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Daniele CORTIS, Stefano GIULIANELLI*, Gabriele MALAVASI
Sapienza University of Rome, Department of Civil, Building and Environmental Engineering
Via Eudossiana 18, 00184, Rome, Italy
Stefano ROSSI
Rete Ferroviaria Italiana
Direzione Tecnica – Piazza della Croce Rossa 1, 00161 Rome, Italy
**Corresponding author*. E-mail: stefano.giulianelli@uniroma1.it

SELF-DIAGNOSIS METHOD FOR CHECKING THE WAYSIDE SYSTEMS FOR WHEEL-RAIL VERTICAL LOAD MEASUREMENT

Summary. Nowadays, wayside measurement systems of wheel-rail contact forces have acquired great relevance for the monitoring of rolling stock, especially for freight trains. Thanks to these solutions, infrastructure managers can check and monitor the status of rolling stock and, when necessary, impose corrective actions for the railway companies. On the other hand, the evaluation of contact forces is part of the rolling stock authorisation process [1] and a mainstone for the study of the running stability. The data provided by these measurements could give useful information to correlate the wear of the track with the frequency of applied loads, helping in the development of a better maintenance strategy of railway networks [2].

In this paper, the monitoring of vertical forces is based on the SMCV (Vertical Loads Monitoring System) method, where shear strains of the rail web are measured with a simple combination of four electrical strain gauges, placed on both sides of the rail web along each span. The research has identified self-diagnosis methods for the SMCV system to ensure the reliability and the quality of the measurements and to extend the knowledge of the system. The recorded signals have been processed and converted into easily interpretable physical quantities by means of MATLAB® algorithm.

1. INTRODUCTION

Nowadays, wayside measurement systems of wheel-rail contact forces have acquired great relevance for the monitoring of rolling stock, especially freight trains. Thanks to these solutions, infrastructure managers can check and monitor the status of rolling stock and, when necessary, impose corrective actions for the Railway Companies. On the other hand, the evaluation of contact forces is part of the rolling stock authorisation process [1] and a mainstone for the study of the running stability. One of the advantages of the “wayside” approach is the possibility to monitor vehicles at a given fixed point of track, analysing the evolution of wheel-rail interaction phenomena over the time. Moreover, the monitoring of wheel-rail vertical contact forces allows to determine overloads and load differences between the sides of a wheelset or bogie. The data provided by these measurements could give useful information to correlate the wear of the track with the frequency of applied loads, helping the development of a better maintenance strategy of railway networks [2]. The study carried out by International Union of Railways (UIC) on “The State of the Art of Axle Load Checkpoints” [3] is an example of the efforts made by the infrastructure managers in this direction. It shows the applications of measuring stations and the operational areas that can take advantage with their use.

Researches on the evaluation of contact forces started several decades ago. The most important works, which opened the way for several technical solutions on this subject, were proposed by Ahlbeck-Harrison [4 - 6] and Moreau [7]. Their works are based on different combinations of electrical strain gauges applied on the rail surface in order to determinate the correlation between applied forces and recorded strains. Recently, literature has proposed new and interesting solutions based on modern approaches, which take into account the decoupling of effects of vertical and lateral loads. For example, Milkovic´ et al. [8] attempted to decouple the mixed signal of recorded strains on the rail surface with a method based on Blind Signal Separation (BSS) and Independent Component Analysis (ICA). Bracciali et al. [9] developed a cylindrical sensor for the measurement of both forces. The sensor is put in a hole inside the rail web close to the horizontal neutral plane, where each force component can be measured separately. In a similar way, Delprete et al. [10] industrialized a simple transducer that allows the separation of vertical force effects from those of lateral, placing it near the shear-torsion centre of the rail web.

On the market, there are several devices based on different physical principles, but often the measurement principle and the processing method of the experimental data are not well clarified. Moreover, there are not clearly indicated procedures or technical solutions to check and evaluate the reliability of measures. Some of them consider the longitudinal bending of the rail between two consecutive sleepers using a laser beam [11] or analysing the light deflection inside an optical fibre cable [12]. Instead, other systems use load cells under the fastenings of the sleepers [13] or measure the shear strains of the rail web in specific longitudinal sections [14]. The literature review confirms that the rail, just as the wheel [15], can be used as useful, feasible, suitable, measuring device for the monitoring and the study of the wheel-rail interaction [16], for the running safety and the maintenance of the railway networks.

In this paper, the monitoring of vertical forces is based on the SMCV (Vertical Loads Monitoring System) method [14, 17], where shear strains of the rail web are measured with a simple combination of four electrical strain gauges, placed on both sides of the rail web along each span. The SMCV was developed by a collaboration between the Department of Civil, Building and Environmental Engineering (DICEA, Sapienza University of Rome) and the Italian Infrastructure Manager (Rete Ferroviaria Italiana, Technical Direction). The collaboration is still ongoing. Systems for the monitoring of wheel-rail lateral contact forces are being investigated [16, 18]. The use of these systems, combined with those regarding vertical loads, could allow in the future the evaluation of the derailment ratio (Y/Q).

The research has identified self-diagnosis methods for the SMCV system to ensure the reliability and the quality of the measurements and to extend the knowledge of the system. Experimental data used in the analysis come from/were provided by the measuring station of "Verona Quadrante Europa". The recorded signals have been processed and converted into easily interpretable physical quantities by means of a MATLAB® algorithm. The achievements obtained from this work add new features to the SMCV measuring system and represent an attempt to guarantee the accuracy of the prescriptions that may be imposed by infrastructure managers.

2. THE ARCHITECTURE OF THE SMCV WAYSIDE MEASUREMENT SYSTEM

The SMCV wayside measurement system for monitoring of vertical loads is based on the shear distribution on the vertical plane of the rail, generated by a vertical load (Q) between two sleepers (Fig. 1).

The difference between the value of the shear (T_1) before and after (T_2) the application point of the force is equal to the applied vertical load (Q):

$$Q = T_1 - T_2 \tag{1}$$

Therefore, the measure of the vertical load (Q) is not affected by the position of the force between the two sleepers. Moreover, considering more than one consecutive span, it is possible to detect the load history over the time and also the geometrical defects of wheels which change the dynamic behaviour of loads. One of the main advantages of this method is that the measurement of the shear is independent of the stiffness of sleepers [14].

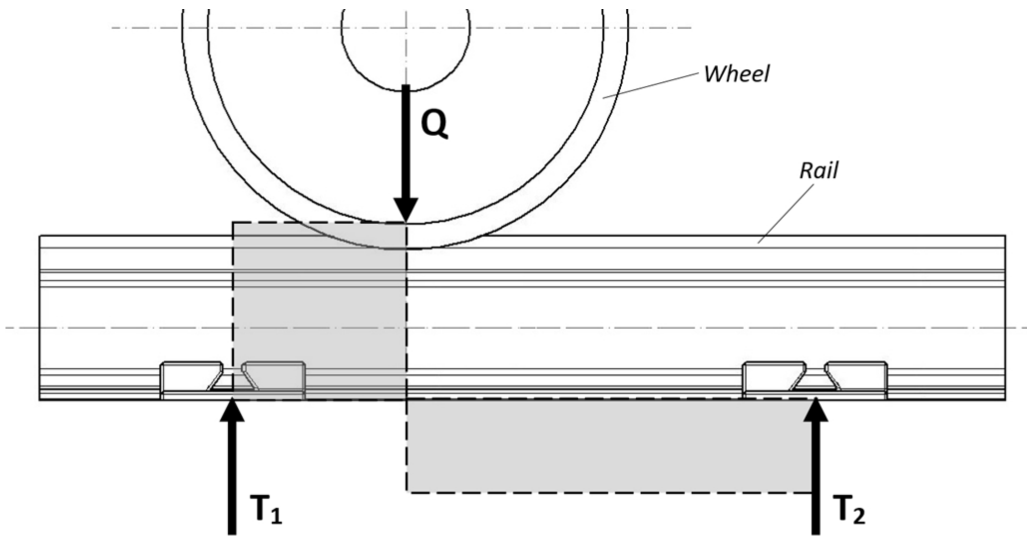

Fig. 1. Shear distribution due to a vertical force (Wheel, Rail)

The SMCV system measures the shear strains on the rail web surface by means of electrical V-shaped strain gauges located on the bending neutral axis of the horizontal rail section. The strain gauges are located on both sides of the rail web, four for each span and two for each measurement section (Fig. 2). The two V-shaped strain gauges, which compose a single measuring section, are connected together with a full Wheatstone bridge circuit. Sensors are placed along 7 spans on the left and on the right rail. Thanks to this configuration, 28 acquisition channels (14 for each rail) are available. Furthermore, the system is able to provide more additional information than the only magnitude of the vertical force (Tab. 1). Data output and technical indicators were examined by the reporting unit that produces the list of anomalies based on some critical thresholds. Indicators are calculated by taking into account the data recorded on the 7 spans.

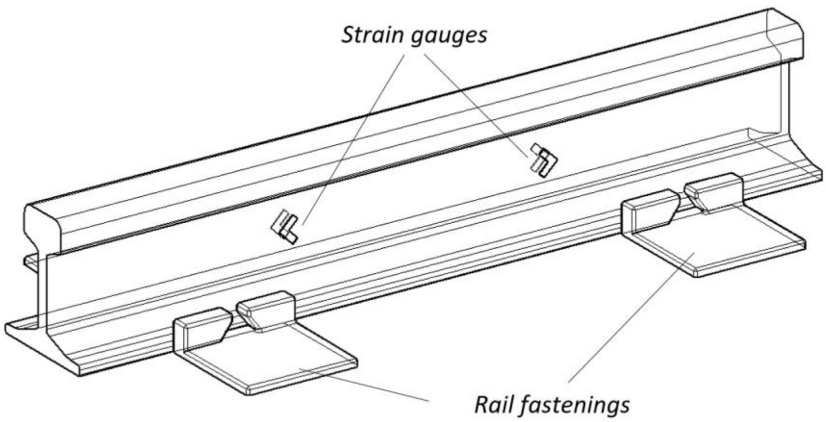

Fig. 2. Position of the strain gauges (Strain gauges and Rail fastenings)

The calibration and the setup of the system are performed in laboratory, determining for each measurement sections the coefficient K_i (2). The value of the shear (T_i) is obtained by multiplying the coefficient for the experimental recorded strain (ε_i).

$$K_i = T_i / \varepsilon_i \tag{2}$$

Table 1

Output data and technical indicators of the SMCV measurement system

Labels	**Expressions and symbols**	**Units**
Train number	N	-
Train date	d	dd/mm/yyyy
Train time	t	hh:mm:ss
Train speed	v	km/h
Bogie number	N_B	-
Axle number	N_A	-
Average vertical load for right wheel	Q_{AR}	kN
Average vertical load for left wheel	Q_{AL}	kN
Average vertical axle load	$Q_{axle} = Q_{AR} + Q_{AL}$	kN
Maximum vertical load for right wheel	Q_{MR}	kN
Maximum vertical load for left wheel	Q_{ML}	kN
Unbalance index for single axle	$I_{axle} = \| Q_{AL} – Q_{AR} \| / Q_{axle}$	-
Unbalance index for single bogie	$I_{bogie} = \| \sum Q_{AL} – \sum Q_{AR} \| / \sum Q_{axle}$	-
Defect index for right wheel	$I_{WR}= Q_{MR}/Q_{AR}$	-
Defect index for left wheel	$I_{WL}= Q_{ML}/Q_{AL}$	-

3. EXPERIMENTAL DATA OF “VERONA QUADRANTE EUROPA”

Within the next few years, the Italian Infrastructure Manager (RFI, Rete Ferroviaria Italiana) will equip its network with some specific access points such as freight plants and ports with wayside measurement systems for the monitoring of dynamic loads of rolling stock. The main strategy is to monitor the loading conditions of freight trains before their entrance inside the network.

Considering this scenario and thanks to the collaboration of the Technical Direction of Rete Ferroviaria Italiana, it was possible to obtain and analyse the data recorded by the wayside measurement station of “Verona Quadrante Europa”, which is one of the most important terminals for freight rail traffic in Italy. For instance, in 2012, the number of freight wagons handled was about 29,000. The trains that pass through this terminal are mostly directed abroad, especially to Germany using the Brennero line (75.8%), then to the Netherlands (6.8%), Denmark (6.1%), Belgium (1.8%) and finally towards other minor destinations (Austria, Poland, France, Czech Republic and Norway). Instead, only 7% of the traffic is directed to Italy.

Data provided by Rete Ferroviaria Italiana refer to the SMCV measurement stations installed on departure tracks. This choice has been made in order to monitor and check the freight wagons leaving the terminal. For each departing train, we analysed and processed the raw signals measured by the SMCV system. In Figure 3, it is possible to see the Control Unit that acquires and records the train data and the 7 spans, with the 14 measurement sections for each rail. Moreover, 28 acquisition channels allowed us to perform a simple statistical analysis of measurement data.

This analysis along with the study of the electric signals allowed us to develop a self-diagnosis method of the SMCV system. The presentation of the algorithm along with a numerical example is reported in the next paragraph.

4. SELF-DIAGNOSTIC METHOD OF THE RECORDED SIGNALS

In the past years, the SMCV measuring system brought encouraging results, which led to the hypothesis of its spread on the Italian Railway Network, with the aim of monitoring the most relevant freight access points. In this scenario, the reliability and the quality of measurements are important aspects to take into account. Consequently, it is mandatory that a measurement system like the SMCV has some self-diagnosis methods to check its own operation.

Fig. 3. SMCV system of "Verona Quadrante Europa" (Measurement sections, SMCV Control Unit)

First attempt to find some self-diagnosis parameters has been performed analysing the waveform of measurement signals. Signals, due to the same wheel passing on different measurement sections of the rail along the same span, should have a similar waveform and a comparable magnitude. If this did not occur, the corresponding measurement channel could have a malfunction. In Figure 4, the raw signal of the first two measurement sections (channel 1 and 2) is reported together with their difference: the Q signal (see the equation 1). Data refer to an empty freight wagon at the head of a train of 10 wagons driven by a locomotive with four axes. On the ordinate there is the strain value, whereas on the abscissa there is the time. The points identified by the capital letters (A, B, C, D, A', B', C' and D') indicate the maximum and the minimum of the peaks for each signal. The figure shows the waveforms of two consecutive wheels recorded by the first two measurement sections. The signal of the channel 1 has the same waveform of the signal of the channel 2, but there is a vertical offset between them. The offset is due to the simultaneous presence of the same wheel inside the same span of the track. The wheel passes first on the measurement section of the channel 2 and then on the measurement section of the channel 1. As a result, the strains recorded by the channel 1 are due to the presence of the first and the second wheel of the axle.

Applying a Butterworth low-pass filter (cut frequency 35 Hz) and then shifting the curves (vertically and horizontally), it is possible to see that the channels 1 and 2 have almost the same waveform (Figure 5). This fact indicates a proper functioning of the measuring sections and thus the correctness of results. Therefore, the identification and analysis of the signal peaks, recorded along the 7 spans, are the main factors to evaluate the accuracy of measures.

A method based on a MatLAB® algorithm was developed in order to perform an automatic identification of signal peaks. The purpose of the algorithm is to find the maximum and the minimum of the wave signal for each measurement section. The calibration of the math function was made using the shortest time between the transit of two consecutive wheels. However, in some circumstances, the automatic identification of signal peaks is not correctly performed. In fact, some signal irregularities can lead to a missed identification. The irregularities are mainly due to the status of the track that causes in a non-inversion of the sign of the wave curves. In Figure 6, there is an example of this failed identification, where the triangles represent the peaks found by the algorithm and the "x" are those not found. Although almost all peaks were correctly identified, in some circumstances this does not occur. This problem was overcomed applying the MatLAB® algorithm at the derivative signal. In this way, it was easy to find all peaks corresponding to the passage of the wheels on the measuring sections (Figure 7) and calculate the correct magnitude of vertical loads.

After the identifications of signal peaks, data collected of wheel-rail vertical forces were analysed by means the BOXPLOT statistical tool. In Table 2 and 3, there are the values of the vertical load for the left and the right wheels of a wagon with four axles recorded by each measurement channel. Thanks to the BOXPLOT, it was possible to find the outliers (Figure 8 and 9) of the values of the vertical force and exclude them from the calculation of the mean. Outliers are probably caused by some malfunction or by the incorrect status of the track, which has to be further investigated. In the example, the channel 12 (3rd wheelset of the locomotive) represents one of these situations. If the number of outliers was high or unrealistic, the entire measuring set should be excluded and the data set should be analysed manually. As it is possible to see, the BOXPLOT is a useful graphic tool to help the SMCV operator in the real-time control of the freight wagons, as well as a quantitative analysis technique.

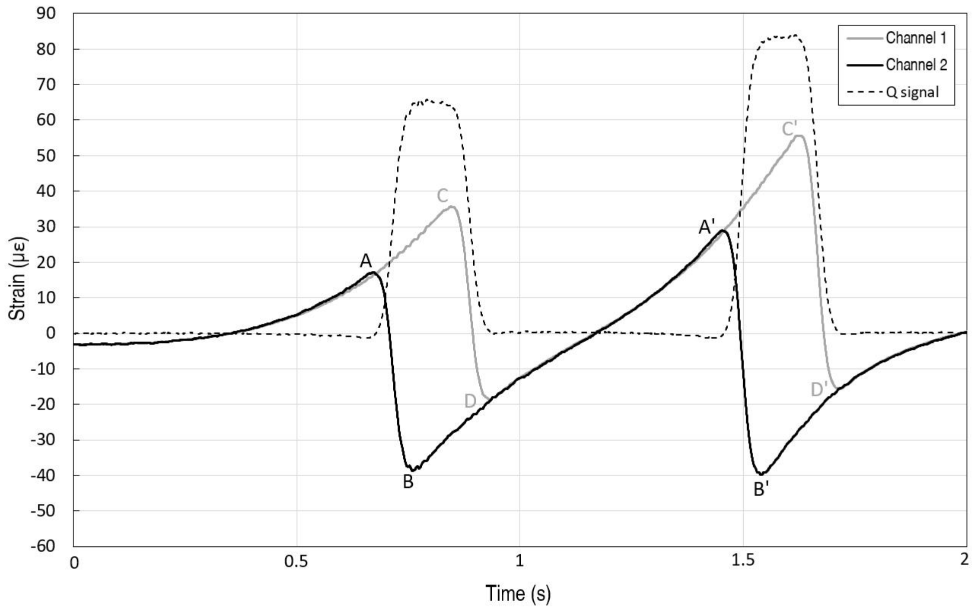

Fig. 4. Raw signal of the first two measurement sections (channel 1, 2 and their difference: Q signal)

5. CONCLUSION

In this paper self-diagnosis methods to check the results of the SMCV measurement system of wheel-rail vertical loads were presented. The research has been made in collaboration with the Italian Infrastructure Manager (Rete Ferroviaria Italiana, Technical Direction). The aim of this work is to ensure the reliability and the quality of measurements extending the knowledge of the system and guaranteeing the accuracy of the prescriptions that Infrastructure Managers could impose on the Railway Companies. The research shows the importance of the post-processing and of the assessment of recorded data by means of qualitative and quantitative analysis, represented here by the first and the second proposed method. This approach gives to operators an easy tool to establish the correctness of measurements without their own interpretations.

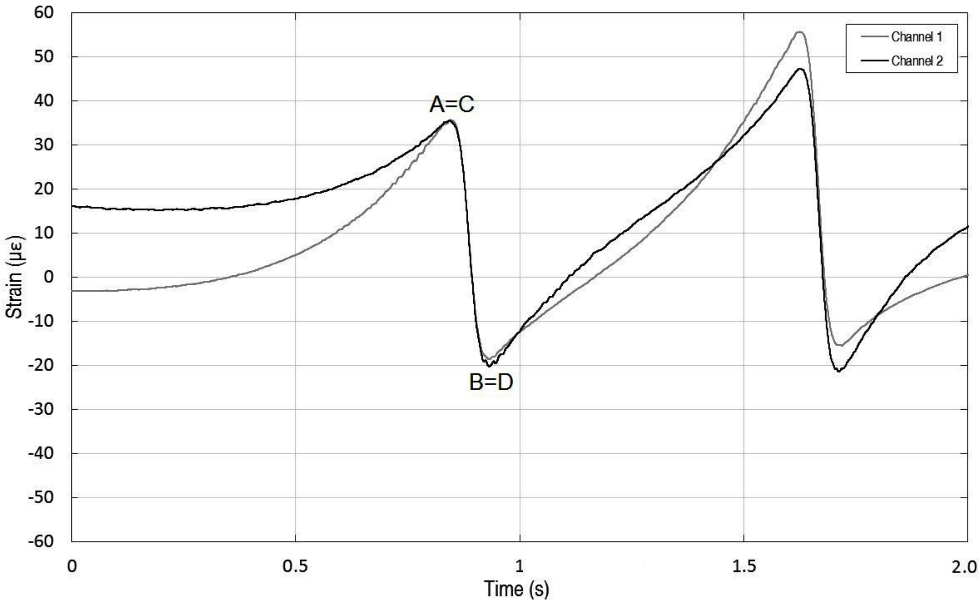

Fig. 5. Cleaned and shifted signal of the first two measurement sections (channel 1 and 2)

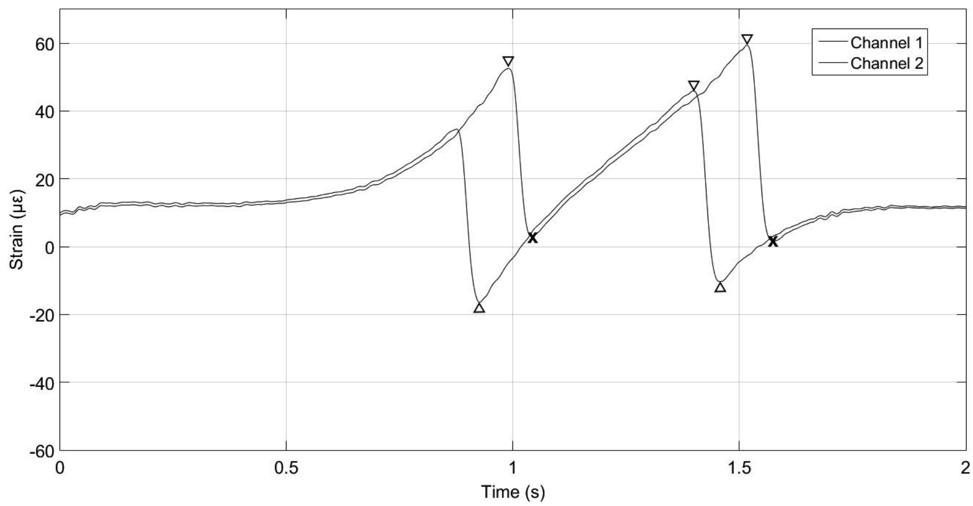

Fig. 6. Lack of signal peaks identification

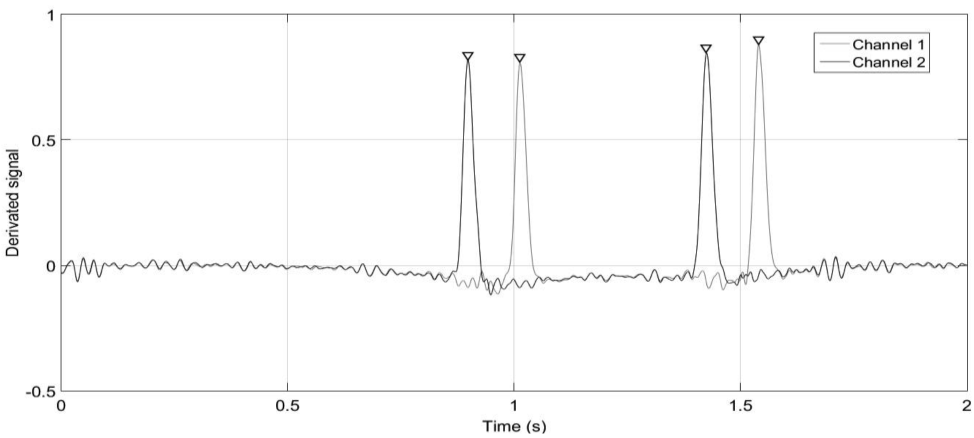

Fig. 7. Derived signal

Table 2

Vertical force of the left wheels

Channels	Wheel 1 – Left (kN)	Wheel 2 – Left (kN)	Wheel 3 – Left (kN)	Wheel 4 – Left (kN)
# 1	78.4	72.8	75.1	75.7
# 2	84.0	78.8	76.7	78.1
# 3	82.0	81.3	76.6	75.3
# 4	79.7	80.1	74.7	79.3
# 5	75.8	73.2	75.7	74.5
# 6	75.9	78.5	76.2	79.8
# 7	78.9	79.6	72.5	74.5
# 8	82.8	83.5	73.4	79.6
# 9	79.6	75.1	73.2	74.5
# 10	76.7	74.9	75.7	78.6
# 11	75.3	75.1	76.2	76.2
# 12	87.9	85.9	82.2	78.0
# 13	86.5	79.2	76.2	72.2
# 14	88.6	84.6	79.6	80.4
Mean value	**80.9**	**78.8**	**76.0**	**76.9**
Standard deviation	**4.5**	**4.2**	**2.5**	**2.5**

Table 3

Vertical force of the right wheels

Channels	Wheel 1 – Right (kN)	Wheel 2 – Right (kN)	Wheel 3 – Right (kN)	Wheel 4 – Right (kN)
# 1	72.1	71.3	72.2	69.0
# 2	77.5	79.6	76.4	78.1
# 3	78.3	81.6	74.2	72.7
# 4	77.6	77.2	72.8	76.5
# 5	75.1	74.7	74.6	75.4
# 6	76.5	77.8	76.6	81.1
# 7	79.2	80.5	74.7	76.5
# 8	84.5	85.0	76.4	82.6
# 9	82.4	77.3	75.0	80.2
# 10	79.0	77.0	76.9	82.0
# 11	74.9	75.3	77.4	78.4
# 12	84.9	85.9	84.4	84.7
# 13	86.3	81.8	80.3	78.6
# 14	84.5	84.0	78.1	83.9
Mean value	**79.5**	**79.2**	**76.4**	**78.5**
Standard deviation	**4.4**	**4.2**	**3.1**	**4.4**

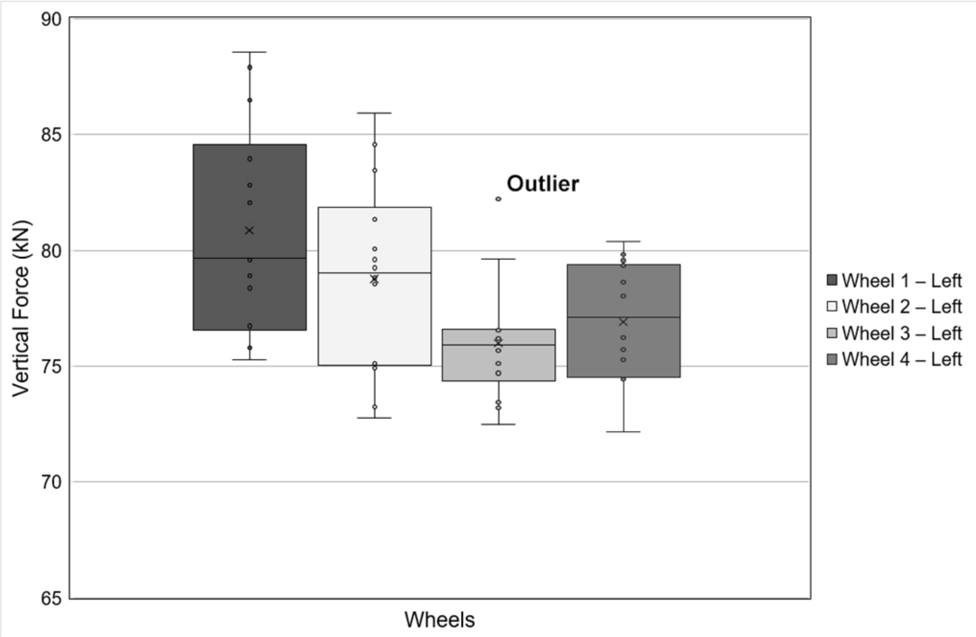

Fig. 8. Box Plot Analysis – Left wheels

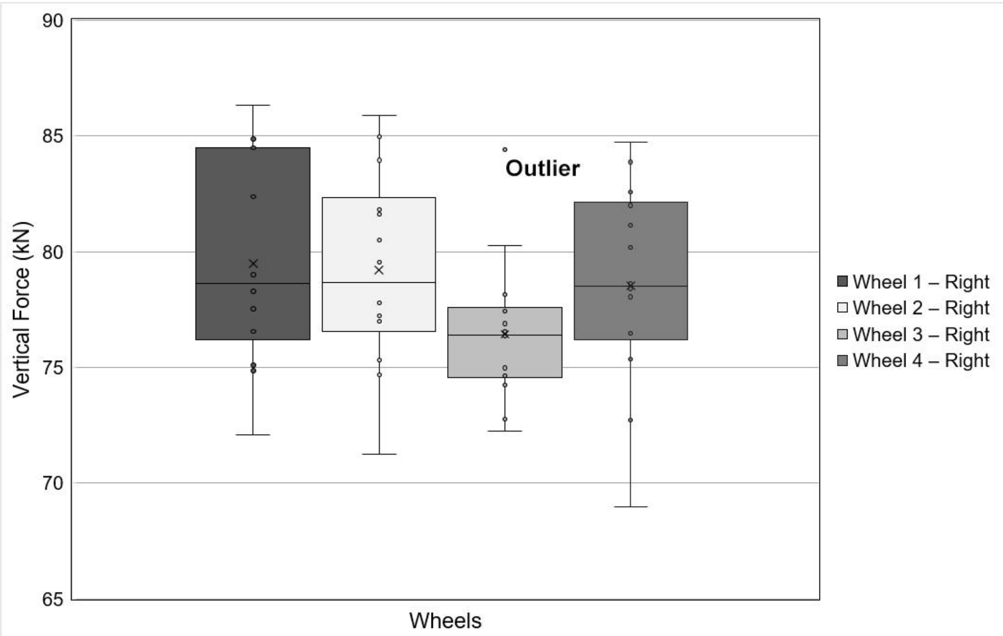

Fig. 9. Box Plot Analysis – Right wheels

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