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Development of a Low-Cost Trackside System for Weighing in Motion and Wheel Defects Detection

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A B S T R A C T

In modern societies, where sustainability, health and comfort are top of priorities, it is critical to devise new strategies to overcome this problem effectively. In line with the expansion of technology, the number of transportation increases, traffic is intense worldwide, and rail traffic is growing all over the world. Therefore, special attention is paid to railway vehicles, infrastructure maintenance and traffic safety. In the case of the interaction between a rolling wheel and a rail, forces arise from physical conditions, metal stress, deformation, noise, etc. In this context, the development of a low-cost trackside monitoring system to reduce maintenance costs and to improve ride quality is necessary. In addition, significant damages that may cause service interruptions or derailments can be prevented by early detection of wheels. In this paper, an application of a wayside monitoring system installed in the Portuguese Northern Railway Line to detect weigh-in-motion (WIM) is presented. The presented WIM system is part of a larger project PEDDIR: the Portuguese acronym for "Weighing in motion and wheel defect detection system." From the load measurement imposed by the axle onto the track, integrated into a proper algorithm, train specification can be calculated.

1. Introduction

The transport system is one of the strategic factors for the sustainable development of modern cities, where environmental requirements play an important role [1, 2]. Growing rail traffic worldwide requests higher safety standards and lower maintenance cost at the same time [3, 4]. The development of an efficient WIM method with high accuracy estimation procedures from track measurements is one of the important subjects that draw the attention of both railway industry and scientific researchers, in order to trigger a warning in the control system when a train is overloaded or operating under abnormal conditions [5, 6]. The importance of train overloaded became highlighted especially when it combines with a lateral load which increases the derailment risk [7]. In general, two approaches are proposed to determine the dynamic load; i) installing sensors in the rolling stock [8] which is not seldom used because it demands installation sensors in all vehicles which only measure few physical quantities, such as the axle-box acceleration [9]; ii) monitoring the dynamic response of the track which infers the loads imposed by the train from the dynamic response of infrastructure [10-14]. The second approach used in this study and it allowed assessing the train conditions for all trains passing in that section.

The development of an efficient WIM method with high accuracy estimation procedures from track measurements is one of the major subjects that draw the attention of both railway industry and scientific researchers [15-17]. O´Brien *et al.* [18] tested two independent WIM systems and compared them for accuracy and durability. Accuracy of the systems is presented for axle and gross vehicle weights

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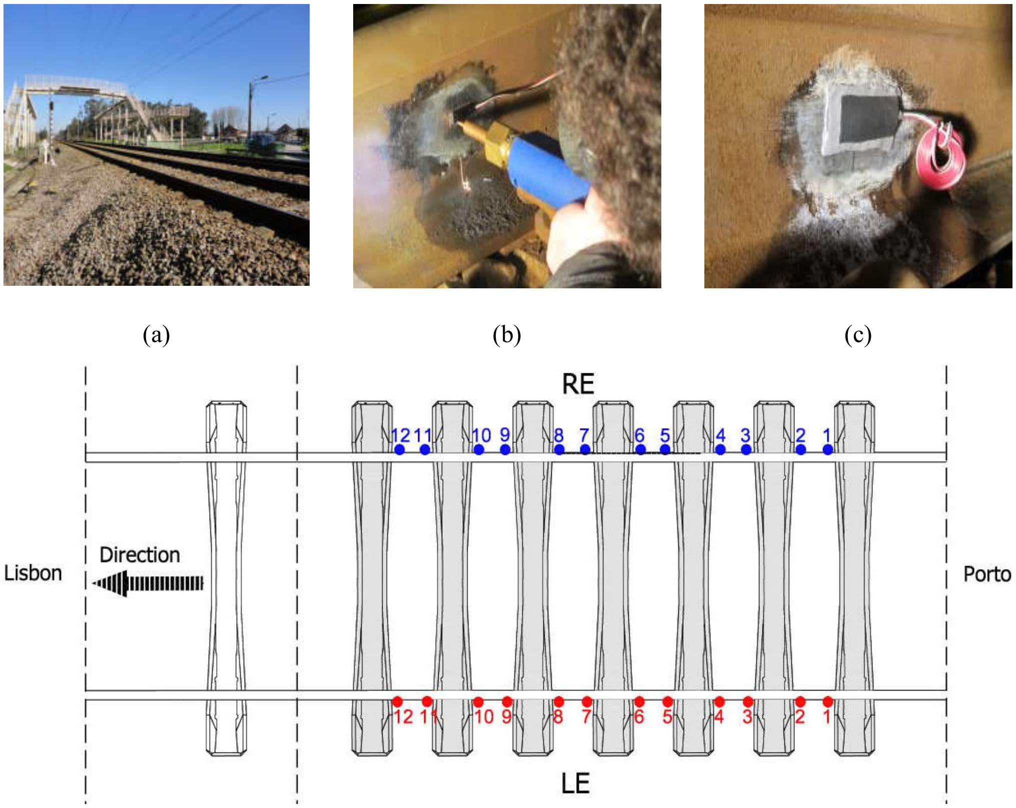
within the framework of the draft European WIM specification. Performance due to durability is discussed with particular emphasis on axle detectors. Allotta *et al.* [19] developed an approach to determine axle and wheel loads of railway vehicles at high vehicle speeds. The proposed algorithm is able to estimate the loads starting from different physical input quantities measured on the track by considering vertical forces on the sleepers. Different monitoring schemes and experimental setups have been proposed for weighing in motion. However, the systems are usually based on the measurement of the dynamic response of the rail, i.e., by installing strain gauges or accelerometers. The system based on strain gauges is more consensual, since shear efforts and bending moments, which are direct consequences of the applied load, can be easily inferred. To estimate rail shear and vertical axle loads, strain measures using strain gauge sensors, piezoelectric or piezoresistive systems [20-22].

The ordinarily homogeneous power transmission from the running wheels to the rails is influenced by this kind of quick faults. This situation may increase stress for vehicles and rails which leads to higher costs for maintenance, enhance noise pollution, significant damage to vehicles and rails, reduced traveling comfort or even derailments due to wheel damages.

Therefore, the analysis of the dynamic loads imposed by the train to the track allows the use of software tools to predict the degradation process of the track. In this context, the Faculty of Engineering of the University of Porto, the SME (Size-Medium-Enterprise) Evoleo Technologies and the Portuguese Railway Administration (IP), developed a wayside monitoring system for weighing in motion and detecting wheel defects in rolling stocks.

2. System Description

The WIM testing site is located at the Northern Railway Line (Figure 1). The presented WIM system is part of a larger project PEDDIR: the Portuguese acronym for "Weighing in motion and wheel defect detection system." The



(a) (b) (c)

(d)

Figure 1. (a) Location of the test site, (b) & (c) Strain gauges installation, (d): Track instrumentation scheme for VD (Porto-Lisbon direction)

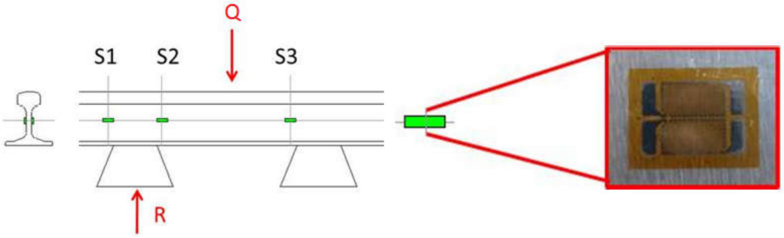


Figure 2. Calculation of axle load and reaction

system is based on 12 strain gauges installed on the rail webs. The strain gauges are located at the neutral axes of the rail, allowing the assessment of the shear in the section during the train passage. For the successful detection of wheel defects, sensors are installed along an equivalent wheel perimeter length. In the present case, strain gages are placed over a total length of 3.6 m that consider seven sleepers equally spaced in 0.6 m intervals. Inductive wheel sensors placed 6 m from the strain gage sensors triggers the system. The measured strains were acquired during the passage of each vehicle for the post-processing process. Subsequently, these stored data were considered as an input for a developed algorithm to identify train characteristics including train geometry, number of axles, axle load, train weight, train speed and acceleration. In the following section, a detailed description of the developed algorithm is presented.

Therefore, the dynamic axle loads induced by the passage of the train are given by the difference between V_2 and V_3 obtained from strains assessed in positions S_2 and S_3 respectively. Difference between V_1 and V_2 leads to an estimation of the rail seat load when the axle load is acting outside the segment of the rail between sections 1 and 2. Both Equations are shown as follow (Figure 2).

$$V_1 - V_2 = R$$
$$V_2 - V_3 = Q \quad (1)$$

3. Algorithm for Data Processing

The developed data processor algorithm with nine subsequent modules is able to recognize the train and its characteristics as shown in Figure 3. The results were obtained by the following processors:

- Self-diagnosis module mainly processes raw data to identify inoperable sensors. This module is related to verify if there is any failure in the sensors, in the acquisition system or in the connections.
- Axle count routine counts the number of train's axles. This information is essential as an input for the subsequent modules. Both speed & acceleration and weight in motion measures modules are dependent on the train's axle count.
- Speed & acceleration module is responsible for the assessment of the speed per axle, the train speed, and acceleration.
- The weigh-in-motion module is able to calculate the static weight of each wheel, axle, vehicle and train concerning vehicle and train due to the dynamic load measurements imposed by the train passage. This information is essential for the infrastructure manager in order to trigger overloaded trains or with inappropriate load distribution.
- Wheel-defect-detection module is responsible for identifying defect detection. Since the flat defect in a wheel produces an increase of the strain, the system can detect it.
- The Train Geometry routine allows calculating the distance between axles and the train length. This information is required as input for the subsequent modules.
- In the train ID module, the algorithm identifies the train type, as well as vehicle type that composes the train due to the axle load, and axle count.

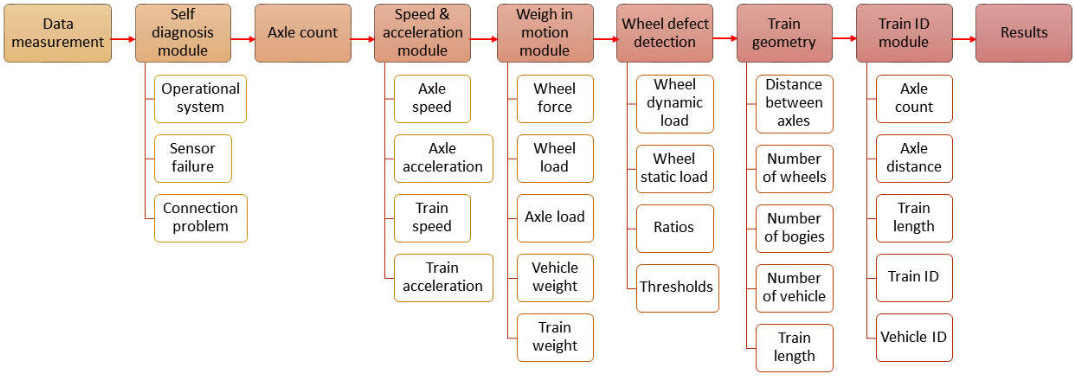


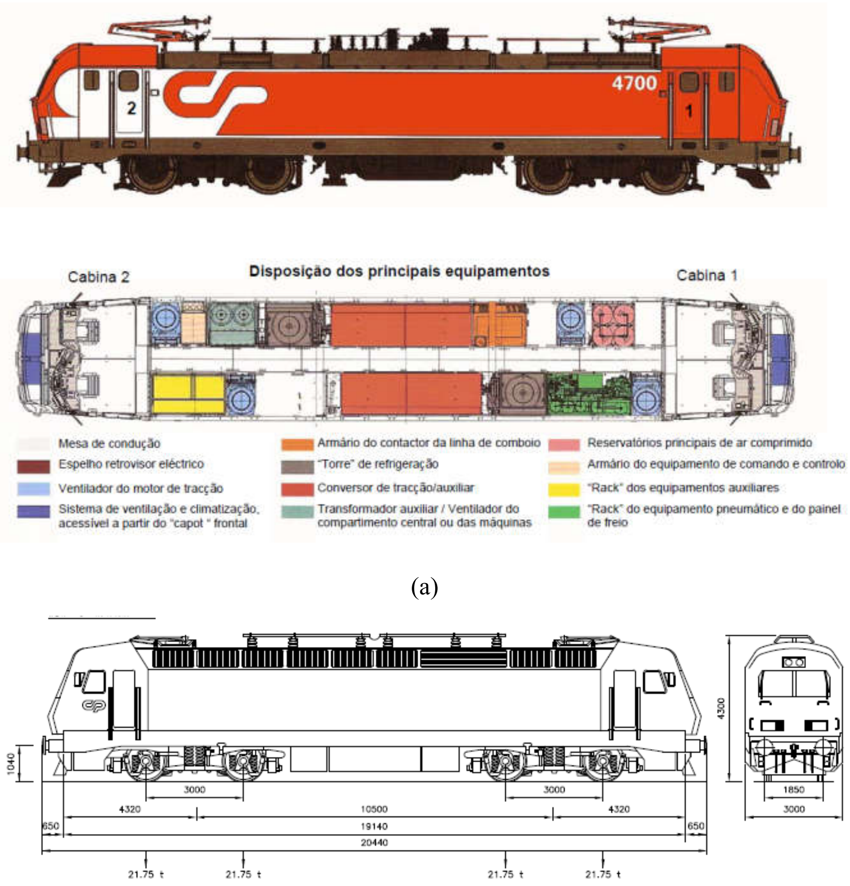
Figure 3. Algorithm scheme

Table 1. Key performance indicators

Key performance indicators	Unit	Description
Axle Count	-	Number of train's axles
Train's speed	Km/hr	Speed of train
Bogie count	-	Number of bogies
Train acceleration	m/s^2	Acceleration of train
Train length	m	Length of train
Wheel right dynamic load	T	Dynamic load measured in the right wheel
Wheel left dynamic load	T	Dynamic load measured in the left wheel
Wheel right static load	T	Static load measured in the right wheel, defined by the dynamic load corrected by a static coefficient
Wheel left static load	T	Static load measured in the left wheel, defined by the dynamic load corrected by a static coefficient
Bogie load	T	Sum of all axle loads per bogie
Vehicle weight	T	Sum of all axle loads per vehicle
Train weight	T	Sum of all axle loads

- In the final module, the information accessible from the previous modules is processing by the algorithm to calculate several key performance indicators and ratios in order to detect faults and to identify their severity and priority level, based on defined thresholds. The defined key performance indicators in the system (as presented in Table 1), are based in the European standard [23], related to the measurement of wheel and axle loads. Finally, the results are saved into a server that could be used for future historical data analysis. In addition, the stored data may be utilized to support the development of tools designed to perform reliable maintenance solutions.

The strain gauges should be perfectly oriented along the principal direction of deformation. However, there may be some variation in this determination, including the geometrical characteristics of the track, the resilient properties of the material or even in the installation of sensors. Hence to eliminate any differences in load measurement, the evaluated loads are calibrated based on a known load scenario that allows to estimate a proportionality factor for each pair of strain gauges. Therefore, to obtain the calibration factor, two locomotives (namely: class 4700 and class 5600) with known loads crossed over the track with low speed. It has to be mentioned the load per axle for locomotive class 4700 and class 5600 is 21.5 & 21.75 ton respectively as shown in Figure 4. The locomotives were passing through the track with low velocity, in order to minimize the variations of the load to dynamic effects. Therefore load



(a)

(b)

Figure 4. (a) Locomotive class 4700, (b) Locomotive class 5600

Table 2. The calibration factor for each pair of strain gauges obtained by passage of the locomotive

	The calibration factor for VD (Porto-Lisbon direction)					
	Pair1	**Pair2**	**Pair3**	**Pair4**	**Pair5**	**Pair6**
LE (Left side)	1.101	1.143	1.109	1.117	1.109	1.084
RE (Left side)	0.991	0.985	0.982	0.988	1.002	0.997
	The calibration factor for VA (Lisbon-Porto direction)					
	Pair1	**Pair2**	**Pair3**	**Pair4**	**Pair5**	**Pair6**
LE (Left side)	0.996	1.026	1.012	1.022	1.01	1.063
RE (Left side)	1.029	1.035	1.032	1.043	1.031	1.088

can be obtained and the calibration factor is the ratio of the load which obtained by the algorithm to the locomotive weight for each pair. Table 2 shows the calibration factor for each pair for VD & VA directions.

4. Measurements and Results

Results obtained by the presented WIM system are presented and analyzed in this section. Figure 5 shows the strain measurement of passage for the Portuguese high-speed train (Alfa-Pendular), which is used for long-distance passenger transportation circulates at around 220 km/h corresponds to the maximum commercial speed allowed in this Portuguese railway line. This electrical railcar is composed of six vehicles, twelve bogies and a total of twenty-four axles. Figure 6 shows the configuration of

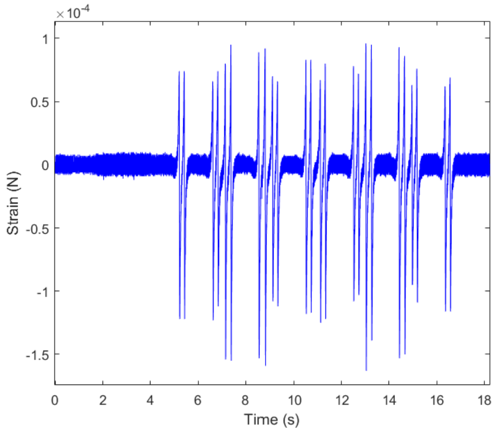


Figure 5. Strain measurement of passage for the Alfa-Pendular train (Strain gauge 1, LE)

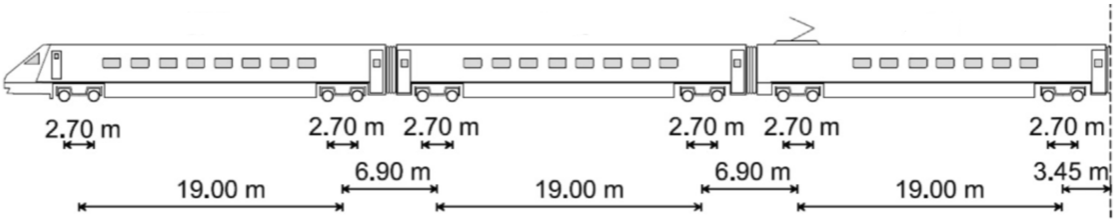


Figure 6. Portuguese high-speed train scheme (Alfa Pendular)

the Alfa Pendular train. In Table 3, the output information attained from the wayside monitoring system is presented for an Alfa-Pendular train.

By analyzing Table 3, the results detected the twenty-four axles that compose the train, twelve bogies in six carriages, with an average speed of 42.7 km/hr. It is also verified that the train circulated with a positive acceleration of 0.034 m/s^2. As mentioned in Table 3 the algorithm was able to detect wheel dynamic load, wheel static load, axle dynamic load and axle static load. The accuracy of detected values highly depends on the train's speed, unevenness profile of the rail and the noise acquisition in the input signal. It is obvious that the track unevenness profile has a significant impact on enhancing the dynamic load by increasing train speed. Also another factor that plays an essential role in the results is the noise in the signal, which perturbs the load assessment.

5. Validation of Algorithm by Real Train's Passages

The experimental test setup was performed with contribution of the Faculty of Engineering of Porto University, the SME (size-medium-enterprise) Evoleo Technologies and the Portuguese Railway Administration (IP) in order to verify the performances of the proposed WIM algorithm. Experimental data were referred to the two weighted trains that passed through the system with very low speed. Strain measured in 12 sections is used as input from the proposed WIM algorithm. The proposed measurement layout is used to measure the axle loads of the train composed of 21 vehicles. The first weighted train (WT1) is implicated by one locomotive and 20 different wagons with different wheelsets. Two locomotives and 19 different vehicles compose the second weighted train (WT2) with different wheelsets. The traveling speeds for the WT1 & WT2 trains in the proposed test cases are about 13 & 10 km/hr respectively. Therefore, to validate the WIM system the wagon's weight obtained by the algorithm were compared against the wagon's weight of two trains that passed through the system. Table 4 presented the relative errors for the vehicle's load estimation due to the proposed

Table 3. Output information: Alfa Pendular

Key performance indicators	Unit	Values
Axle Count	-	24
Wheel left dynamic load	T	[8.78, 8.59, 8.40, 8.20, 9.96, 10.23, 10.73, 10.70, 8.43, 8.29, 8.65, 8.33, 8.35, 8.37, 7.83, 7.57, 10.56, 10.09, 13.01, 10.40, 7.01, 8.10, 7.73, 8.00]
Wheel left static load	T	[8.43, 8.35, 7.67, 7.90, 9.67, 9.98, 10.28, 10.37, 7.76, 7.57, 8.20, 8.15, 7.96, 8.01, 7.51, 7.39, 10.29, 9.80, 10.87, 10.01, 6.79, 7.74, 7.59, 7.83]
Axle dynamic load	T	[17.55, 17.19, 16.81, 16.39, 19.91, 20.46, 21.46, 21.39, 16.85, 16.57, 17.29, 16.65, 16.70, 16.74, 15.66, 15.13, 21.13, 20.18, 26.02, 20.80, 14.01, 16.21, 15.46, 16.01]
Axle static load	T	[16.85, 16.70, 15.34, 15.80, 19.33, 19.96, 20.56, 20.75, 15.52, 15.14, 16.40, 16.30, 15.93, 16.02, 15.01, 14.78, 20.58, 19.59, 21.74, 20.01, 13.58, 15.48, 15.18, 15.66]
Bogie load	T	[33.55, 31.13, 39.29, 41.31, 30.67, 32.70, 31.95, 29.79, 40.17, 41.76, 29.06, 30.83]
Bogie count	-	[١٢,٠]
Vehicle count	-	[6.0]
Vehicle weight	T	[64.68, 80.60, 63.37, 61.74, 81.93, 59.89]
Speed per axle	Km/hr	[42.1, 43.1, 41.1, 42.4, 42.4, 42.5, 42.3, 42.3, 42.4, 42.3, 43.2, 42.6, 43.1, 43.2, 42.9, 42.2, 43.2, 43.2, 43.2, 43.4, 42.0, 41.9, 43.4, 43.5]
Train's speed	Km/hr	[42.7]
Train acceleration	m/s^2	[٠,٠٣٤]
Train length	m	[١٣٩,١٢]
Train weight	T	[412.21]

WIM algorithm and for the weighted trains (WT1 & WT2).

6. Conclusions

In this paper, an application of a wayside monitoring system installed in the Portuguese Northern Railway Line for weighing in motion rolling stock in a wide speed range is presented. From the load measurement imposed by the axle onto the track, integrated into a proper algorithm, train specification including train geometry, train axle number, axle load and train weight, and train speed can be calculated. Furthermore, a historical database could be stored for trending and eventual predictive maintenance. The huge amount of information provided by the experimental setup treated, in order to obtain a high-quality database. This monitoring is a key factor to minimize rail breaks and help avoid catastrophic events such as derailments, monitoring the performance of wheels and trying to remove them before they start affecting the rails. A weighing in motion system can help keep vehicles optimally maintained, extending the useful service life of the assets. In general, the advantages of utilizing such a system are:

- Protection of rolling stock and rail infrastructure assets
- Monitoring of weight and load distribution
- Identification of wheel defects
- Improving operational performance by reducing train interruptions
- Performance and utilization monitoring
- Covering the complete circumference of the wheel

- Finally, the use of this system has cost benefits over time and it will increase environmental sustainability and can be adopted by the railway industry.

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Table 4. Relative errors for vehicle load estimation due to the proposed WIM algorithm and for the weighted trains

	WT1			**WT2**		
Wagon's number	**Real Measure (t)**	**Measured by algorithm (t)**	**Error (%)**	**Real Measure (t)**	**Measured by algorithm (t)**	**Error (%)**
1	32,9	33,53	-1,92	59,15	58,87	0,48
2	37	36,47	1,42	59,95	62,83	-4,81
3	33,8	33,71	0,26	33,95	33,10	2,50
4	36,15	36,19	-0,11	32,85	33,22	-1,13
5	35,5	35,12	1,08	35,35	35,30	0,14
6	35,1	35,16	-0,19	38,15	39,84	-4,42
7	59,8	59,45	0,59	35,6	35,92	-0,90
8	37,85	37,60	0,66	36,6	36,43	0,47
9	53,45	52,59	1,61	39,25	38,88	0,95
10	38,05	38,23	-0,48	35,3	35,26	0,11
11	39	41,05	-5,25	34	34,37	-1,08
12	38,7	38,32	0,98	58,8	58,82	-0,04
13	64,6	64,91	-0,48	37,8	38,69	-2,36
14	60,9	60,17	1,20	60,45	59,57	1,45
15	60,2	64,08	-6,44	36	36,78	-2,18
16	36	35,50	1,39	56,05	55,70	0,62
17	34,5	35,09	-1,72	55	53,65	2,45
18	38,05	38,57	-1,37	55,75	54,57	2,11
19	36,8	37,99	-3,23	57,2	56,56	1,12
20	34,35	34,63	-0,81	53	54,74	-3,28
21	38,8	38,73	0,18	38,4	38,11	0,77

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