ЗАЛІЗНИЧНА КОЛІЯ

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ESTABLISHMENT OF THE PERMISSIBLE TRAIN SPEED ON THE CURVED TURNOUTS

Purpose. Turnouts play a key role in the railway transportation process. One-sided and many-sided curved turnouts were railed over the last 20 years in difficult conditions (curved sections, yard necks). They have a number of geometric features, unlike the conventional one-sided turnouts. Today the normative documents prohibit laying such turnouts in curved track sections and only partially regulate the assessment procedure of their real condition. The question of establishment the permissible train speed within the curved turnouts is still open. In this regard, authors propose to set the train speed according to the driving comfort criterion using the results of field measurements of ordinates from the baseline for the particular curved turnout. **Methodology.** The article considers the criteria using which one can set the permissible speed on the turnouts. It defines the complexity of their application, advantages and disadvantages. **Findings.** The work analyzes the speed distribution along the length of the real curved turnout for the forward and lateral directions. It establishes the change rate values of unbalanced accelerations for the existing norms of the curved track sections maintenance according to the difference in the adjacent bend versine at speeds up to 160 km/h. **Originality.** A method for establishing the trains' speed limit within the curved turnouts was developed. It takes into account the actual geometric position in the plan of forward and lateral turnout directions. This approach makes it possible to establish a barrier places in plan on the turnouts limiting the train speed. **Practical value.** The proposed method makes it possible to objectively assess and set the trains' permissible speed on the basis of the ordinate measurement of the forward and lateral directions of the curved turnouts from the baseline using the driving comfort criteria. The method was tested using real turnouts, which are located within the Pridneprovsk Railway.

Keywords: turnouts; criterion; speed; acceleration; radius; driving comfort

Introduction

In recent years a tendency to reduce the cost of maintenance and operation of railway transport by introducing the resource-saving and advanced technologies, including scientific research and reasoning was targeted [13]. In the multifaceted field of railway transport travel track facilities play a key role in ensuring transportation needs, it is a functional link between the conditional supplier and a consumer using rail tracks.

The operating length of railway tracks in the territory of Ukraine is 22.5 thousand km. Tracks at stations and running lines combine approximately 5.5 thousand of various connections and intersec-

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tions, 95% of which are turnouts. This is one of unique and at the same time demanding construction of a permanent way. If we analyze maintenance standards that are set up to the whole track, the turnouts take very nearly the first place in a variety of demands exactly to them. This is due to several design solutions that ensure locomotion of rolling stock from one track to another.

Requirements to the norms for organization and maintenance of turnouts are based on numerous theoretical and experimental studies as well as long experience of their operation.

During maintenance violations of turnouts the question arises as for their further exploitation – whether to close or limit the speed of rolling stock. Making such decisions should have well founded reasons, which can be obtained from existing regulations [7].

Among all currently laid turnouts on the main and receipt-dispatch tracks, conventional single turnouts have the largest part (about 97%). But in tight terms of stations and railway haul, limiting the use of conventional turnouts, there is a need of laying the turnouts of more complex design. To such turnouts one can include curved type P65 mark 1/1, project 2 889. Also on the railways of Ukraine there are cases of conventional turnouts presence in curved sections. In paper [6] main principles concerning setting speeds for such special cases are considered.

At present laying of conventional and curved turnouts in curve sections of the track is prohibited. But questions regarding service of those turnouts that are already been within the curves remain open. Reffering to the existing regulations, turnout's standards are regulated by track gauges in different sections, ordinates of lateral direction, wear and indexes of relative position between separate elements of turnouts (e.g., contact tongue and stock rail). At determination the state of curved turnouts it is necessary to check not only the lateral direction ordinates but also the core one. If there are deviations from the ordinates by value longer than specified in the project, what speed is allowable?

Purpose

The purpose of this paper is to provide proposals for setting the permissible speeds of trains within the main and lateral directions of curved turnout accordingly the results of ordinates field measurements from the baseline. It is a continuation of a forward direction of a stock rail. On the basis of the developed methodology to determine the locations of speed limits and reduce expenditures for regulation of ordinates.

Methodology

One can say with reasonable confidence that today there is no integrated practice for determining and setting the permissible speeds of trains within turnouts. This is primarily due to the presence of complex structural assemblies to ensure implementation of functions assigned on turnouts. However, the work [4] formulates the requirements at turnouts design meaningfully enough, which can be transformed into criteria for permissible speeds settings.

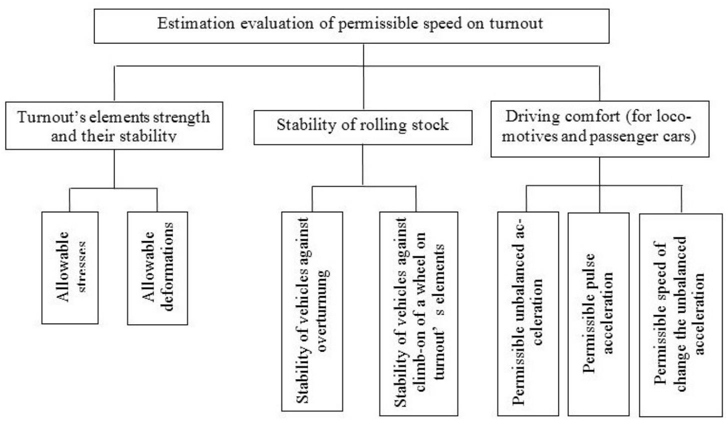

Fig. 1. The criteria for setting of the permissible speed of trains on the turnouts

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In general, the speed on turnouts can be set with three main criteria (Fig. 1):

- strength and stability of turnouts elements;
- stability of rolling stock;
- driving comfort.

The speed of trains upon the criteria of strength and stability of turnout's elements can be presented as shape function:

$$[V] = f([\sigma], \Delta x, \Delta y), \quad (1)$$

where $[\sigma]$ – permissible stresses in elements; $\Delta x, \Delta y$ – displacements (strains) of elements in appropriate planes.

The permissible speed upon the criterion of turnout's elements strength is set on the base of stresses determination in the edges of the rail plinth by the results of theoretical calculations and experimental studies.

Theoretical calculations by the existing methodology [3] make it possible to determine stresses in rails of conventional section without many features, such as the impact of unloaded rail lines. For contact tongues, frog and counter battens aforementioned method generally can not be used because of the structure complexity and changes in cross sections of these elements of turnouts in length (Fig. 2).

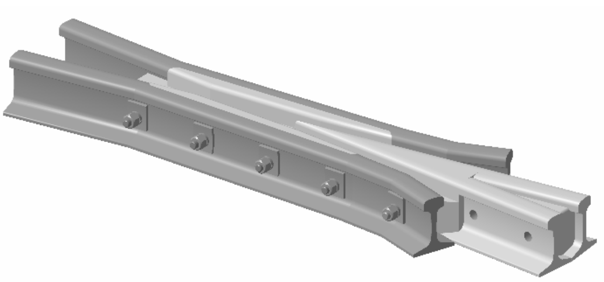

Fig. 2. Turnout frog

A more adequate assessment of stresses distribution in complex elements at theoretical calculations can be given by numerical methods for solving boundary value problems, such as the finite element method (FEM). In papers [9, 15, 16] the finite-element model elements of the permanent way, including the contact tongue with a stock rail, which are under dynamic loads were considered. That is, the FEM allows to set stresses in the elements of any geometric configuration, including prefabricated structures. The only significant disadvantage of this method is time for solving the problem, which varies with the finite element mesh refinement and can be increased from minutes to several hours.

Experimental studies to determine the stresses which allow setting the permissible speeds of trains motion, it is reasonable to conduct for new and upgraded designs of turnouts or rolling stock [11] from the standpoint of the high prime cost of this research method.

Let us consider the following criteria for setting the permissible speed of movement within turnout (see. Fig. 2) – rolling stock stability.

In general, the dependence of speed motion subject to ensure stability of rolling stock can be presented as shape function:

$$[V] = f(R, [n], W_{\text{w}}, [K_{\text{st}}]), \quad (2)$$

where R – radius of transmission curve; $[n]$ – permissible stability factor against overturning of rolling stock; W_{w} – wind force; $[K_{\text{st}}]$ – stability factor of wheelset against climb-on of a wheel.

As shown theoretical calculations [4], the motion speed of trains subject to overturning within the transmission curve substantially exceed (≈1,5 times) the maximum traffic speed on the lateral direction of the turnout for appropriate mark. Therefore, this criterion within the work is not considered.

In [2] the stability factor of wheelset against wheel flange climb-on the rail is considered in depth. Attention is focused that this factor depends on the dynamic indexes of a particular type of rolling stock. They can be set accordingly the results of mathematical modeling and experimental research.

Let us consider the last criterion – driving comfort.

Permissible speed of train's motion by driving comfort criterion can be presented as:

$$[V] = f([\alpha_{\text{ua}}], [\alpha_{\text{pulse}}], [\psi]), \quad (3)$$

where $[\alpha_{\text{ua}}]$ – permissible unbalanced acceleration; $[\alpha_{\text{pulse}}]$ – permissible pulse lateral acceleration; $[\psi]$ – change rate of unbalanced acceleration.

Lateral acceleration of pulsed nature α_{pulse} appears at rolling stock entry on turnout in the area of

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contact tongue and transition from frog to transmission curve. At a speed of 40 km/h pulsed acceleration occurs 1,6-3,3 m/c^2 at 50 km/h – 2,2-4,3 m/c^2 [5]. At speed increasing the pulse acceleration can be up to 12 m/c^2. [17]. Contact tongues area and frog is not highlighted as a part of this study.

Two indexes that had remained in the formula (3) is often used to set the permissible speeds not only within turnouts [1, 14], but also for circular and transmission curves [8].

According to existing maintenance norms permissible speeds of trains in the curved sections are set by the difference in adjacent bend versines [7]

$$\Delta f = \left| f_{i+1} - f_i \right|, \tag{4}$$

where f_{i+1}, f_i – bend versines in the adjacent points.

Bend versines at any point of the circular curve is [7]:

$$f_i = \frac{1000a^2}{8R}, \tag{5}$$

where a – chord length; R – curve radius.

Let us make elementary transformations

$$f_i = 125\,\frac{a^2}{V^2}\,\frac{V^2}{R}, \tag{6}$$

Fraction $\frac{V^2}{R}$ is centrifugal lateral acceleration at this point of curve α_{rad}.

The most important feature of curve section track arrangement is the presence of outer rail cant, one of the establishing criteria is lateral unbalanced acceleration [7, 1]:

$$\alpha_{\text{ua}} = \frac{V^2}{R} - \frac{g}{S}h, \tag{7}$$

where V – trains motion speed; g – free-falling acceleration; S – distance between the axes of rails; h – cant of the outer rail.

In the formula (7) subtrahend $\frac{g}{S}h$ – is a horizontal component of vehicle gravity when driving in a curve, which is due to differences in the level of rail heads for the value h. Accordingly, if we consider the vast majority of turnouts at the railway network of Ukraine (99%), the limit rail of lateral direction is without increase. Accordingly, the expression is valid:

$$\alpha_{\text{lat}} = \alpha_{\text{ua}} = \frac{V^2}{R}. \tag{8}$$

Then equation (6) will be as follows:

$$f_i = \frac{125a^2}{V^2}\left|\alpha_{\text{ua}}\right|. \tag{9}$$

In turn, the allowable motion speed accordingly to the criterion of permissible unbalanced acceleration, which today regulate the standards (9) is as follows:

$$V_{[\alpha_{\text{ua}}]} \le a\sqrt{\frac{125\left[\alpha_{\text{ua}}\right]}{\left|f_i\right|}}. \tag{10}$$

As it is known, chord length a is set in dependence of curve radius [7]:

$$a = \begin{cases} 10\big|_{R \le 400} \\ 20\big|_{R > 400} \end{cases}. \tag{11}$$

The length of turnout, marks 1/9 and 1/11 is approximately 31 and 33.3 meters, and the mileage of transmission curve – 11.9 and 16.5 meters. If measurements are performed in accordance with the regulations, we will obtain 2 values of bend versines *f* for marks 1/9 and 3 for mark 1/11. One can see that it is insufficient to set the movement speed by such limited number of data. Measuring the bend versines within the transitions curves also is complicated by presence of wings within frogs. Therefore, to assess the transfer curve position, in our opinion, is better with measurement results of ordinates (every 2 meters). Bend versines in this case are determined by the following formula [10]:

$$f_i = F_i - \frac{1}{2}\left(F_{i+1} + F_{i-1}\right), \tag{12}$$

where F_{i-1}, F_i, F_{i+1} – ordinates, that are measured from the baseline, mm. For curved turnouts the base is such line which is a conditional extension of the forward direction of the stock rail (Fig. 3).

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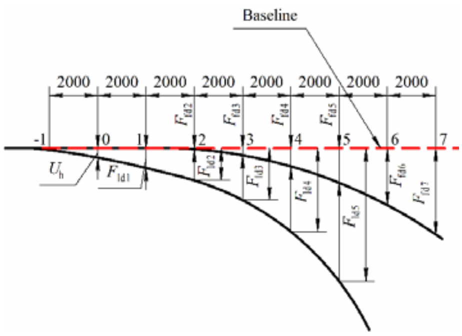

Fig. 3. Measuring ordinate scheme of the forward and lateral directions of the curved turnouts

In Fig. values $F_{\text{o}\,i}$, $F_{\text{б}\,i}$ – are ordinates for main and lateral directions of turnouts.

Ignoring the angle value of chord rotation a within the transfer curve, formula (10) with (12) will be:

$$V_{[\alpha_{\text{ua}}]} \le \sqrt{\frac{2000[\alpha_{\text{ua}}]}{\left|F_i - \frac{1}{2}\left(F_{i+1} + F_{i-1}\right)\right|}}. \qquad (13)$$

Unbalanced acceleration rate in view of physical concept of derived function can be represented as:

$$\psi(t) = \frac{d}{dt}\alpha(t) = \lim_{\Delta t \to 0}\frac{\Delta\alpha(t)}{\Delta t} = \lim_{\Delta t \to 0}\frac{\alpha(t+\Delta t) - \alpha(t)}{\Delta t} \approx \frac{\alpha(t+\Delta t) - \alpha(t)}{\Delta t}. \qquad (14)$$

where Δt – growth time during which acceleration value changes.

We provide replacement of variable at differentiation for constant motion speed:

$$\frac{d}{dt}\alpha(t) = \frac{d}{dx}\alpha(x)\frac{dx}{dt} = V\frac{d}{dx}\alpha(x) \approx V\frac{\Delta\alpha}{\Delta x}. \qquad (15)$$

Taking into account (4) i (9) we will find speed by criterion of permissible speed at unbalanced acceleration rate $[\psi]$:

$$V_{[\psi]} \le 5\sqrt[3]{\frac{a^2[\psi]\Delta x}{|\Delta f|}}, \qquad (16)$$

Rewrite the formula (4), using expressions (12):

$$\Delta f = \frac{1}{2}\left[F_{i-1} - 3\left(F_i - F_{i+1}\right) - F_{i+2}\right]. \qquad (17)$$

Formula (16) will have final form:

$$V_{[\psi]} \le 20\sqrt[3]{\frac{[\psi]}{\left|F_{i-1} - 3\left(F_i - F_{i+1}\right) - F_{i+2}\right|}}. \qquad (18)$$

On the basis of obtained formulas (13) and (18) speed definition is accepted the least one:

$$V_{\text{per}} = \min\left\{\begin{matrix}\min\left\{V_{[\alpha_{\text{нп}}]i}\right\},\ i = \overline{1,\,n} \\ \min\left\{V_{[\psi]j}\right\},\ j = \overline{1,\,n-1}\end{matrix}\right\}, \qquad (19)$$

where n – the number of measuring points.

Referring to the existing regulations, the recommended values of allowable accelerations and changes of unbalanced acceleration in accordance with [12] are:

– $[\alpha_{\text{ua}}]$ = 0,7 m/c^2 (1,0 m/c^2);

– $[\psi]$ = 0,6 m/c^3.

The above mentioned values of acceleration act on the floor level of the passenger car or locomotive in the center pivot section. These values are significantly different from the acceleration acting on the level of the wheelset box. This is explained by the presence of spring suspension, which acts as a filter of low-frequency vibrations of sprung mass. We believe that to set the allowable movement speed in a curved sections of the track one should use it is this acceleration, acting at the level of box, because the motion trajectory of the gravity center in the wheelset when movement in a curve almost coincides with the forms of horizontal and vertical inequalities (provided that the wheel flange is pressed to the limit rail).

Using formulas (10) and (16) it should be analyzed existing regulations of curved sections maintenance of the track upon direction in the plan and establish values α_{ua} and ψ for appropriate difference in adjacent bend versines Δf (Table 1).

Unbalanced accelelration α_{ua} (Table 1) was obtained at maximum value of curved radius for given grade of failure (e.g. for I and V degrees and R = 4000 m). Bend versines is determined by the formula (4).

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In some cases obtained values α_{ua} and ψ exceed recommended ones and explains this is the place of performance data by driving comfort.

Table 1

α_{ua} and ψ values with deviation towards the railway track in plan for the sections at movement speeds of 140-160 km/h

Degree of deviation	Radius, m	Difference in bent versines, measured after 10 m from mid-chord, length 20 m, mm	Allowable speed, km/hour, at length deviation, m		Unbalanced acceleration, m/c^2	Change rate of unbalanced acceleration, m/c^3
			to 20 incl.	above 20 to 40 incl.		
1	2	3	4	5	6	7
I	At all radii[1]	ot10 (incl.)	160/90[4]		1,71/0,54	1,76/0,31
II	to 2000 (incl.)[1]	–			–	–
	over 2000	over 10 to 18 (incl.)			1,7/0,54	3,16/0,56
III	to 2000 (incl.)[1]	–			–	–
	over 2000	over 18 to 25 (incl.)			1,98/0,63	4,39/0,78
IV	to 1800 (incl.)[2]	over 10 to 25 (incl.)	140/90	140/90	2,27/0,94	2,94/0,78
		over 25 to 35 (incl.)	80/60	120/90	0,84/0,47	0,77/0,32
	>1800 to 2000 (incl.)	over 18 to 25 (incl.)	140/90	140/90	1,6/0,66	2,94/0,78
		over 25 to 35 (incl.)	80/60	120/90	0,62/0,35	0,77/0,32
	over 2000	over 25 to 35 (incl.)			0,59/0,33	0,77/0,32
V	At all radii[3]	over 35 to 65 (incl.)	40/40	80/80	0,57/0,57	0,18/0,18
		over 65 to 90 (incl.)	15/15	40/40	0,09/0,09	0,01/0,01
		over 90	Motion is closed		–	–

Notes: [1]radius, which is taken in the calculations is 1500 m; [2]radius, which is taken in the calculations is 1 000 m; [3]radius, which is taken in the calculations is 300 m; [4]numerator – for passenger trains, the denominator – for freight ones

With similar analogy we will determine value α_{ua} i ψ for turnout, type P65 mark 1/11 in project 2889 with radii of turnout curve:

- for forward direction – 600 m;
- for lateral direction – 200 (350) m.

At this the maximum speed of rolling stock for this turnout project is:

- for forward direction – 70 km/h;
- for lateral direction – 40 km/h.

Due to the requirement that the difference of ordinates deviation of transmission curve in adjacent points should not exceed ± 2 mm [7], we will get:

- for forward direction – α_{ua} = 0,95 m/c^2; ψ = 7,35 m/c^3;
- for lateral direction – α_{ua} = 0,83 m/c^2, ψ = 2,7 m/c^3.

We see that obtained values differ significantly from the recommended ones.

Findings

Taking into account, that standards α_{ua} and ψ, operating at the level of the wheel pair axle box, to day, is not established, one can use an analogue method (which, by the way, is used at initial angle definition on turnouts [4]) to determine the permissible speed of trains within turnouts.

Method of determining the permissible speed upon the travelling comfort criterion was tested at

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a real turnout. Tests and calculation results for the lateral direction are presented at Table 2.

Table 2

Evaluation of the allowable speed on the lateral direction of the turnouts

Point number	Distance from the root of contact tongue X_i, mm	Ordinates F_i, mm	$V_{[\alpha]}$	$V_{[\psi]}$
1	2	3	4	5
-1	-2	116	-	-
0	0	181	60	70[1]
1	2	258	57	70[1]
2	4	348	62	40
3	6	449	40	30
4	8	578	64	30
5	10	696	40	40
6	12	842	61	70[1]
7	14	999	57	68
8	16	1169	65	47
9	18	1350	70[1]	70[1]
10	20	1531	70[1]	70[1]
11	22	1713	70[1]	-
12	24	1894	-	-

Note: [1]speed is limited till maximum by forward direction

We see that the limitation is reached only by criterion ψ in two places. Having corrected in the plan value of ordinates in pointed areas one can achieve increasing the speed, set for given curved turnout.

Originality and practical value

The method of establishing the permissible speed of movement within the curved turnouts upon the travelling comfort criterion was proposed. This approach takes into account the actual geometric position of the turnout's lateral direction. Versatility of technique gives the possibility to control and direct direction of turnouts.

The theoretical results were tested on the results of ordinates field measurements for curved lateral direction of turnouts.

Conclusions

1. Objectively the main criteria for permissible speeds set of trains within the turnouts that exist today were analyzed.
2. Technique for measuring the coordinates of forward and curved lateral direction of curved turnouts that are in curved sections is recommended. The proposals are offered to determine the permissible speed of trains within the curved turnouts by the driving comfort criterion based on ordinates measurements from the baseline.

Permissible values α_{ua} and ψ were gounded for curved turnouts, based on the deviation of curve ordinates in adjacent locations.

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ВСТАНОВЛЕННЯ ДОПУСТИМИХ ШВИДКОСТЕЙ РУХУ ПОЇЗДІВ ПО КРИВОЛІНІЙНИХ СТРІЛОЧНИХ ПЕРЕВОДАХ

Мета. Стрілочні переводи відіграють одну з ключових ролей при виконанні перевізного процесу на залізничному транспорті. Протягом останніх 20 років у складних умовах (криві ділянки, горловини станцій) укладали одно-та різносторонні криволінійні стрілочні переводи, які мають ряд геометричних особливостей, на відміну від односторонніх звичайних. На сьогоднішній день нормативні документи забороняють нове

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укладання таких переводів у криві ділянки колії та тільки частково регламентують порядок оцінки їх реального стану. Залишається відкритим питання встановлення допустимої швидкості руху в межах криволінійних стрілочних переводів. Тому в науковому дослідженні пропонується встановлювати швидкість руху поїздів за критерієм комфортабельності їзди, спираючись на результати натурних вимірювань ординат від базисної лінії для конкретного криволінійного стрілочного переводу. **Методика.** Розглянуто критерії, за допомогою яких можна встановити допустимі швидкості руху на стрілочних переводах. Встановлено складність їх застосування, переваги та недоліки. **Результати.** Проаналізовано розподіл швидкостей по довжині реального криволінійного стрілочного переводу для прямого та бокового напрямку. Встановлено величини швидкості зміни непогашених прискорень для існуючих норм утримання кривих ділянок колії за різницею у суміжних стрілах вигину при швидкостях до 160 км/год. **Наукова новизна**. Авторами розроблено методику встановлення допустимої швидкості руху поїздів у межах криволінійного стрілочного переводу, яка враховує реальне геометричне положення у плані основного та бокового напрямків переводу. Даний підхід дає можливість встановити місця у плані на стрілочному переводі, які лімітують швидкість руху. **Практична значимість.** Запропонована методика дає можливість об'єктивно оцінити та встановити допустиму швидкість руху поїздів на основі вимірювання ординат основного і бокового напрямку криволінійного стрілочного переводу від базисної лінії за критерієм комфортабельності їзди. Методика була апробована на реальних стрілочних переводах, які знаходяться в межах Придніпровської залізниці.

Ключові слова: стрілочні переводи; критерій; швидкість; прискорення; радіус; комфортабельність їзди

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УСТАНОВЛЕНИЕ ДОПУСТИМЫХ СКОРОСТЕЙ ДВИЖЕНИЯ ПОЕЗДОВ ПО КРИВОЛИНЕЙНЫМ СТРЕЛОЧНЫМ ПЕРЕВОДАМ

Цель. Стрелочные переводы играют одну из ключевых ролей при выполнении перевозочного процесса на железнодорожном транспорте. В течение последних 20 лет в сложных условиях (кривые участки, горловины станций) укладывали одно- и разносторонние криволинейные стрелочные переводы, которые имеют ряд геометрических особенностей, в отличие от односторонних обыкновенных. На сегодняшний день нормативные документы запрещают вновь укладывать такие переводы в кривые участки пути и только частично регламентируют порядок оценки их реального состояния. Остается открытым вопрос установления допустимой скорости движения в пределах криволинейных стрелочных переводов. Поэтому в научном исследовании предлагается устанавливать скорость движения поездов по критерию комфортабельности езды, опираясь на результаты натурных измерений ординат от базовой линии для конкретного криволинейного стрелочного перевода. **Методика.** Рассмотрены критерии, с помощью которых можно установить допустимые скорости движения на стрелочных переводах. Установлена сложность их применения, преимущества и недостатки. **Результаты.** Проанализированы распределения скоростей по длине реального криволинейного стрелочного перевода для основного и бокового направления. Установлены величины скорости изменения непогашенных ускорений для существующих норм содержания кривых участков пути по разнице в смежных стрелах изгиба при скоростях до 160 км/ч. **Научная новизна.** Учеными разработана методика установления допустимой скорости движения поездов в пределах криволинейного стрелочного перевода, которая учитывает реальное геометрическое положение в плане основного и бокового направления перевода. Данный подход дает возможность установить места в плане на стрелочном переводе, которые лимитируют скорость движения. **Практическая значимость.** Предложенная методика дает возможность объективно оценить и установить допустимую скорость движения поездов на основе измерения ординат основного

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и бокового направления криволинейного стрелочного перевода от базисной линии по критерию комфортабельности езды. Методика была апробирована на реальных стрелочных переводах, которые находятся в пределах Приднепровской железной дороги.

Ключевые слова: стрелочные переводы; критерий; скорость; ускорение; радиус; комфортабельность езды

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