TRANSPORT
ISSN 1648-4142 print / ISSN 1648-3480 online
2012 Volume 27(3): 229–236
doi:10.3846/16484142.2012.719198

INVESTIGATION INTO THE CALCULATION OF SUPERELEVATION DEFECTS ON CONVENTIONAL RAIL LINES

Inesa Gailienė

Dept of Roads, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania
E-mail: inesa.gailiene@vgtu.lt

Submitted 24 November 2011; accepted 30 January 2012

Abstract. Railway curves have influence on train speed on a curve and/or wheel/rail interface. Additional forces that have to be compensated appear in the curves. The purpose of superelevation is to compensate acceleration emerging in the curve thus assuring comfortable passenger transportation and equal wearing of both rails. However, it is very difficult to calculate superelevation when designing and maintaining a railway track, because the estimation of actual train speed on the curves is very complicated. As we know, railway lines can be divided into conventional, high speed and heavy haul ones. As these lines are absolutely different, requirements for the installation and maintenance of the track may also differ. Conventional rail lines are the object of research discussed in this article. The speed of freight and passenger trains is different on conventional rail lines, which is an essential factor in determining superelevation. On the ground of scientific researches, the article analyzes and evaluates the factors influencing wheel/rail interface on the curves. The paper also deals with railway line curves, superelevation and uncompensated lateral acceleration. The article presents the method used in Lithuania for calculating superelevation in the railway curves and analyzes calculation defects. For research purposes, analytical and statistical methods have been used. The obtained results have shown that actual superelevation in the researched curves does not match the calculated one. The calculations and obtained results of superelevation depend on how average train speed in the curves is estimated and used for calculations. As most of the results show that even small variations in the curve have a great influence on track/vehicle behaviour, it is necessary to find more precise methods for calculating superelevation, evaluating actual train speed and considering permissible uncompensated lateral acceleration in the curves.

Keywords: superelevation, conventional rail lines, curve, train speed, uncompensated lateral acceleration, railway.

1. Introduction

Track geometry is very important for the behaviour of vehicles. Track geometry and track/vehicle system are usually analyzed while researching wheel-rail interface, track and vehicle system modelling, various track and rolling stock parameters and behaviour modelling, the influence of various parameters on the estimation of rail side wear, contact stresses, derailment, etc. (Jin *et al.* 2007, 2009; Enblom 2009; Grassie, Elkins 2005). The typical conditions used for the simulations of curving are shown in Table 1 (Polach *et al.* 2006). Research is sometimes carried out analyzing track degradation models and estimating the degradation of the track substructure, super-structure and track geometry (Sadeghi, Askarinejad 2007; Larsson 2004; Zhang *et al.* 2000). As transverse, longitudinal and vertical forces acting in the curves are markedly larger than the ones acting in the straight sections of the track, they are usually used as an object of research on estimating the influence of rail wear and track geometrical parameters on the track/vehicle system. Research substantially differs if high-speed lines with no freight traffic are analyzed and if conventional rail lines are analyzed where traffic is mixed. Speed is supposed to be the essential difference. This article discusses only conventional rail lines and their curves.

Designing a railway track, a track gauge, superelevation, a transition curve, horizontal curve radius, vertical curve radius and a gradient are identified in the curves. The supervision of the railway track is very important for maintaining it because the above mentioned parameters have to be kept in their permissible limits. Therefore, allowable deviations from all these parameters are regulated. This is very important for traffic safety and for lowering the expenses of railway repair and supervision, because even small changes can sometimes cause derailment, for example, superelevation can markedly change acting forces and vehicle behaviour having a negative impact on rolling stock wheels and rail wear.

Research on rail wear in the curves, wear intensity and determinant factors has disclosed that the rail wear

Table 1. Typical conditions for curving simulations

Input parameters	Recommended value or conditions
Track design	Typical curve radius including transitions and the smallest curve radius on the network
Track irregularity	According to the specification and conditions on the railway network; measured track irregularity if possible
Wheel/rail contact geometry	Nominal wheel and rail profiles, nominal gauge, gauge widening in tight curves according to specification; influence analysis of worn wheel and rail profiles, mainly for self-steering wheel sets
Wheel/rail creep-force law	Nonlinear theory, friction coefficient 0.4 (dry rail)
Vehicle state	Intact
Vehicle loading	Full (crush) load; Tare (empty) relevant for derailment safety investigation
Vehicle speed	Speed variation in the function of curve radius and superelevation deficiency

volume greatly depends on curving speed, the geometry sizes of the track, the curvature radius of the curved track, the profiles of the wheel/rail, the dynamic characters of the vehicle and track, axle loads, material physical properties and the friction coefficient of the wheel/rail (Jin *et al.* 2007). For that purpose, the models of a railway vehicle coupled with a curved track are composed. Sometimes, already knowing the factors that have been determined by many researches and have a negative impact on rail wear in the curves and traffic safety (derailment probability), new researches are carried out to choose one or several geometric parameters such as the research object and to evaluate their design and supervision peculiarities (Wolf 2006; Klauser 2005). Research on the intensive formation of external rail side wear in the curve points to the following factors: uncontrolled (railway line plan and profile), partially controlled (train weight, axial loads) and controlled (train speed, rail and wheel steel toughness, wheel and rail lubrication, superelevation, gauge) (Povilaitienė, Laurinavičius 2004). Researches remain topical and necessary, because expenses concerning the maintenance of track geometry are high in all countries (Bouch *et al.* 2010). Although the controlled factors are analyzed, however, no concrete proposals are usually given and only a theoretical analysis of the models not including practical conclusions and proposals is done.

The article looks at geometrical track parameter – superelevation the determination of which may vary in different countries; however, the essence remains the same – superelevation is calculated in respect of rated track parameters: track radius and average and/or maximum permissible rated train speed. Nevertheless, during track maintenance, the value of rated superelevation is no longer important unlike uncompensated lateral acceleration as superelevation excess, superelevation deficiency expression, equilibrium superelevation and balanced speed. Therefore, the paper primarily discusses and analyzes the influence of superelevation on wheel-rail interface. The article reviews the influence of determining superelevation on wheel/rail interface, focuses on how uncompensated lateral acceleration and other parameters have a negative impact on track and rolling stock emerge, describes the determination of superelevation and explains the importance of the value of uncompensated lateral acceleration. Lithuanian railway curves having different radii have been chosen and detailed analysis estimating the value of superelevation, speed and uncompensated lateral acceleration has been performed. Separate curves have been examined to estimate how the value of actual superelevation differs from the one calculated according to the valid methodology. The paper suggests the means that correctly calculate superelevation regulating permissible uncompensated lateral acceleration for freight trains and evaluating train speeds.

2. Superelevation Deficiency, Superelevation Excess and Uncompensated Lateral Acceleration

While analyzing railway curves and superelevation, the following parameters are usually taken into account: curve radius R, superelevation h, superelevation excess h_e, superelevation deficiency h_d, lateral acceleration a, balanced speed v_{eq}. The parameters that influence superelevation in the curve are shown in Fig. 1.

The difference between the levels of two rails in the curve is called superelevation and is arranged to compensate a part of lateral acceleration. The maximum values are set for superelevation because of the following problems that arise in case a train is forced to stop or run slowly in a curve: passenger discomfort at standstill or low speed; the risk of the derailment of freight trains in a sharp curve due to the combined effect of high lateral and low vertical load on the outer wheel at low speed; possible displacement of wagon loads (Lindahl 2001). Acceleration a is lateral acceleration. If $a \neq 0$, it is called uncompensated lateral acceleration. Lateral acceleration is calculated as follows:

$$a = \frac{v^2}{R} \cdot \cos\varphi - g \cdot \sin\varphi = \frac{v^2}{R} \cdot \cos\varphi - g = \frac{v^2}{R} - g \cdot \frac{h}{2 \cdot b_0} \left[\mathrm{m/s^2} \right], \quad (1)$$

where: v – train speed in the curve, km/h; φ – superelevation angle; g – gravitational acceleration, m/s^2; R – curve radius, m; $2 \cdot b_0$ – the distance between rail axes m; h – actual superelevation, mm.

Because g = 9.81 m/s^2 and $2 \cdot b_0$ = 1535 mm (Russian gauge), then, inserting these values into formula (1)

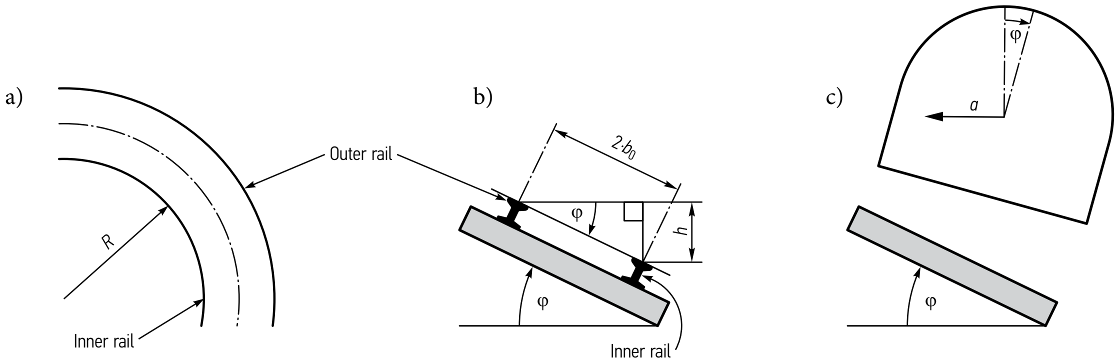

Fig. 1. The curve in plane and longitudinal profile: R – curve radius; φ – superelevation angle; h – superelevation; $2 \cdot b_0$ – the distance between rail axes (when a track gauge is 1435 mm, the value is equal to 1.500 m; when a track gauge is 1520 mm, the value is equal to 1.535 m); a – lateral acceleration

we obtain that uncompensated lateral acceleration in Russian gauge is calculated according to the following formula:

$$a = \frac{v^2}{3.6^2 \cdot R} - 0.00613 \cdot h \left[\mathrm{m/s^2}\right], \qquad (2)$$

where: v^2 – train speed in the curve, km/h; R – curve radius, m; h – actual superelevation, mm.

Equilibrium superelevation exists when lateral acceleration is equal to zero and is calculated according to the following formula:

$$h_{eq} = 12.5 \cdot \frac{{v_v}^2}{R} \text{ [mm]}, \qquad (3)$$

where: v_v – actual train speed in the curve, km/h.

Balanced speed, when lateral acceleration is zero, is calculated according to the following formula:

$$v_{eq} = \sqrt{\frac{R \cdot h}{12.5}}. \qquad (4)$$

For several reasons, fully compensated lateral acceleration cannot be achieved in all cases: it is possible that a train stops or runs slowly in the curve. Thus, maximum superelevation has to be limited and not all trains have the same speed. Therefore, it would not be possible to achieve fully compensated lateral acceleration for all trains anyway (Lindahl 2001). Accordingly, superelevation deficiency and superelevation excess are estimated and regulated. When superelevation is less than equilibrium superelevation, the so called superelevation deficiency arises, which is a value necessary to achieve equilibrium superelevation when lateral acceleration is equal to zero. Hence, it can be calculated as the difference between equilibrium superelevation and actual superelevation:

$$h_d = h_{eq} - h. \qquad (5)$$

Inserting formula (3) to formula (5), the following formula for calculating superelevation deficiency is obtained:

$$h_d = 12.5 \cdot \frac{v^2}{R} - h. \qquad (6)$$

Superelevation deficiency is determined by the following factors (Lindahl 2001; Klauser 2005): track construction; track alignment, a type of the vehicle and running gear; axle loads and unsprung masses; the state of maintaining rolling stock. The limit of superelevation deficiency is typically dictated by maximum uncompensated lateral accelerations. Superelevation excess limit is equivalent to maximum allowable superelevation.

Superelevation excess is formed if actual superelevation is higher than equilibrium superelevation. Superelevation excess is achieved when the vehicle is running at a lower speed than the design speed of the track. Superelevation excess is the difference between actual superelevation and equilibrium superelevation and is defined as:

$$h_e = h - h_{eq}. \qquad (7)$$

If superelevation excess and superelevation deficiency are not equal to zero, it means that there is uncompensated lateral acceleration in the curve. In that case, the main question considers permissible uncompensated lateral acceleration (i.e. superelevation excess and superelevation deficiency) in the event we cannot precisely calculate h_{eq}. Having mixed traffic when more than one speed exist (permissible passenger train speed, permissible freight train speed, actual passenger and freight train speed that is usually different from the rated (permissible) one), a precise calculation of h_{eq} becomes very complicated. Therefore, there is no purpose to discuss superelevation excess or superelevation deficiency in the mixed traffic lines, because everything depends on passenger and freight train speed.

Uncompensated lateral acceleration, superelevation deficiency and superelevation excess have different regulations in different countries where they are regulated in respect of traffic intensity. For example, in England, Germany, the Check Republic and Bulgaria, average speed is used only in case trains are running on similar speeds (Povilaitienė 2004). In France, average train speed is calculated according to the formula (Kamensky 2002):

$$v^2 = \frac{v_{\max}^2 + v_{\min}^2}{2} \text{ [km/h]}. \qquad (8)$$

Superelevation is determined regulating uncompensated lateral acceleration in a number of countries. Such calculation method can be used when freight rolling stocks are in a good condition and freight traffic forms only a small part of all traffic. The use of this calculation method shows that average train speed must not be determined as it is difficult to define this value with the required preciseness (Kamensky 2002).

It is also difficult to find out the correctness of calculating superelevation according to maximum speeds. The main disadvantage of determining superelevation according to average square train speeds is a complicated estimation of quantity, mass and speed of the trains passing a particular curve within a year, because maintenance conditions can change, aged locomotives do not develop the rated speed, train speeds are limited with speed warnings, etc.

3. Superelevation Influence on Wheel/Rail Interface and Rail Wear

As noted above, different methods of calculations can be used for estimating superelevation; however, one of the negative outcomes of incorrectly calculated superelevation is rail wear (Sadeghi, Akbari 2006). Superelevation is one of the important factors affecting wear, especially lateral wear in the curves. If superelevation is less than the expected amount, lateral wear occurs on the outer rail. If superelevation is more than the theoretical value, the inner rail of the curve goes under extensive stresses that result in wearing the inner rail. Rail replacement because of exceeded wear is a very important factor because it concerns large expenses for railway supervision that can be distributed as follows (Bouch *et al.* 2010): switches and crossings (19%), inspection (17%), rail changing (17%), tamping (15%) and re-sleepering (13%). The replacement of rails because of exceeded permissible side wear constitutes 20÷30% of all replaced rails (Povilaitienė 2004).

Uncompensated lateral acceleration that forms in the curve also has an influence on lateral wheel displacement when wheel stability on rail and wheel climb has to be estimated. Following research on the influence of curve radius and the superelevation of the track on the stability of the vehicle system (Zeng, Wu 2004), it has been estimated that curve radius and outer rail superelevation have tremendous effects on the stability of vehicle systems. This is due to the fact that the stability of the vehicle system is related to creep forces between wheels and rails, and creep forces on the straight track and different curved tracks are quite different.

The studies have shown that rail wear intensity is minimal when uncompensated lateral acceleration is 0÷0.1 m/s^2, and wear intensity begins increasing when uncompensated lateral acceleration reaches 0.5÷0.6 m/s^2 (Redkin 1999). When uncompensated lateral acceleration increases up to 0.5 m/s^2, the intensity of rail head side wearing increases three times (Karpuschenko, Ostashko 1996). If actual superelevation is larger than the calculated one, the wheel-set of the locomotive slides on the external rail of the curve and if superelevation is insufficient, the wheel-set slides on the internal rail. When the wheels slide on the internal rail, the wear of the external rail is smaller; however, the train can derail. When the wheels slide on the internal rail, wheel flange wearing increases (Bujnosov 1999).

The value of uncompensated lateral acceleration and superelevation act on the intensity of rail head side wearing as well as on the intensity of rail head vertical wearing: the faster is uncompensated lateral acceleration the higher is the intensity of external rail vertical wearing. It is suggested to multiply average speed by the coefficient equal to 0.9 and square speed by 0.8 in the curves with longitudinal wear greater than 6÷12% or in the curves near the stations (Karpuschenko, Ostashko 1997).

Following the review of researches and on the basis of foreign experience it can be concluded that maximum uncompensated lateral acceleration may vary in different countries. The main problem in Lithuanian railway lines is that uncompensated lateral acceleration is regulated only for passenger trains but not for the freight ones.

4. Determining Superelevation in Lithuania

In Lithuania, superelevation is defined using two formulas (3) and (9). Actual speed is necessary for formula (3) and maximum speed for formula (9). Formula (9) evaluates uncompensated lateral acceleration for passenger trains 0.7:

$$h_{p\min} = 12.5 \frac{v_{\max}^2}{R} - 115, \tag{9}$$

where: $h_{p\min}$ – minimal superelevation, mm; $v_{\max}$ – maximum permissible train speed, km/h; 115 – maximum superelevation in millimetres when uncompensated lateral acceleration rate is not exceeded (0.7 m/s^2).

When superelevation is calculated according to formulas (3) and (9), a higher value is chosen as the final result. However, the chosen value must be lower than 150 mm because this number is the highest possible value of superelevation according to the current standards.

Uncompensated lateral acceleration is not regulated for freight trains on Lithuanian railway lines; nevertheless, it is necessary for conventional rail lines and is significant superelevation deficiency for calculations. For example, in Poland, permissible uncompensated lateral acceleration for freight trains varies from 0.2 to 0.6 m/s^2 (depending on traffic intensity), whereas in Russia it makes ±0.3 m/s^2. Considering Russian experience, it would be useful to use a permissible uncompensated lateral acceleration norm of 0.3 m/s^2 in Lithuania.

5. Research on Superelevation and Uncompensated Lateral Acceleration in the Curves on Lithuanian Railway Lines

The length of railways maintained in Lithuania makes 1767.6 km. Two Trans-European corridors I and IX go across Lithuania. The branches of the corridors coincide with the main Lithuanian railway lines. I A branch of corridor I begins in Riga (Latvia), crosses Šiauliai (Lithuania) and Kaliningrad (Russia) and goes to Gdansk (Poland). Corridor IX connects Baltic Sea, Black Sea and Mediterranean Sea and is the longest corridor that almost forms a network having many branches in the East and West. Two branches of corridor IX, namely IX B and IX D, cross Lithuanian territory. The branches crossing Lithuania are as follows: IX B (Kiev–Minsk–Vilnius–Klaipėda) connects Klaipėda Sea Port – the main Lithuanian freight and logistics centre – with Vilnius, Belorussia, Ukraine and Russia; IX D (Kaišiadorys–Kaunas–Kaliningrad) is the main railway line connecting the Russian Federation with its enclave – Kaliningrad region and serving the major transit flows.

As traffic intensity in these corridors is the highest, lines Vilnius–Kena (61 curves) and Kaišiadorys–Kybartai (93 curves) are chosen for research during which the values such as actual superelevation (h), superelevation calculated according to the rules valid for Lithuanian railways (h_p) and uncompensated lateral acceleration (a) were estimated and analyzed.

Line characteristics. Permissible speed in the line Vilnius–Kena for passenger trains – 120 km/h and freight trains – 90 km/h (in 42 researched curves), for passenger trains – 120 km/h and freight trains – 80 km/h (in 11 researched curves) and for passenger trains – 100 km/h and freight trains – 80 km/h (in 8 researched curves). Permissible speed in the line Kaišiadorys–Kybartai for passenger trains – 120 km/h and freight trains – 90 km/h (in 79 researched curves), for passenger trains – 120 km/h and freight trains – 80 km/h (in 5 researched curves), for passenger trains – 100 km/h and freight trains – 90 km/h (in 3 researched curves) and for passenger and freight trains – 80 km/h (in 6 researched curves).

First of all, actual superelevations are compared to the calculated ones (according to the methodology valid in Lithuania) in the researched curves in railway lines Vilnius–Kena and Kaišiadorys–Kybartai. As we know, superelevation is calculated according to two formulas – (3) and (9) – choosing a higher value. Therefore, in the curves with smaller radius, superelevation calculated for a passenger train is installed and if radius is larger, superelevation calculated for average speed is installed. Another studies indicate that actual train speed in the curve is about 20% less than the permissible speed, and therefore the following options are calculated: $v = 0.8{\cdot}v_{max}$ or $v = 0.9{\cdot}v_{max}$. The results are shown in Figs 2 and 3.

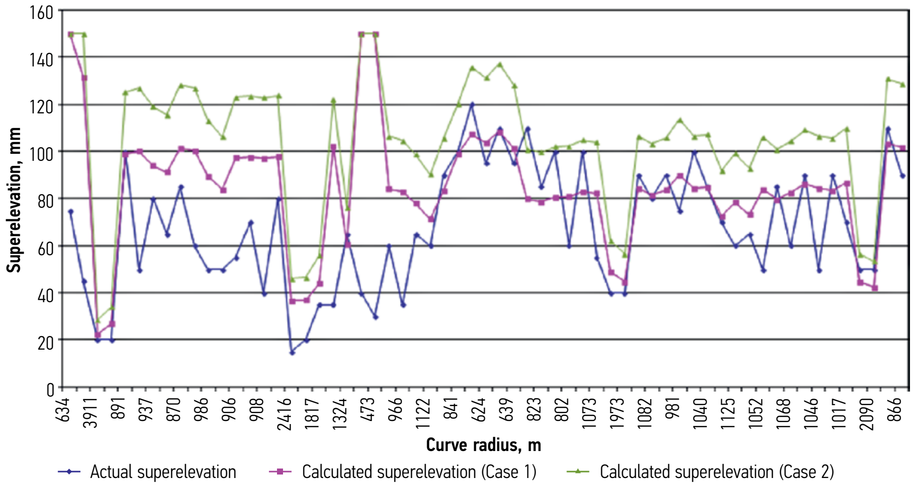

Fig. 2. Superelevation in the curves following the line Vilnius–Kena: Case 1 – $v = 0.8{\cdot}v_{max}$; Case 2 – $v = 0.9{\cdot}v_{max}$

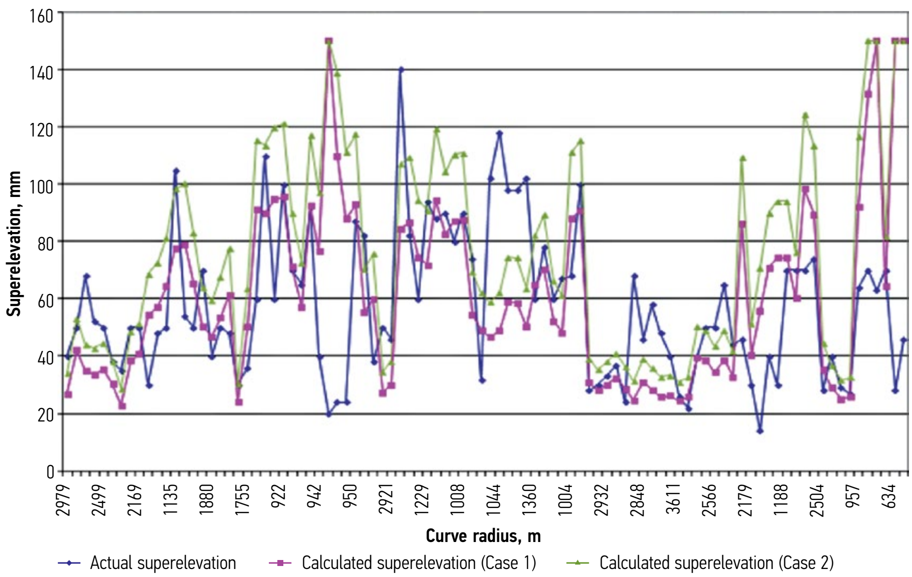

Fig. 3. Superelevation in the curves following the line Kaišiadorys–Kybartai: Case 1 – $v = 0.8{\cdot}v_{max}$; Case 2 – $v = 0.9{\cdot}v_{max}$

The carried out research concludes that actual superelevations are calculated using other speeds that are usually less than 0.8 or 0.9 from the max permissible speeds. For further research, following curve analysis, the curves with a permissible speed of 120/90 km/h have been chosen from both railway lines. Such curves are the most frequent and permissible speed is the highest on Lithuanian railway lines. Fig. 4 shows actual and calculated superelevation in the curves where permissible train speed is 120/90 km/h. Therefore, uncompensated lateral acceleration in the curves when passenger and freight trains run in max permissible speed is further calculated and graphically depicted (Fig. 5).

Assuming that the norm of permissible uncompensated lateral acceleration for passenger trains is 0.7 m/s^2 and for freight trains it makes ±0.3 m/s^2, it can be seen that the rated values in most of the curves would be violated if train speed in the curve was the maximum permissible and freight train speed was presumably the lowest.

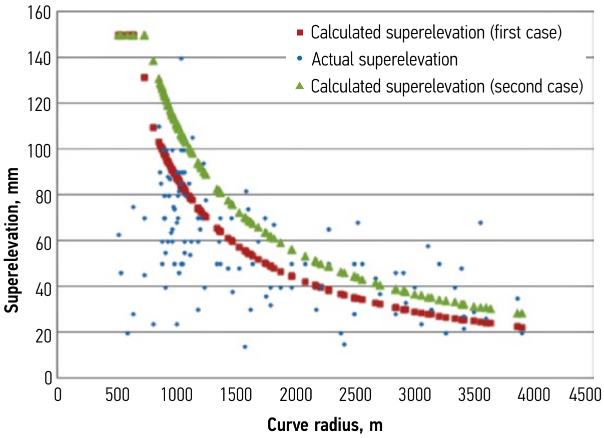

Fig. 4. Actual and calculated superelevation in the curves where permissible train speed is 120/90 km/h

When reaching $a \rightarrow \min$, however, it is impossible to change the radius of the curve. The other two variables – superelevation and speed – are dependent on each other, and therefore it would be useful to search for a balance between them while calculating superelevation. For that purpose, the analysis of the exact curve is required. Curve radius is 931 m, permissible passenger train speed – 120 km/h, freight train speed – 90 km/h and actual superelevation – 60 mm. This means that if using formula (3), it can be estimated that superelevation is calculated for an average speed of 67 km/h. Superelevation is not calculated according to formula (9) because in such a case superelevation should be 80 mm. Thus, if a train runs in a max permissible speed of 120 km/h in the curve, uncompensated lateral acceleration is 0.8 m/s^2, i.e. larger than the permissible one (0.7 m/s^2 for passenger trains). To make a conclusion, it is necessary to find a way for calculating superelevation realizing maximum permissible train speeds, evaluating possible speed decrease, not overrunning limits to uncompensated lateral acceleration and estimating that along with considering the uncompensated lateral acceleration of the passenger train, the norm of the uncompensated lateral acceleration of the freight train should be ±0.3 m/s^2.

Suppose that for calculation purposes we assume that average train speed $v = 0.9 \cdot v_{max}$ and calculated superelevation is 120 mm. In this case, we receive that if the passenger train runs in maximum permissible speed, uncompensated lateral acceleration is 0.5. However, if superelevation is 120 mm and freight train speed is

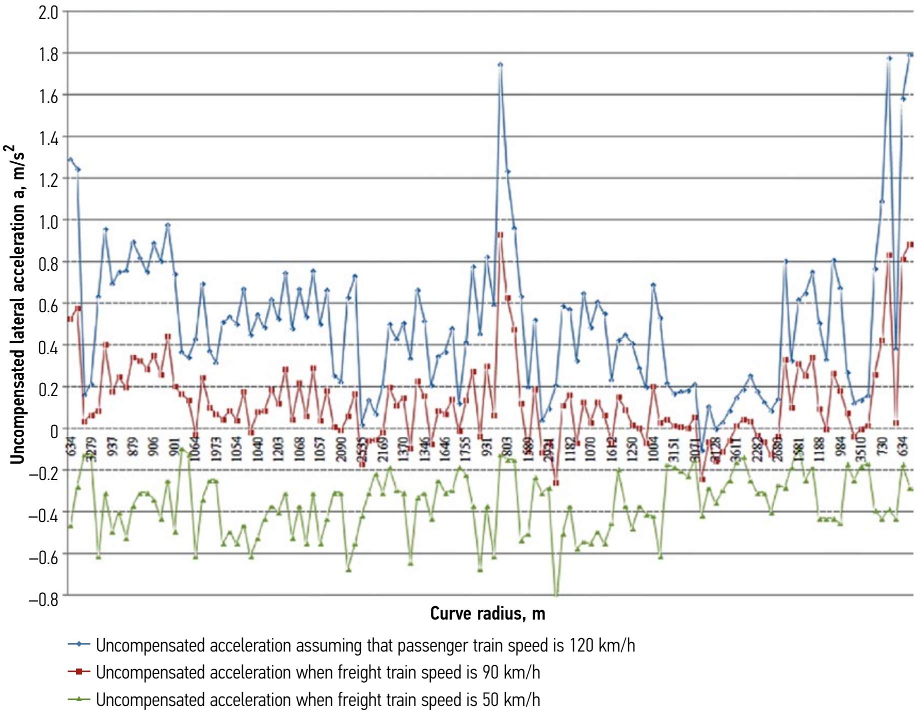

Fig. 5. Uncompensated lateral acceleration calculated according to actual superelevations

Table 2. Modelling superelevation and uncompensated lateral acceleration

Uncompensated lateral acceleration, m/s^2	Actual passenger train speed, km/h	Actual freight train speed, km/h	Actual superelevation, mm	Calculated superelevation, $v = 0.7 \cdot v_{max}$	Calculated superelevation, $v = 0.8 \cdot v_{max}$	Calculated superelevation, $v = 0.9 \cdot v_{max}$
0.8	120	–	60	–	–	–
0.7	120	–	–	80	–	–
0.6	120	–	–	–	95	–
0.5	120	–	–	–	–	120
0.3	–	90	60	–	–	–
0.2	–	90	–	80	–	–
0.1	–	90	–	–	95	–
–0.1	–	90	–	–	–	120
–0.2	–	50	60	–	–	–
–0.3		50	–	80	–	–
–0.4	–	50	–	–	95	–
–0.5	–	50	–	–	–	120

50 km/h, the rated uncompensated lateral acceleration is exceeded. Therefore, such speed or superelevation is inappropriate (calculation results are presented in Table 2). The same results are obtained assuming that $v = 0.8 \cdot v_{max}$.

In other case, assuming that average train speed $v = 0.7 \cdot v_{max}$, we obtain calculated superelevation that is equal to 80 mm. Rated uncompensated lateral acceleration for passenger and freight trains is not exceeded even if freight train speed is 50 km/h. Thus, it is necessary to know that freight train speed that is less than 50 km/h has a negative effect on rail/wheel interface. Therefore, it would be purposeful to have a concept of critical freight train speed on conventional rail lines. The concept could be determined for every exact curve estimating superelevation.

If superelevation is 80 mm, the speed of the passenger train is 120 km/h and maximum permissible uncompensated lateral acceleration is 0.7 m/s^2. Thus, if freight trains are moving with a maximum permissible speed of 90 km/h, uncompensated lateral acceleration will make 0.2 m/s^2. Still, if freight trains do not reach permissible speed, for example 40 km/h, uncompensated lateral acceleration will reach – 0.35 m/s^2, which means that uncompensated lateral acceleration would exceed permissible standards and make ±0.3 m/s^2. In that case, it is necessary to calculate a critical speed of freight trains (minimum permissible) using the condition:

$$-0.3 \geq \frac{v_{cr}^{2}}{12.96 \cdot R} - 0.00613 \cdot h. \quad (10)$$

We obtain that:

$$v_{cr} \geq \sqrt{R \cdot \left(h \cdot 0.08 - 3.89\right)}. \quad (11)$$

Thus, the considered curve discloses that calculated superelevation is 80 mm. We then proceed with calculating critical speed according to formula (11) and obtain that following such a curve freight trains should run at the speed of no less than 50 km/h. Only then the permissible uncompensated lateral acceleration standard of freight trains would not be exceeded and permissible speeds would reach 120 km/h for passenger trains and 90 km/h for freight trains, though critical speed for freight trains would be 50 km/h.

6. Conclusions

1. The studied literature makes clear that superelevation is a very important factor influencing wheel/rail interface because uncompensated lateral acceleration appearing in the curves has an essential influence on wheel/rail interface.
2. When superelevation in the curves is calculated on conventional rail lines, the most difficult task is to estimate actual train speeds. Differences between permissible freight and passenger train speeds and between permissible and actual speeds determine that actual superelevation is not always calculated as optimal, and therefore does not always conform with actual train speeds.
3. The purpose of the performed research on Lithuanian railway lines was to determine the difference between actual and calculated superelevation in the curves modelling different average train speeds. The actual value of superelevation did not meet the calculated one in almost all of the researched curves.
4. The methodology of calculating superelevation used on Lithuanian railway lines should be corrected. First, permissible uncompensated lateral acceleration for freight trains should be standardized, which might be achieved additionally using formula (11) in superelevation calculations. This formula allows obtaining critical speed (minimum permissible speed) for freight trains.

References

Bouch, C. J.; Roberts, C.; Amoore, J. 2010. Development of a common set of European high-level track maintenance cost categories, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 224(4): 327–335. http://dx.doi.org/10.1243/09544097JRRT316

Bujnosov, A. P. 1999. Vzaimodejstvie kolesa i rel'sa, *Put' i putevoe khoziaistvo* (11): 6–15 (in Russian).

Enblom, R. 2009. Deterioration mechanisms in the wheel–rail interface with focus on wear prediction: a literature review, *Vehicle System Dynamics* 47(6): 661–700. http://dx.doi.org/10.1080/00423110802331559

Grassie, S. L.; Elkins, J. A. 2005. Tractive effort, curving and surface damage of rails: Part 1. Forces exerted on the rails, *Wear* 258(7–8): 1235–1244. http://dx.doi.org/10.1016/j.wear.2004.03.064

Jin, X.; Wen, Z.; Xiao, X.; Zhou, Z. 2007. A numerical method for prediction of curved rail wear, *Multibody System Dynamics* 18(4): 531–557. http://dx.doi.org/10.1007/s11044-007-9073-3

Jin, X.; Xiao, X.; Wen, Z.; Guo, J.; Zhu, M. 2009. An investigation into the effect of train curving on wear and contacts tresses of wheel and rail, *Tribology International* 42(3): 475–490. http://dx.doi.org/10.1016/j.triboint.2008.08.004

Kamensky, V. B. 2002. Opredelenie raschiotnykh skorostej dvizhenia poezdov dlia vozvyshenia naruzhnogo rel'sa v krivykh uchastkakh puti, *Put' i putevoe khoziaistvo* (2–3): 47–59 (in Russian).

Karpuschenko, N. I.; Ostashko, I. A. 1996. Parametry kolei i iznos rel'sov, *Put' i putevoe khoziaistvo* (8): 6–7 (in Russian).

Karpuschenko, N. I.; Ostashko, I. A. 1997. Sposob opredeleniia srednevzveshennoj skorosti, *Put' i putevoe khoziaistvo* (2): 12–13 (in Russian).

Klauser, P. 2005. Operating at high cant deficiency, *The Journal of Wheel/Rail Interaction.* 5 p. Available from Internet: http://www.interfacejournal.com/features/09-05/cant/1.html

Larsson, D. 2004. *A Study of the Track Degradation Process Related to Changes in Railway Traffic*. Licentiate Thesis. Luleå University of Technology. 56 p. Available from Internet: http://epubl.ltu.se/1402-1757/2004/48/LTU-LIC-0448-SE.pdf

Lindahl, M. 2001. *Track geometry for high-speed railways: a literature survey and simulation of dynamic vehicle response*. TRITA-FKT Report 2001:54. 148 p. Available from Internet: http://www.europakorridoren.se/spargeometri.pdf

Polach, O.; Berg, M.; Iwnicki, S. 2006. Simulation, in *Handbook of Railway Vehicle Dynamics* (Edited by S. Iwnicki). Taylor & Francis, London, 359–422.

Povilaitienė, I. 2004. *Geležinkelio vėžės geometrinių parametrų įtaka bėgių ilgaamžiškumui kreivėse*. Daktaro disertacija: Technologijos mokslai, statybos inžinerija (02T). Vilniaus Gedimino technikos universitetas. 109 p. (in Lithuanian).

Povilaitienė, I.; Laurinavičius, A. 2004. Reduction of external rail wearing on road curves, *Journal of Civil Engineering and Management* 10(2): 123–130. http://dx.doi.org/10.1080/13923730.2004.9636296

Redkin, V. I. 1999. Iznos rel'sov stal men'she, *Put' i putevoe khoziaistvo* (5): 19–21 (in Russian).

Sadeghi, J.; Akbari, B. 2006. Field investigation on effects of railway track geometric parameters on rail wear, *Journal of Zhejiang University Science A* 7(11): 1846–1855. http://dx.doi.org/10.1631/jzus.2006.A1846

Sadeghi, J.; Askarinejad, H. 2007. Influences of track structure, geometry and traffic parameters on railway deterioration, *International Journal of Engineering: Transactions B: Applications* 20(3): 291–300.

Wolf, G. 2006. Curve superelevation: problems and solutions, *The Journal of Wheel/Rail Interaction.* 5 p. Available from Internet: http://www.interfacejournal.com/features/01-06/superele/1.html

Zeng, J.; Wu, P. 2004. Stability analysis of high speed railway vehicles, *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing* (47)2: 464–470. http://dx.doi.org/10.1299/jsmec.47.464

Zhang, Y. J.; Murray, M. H.; Ferreira, L. 2000. Modelling rail track performance: an integrated approach, *Proceedings of the ICE – Transport* 141(4): 187–194. http://dx.doi.org/10.1680/tran.2000.141.4.187