the containers. In order to make the load and unload stages easier, these wagons are designed to minimise the height of the flatcar with respect to the rail level. In particular, the bogie design includes 4 axes equipping small-radius wheels and a particular design of the suspension system. This solution has a significant influence on the vehicle dynamics, providing poor steering capabilities and consequent high lateral forces on the driving wheels. This problem becomes particularly critical on low-radius curves and turnouts. Consequently, the Italian agency for rail safety imposed a strong limitation of the train speed when crossing turnouts. This causes an increase of the travel time and a consequent loss of competitiveness with respect to road transportation.

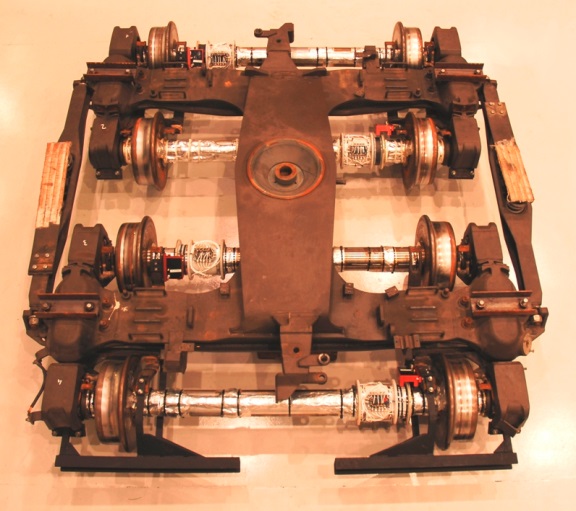
Aim of this work is the characterization of the dynamic behaviour of low-flatcar wagons, in order to analyse their running safety and to homologate them up to the standard speed of freight wagons for all the running conditions (straight track, curves and turnouts). For this reason, a low-flatcar bogie has been instrumented with four dynamometric wheelsets to measure the wheel-rail contact forces and 3-axes accelerometers placed on the axle-box, on the bogie and on the wagon. Moreover, the buffers have been instrumented with potentiometers in order to measure the interaction with the adjacent wagons.

The instrumented wheelsets have been calibrated on a dedicated test-rig and by means of a specific procedure. Then, different tests have been carried out following the specifications of the EN14363 standard [1] to achieve the trainset homologation. Moreover, a numerical and experimental campaign aiming at characterizing the trainset behaviour when negotiating turnouts has been carried out. Both the equipment and the experimental campaign will be described in detail in the paper.

1. **Description of low-flatcar wagons**

Low-flatcar wagons are designed to minimize the total height of the flatcar with respect to the top of the rail, so that full articulated trucks can be loaded without exceeding the railway gauge.

This goal is accomplished by means of a particular 4-axle bogie (Figure 1) equipped with wheelsets having small wheel radius (190 mm). Also the suspension elements are designed to keep the height of the wagon as low as possible. The primary suspension is replaced by elastomeric elements connecting the bogie frame with two secondary units, made up of two wheelsets connected by two longitudinal beams, working as a 4-bar linkage. This system permits only very small relative rotations and, for this reason, the steering capabilities of the bogie are worsen.



*Figure 1: The bogie of low flatcar wagons.*

The connection between the bogie and the carbody is made up of a central pivot, working as a spherical hinge, and two side-bearers providing energy dissipation through friction. The connection between two adjacent wagons is provided by small buffers placed below the flatcar level. In this way, the distance between two adjacent wagons can be minimized, allowing trucks to move along the trainset.

1. **Instrumentation layout**

In order to achieve the homologation of low-flatcar wagons, a vehicle has been instrumented as follows.

* 4 instrumented wheelsets [2,3], in order to measure the wheel-rail contact forces on the leading bogie of the wagon;
* Triaxial accelerometers on the bushings, bogie and carbody, as prescribed by the EN14363 regulation;
* 4 potentiometers on the buffers, to get a measurement of the interaction forces between the wagon and the adjacent ones (obtained from the knowledge of the buffer characteristic curve and geometry).

For what concerns the instrumented wheelsets, at least five independent strain signals on the wheelset are needed to estimate the six force components (vertical, lateral and longitudinal) of the wheel-rail interaction. Indeed, under the assumption of no traction or braking forces on the wheelset, the two longitudinal forces are opposite one to the other. One of the typical layouts is made up by instrumenting the wheel webs in order to get a direct measurement of the lateral forces. Anyway, the wheel low radius makes the wheel webs poorly flexible, leading to a very low signal-to-noise ratio. For this reason, the only available solution is the instrumentation of the axle. Figure 2 shows the position of the strain sensors along the axle itself: sensors A, C, D, F are used as a “minimum set” together with the torsion measurement, while the other sensors have been placed for redundancy.

SalaStrumentata

*Figure 2: Position of the sensors on the instrumented wheelset.*

Assuming a linear relationship between the vector of the measured deformations and the vector of the applied forces , the sensitivity matrix can be defined so that

(1)

The calibration matrix of the instrumented wheelset can be obtained as the inverse of the sensitivity matrix

(2)

The coefficients contained in the calibration matrix depend on the characteristics of the dynamometric wheelset (such as the Young modulus of the material, the inertia moment of the measuring section) and on the position of the sensors. The calibration procedure consists of a least square minimisation, where the calibration matrix is computed as a pseudo-inverse matrix of the deformation matrix pre-multiplied by the force matrix

(3)

where represents the estimation of the calibration matrix, each row of the force matrix represents the measured force components imposed at the wheelset, while each column represent a single calibration test. The same structure is applied to the deformation matrix: the measurements of each section for a single test are stored in each column. The number of tests needed for the minimization process has been defined through a full factorial plane obtained combining the load conditions of the two wheels. The load levels (number and corresponding force values) associated to each force component are defined depending on the expected loads during the on-track tests. The calibration of the instrumented wheelset has been performed on a dedicated test rig, installed in the laboratories of Politecnico di Milano (figure 3). The characteristics of the test rig are described in detail in [4,5].

1. **Numerical analysis**

The numerical analysis of the behaviour of low-flatcar wagons when negotiating turnouts has been performed through a numerical model developed at Politecnico di Milano and described in detail in [6].The model simulates the behaviour of a trainset in the horizontal plane considering each wagon as a 1-degree-of-freedom system, where position and speed of each vehicle along the curved abscissa represent the state variables. Dynamic models of the electrical motors and of the braking system are included, so that the transient dynamics of the trainset subsequent to the application of traction/braking forces can be analysed. The coupling between adjacent vehicles is obtained considering one central draw gear and one or two buffers. The draw gear is represented with a nonlinear spring-damper system. A similar model is adopted to reproduce the elastic response of the buffer and to compute the force developed by the buffer consequent to its compression [7]. The interaction between two buffers is described also taking into account their geometry.

Through this mathematical model, the longitudinal dynamics of the typical trainset composition has been analysed. The composition is made up of a locomotive, a passenger car and a series of empty or laden low-flatcar wagons. Different simulations were carried out to investigate how the trainset composition (number and distribution of empty/laden vehicles) affects the trainset dynamics of each wagon if an emergency braking is performed while running over switches. This condition is particularly critical for the running safety as confirmed by the experience, since in the past years this kind of trainset experienced several problems while running over small-radius turnouts and in presence of a sudden braking input. The reason is that, due to the delay in the propagation of the braking command, the rear vehicles run against the front ones, leading to a sudden increase of buffer forces. Consequently, the central vehicles are compressed by the buffers and, if traveling a S-shaped curve, this results in an understeering yaw moment which influences the cornering dynamics increasing the lateral force on the external wheels.

The numerical tests have been carried out to identify the most critical condition to be reproduced by the experimental campaign. Convoys including 21 and 25 low-flatcar wagons have been considered with 0-20 and 0-24 empty vehicles respectively. For the sake of brevity, figure 3 shows the results for the 25-wagon case, which resulted to be the most critical one. Indeed, the result for the other case is similar, but with lower forces. The left figure shows the maximum understeering yaw moment on each wagon (y-axis) varying the trainset composition (x-axis). The upper part of the right figure reports the maximum value of yaw moment for each composition while the lower part of the figure indicates the corresponding wagon where the maximum yaw moment is recorded. Two colours are used to simplify the identification of whether the wagon with the maximum yaw moment is loaded (dark blue) or empty (light blue).

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*Figure 3: Maximum yaw moment on each wagon for each trainset composition (on the left) and maximum yaw moment and corresponding wagon for each loading configuration (on the right).*

The maximum yaw moment (around 140 kNm) is obtained with the fully loaded trainset almost at the centre of the trainset (9th vehicle). As the number of empty vehicles increases, the maximum value of the positive yaw moment is reduced, especially in the rear part of the trainset where empty vehicles are located. Indeed, due to reduced inertia and consequent higher deceleration capability, empty vehicles do not run against the laden ones during emergency braking and buffer forces are therefore smaller. Increasing again the number of empty vehicle (above 17 empty vehicles), the homogeneity of the trainset both in terms of mass and braking capabilities is regained. Consequently, the maximum yaw moment increases again up to 55 kNm for the empty trainset. The maximum yaw moment on a laden wagon is almost three times the one recorded on an empty vehicle. However, considering that the mass of an empty wagon is almost 1/5 of the mass of a loaded one, the operating conditions of the empty vehicle is more critical from a running safety point of view. For this reason, the experimental campaign has been done measuring the wheel-rail contact forces on the 10th vehicle of a 25-wagon trainset with 24-empty-vehicles.

1. **On-track experimental campaign**

The layout of the trainset corresponds to the most critical one identified in the numerical simulations: the trainset is composed by a locomotive, pulling the convoy, a measurement coach (the passenger car) and 25 low-flatcar wagons. This layout can be used for the test about the turnout negotiation, while a trainset with a reduced number of wagons has been considered for the statistical analysis imposed by the EN14363 norm. Being this a standard procedure, for the sake of brevity we will not report its results here. On the contrary, this section will be focused on the campaign on the turnouts, held in the railway yard of Roncafort (TN, Italy). The test track has been chosen so that the desired turnout sequence can be negotiated. Two low-radius turnouts S160UNI/170/0.12dp (a left and a right turnout with 170 m radius respectively) have been negotiated by the trainset considering different speed values, from the current speed limitation (10 km/h) up to the standard limit on these turnouts (30 km/h). Moreover both constant speed and braking condition have been considered.

Figure 4 and 5 show the result for the maximum speed for the constant speed and braking condition respectively. Many braking tests have been performed in order to apply the braking command so that the most critical wagon is in the middle on the braking curve when the maximum compression forces are applied. The yaw moment is derived from the measurement of the potentiometers and knowing the characteristic curve of the buffers, while the derailment coefficient Y/Q is computed from the forces estimated by the dynamometric wheelsets described in section 3. It can be noticed that, as expected, the braking forces cause an increase of the yaw moment and a consequent increase of the derailment coefficient. Anyway, the value is well below the Nadal limit represented by the red dashed line (equal to 1.44 considering a maximum flange angle of 75° and assuming a friction coefficient equal to 0.36).



*Figure 4: Constant speed test on the turnouts: derailment coefficient on the left (outer) wheel of the front wheelset (on the left) and corresponding yaw moment (on the right).*



*Figure 5: Braking tests on the turnouts: derailment coefficient on the left (outer) wheel of the front wheelset (on the left) and corresponding yaw moment (on the right).*

1. **Conclusion**

The paper presented the homologation of low-flatcar wagons on the Italian railways up to the standard speed of freight trains. Due to the peculiarities of these wagons, the standard homologation procedure was not sufficient to demonstrate the running safety of these wagons. For this reason, a deep analysis of flatcar wagons’ dynamics on curves and turnouts has been performed both numerically and experimentally, identifying the most critical running conditions and reproducing them during the on.track tests. The results obtained permitted to demonstrate the running safety of these vehicles, leading to a full homologation on the Italian railways.

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