ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-4-4

World of Transport and Transportation, 2023,
Vol. 21, Iss. 4 (107), pp. 176–185

Comparison of Train Traffic Parameters for Various Virtual Coupling Use Cases




Efim N. ROZENBERG **Alexey V. OZEROV** **Valery I. KUZNETSOV** **Sergey S. TIKHONOV**

Efim N. Rozenberg [1], Alexey V. Ozerov [2], Valery I. Kuznetsov [3], Sergey S. Tikhonov [4]
[1, 2, 3, 4] JSC «Research and Design Institute for Information Technology, Signalling and Telecommunications in Railway Transport» (JSC NIIAS), Moscow, Russia.
✉ [2] a.ozerov@vniias.ru.
[1] SPIN-код 5648-5186.
[2] SPIN-код 4102-5984, Scopus ID 57210556089? ORCID 0000-0001-5057-9821.

ABSTRACT

New principles of train separation allowing for capacity increase are in high demand under the conditions of infrastructure constraints, considering also ever-growing freight turnover at the Eastern segment of railway network.

Currently, the most promising option is train separation based on virtual coupling technology, which, according to calculations, can provide an increase in carrying and transit capacity of up to 20 % compared to the classical technology of rigid coupling. At the same time, there are no methods for determining the use cases for applying the virtual coupling technology for specific sections of the railway supported by mathematical calculations.

The article discusses five use cases for virtual coupling for sections with speed limits and presents graphical estimates of capacity for various speeds and lengths of sections with speed limit. It is concluded that virtual train coupling is advantageous for capacity increase on sections with infrastructure constraints, and further research is needed to justify the practical methods of its application.

Keywords: *railway, train separation control, radio channel, virtual coupling, capacity.*

For citation: *Rozenberg, E. N., Ozerov, A. V., Kusnetsov, V. I., Tikhonov, S. S. Comparison of Train Traffic Parameters for Various Virtual Coupling Use Cases. World of Transport and Transportation, 2023, Vol. 21, Iss. 4 (107), pp. 176–185. DOI: https://doi.org/10.30932/1992-3252-2023-21-4-4.*

The Russian text of the article originally submitted in Russian and English is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

Increasing infrastructure capacity of railway mainlines with unconditional assurance of traffic safety is the unvarying strategic goal of the railway industry. It is achieved through introduction of modern train separation systems [1]. One of the promising train separation technologies is virtual coupling (VC). It is a connection of locomotives of successive trains via a radio channel, in which the following («slave») train is driven taking into account information about the speed and cab signalling aspects of the first («master») train [2].

A lot of work has been done at JSC Russian Railways regarding practical testing of the virtual coupling technology, and considerable experience has been accumulated. For the first time, the virtual coupling technology was tested in 2019 on a 400 km Khabarovsk – Ruzhino section of the Far Eastern Railway [3]. To date, about 30,000 trips in the «virtual coupling» mode have been made, while the technology implementation range within the railway network is expected to have attained about 6,000 km by the end of 2023. The virtual coupling technology is in high demand throughout the entire Eastern segment of the railway network. Calculations showed that the introduction of the virtual coupling technology can increase the capacity of the railway line by almost 20 % relative to the existing traffic schedule using dual trains [4].

Naturally, like any new technology, it needs in-depth study, including consideration of possible infrastructure constraints and various options for its application. At JSC NIIAS, such work is carried out as part of an integrated approach to capacity increase problem, including using computer simulation tools [5].

It should be noted that on the railways of other countries, this technology has not yet been fully developed technically and has not been used for mainline railway transport but is being studied in research projects and works as a promising option for the development of the train separation system based on radio communication of the ERTMS Level 3 system type [6–10]. A number of European studies have demonstrated the analysis of an impact on capacity of a possible ERTMS based on virtual coupling compared with a typical ERTMS Level 2, and a possible future ERTMS Level 3 with moving block. The simulation results indicate a significant potential of this technology [11–13].

RESULTS

There are two options for the virtual coupling implementation: the organisation of a «train-to-train» radio channel data exchange or data exchange through the radio block centre (RBC). The JSC Russian Railways currently uses the first option since it does not require a large-scale construction of radio block centres [14].

The article presents some capacity estimates for various virtual coupling use cases for trains moving on sections with speed limits (see Pic. 1).

The picture shows:

t_0 –the moment the first train starts moving;

t_1 – the moment the second train starts moving;

t_2 – the moment the first train reaches the border of a section with speed limit – the moment the first train starts moving at a limited speed;

t_3 – the moment the second train starts moving at a limited speed;

t_4 – the moment the second train reaches the border of the section with speed limit;

t_5 – the moment the first train leaves the section with speed limit – the moment the first train is halted from moving at a set speed;

t_6 – the moment the first train starts moving at a set speed after leaving the section with speed limit;

t_7 – the moment the second train leaves the section with speed limit;

S_1 – the entry border of the section with speed limit;

S_2 – the end border of the section with speed limit;

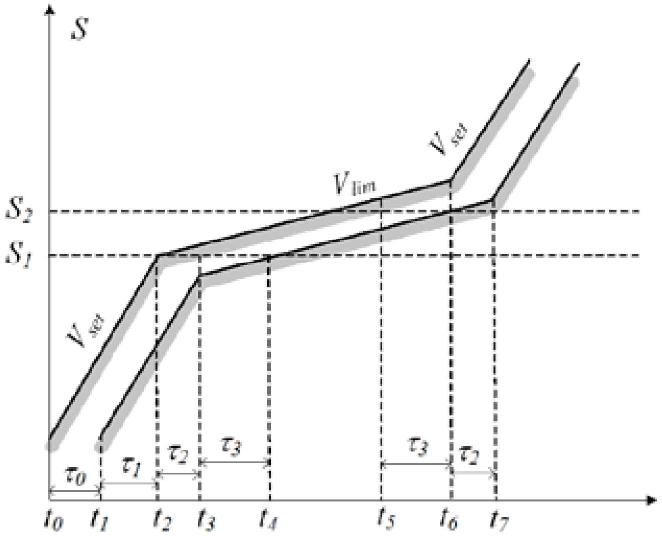
V_{lim} – limited speed;

V_{set} – set speed, and the corresponding time intervals $\tau_0, \dots, \tau_3$.

The grey shading conventionally represents the train's length L_T.

Pic. 1 shows time interval $\tau_3 = [t_5, t_6]$, when the first train has to be halted from moving at a set speed after leaving the section with speed limit.

We assume that the considered nature of the movement is symmetric: the relative position of trains in front of the section with speed limit corresponds to the relative position of trains after the section with speed limit. This means that the desired value is determined by the equations:



Pic. 1. Time–distance graph for trains running on a track section with speed limit [performed by the authors].

$\tau_3 = t_6 - t_5 = t_4 - t_3$,

which simplifies the consequent analysis reducing it to the following:

– firstly, it is necessary to determine the time interval $\tau_2 = t_3 - t_2$, when the second train reduces the headway from Z_{set} to Z_{min}, which can be described as follows:

$$L + Z_{set} + V_{lim} \cdot \tau_2 = L + Z_{min} + V_{set} \cdot \tau_2 ;$$

– then to determine the required value:

$$\tau_2 = \frac{Z_{set} - Z_{min}}{V_{set} - V_{lim}} .$$

It should be noted that at certain ratios of times, speeds, established headways and the length of the section with speed limit $S_{lim} = S_2 - S_1$ situations are possible when the second train does not have time to reach the limit value Z_{min} (see Pic. 2). In this case (due to the symmetry of the movement) there is no need to halt the first train from moving at a set speed after it leaves the section with speed limit.

Formally, this outcome is described by the following relation:

$$Z_{set} - (V_{set} - V_{lim}) \cdot \tau_0 + V_{set} \cdot \tau' > Z_{min} , \qquad (1)$$

where τ' is the time during which the first train moves at a set speed V_{set} until the moment the second train reaches the section with speed limit.

The last relation (1) takes into account that $\tau_0 = \tau_2$ since the time interval between trains leaving the section with speed limit corresponds to the interval between their arrival at the border of the section with speed limit.

In other words, if the inequality (1) is true, time delay τ_3 takes on a value of zero.

For subsequent comparison of the estimates obtained, the capacity in the absence of sections with imposed speed limit and without virtual coupling (reference case) is first determined, the capacity is also determined in cases where there are sections with speed limit and for various virtual coupling use cases (cases 1–5).

Reference case. The initial data assumed for the reference case are:

– no sections with speed limit,

– trains depart at t_{set} min. intervals,

– no virtual coupling.

The number of trains per day (22 hours) is determined by the known relation[1] as follows:

$$n = \frac{T}{I} , \qquad (2)$$

where T is the time in hours; I is the time interval between trains in hours.

Case 1. The initial data for the first use case are:

– there are $N_{lim\ sec}$ sections with speed limits,

– trains depart at t_{set} min. intervals,

– trains move while maintaining the time interval between them.

This case is characterised by the fact that each section with speed limit implies a time delay, determined by the following equation:

$$\Delta I = \frac{L_T + S_{lim}}{V_{lim}} - \frac{L_T + S_{lim}}{V_{set}} = \frac{V_{set} - V_{lim}}{V_{lim} \cdot V_{set}} \cdot (L_T + S_{lim}) . \qquad (3)$$

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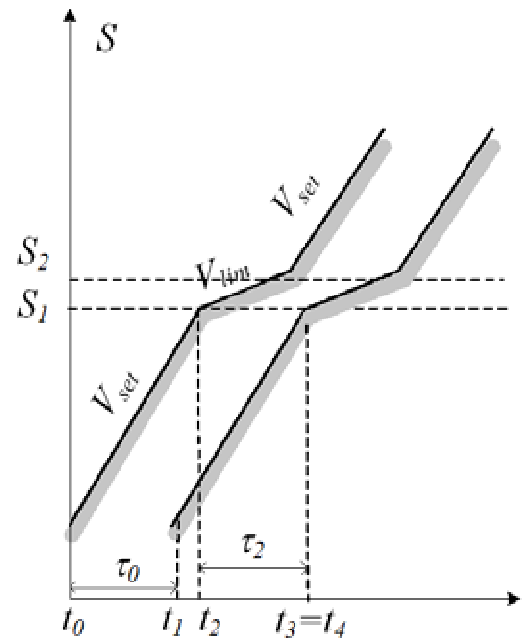
[1] Instruction of JSC Russian Railways dated November 10, 2010 No. 128. «Instructions for calculating the available capacity of railways» [*Instrukciya po raschyotu nalichnoj propusknoj sposobnosti zheleznyh dorog*] JSC Russian Railways, 2010, 305 p. [Electronic resource]: https://jd-doc.ru/2010/noyabr-2010/5907-instruktsiya-oao-rzhd-ot-10–11–2010-n-128. Last accessed 26.07.2023.



Pic. 2. Time–distance graph for trains running on a track section with speed limit when the introduction of a time delay is not required [performed by the authors].

This time delay (3) affects the time of passage of the track section but does not affect the time interval between trains at the end of the section.

Therefore, the total number of trains per day will be determined by the ratio that considers the time losses that occur during the movement of the first train:

$$n_1 = \frac{T - N_{limsec} \bullet \Delta I}{T} \bullet n_1 = \frac{T - N_{limsec} \bullet \Delta I}{T} \bullet \frac{T}{I} = \frac{T - N_{limsec} \bullet \Delta I}{I}, \quad (4)$$

where $N_{lim\,sec}$ is the number of sections with speed limit.

Case 2. In this use case the number of departed trains is increased due to virtual coupling of two trains and reduced headway. The initial data for this case are:

– there are $N_{lim\,sec}$ sections with speed limit,

– trains depart at t_{set} min. intervals,

– a virtually coupled train with a reduced interval $t_{vc}<t_{set}$ min. departs once an hour,

– time interval and distance between trains remain unchanged.

When the first train runs on a section with speed limit the second train also slows down from V_{set} to V_{lim}, which increases time interval between trains (the first and the second one) after passing the section with speed limit.

The time delay for the first train consists of two components:

– time delay when passing the section with speed limit:

$$\Delta I_1 = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \left(L_T + S_{lim} \right); \quad (5)$$

– additional time delay after leaving the section with speed limit:

$$\Delta I_2 = \frac{L_T + Z_{set}}{V_{lim}}. \quad (6)$$

The total delay in the movement of the first and second trains when passing through one and the same section with speed limit is determined by the following equation:

$$\Delta I_{1,2} = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \left(L_T + S_{lim} \right) + \frac{L_T + Z_{set}}{V_{lim}}. \quad (7)$$

Taking into account this time delay (7) the number of trains per day (22 hours) is determined by the following relation:

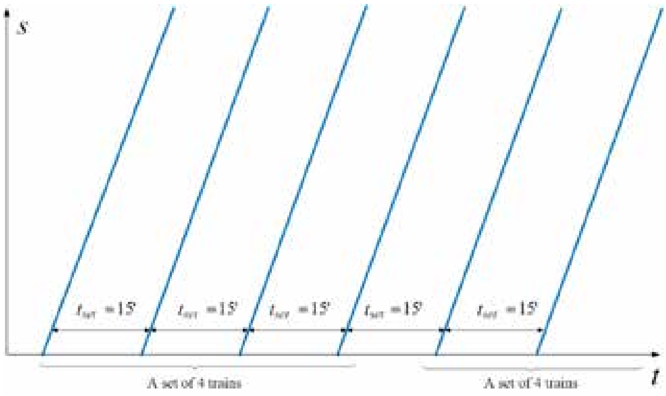
$$n_2 = \frac{4t_{set}}{3t_{set} + t_{vc}} \bullet \frac{T - N_{limsec} \bullet \Delta I_{1,2}}{T}. \quad (8)$$

Case 3. In this use case the number of departed trains is also increased due to virtual coupling of two trains and reduced headway, however the distance between trains can change. The initial data for this use case are:

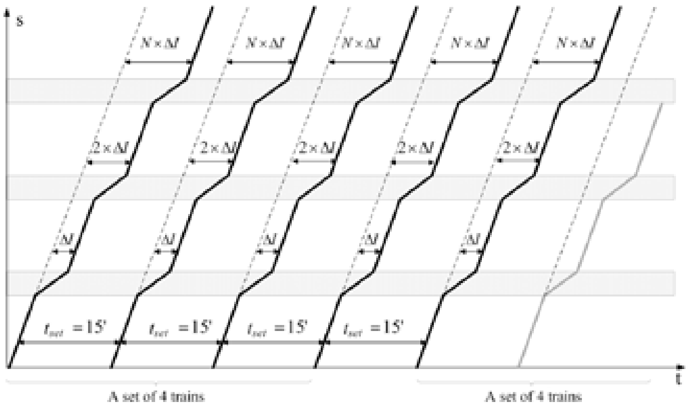
– there are $N_{lim\,sec}$ sections with speed limit,

– trains depart at t_{set} min. intervals,

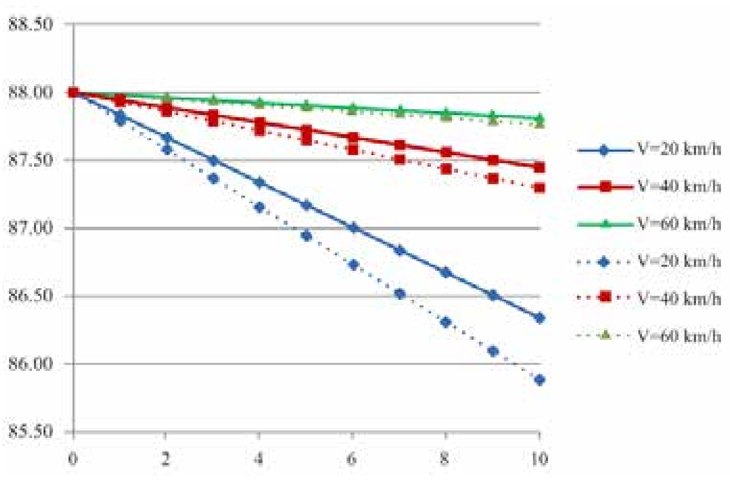
– a virtually coupled train with a reduced interval $t_{vc}<t_{set}$ min. departs once an hour,



Pic. 3. Graph of trains' movement in reference case [performed by the authors].



Pic. 4. Graph of trains' movement in case 1 [performed by the authors].



Pic. 5. Capacity graphs for different values of V_{lim} and lengths of sections with speed limit [performed by the authors].

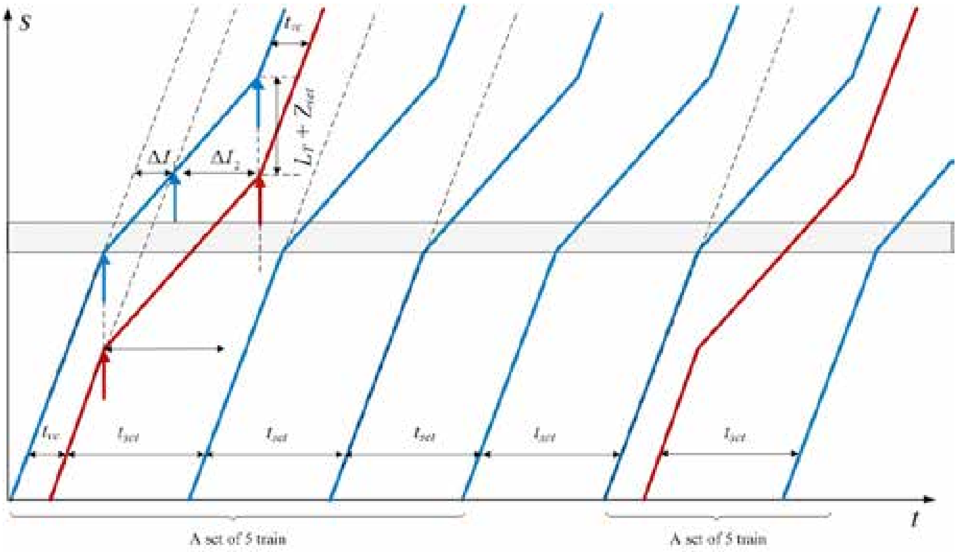
– time interval remains unchanged, distance between trains can change.

The situation is considered when the second train reaches the border of the section with speed limit, and the distance between trains is equal to at least three block sections. In this case, there is no additional time delay ΔI_2, so the number of trains per day (22 hours) will be determined taking into account only the time delay (5) as follows:

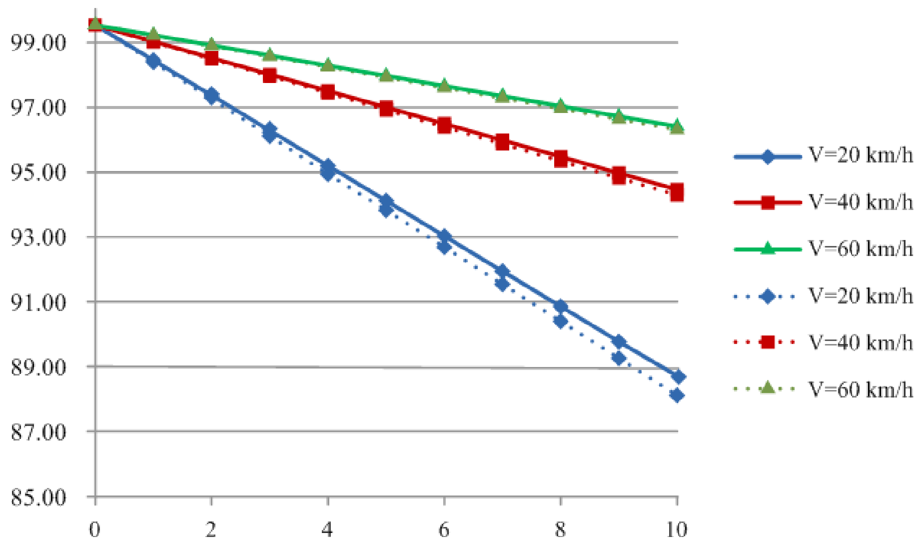
$$n_3 = \frac{4t_{set}}{3t_{set} + t_{vc}} \bullet \frac{T - N_{limsec} \bullet \Delta I_1}{T}. \quad (9)$$

All other intermediate cases fall within the range between relations (8) and (9).

Case 4. The next case describes the delay in movement of the second virtually coupled train



Pic. 6. Graph of trains' movement in case 2 [performed by the authors].



Pic. 7. Capacity graphs for different values of Vlim and lengths of sections with speed limit [performed by the authors].

moving a t_{vc} interval before entering the section with speed limit, so that the time interval between trains at the end of the section with speed limit should be the set value t_{set}. The initial data for this use case are:

– there are $N_{lim\ sec}$ sections with speed limit,

– trains depart at t_{set} min. intervals,

– a virtually coupled train with a reduced interval $t_{vc}<t_{set}$ min. departs once an hour,

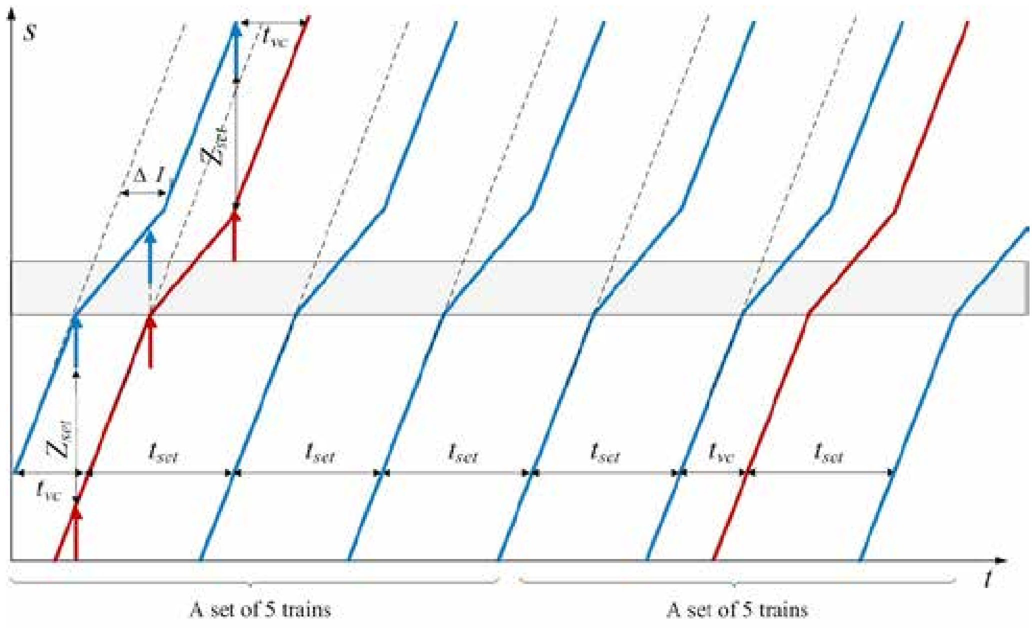
– time interval between trains at the entry of the first section with speed limit is t_{vc}, time interval between trains at the end of the first section with speed limit is t_{set}.

This means that the trains leave the line with t_{set} interval, which is fully described by relations (3) and (4), i. e.:

– time delay when passing through one section with speed limit is:

$$\Delta I = \frac{L_T + S_{lim}}{V_{lim}} - \frac{L_T + S_{lim}}{V_{set}} = \frac{V_{set} - V_{lim}}{V_{lim} \cdot V_{set}} \cdot (L_T + S_{lim}); \quad (10)$$

– the total number of trains per day, taking into account time losses arising during movement of the first train is:



Pic. 8. Graph of trains' movement in case 3 [performed by the authors].

$$n_4 = \frac{T - N_{lim\,sec} \cdot \Delta I}{I}, \qquad (11)$$

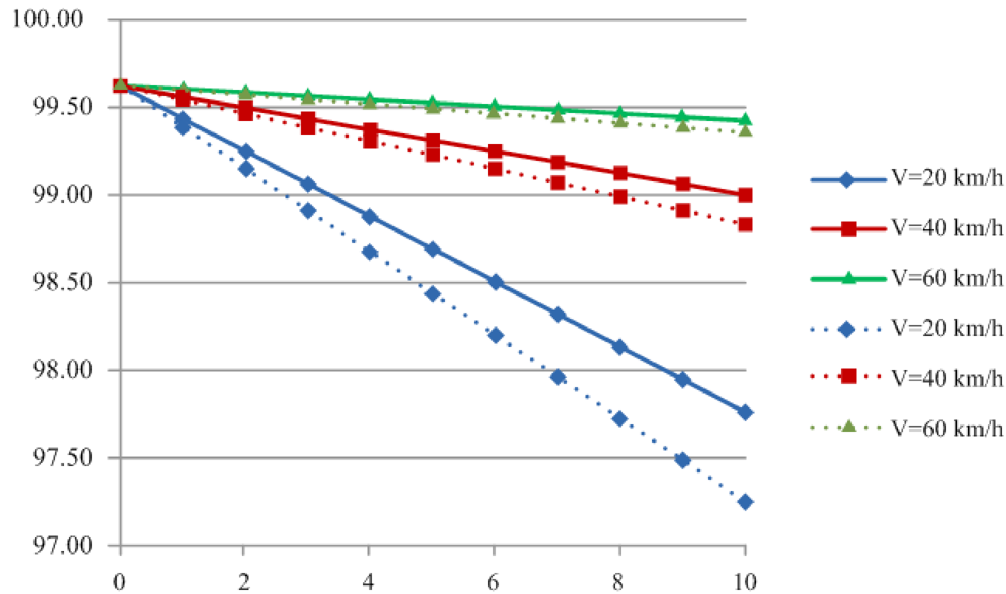
where $N_{lim\,sec}$ is the number of sections with speed limit.

However, for this use case, it must be taken into account that for each set of five trains entering the line, an additional time delay occurs when they pass the first section with speed limit:

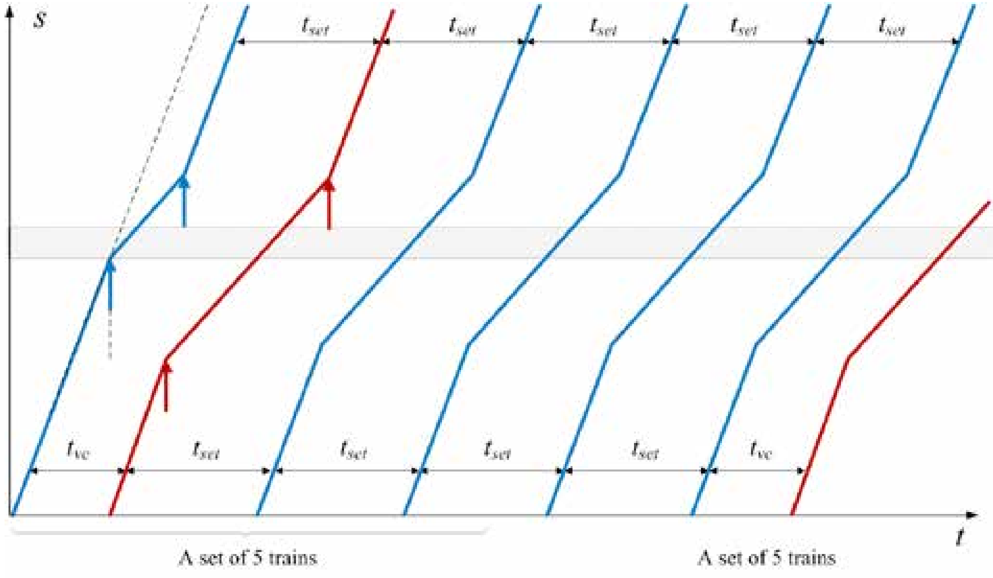
$$\Delta t = t_{set} - t_{vc}.$$

In total, $m_4 = \frac{T}{4I}$ sets of five trains each can depart at an interval of $t_{set}=I$, which leads to the accumulation of a time delay determined by the relation:

$$\Delta t(m_4) = m_4 (t_{set} - t_{vc}). \qquad (12)$$



Pic. 9. Capacity graphs for different values of V_{lim} and lengths of sections with speed limit [performed by the authors].



Pic.10. Graph of trains' movement in case 4 [performed by the authors].

From the last relation follows that when the train travel time along the line exceeds the accumulated time delay (12), i. e.

$$t_{travel} > m_4\left(t_{set} - t_{vc}\right) = \frac{T}{4I}\left(t_{set} - t_{vc}\right),$$

the section capacity is determined by relation (11). At the same time, the necessary time for the formation of trains sent on the line will be determined by the dependence:

$$T_{vc} = \frac{3I + t_{vc}}{4I} \bullet T\,. \qquad (13)$$

Otherwise, when the train travel time on the route is less than the accumulated time delay (12), i. e.

$$t_{travel} < \frac{T}{4I}\left(t_{set} - t_{vc}\right),$$

the departure of the next set of five trains on the route is delayed, which reduces the virtual coupling's effectiveness. However, in such case the line capacity is still determined by relation (11), while time T_{vc} approaches T.

Case 5. This use case is similar to the previous one, the only difference being that it describes the movement with delay of the second virtually coupled train following at a t_{vc} interval before entering the section with speed limit, so that the time interval between trains at the end of the section with speed limit is $t'_{set} < t_{set}$. The initial data for this use case are:

– there are $N_{lim\,sec}$ sections with speed limit,

– trains depart at t_{set} min. intervals,

– a virtually coupled train with a reduced interval $t_{vc} < t_{set}$ min. departs once an hour,

– time interval between trains at the entry border of the first section with speed limit is t_{vc}, time interval between trains at the end of the first section with speed limit is $t'_{set} < t_{set}$.

In this case the trains leave the line at an interval $t'_{set} < t_{set}$, which is described by relations (3) and (4), i. e.:

– time delay when passing through one section with speed limit is:

$$\Delta I = \frac{L_T + S_{lim}}{V_{lim}} - \frac{L_T + S_{lim}}{V_{set}} = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet \left(L_T + S_{lim}\right); \qquad (14)$$

– the total number of trains per day, taking into account time losses arising from the running of the first train is:

$$n_5 = \frac{T - N_{lim\,sec} \bullet \Delta I}{I}, \qquad (15)$$

where $N_{lim\,sec}$ is the number of sections with speed limit.

Similar to the previous use case, it must be taken into account that for each set of four trains entering the line, an additional time delay occurs when they pass the first section with speed limit: $\Delta t' = t'_{set} - t_{vc} < t_{set} - t_{vc}$.

In total, $m_5 = \dfrac{4\left(T - N_{lim\,sec} \bullet t'\right)}{3I + t'_{set}}$ sets of five trains can depart with intervals of $t_{set} = I$ and $t'_{set} < t_{set}$, which leads to the accumulation of a time delay determined by the relation:

$$\Delta t\left(m_5\right) = m_5\left(t'_{set} - t_{vc}\right). \qquad (16)$$

Table 1

Use case	V_{lim} = 40 km/h	V_{lim} = 60 km/h
Case 1. Operation without virtual coupling. Calculated relations: $\Delta I = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet (L_T + S_{lim})$; $n_1 = \frac{T - N_{limsec} \bullet \Delta I}{I}$.	n_1 = 88	n_1 = 88
Case 2. A train with an interval t_{vc} min. departs once an hour (the distance between trains does not change). The delay time of the first train is t_d. (The first train continues to move at a speed V_{lim} for t_d after leaving the section). Calculated relations: $\Delta I_{1,2} = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet (L_T + S_{lim}) + \frac{L_T + Z_{set}}{V_{lim}}$; $n_2 = \frac{4t_{set}}{3t_{set} + t_{vc}} \bullet \frac{T - N_{limsec} \bullet \Delta I_{1,2}}{T}$.	n_2 = 97 t_d = 6 min	n_2 = 98 t_d = 4 min
Case 3. A train with an interval t_{vc} min. departs once an hour (the distance between trains may change). The time of reducing distance to three block sections (3 km) is t_{dis}. Calculated relations: $\Delta I_1 = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet (L_T + S_{lim})$; $n_3 = \frac{4t_{set}}{3t_{set} + t_{vc}} \bullet \frac{T - N_{limsec} \bullet \Delta I_1}{T}$.	n_3 = 99 t_{dis} = 10 min	n_3 = 100 t_{dis} = 20 min
Case 4. A train with an interval t_{vc} min. departs once an hour. Time interval between trains at the end of the line is t_{set}. Calculated relations: $\Delta I = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet (L_T + S_{lim})$; $n_4 = \frac{T - N_{lim\,sec} \bullet \Delta I}{I}$.	n_4 = 88	n_4 = 88
Case 5. A train with an interval t_{vc} min. departs once an hour. Time interval between trains at the end of the line is t'_{set} for the second train in the group, and t_{set} for the third and fourth trains in the group. Calculated relations: $\Delta I = \frac{V_{set} - V_{lim}}{V_{lim} \bullet V_{set}} \bullet (L_T + S_{lim})$; $n_5 = \frac{4t_{set}}{t'_{set} + 3t_{set}} \bullet \frac{T - N_{lim\,sec} \bullet \Delta I}{I}$.	n_5 = 91	n_5 = 91

From the last relation, it follows that when the train travel time on the line exceeds the accumulated time delay (12), i. e.

$$t_{travel} > m_5 \left(t'_{set} - t_{vc}\right) = \frac{4\left(T - N_{\lim sec} \bullet t'\right)}{3I + t'_{set}} \left(t'_{set} - t_{vc}\right),$$

the section capacity is determined by relation (15). At the same time, the necessary time for the formation of trains sent to the line will be determined by the dependence:

$$T'_{vc} = \frac{3I + t'_{set}}{4I} \bullet T. \tag{17}$$

Otherwise, when the train travel time on the line is less than the accumulated time delay (16), i. e.

$$t_{travel} < \frac{4\left(T - N_{\lim sec} \bullet t'\right)}{3I + t'_{set}} \left(t'_{set} - t_{vc}\right),$$

the departure of the next set of four trains to the line is delayed, which reduces the virtual coupling's effectiveness. However, the line capacity is still determined by relation (15), while time T'_{vc} approaches T.

For example, for actual data:

$L_T=1000$ m; $S_{lim}=100$ m; $N_{lim\ sec}=4$; $V_{set}=80$ km/h; $V_{lim}=60$ and 40 km/h; $t_{set}=15$ min; $t'_{set}=13$ min; $t_{vc}=8$ min, the estimates will be obtained that are shown in Table 1.

Comparison of the obtained estimates shows the following:

– In cases 1, 4 of virtual coupling, the capacity does not decrease.

– In cases 2, 3 of virtual coupling, the capacity increases.

CONCLUSIONS

It is possible to make the preliminary assumption confirmed by calculations: the virtual train coupling, at least, does not reduce the capacity of the sections with speed limit, while in some cases and with current speed limits it provides an increase in capacity. This already suggests the feasibility of the implementation of virtual coupling on certain sections of railways; however, to justify practical methods for determining use cases for specific railway sections, a more detailed study is required, including computer simulation of the virtual coupling considering a wider range of parameters.

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Information about the authors:

Rozenberg, Efim N., *D.Sc. (Eng.), Professor, First Deputy Director General of JSC NIIAS, Moscow, Russia, info@vniias.ru.*

Ozerov, Alexey V., *Head of the International Department of JSC NIIAS, Moscow, Russia, a.ozerov@vniias.ru.*

Kuznetsov, Valery I., *D.Sc. (Eng), Associate Professor, Chief Researcher at the Research Department of JSC NIIAS, Moscow, Russia, v.kuznetsov@vniias.ru.*

Tikhonov, Sergey S., *Chief Specialist at the Research Department of JSC NIIAS, Moscow, Russia, s.tihonov@vniias.ru.*

Article received 23.08.2023, approved 26.09.2023, accepted 02.10.2023.