XXI INTERNATIONAL SCIENTIFIC-EXPERT CONFERENCE ON RAILWAYS
RAILCON '24
October 10-11, 2024; Niš, Serbia

Original scientific paper DOI: 10.5937/Railcon24013S

IN-SERVICE ASSESSMENT OF EQUIVALENT CONICITY WITH THE AIM OF PREVENTING THE UNSTABLE RIDE OF RAIL VEHICLES

Goran SIMIĆ[1]
Dragan MILKOVIĆ[2] [0000-0002-3739-4600]
Saša RADULOVIĆ[3] [0000-0001-6337-0699]
Aleksandra KOSTIĆ-MILIČIĆ[4] [0000-0002-5654-757X]

Abstract – *The paper provides a general survey of methods for equivalent conicity assessment. Different aspects of interest are addressed: type tests of new rail vehicles, acceptance of new railway tracks, as well as vehicles and infrastructure in-service. The paper discusses the procedure if the ride instability appears in service. According to European legislation, this situation requires equivalent conicity assessment on vehicle and infrastructure. The procedure is demonstrated for one vehicle in service, combined with reference rail profiles and rail profile samples acquired by track recording vehicle at the new Belgrade-Novi Sad railway line for 200 km/h, in combination with reference wheel profiles.*

Keywords – equivalent conicity, assessment methods, ride stability, in-service assessment, rail vehicles, rail infrastructure.

1. INTRODUCTION

Even before the birth of the railways the experience with mining wagons led to usage of conned wheels on wheelsets. Compared to cylindrical wheel profiles this resulted in lower curve resistance and lower wheel wear. Half a century of railway history passed before Klingel, in 1883, derived formula for sinusoidal motion of a free wheelset with conned wheels.

Vehicle wheelsets show stable ride up to some “critical speed” depending on connection characteristics and wheel-rail geometry. The wheel-rail geometry in service is influenced by wear. Therefore, equivalent conicity is recognized nowadays in European legislation [1,2] and standards [3,4] as a parameter which should be controlled in the design phase and in service of rail system.

2. WHEEL-RAIL CONTACT GEOMETRY

Conned wheels allow the wheelset to move in curves toward the outer rail by *y*, as presented in Fig. 1. The outer wheel then rolls at radius $r_2 > r_o$, and

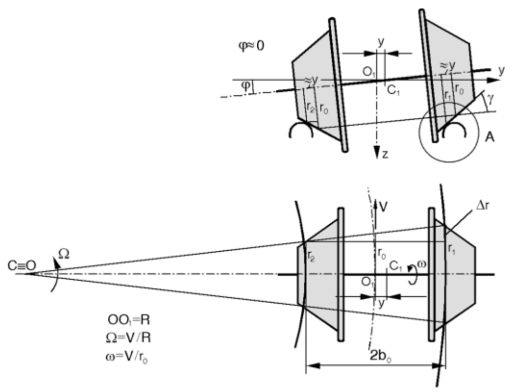

Fig. 1. Theoretical position of the wheelset with conned wheels in curve [5]

inner wheel at radius $r_2 < r_o$. The difference:

$$\Delta r = r_1 - r_2 = 2n \cdot y \quad (1)$$

allows the wheelset to pass the curve by pure rolling up to the maximum available lateral play of the wheelset in the track, i.e.:

$$y \leq \frac{TG\text{-}SR}{2} \quad (2)$$

Here is:

γ - cone angle of wheel profile (fig. 1, 3)
n=tanγ - slope of the conned wheel profile
TG - track gauge

[1] University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, gsimic@mas.bg.ac.rs
[2] University of Belgrade Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, dmilkovic@mas.bg.ac.rs
[3] University of Belgrade Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, sradulovic@mas.bg.ac.rs
[4] University of Belgrade Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Belgrade, akostic@mas.bg.ac.rs

SR - distance between active faces of wheel flanges (measured 10 mm below the nominal circle)

When the wheelset with conned wheel profiles is positioned laterally by y_o, at straight track (Fig. 2), its kinematic rolling, without slip in contact with rails produce so called hunting motion with center of wheelset describing sinusoid. Klingel's solution of such motion gives wavelength of sinusoid:

$$L = 2\pi\sqrt{\frac{b_o \cdot r_o}{n}} \quad (3)$$

Here is:

$2b_o$ - lateral distance of nominal wheel diameters

r_o - nominal wheel radius

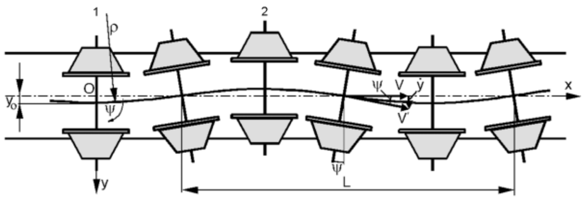

Fig. 2. Hunting motion of the wheelset

From formula (3) follows that if the wheel profile is cylindrical, n=0, $L \Rightarrow \infty$, and there is no sinusoidal motion. But cylindrical wheel profile gives no ability to pass a curve with pure rolling as presented in Fig. 1. Guiding of the wheelset is then performed only by forces on wheel flange, with presence of high resistance and intensive wheel flange wear.

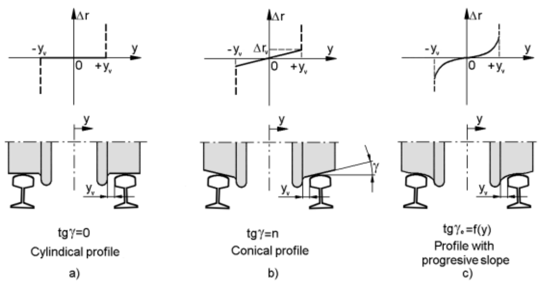

Fig. 3. Δr function of different profiles [5]

Equation (1) is so called Δr function which is for conned wheel profile linear (Eq. 1), up to the limit given by equation (2), Fig. 3b. Fig. 3a shows the Δr function of the cylindrical wheel.

As a compromise, profiles with progressive slope of Δr function (Fig. 3c) are preferred. The goal is to have the slope of the Δr function around center position of the wheelset (y=0) near zero, like with cylindrical wheel profiles, which is preposition for stable ride on straight track. In the curves Δr shall progressively rise, what is favorable for curving performances.

While in case of cylindrical or conical profiles Δr function does not depend on the rail head profile, in case of nonlinear profiles, both, wheel and rail profiles are influencing. Therefore, there is no ideal wheel profile. Real combinations of wheel and rail profiles in service usually have nonlinearities in form of jumps in Δr function which denotes two-point wheel rail contact, as well as asymmetry.

2.1 Equivalent conicity calculation

Equivalent conicity $\tan\gamma_e$ is defined as the cone angle of a wheelset with coned wheels whose lateral motion on straight track has the same kinematic wavelength as the given wheelset. This parameter is the main indication for the hunting motion of the wheelsets.

Determination of equivalent conicity is based on known wheel and rail profiles. In service conditions, this requires devices for profile measuring, based on optical or mechanical principles. For the calculation of the wheel-rail contact geometry, specialized software is required, which includes the calculation of the Δr function.

Starting from Δr function, in [3] are defined four methods for determination of wheel-rail contact parameters including equivalent conicity. In this paper, linear regression of the Δr function was applied.

Real wheel profiles were recorded using the device PGS2, which represents improvement of the PGS device developed for [6], Fig. 4. Recording of the rail profiles was performed using the measuring devices installed on the track recording vehicle „SEVER". For the calculations software EQ, enhancement of the GED software developed for [6], is used.

Fig. 4. Wheel profile recording

Processing of the recorded profiles includes removal of spikes, averaging, smoothing etc. Checking of all measured profiles after a processing was necessary to avoid artificial distortion of profiles.

Linear regression of the Δr function gives the approximation of the equivalent conicity as:

$\tan\gamma_e(\hat{y}) = B/2$

where B is the slope of the regression line, $\hat{y}$ -amplitude of kinematic wheelset motion.

Generally, non-symmetric wheel and rail profiles in service cause the mid position of wheelset motion to differ from y=0, and amplitudes on left and right are different. Fig. 5 shows such an example of Δr function obtained using real wheel and rail profiles recorded in-service.

It is necessary to calculate asymmetric amplitudes for given amplitude span $2\hat{y}$, which makes the limits for linear regression interval. For that purpose, it can be started from the following form of Klingel's equation:

$$\psi \cdot d\psi = \frac{-1}{2b_o r_o} \Delta r(y) \cdot dy$$

Integration of the equation results in:

$$(\psi_2^2 - \psi_1^2) = \frac{-1}{2b_o r_o} \int_{y_1}^{y_2} \Delta r(y) \cdot dy$$

When we chose a half wave between two peak positions, denoted as 1 and 2 in Fig. 2, it means $\psi_1=\psi_2=0$, $y_1=y_{emin}$, $y_2=y_{emax}$ and consequently:

$$\int_{y_{emin}}^{y_{emax}} \Delta r dy = 0$$

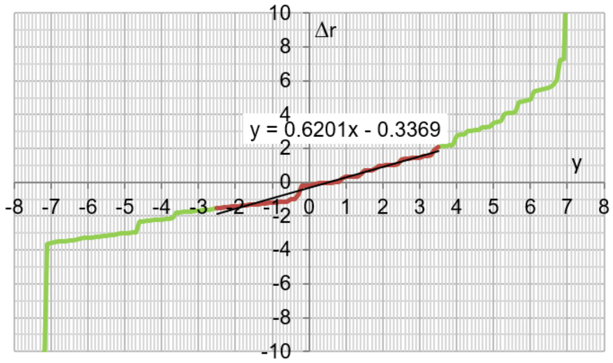

Fig. 5. Example of a Δr function in service

This integral can be calculated over complete range of y. For the Δr function given in Fig. 5 the integral value is shown in Fig. 6. Starting from the integral value at y_{emin} we need to identify second $y=y_{emax}$ with the same value of the integral. In that way it is possible to find limits for each desired double amplitude value $2\hat{y}=y_{emin}+y_{emax}$.

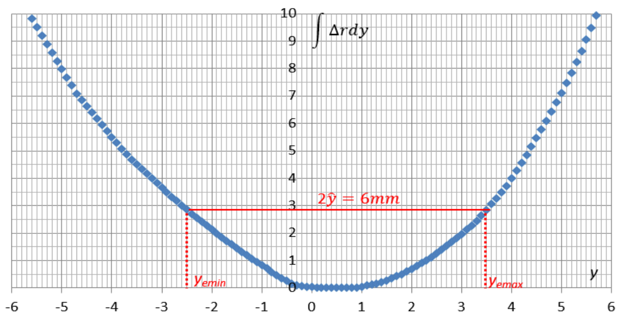

Fig. 6. Δrdy integral

For example, for amplitude $\hat{y}$=3 mm, in Fig. 6 are determined y_{emin}=-2.5 mm and y_{emax}=3.5 mm. These values are limits for linear regression in Fig. 5, from which can be obtained:

$\tan\gamma_e(\hat{y} = 3)$ = B/2=0.620/2=0.31

In the same way values of equivalent conicity are calculated for the whole interval of amplitudes of interest, usually for $\hat{y}$ = 1 to 7 mm.

3. EQUIVALENT CONICITY REQUIREMENTS

There are different requirements for equivalent conicity. According to [4], for the acceptance of new types of rail vehicles the stability tests with speed $1{,}1\cdot V_{max}$ at test sections of 100 m length, with following minimum average equivalent conicity are necessary:

- for $v \leq 120$ km/h: $\tan\gamma_e \geq 0.40$
- for 120 km/h < $v \leq 300$ km/h: $\tan\gamma_e \geq$ 0.534 - V/900) (rounded to two decimal digits)
- for v > 300 km/h: $\tan\gamma_e \geq 0.0$

Equivalent conicity should be calculated with real wheel and rail profiles used in test. For new track sections upper limits of equivalent conicity are given in Table 1 [1]:

Tab. 1. Infrastructure, design limits for $\tan\gamma_e$

	Wheel profile
Speed range [km/h]	S1002, GV1/40, SR=1420 and 1426 mm
$v \leq 60$	Assessment not required
$60 < v \leq 200$	0.25
$200 < v \leq 280$	0.20
$v > 280$	0.10

If instability arises in service, according to [2], the railway undertaking shall measure the wheel profiles of the vehicle and the distance of active faces of the wheelsets. The equivalent conicity shall be calculated using the scenarios provided in Table 2 to check if compliance with the maximum equivalent conicity the vehicle was designed and tested is met. If this is not the case, the wheel profiles have to be machined.

Tab. 2. Scenarios for equivalent conicity calculations

Rail head profile	Rail inclinatio n	Track gauge	Note
60E1	1:20 and 1:40	1435 and 1437 mm	4 cases
54E1	1:20 and 1:40	1435 and 1437 mm	4 cases
60E2	1 in 40	1435 and 1437 mm	2 cases

Tab. 3. Vehicles, limits for in service instability

Vehicle v_{max}	Equivalent conicity limit values	Test conditions from table 2
≤ 60	N/A	N/A
> 60 and < 190	0.30	All
≥ 190 and ≤ 230	0.25	1 to 5, 2, 3, 4, 5 and 6
> 230 and ≤ 280	0.20	1, 2, 3, 4, 5 and 6
> 280 and ≤ 300	0.10	1, 3, 5 and 6
> 300	0.10	1 and 3

The equivalent conicity value is determined at the following amplitude:

$\hat{y}$ = 3 mm, if (TG – SR) ≥ 7 mm

$\hat{y} = \dfrac{(TG - SR) - 1}{2}$, if 5 mm ≤ (TG - SR) < 7 mm

$\hat{y}$ = 2 mm, if (TG – SR) < 5 mm

At the other hand, in case instability motion appears, according to [1], the infrastructure manager shall measure rail profiles for equivalent conicity assessment at the site in question at a step of approximate 10 m along track. The moving average over 100 m shall be calculated and their maximum compared to limit value in table 4. The same wheel profiles shall be used as in case for new infrastructure.

Tab. 4. Infrastructure, limits for in-service instability

Speed range [km/h]	Maximum value of mean equivalent conicity over 100 m
$v \leq 60$	assessment not required
$60 < v \leq 120$	0.40
$120 < v \leq 160$	0.35
$160 < v \leq 230$	0.30
$v > 230$	0.25

4. EXAMPLE OF VEHICLE ASSESSMENT

In this example the wheels of the 4-axle track recording vehicle were measured and processed for equivalent conicity assessment. The vehicle has travelled about 2000 km after wheel machining.

Fig. 7 shows calculated equivalent conicities for amplitudes of the wheelset 3in the range from 1 to 7.5 mm, in combination with different prescribed rail profiles. The relevant amplitude is $\hat{y}$ = 3 mm. The highest value of $\tan\gamma_e(\hat{y} = 3)$ = 0.239. For vehicle maximum speed of v=160 km/h this value is below the limit 0.30 given in Table 3.

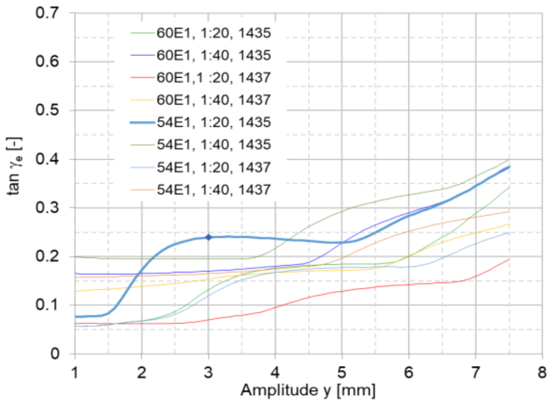

Fig. 7. Equivalent conicity, 3rd wheelset

For all sections, calculation is made in combination with prescribed wheel profiles. The highest values are obtained in combination with wheel profile S1002, and SR=1426 mm, as shown in Fig. 8.

Each line corresponds to one track cross-section. Relevant is the maximum 100 m moving average for amplitude $\hat{y}$ = 3 mm, which in this case equals to 0.158. This value is within both limits, for the new railway infrastructure (table 1) as well as for in-service instability (Table 4).

5. EXAMPLE OF TRACK ASSESSMENT

As an example, 300 m section of the right track on the new line between Belgrade and Novi Sad from km 56+700 to 57+000 is used. The rail profiles were recorded using devices of the track recording vehicle "SEVER 2000" of Infrastructure of Serbian Railways, with measurement step 25 m.

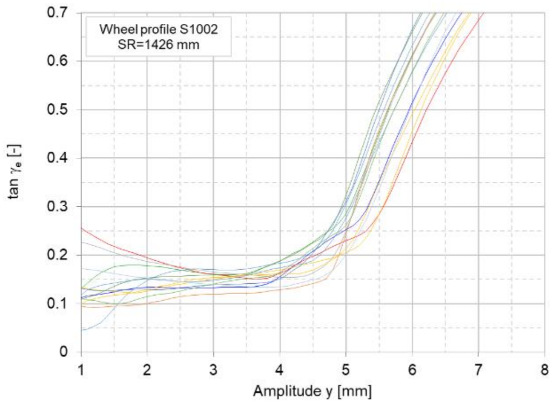

Fig 8. Equivalent conicity for track section example

6. CONCLUSION

With the introduction of the new Belgrade – Novi Sad line of Serbian Railways for 200 km/h, in-service control of equivalent conicity became extremely important. Presented requirements, calculation procedures and results examples can be considered as a guide for implementing actions.

ACKNOWLEDGEMENT

Authors express gratitude to the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Grant number: 451-03-65/ 2024-03/ 200105.

REFERENCES

[1] TSI INF, COMMISSION REGULATION (EU) No 1299/2014, of 18 November 2014, on the technical specifications for interoperability relating to the 'infrastructure' subsystem of the rail system in the European Union, including Implementing Regulations M1 (2019) and M2 (2023)

[2] TSI LOC PAS, COMMISSION REGULATION (EU) No 1302/2014, of 18 November 2014, concerning a technical specification for interoperability relating to the 'rolling stock - locomotives and passenger rolling stock' subsystem of the rail system in the European Union, including Implementing Regulations M1 (2016), M2 (2018), M3 (2019), M4 (2020) and M5 (2023)

[3] EN 15302: 2021, Railway Applications - Wheel-rail contact geometry parameters - Definitions and methods for evaluation

[4] EN 14363:2016+ A2:2022, Railway applications - Testing and simulation for the acceptance of running characteristics of railway vehicles - Running behaviour and stationary tests

[5] Milutinović, D., Simić, G., Opterećenja i proračun točkova železničkih vozila, 2006., Mašinski fakultet, Beograd

[6] Simić, G. Istraživanje realne geometrije dodira točak-šina i njenog uticaja na kretanje šinskih vozila i na habanje sistema točak-šina, Doctoral dissertation, University Belgrade-Faculty of Mechanical Engineering, 1997.