sciendo

Civil and Environmental Engineering
Vol. 18, Issue 1, 29-38, DOI: 10.2478/cee-2022-0003

REDUCING ENERGY CONSUMPTION IN THE DESIGN OF RAILWAY LINES - COMPENSATED CURVE OF THE VERTICAL TRACK GRADIENT

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Abstract

Trains that pass through several structural objects must overcome resistances acting against the train run. In case the track gradient of railway line is designed in values approaching the maximum allowable standard track gradient. Further adjustment of the elevation curve is possible by using secondary changing points between the main changing points of gradient, especially in the curve sections and tunnels. The elevation course will be modified by reducing the gradients in those sections by the anticipated resistances from these construction objects as circles, tunnels, etc.). A compensated curve can be designed to provide a smoother pass through the individual secondary sections of the track in rising gradient with reduced gear shifting of the locomotive engine and the train continues with fluent output, thus saving some energy consumed by the engine. The compensated curve is particularly suitable for long and heavy freight trains in mixed operation, but all other types of trains running on the track can also use this. The paper describes the compensated curve of the level of the gradient from the point of view of the designer in railway construction with practical calculations.

Keywords:

Railway engineering;
Track section;
Constant gradient resistance;
Reducing energy consumption;
Compensated curve.

1 Introduction

Reducing the energy demand of a railway line can be achieved also by construction-technical solutions already in the design phase of the track structure or in within reconstruction or modernization of the lines, [1] and [2]. Subsequently, a lower amount of energy consumed by the locomotive will be used to overcome the elements of the proposed line and the uniform engine power will be kept without shifting gears. Some design solutions are in [3-5]:

- lowering the track gradient,
- lost gradients Δh_{lost} are not designed on the track,
- in a directional solution by aligning the axis of the track, it means the radii of the circles and the transition spirals of different shapes are increasing – spirals,
- a track section is proposed as a section of the constant gradients resistance (CGR) at rising gradients that are approaching the maximum standard, i.e. standard gradient s_s.

For example, in case of loss of altitude Δh_{lost} in the lost gradient, where energy is again consumed to climb this height difference to altitude (double amount of energy consumption). If a reverse gradient was then proposed, this energy would have to be used again by the locomotive to climb to the same height it was already in. The main points of change in the vertical layout of the axe of the track are marked as the gradient changes line (GL_i) of the longitudinal profile. On the track, it would be necessary to overcome the same altitude difference again Δh_{lost} so it is good to propose construction measures when designing the line project (this does not apply to large valleys, etc.).

If the gradient is large, approaching the maximum gradient s_s, a track section with constant grade resistance (CGR) can be designed as a compensated curve, Fig. 2 to Fig. 7. It is known from railway operation that trainsets have to overcome resistances such as circle, tunnel, etc., therefore we propose lower gradients of the longitudinal profile in these sections so that the train can drive through

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these sections with the same locomotive engine power with the required traction force. Of course, other resistances (track and rolling), such as aerodynamic (trains in tunnels, opposite train movements in the tunnel and on track), are also considered in the project. The running resistance depends on the aerodynamic component given by the speed of the train, the shape, and characteristics of the vehicles, the cross-section profile, and the length of the tunnel [6].

In the experiments presented in the paper, mixed train operation (passenger and freight) is considered. Some resistances are influenced by the magnitude of the curve radii, gradients on the track, and others increase with increasing track speed in [7-10]. Very long freight trains with high transported weight have the biggest problem.

2 Compensated curve of track level with constant resistance of structural elements

The track section with constant gradient resistance (CGR) is proposed in the detailed design documentation because of shifting gears in locomotive control units (as little as possible to shift the power) as there is increased driving resistance in circles, tunnels, turnouts, and so on, that must be overcome by shifting to lower or higher power in [11]. The new design of the track vertical leveling will be done by use of a compensated curve that has a smooth course in practice but will be projected only in the secondary changing points of the track gradient as a broken curve, Fig. 2. In order, the trainset could run at constant speedy with the stabile power, we will reduce the gradient elevation of the leveling in relation to the slope of the line. The design is carried out in ascending gradients in both directions of the track section. These physical laws are manifested mainly in large rising gradients and the standard [6] there is a design of track section with constant gradient resistance (hereinafter CGR) only at gradients approaching the maximum ascending gradient. It is up to the designer whether he/she designs a section with CGR, or a locomotive itself will have to cope with using its performance (it is now possible to use more powerful locomotives), and also it depends on the character of the line (passenger, freight, mixed operation, high-speed traffic, etc.) by [12,13], and VEGA 1/0084/20 [15].

For simplicity, we propose a reduced gradient in these parts of the line - secondary changes are formed between the main points of GL_i (part of the section of railway double track No.1 in the ascending gradients is shown in Fig. 1):

- if the circle arch is without transition spirals, the resistance is reduced in part from the beginning of the circle *TC* to the end of the circle *CT* (in this case *T* - tangent, *C* – circle),
- in the case of a variant design at a scale of 1:10 000, if there is a circle with transitions, in this case, it is from the midpoint of the first transition spiral to the midpoint of the second transition spiral at the points *MS* of this arc (the drawing does not give details at the given scale),
- but with a detailed design of the project at a scale of 1:1 000, if the circle is with transitions, the gradient from the beginning of the transition spiral *TS* to the end of this circle *CS* is reduced,
- similarly applies in the turnouts and crossings, including resistance of passing through their components (resistance from the turnout plus circle part resistance),
- in tunnels longer than 100 m from the portal to the portal (in the mountainous terrain with long tunnels, the entire ascending gradient may be in the tunnel).

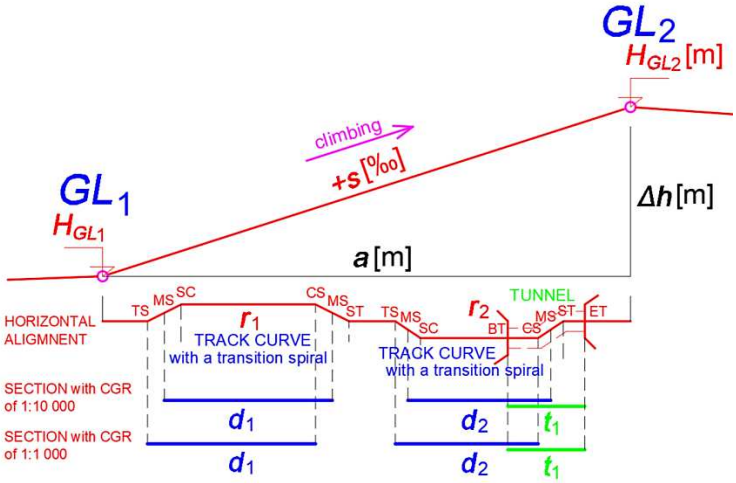


Fig. 1: Horizontal alignment of part of the section – track No.1, (up grade s = 10.500 ‰ $GL_1 \rightarrow GL_2$, *RP*4, V = 130 km/h).

If the train enters the transition spiral at the point *TS*, the running resistance in the circle increases until the end of the transition spiral at the point *SC* (of course, it depends on the length of the vehicle's engagement, too) and this resistance Re_{ri} continues to the end of the same circle *CS*, the horizontal alignment of the part of the section is by Fig. 1. In the transition spiral at the end of the track circle, it gradually begins to decrease as the curvature *k* changes from a line to zero, $k = 1/r$. The calculation of the CGR only takes place after reaching the elevation of the main gradient point GL_2, which means only in the rise of the track.

Two design methods can be used in the design, Fig. 2 and Fig. 6. In the first case, the gradient *s* (experiment No. 1), which is to comply, is reduced by approx. 2 ‰ so that the calculated compensated gradient s_c of all secondary gradients s_i at the section CGR does not exceed this given maximum gradient $s_c \leq s_s$ and also $s_i \leq s_s$, while *s* [‰] is the overall gradient from the project; Fig. 2. It is a practical way of calculation at the proposed gradient by a designer. The second method of calculation is an extreme solution (experiment No. 2, Fig. 6), where the maximum gradient s_s must not be exceeded by the respected changing points and at the same time it is equal to the compensated changing point at the tangent height sections $s_c = s_s$, while the other secondary changing points s_i will be from the calculation. In the paper, practical examples of compensated circles of the vertical elevation gradient are described. The horizontal and vertical alignment solutions of the section for both experiments are the same as in Fig. 1 (with or without tunnel).

3 Discussion

3.1 Design of gradient approaching the characteristic standard gradient - experiment No. 1

In this case, the section with the CGR by Fig. 2 with a tunnel on the track where the gradient value *s* is near the characteristic gradient s_s ($s \leq s_s$). And maximum standard gradient of s_s = 12,500 ‰ for mixed traffic (passenger and freight transport) is permitted on the railway track, while the track design will be at the elevation gradient *s* = 10,500 ‰, for example, the horizontal alignment is shown in the lower section of the longitudinal profile.

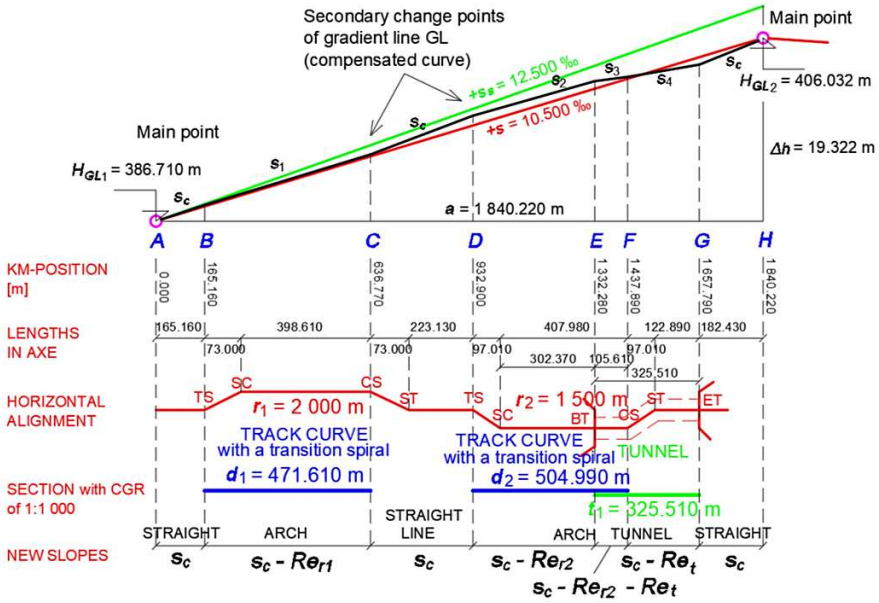


Fig. 2: The compensated curve of constant resistance – height solution of track gradient.

First of all, the Re_{ri} [‰] resistances that originate in both circles by Eq. (1) are determined according to the empirical formula $Re_{ri} = 600/r_i$ [6].

$$Re_{r1} = \frac{600}{r_1} = \frac{600}{2000} = 0.300\ ‰ \quad \text{and} \quad Re_{r2} = \frac{600}{r_2} = \frac{600}{1500} = 0.400\ ‰, \tag{1}$$

and in the double-track tunnel, the resistance Re_t = 1 ‰ is considered, Table 2. The running resistance in the tunnel is influenced by the aerodynamic component of the speed, shape and characteristics of the vehicle, the cross-section and the length of the tunnel. At a speed of *V* < 200

km/h, the values are in the range from 1 to 5 ‰, at a higher speed the tunnel construction documentation is used, while for the calculation the tunnel should be longer than 100 m.

To calculate the CGR circle, the total compensated gradient s_c is determined according to Eq. (2), in the up gradient section in the length *a* and between the main changing points of gradient (with practical calculation):

$$s_c = s + \frac{\sum Re_{ri} . d_i + \sum Re_{ti} . t_i}{a} = 10.500 + \frac{0.300 . 471.61 + 0.400 .504.99 + 1.000 .325.51}{1840.22} = 10.864 \text{ ‰}. \quad (2)$$

On sections of the track that are located in curves and tunnels, the compensated gradient s_c for calculating the secondary track sections s_i will be reduced by the values of the particular resistances in the direction of upgrading according to Eq. (3) for parts *BC:* $s_1 = s_c - Re_{r1}$; *DE:* $s_2 = Re_{r2}$; and for tunnel *EF:* $s_3 = s_c - Re_{r2} - Re_t$; *FG:* $s_4 = s_c - Re_t$ [‰], which is used to calculate the compensated curve heights, Table 1.

Table 1: Up gradient heights – compensated curve without and with CGR (comparison of both track vertical profiles).

Point	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***
KM-position [m]	0.000	165.160	636.770	932.900	1332.280	1437.890	1657.790	1840.220
Length d_i [m]		165.160	471.610	296.130	399.380	105.610	209.900	182.430
Length *a* [m]	1840.220 (Δh = +19.322)							
Section without CGR - heights								
Gradient *s* [‰]	10.500							
Difference [m]	0.000	+1.734	+4.952	+3.109	+4.194	+1.109	+2.309	+1.915
Increase *A*	0.000	+1.734	+6.686	+9.795	+13.989	+15.098	+17.407	+19.322
Heights [m]	386.710	388.444	393.396	396.505	400.699	401.808	404.117	406.032
Section with CGR (with tunnel) - heights								
Slopes adjustment		s_c	s_c - Re_{r1}	s_c	s_c - Re_{r2}	s_c - Re_{r2} - Re_t	s_c - Re_t	s_c
Slope s_i [‰]		10.864	10.564	10.864	10.464	9.464	9.864	10.864
Difference [m]	0.000	+1.794	+4.982	+3.217	+4.179	+0.999	+2.169	+1.982
Increase *A*	0.000	+1.794	+6.776	+9.993	+14.172	+15.172	+17.341	+19.322
Heights [m]	386.710	388.504	393.486	396.703	400.882	401.881	404.050	406.032
Section with CGR (without tunnel design) - heights								
Slopes adjustment		s_c	s_c - Re_{r1}	s_c	s_c - Re_{r2}		s_c	
Slope s_i [‰]		10.687	10.387	10.687	10.287		10,687	
Difference [m]	0.000	+1.765	+4.899	+3.165	+4.108	+1.086	+2.350	+1.950
Increase *A*	0.000	+1.765	+6.664	+9.829	+13.937	+15.023	+17.373	+19.322
Heights [m]	386.710	388.475	393.374	396.539	400.647	401.733	404.083	406.032
Height differences of the section with/without CGR (with tunnel, Figure 4)								
Δh [mm]	0	+60	-90	+198	+183	+73	-67	0
Height differences of the section with/without CGR (without tunnel, Figure 5)								
Δh [mm]	0	+31	-22	+34	-52	-75	-34	0

In the other sections *A-B*, *C-D*, *G-H* in the up-grade direction, the gradient will be equal to the calculated total compensated gradient s_c, Fig. 2, while none of gradients of the detailed height solution must exceed the characteristic standard gradient s_s. The inserted new gradient with CGR starts at the point of elevation change GL_1 and ends at the height of the point GL_2. The entire section between GL_1 and GL_2 will have the reduced resulting running resistance acting against the trainset run, allowing the same power of the locomotive engine to be used to pull the load (passenger and freight transport).

To calculate the heights H_i of the sub-vertical changing point of track gradient at the points of change of resistance *A* to *H* (indication of the lengths of both circles $d_1 = d_{BC}$ and $d_2 = d_{DE}$, according to Fig. 2).

In the case of a tunnel design, the heights of the track gradient are calculated too and serve to compare the vertical profiles of the two variants in Table 1 for experiment No. 1.

However, if a tunnel is not designed on the given railway line, the gradient s_c according to Eq. (3) will be determined (with practical calculation):

$$s_c = 10.500 + \frac{0.300\,.\,471.61 + 0.400\,.504.99}{1840.22} = 10.687\ ‰\,. \quad (3)$$

Then the gradients of the secondary gradients without tunnel are shown in Table 1, the resistances are considerable for parts *BC:* $s_1 = s_c - Re_{r1}$; *DE:* $s_2 = Re_{r2;}$ *EF:* $s_3 = s_c - Re_{r2}$; *FG:* $s_4 = s_c$ [‰]. The resistance from the circles is in the sections *B-C* and *D-F,* a different course of vertical elevation is achieved with the same directional radii, the secondary gradient values are less than *s* = 10,500 ‰.

Although the route altitudes H_i with tunnel and CGR gradient are partly above the original gradient *s*, here a gear shift of a locomotive is important as the whole section can be climbed at the constant power by reducing part of the track resistances in circles and tunnels (although the first secondary gradients increase at point GL_1, then they are kept constant and finally returned to the original height at point GL_2), Fig. 4. Or, to reduce energy intensity, the gradient *s* may be decreased over the entire section GL_1 to GL_2 without calculating the CGR. The gradients of the track axis in parts of the circles in the upgrade where the track resistances are generated are lower than the designed overall uniform gradient (even if they have a higher situated elevation). Since it is also a reduction energy consumption in question, it is also possible to adjust the radius of the horizontal curves, i.e. there is a reduction in track resistance by increasing them (various structural-technical solutions). The line between GL_1 to GL_2 still rises in all sections (in Fig. 4, the height differences Δh_i are at a scale of 1:1 from the basic determining line with gradient *s*).

In the case of a section without a tunnel, the CGR is already below the gradient level *s* at the beginning of the section in the point GL_1. We can imagine track resistances where, at curve radii (r = 1 500 to 2 000 m), the resistance of the tunnel Re_t will greatly affect their course, Fig. 4. In the case of smaller radius at lower speed sections *RP*1 to *RP*3 [6], track resistance values from curves and tunnels are similar; for illustration of track resistance, values from the horizontal curve are in Table 2 and the dependence on its radius is in Fig. 3. The resistances of the tunnel located in the curve for the resulting track resistance act together.

Table 2: Track resistance Re_r for various curve radii r_i and tunnel types.

The radius of the horizontal curve r_i [m]	**Resistance of curve Re_{ri} [‰]**	**Tunnel type**	**Resistance of the tunnel Re_t [‰]**
300	2.000	Single track	2.000
500	1.200	Double track	1.000
700	0.857	If speed $V \leq 200$ km/h designed resistance is Re_t = 1 to 5 ‰. If $V > 200$ km/h, Re_t should be determined in the construction design.	
1000	0.600		
1500	0.400		
2000	0.300		
3000	0.200		
5000	0.120		

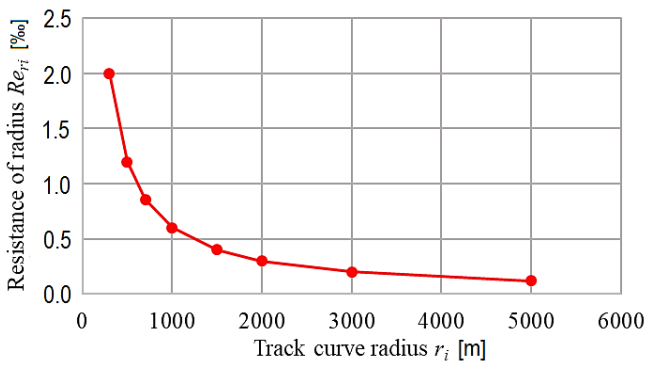


Fig. 3: Track curve resistance Re_{ri} for CGR, dependence on its radius r_i.

The vertical profile of the track at a gradient close to the characteristic gradient s_s shall be adjusted if the resistance from the track curvature expressed by the gradient in ‰ and the calculated resistance Re_{ri} according to Table 2 is greater than 0.500 ‰, or an adjustment value from 0.300 ‰ is used. In experiment No. 1, this is particularly evident in the tunnel area, Fig. 4, since the radius values r_i on the track are high and the resistance from curve Re_{ri} does not need to be solved everywhere. In the case where the railway line is without a tunnel, the compensated curve is shown in Fig. 5.

CGR is only one part of reducing the energy consumption of the section at maximum altitude gradients approaching the value of standard gradient s_s.

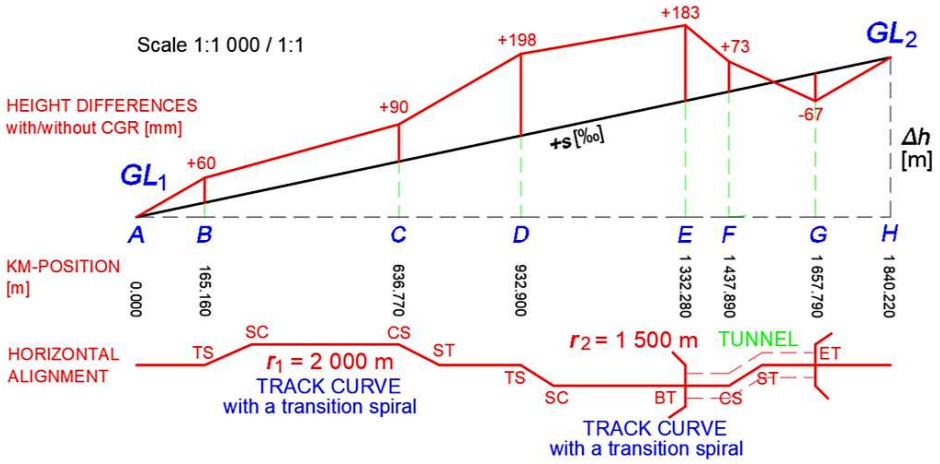


Fig. 4: Height comparison – compensated curve with/without CGR (with tunnel) s = 10.500 ‰.

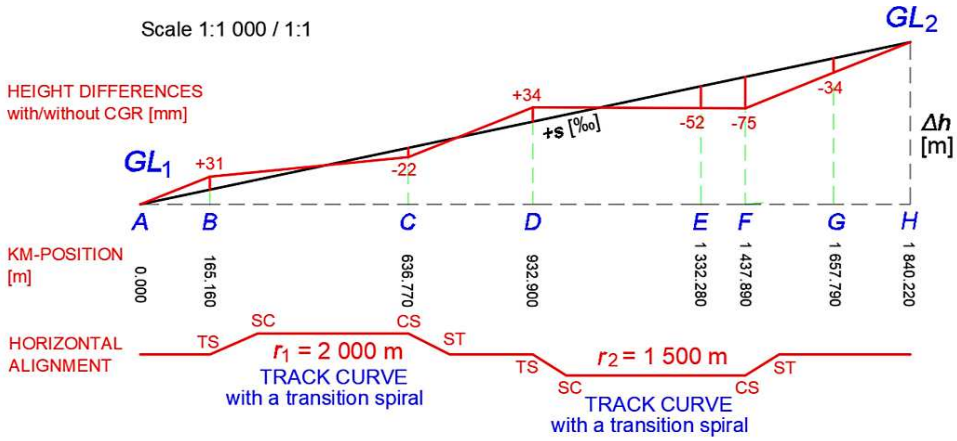


Fig. 5: Height comparison – compensated curve with/without CGR (without tunnel) s = 10.500 ‰.

In the case of preparatory works of the project in the phase of variant solutions of the elaboration of track sections, which are carried out in the maps of the middle scales of 1:10 000, 1:20 000, 1:25 000, etc., it is not necessary to distinguish the transitions for the CGR section; it is sufficient on this line to calculate the reduction of the gradient by its resistances from midpoint to midpoint MS_i of transition spiral of the designed railway curved track, Fig. 1. Only in a detailed design of the selected variant in scales of 1:1 000 / 100 (for example, Fig. 5) and so on is the detailed elevation course of CGR calculated from the beginning of *TS* transition spiral to the end of the curve, where the beginning of the second end transition spiral is in the point *CS*. If the curve design is without transitions, the secondary gradient is considered from the beginning of the *TC* through the entire curve to the point *CT*.

In the case where the curve continues beyond the point of height change of the gradient GL_2 according to Fig. 5, but the vertical profile has a declining gradient, the resistance is no longer calculated beyond the GL_2 point, as other forces, such as Earth's gravity has a favorable effect on the resistance forces. However, it will be necessary to calculate the elevation in the opposite direction (only on the track ascends), as the trainsets can run in both directions (from GL_3 to GL_2 point).

In rail practice, a gradient s is being designed reduced by 1 to 2 ‰ in the line section so that the gradient values that must be less than the standard gradient $s \leq s_s$ (designer retains a reserve of the

gradient) are kept when calculating the CGR section.

In the second case (experiment No. 2), if the extreme solution with the maximum permissible track gradient s_s was required, it means it would be necessary to calculate the vertical profile directly, so that the particular compensated gradients s_c in the tangent sections are equal to the standard gradient s_s, the following procedure according to Fig. 6 would be used (beware of the +/– signs and the individual variables in both cases, s_s is entered directly into the formulas).

3.2 The design of compensated gradient is equal to standard track gradient - experiment No. 2

The constant gradient resistance (CGR) of Fig. 6 in the section of the upgradient section, whereby it is required that the aligned compensated gradient s_c be also the standard gradient $s_c = s_s$. For example, there are two reversed curves with their radii r_1 = 2 000 m and r_2 = 1 500 m on the up gradient, i.e. the horizontal alignment of the track axis is according to experiment No. 1. The total length of the section of the upgradient is a = 1840.22 m and has a designed standard gradient s_s = 12.500 ‰ (i.e. the maximum gradient for mixed train operation on the international rail corridors) and all secondary gradients s_i must be of lower value. To compare the compensated curve in experiment No. 2, the tunnel is not considered in the design.

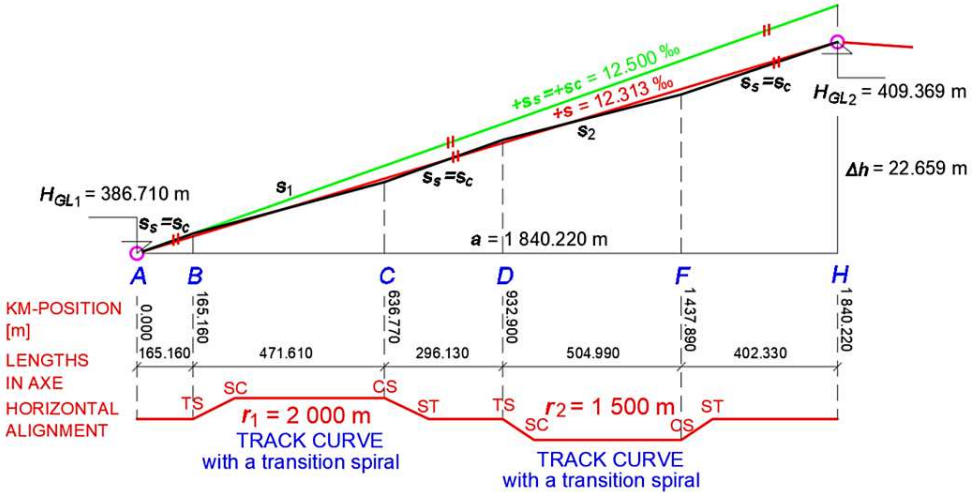


Fig. 6: Compensated constant grade resistance curve, if $s_c = s_s$.

The calculation of the resistances in the curve Re_{ri} is again according to Eq. (1). From Eq. (2) retroactively the required gradient s is derived, substituting $s_c = s_s$, and its value results from (4). There is no tunnel in the experiment, so the tunnel resistances are not considered (comparison of the section with tunnel): Re_{ti} = 0, i.e. this does not affect the compensated curve as $\sum Re_{ti} \,.\, t_i = 0$.

The required calculated gradient s according to Eq. (4) is (with practical calculation):

$$s = s_s - \frac{\sum Re_{ri} \,.d_i + \sum Re_{ti} \,.\, t_i}{a} = 12.500 - \frac{0{,}300 \,.471{,}61 + 0.400 \,.504.99}{1840.22} = 12.500 - 0.187 = 12.313\ ‰\,. \quad (4)$$

With this gradient s, the elevation difference between the main changing points of the track gradient $\Delta h_{GL1\text{-}GL2}$ = +22.659 m according to Eq. (5):

$$\Delta h = s.a\ /1000 = 22.659\ \text{m}. \quad (5)$$

In the experiment No. 2, the gradients s_1 and s_2 are applied in both curves (*BC:* $s_1 = s_s - Re_{r1}$; *DF:* $s_2 = s_s - Re_{r2}$).

The heights H_i of the secondary changing points of the track vertical profile at the points of change of resistances (according to Fig. 6), without a tunnel, are shown in Table 3 (marking the track sections according to Fig. 7). The comparison of the vertical profiles of both designs is shown in Table 3.

Table 3: Calculation of the upgradient heights – section without and with CGR without tunnel (comparison of both track vertical profiles).

Point	***A***	***B***	***C***	***D***	***F***	***H***
KM-position [m]	0.000	165.160	636.770	932.900	1437.890	1840.220
Length d_i [m]		165.160	471.610	296.130	504.990	402.330
Length *a* [m]	1840.220					
Section without CGR - heights						
Average gradient *s* [‰]	12.313					
Difference [m]	0.000	+2.034	+5.807	+3.646	+6.218	+4.954
Increase *A*	0.000	+2.034	+7.841	+11.487	+17.705	+22.659
Heights [m]	386.710	388.744	394.551	398.197	404.415	409.369
Section with CGR (without tunnel design) – heights						
Gradient s_s [‰] - max.	12.500					
Slopes adjustment		s_s	s_s - Re_{r1}	s_s	s_s - Re_{r2}	s_s
Slope s_i [‰]		12.500	12.200	12.500	12.100	12.500
Difference [m]	0.000	+2.064	+5.754	+3.702	+6.110	+5.029
Increase *A*	0.000	+2.064	+7.818	+11.520	+17.630	+22.659
Heights [m]	386.710	388.774	394.528	398.230	404.340	409.369
Height differences of the section with/without CGR (without tunnel, Figure 7)						
Δh [mm]	0	+30	-23	+33	-75	0

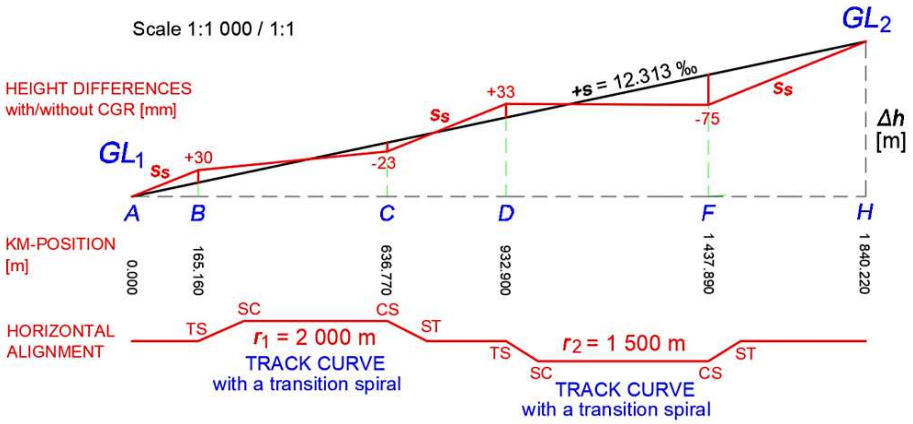


Fig. 7: Height comparison - compensated curve with/without CGR (without tunnel), *s* = 12.313 ‰.

In some parts of the track, the gradients will not be corrected by the compensated curve CGR, as the differences are less than 0.500 ‰ (or 0.300 ‰ for greater resistance elimination). Other values are eliminated within the used power of the locomotive engine that overcomes resistances up to 0.500 ‰.

4 Conclusions

A train on a track (long and heavy freight train - according to UIC maximum 750 m in [9, 14], but in some countries even longer trains) can overlap through more building elements, for example, two curves and also with 1 to 2 tunnels. The overall climbing in gradient s_i is one thing, but the resistances *Re* from curves and tunnels are added to the sum of running and track resistances. The Slovak Republic, as well as other countries, has mountainous regions, such as the region of the High Tatras, as well as the regions of the cities of Žilina, Trenčín, Banská Bystrica, Poprad, Prešov, etc., where several buildings are designed. The compensated curve is only solved for the track axis in the ascending gradients and not in the opposite direction in the descent, where the Earth's gravity acts positively. Gravitation force helps the engine of the locomotive in a downhill run and there is an opposite problem with the braking. When the track descends, the compensated curve is not designed, the designed gradient s_i stays (without the secondary gradients), i.e. in the double-track line only in

one track in the upgradient direction is designed. A long train can enter into the construction objects, or be located on these objects, or the trainset is leaving them, or the upgradient of the track axis ended. This applies not only when passing through the construction objects, but also when braking and starting the train on this section. There may be a situation in the mountainous region that the entire up gradient will be in the tunnel (several tunnels or very long tunnels), then the resistances of these curves will be added to the tunnel resistance

Although it is possible to use a locomotive with a higher traction power, this does not guarantee that the trainset can easily pass through curves and tunnels. There may be a ripping of a trainset, eventually derailment of wagons into the inner side of a passing circle, etc. The paper deals with adjusting track gradient heights for the high track gradients approaching o the maximum permissible track gradient s_s (for freight trains 12.500 ‰ and passenger trains 40.000 ‰, V = 160 km/h), especially for mixed train operation [6].

In the case of not solving this problem, when these track resistances (curves, tunnels) start to act on a train set, train speed is suddenly decelerated, and therefore a compensated curve can be designed which reduces the secondary gradients in these sections with resistances (upgrade between the two main gradient changing points GL_i). This will also reduce the resistance of the longitudinal axis of the train set, i.e. the traction force on the locomotive coupling increases on which the entire mass of the train is being pulled, and the trains do not need to generate extra energy.

Acknowledgments

The presented parts of the paper were created within the framework of the research activities VEGA 1/0084/20 (2020-2023) [15] by the Department of Railway Engineering at the Faculty of Civil Engineering of the University of Žilina (DRE-FCE-UNIZA). The authors would like to thank the Editor and Reviewers for their constructive comments and valuable suggestions to improve the quality of the article.

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