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Aerodynamic Phenomena Caused by the Passage of a Train. Part 3: Slipstream Effect

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Summary

In the series of articles describing the aerodynamic phenomena caused by the passage of a train, the effects of a train running at high speed on itself, on other trains, on objects on the track and on people are characterized. This impact can be of two types – generated pressure and slipstream. Apart from the literature analysis, the author's research is also taken into account. The third part presents the characteristic features of the slipstream and its impact on the environment (in the form of forces acting on objects) and railway infrastructure.

Keywords: rolling stock, high speed railways, aerodynamic phenomena

1. Introduction

The first part [1] discussed a general classification of aerodynamic phenomena divided into pressure changes and slipstream by the type of effects. It also presented changes of pressure in the open air, caused by a train passage, and the influence of pressure on various objects located near the track. Primary normative documents concerning aerodynamic issues were specified as well. It also depicted conclusions on the construction of a high-speed railway vehicle as well as durability and location of the structure at high-speed lines. The second part [2], which continued issues regarding pressure changes, focused on the mutual impact of moving trains on their front and side surfaces. It was concluded that it is the high-speed train that influences the slower train and other objects, not the other way round. The consequence of this is a significant – even over 6 times – rise in the pressure on the windscreen of an older train with a maximum speed of 120 km/h, passing a train running at 350 km/h, which may entail the risk of damaging the windscreen of the rolling stock with a lower maximum speed.

The third part is devoted to slipstream, which is the second, in addition to pressure, main type of aerodynamic effects caused by a train passing at high speed.

2. Slipstream Effect

A passing train set air masses in motion, causing their displacement and interaction with objects in the vicinity of the track. In contrast to the pressure changes, which reach their highest values during the train passage itself and immediately behind the train – at a time of 0.1 ÷ 0.3 s (Fig. 4 in the first part [1]), and then are quickly suppressed, the slipstream phenomenon is characterised by a large variation of the course and "pulling" of air masses quite long behind the train – even up to several seconds, which is recorded by air speed sensors and "unnoticeable" for pressure sensors. Moreover, the airflow behind the train is accompanied by turbulences.

Different slipstream curves are possible – those where the maximum is reached during the passage of a train and those where the slipstream reaches its maximum after the passage of a train. Figures 1 and 2 show example slipstream courses for two different rides at the same speed. In addition, two vertical lines mark the start and end of the train passage. The beginning of the rise in the slipstream curve can be observed just before the head of the train, which is the result of the air mass being pushed by the train. In open space, this phenomenon is not as pronounced as in the underground, where the slipstream is felt

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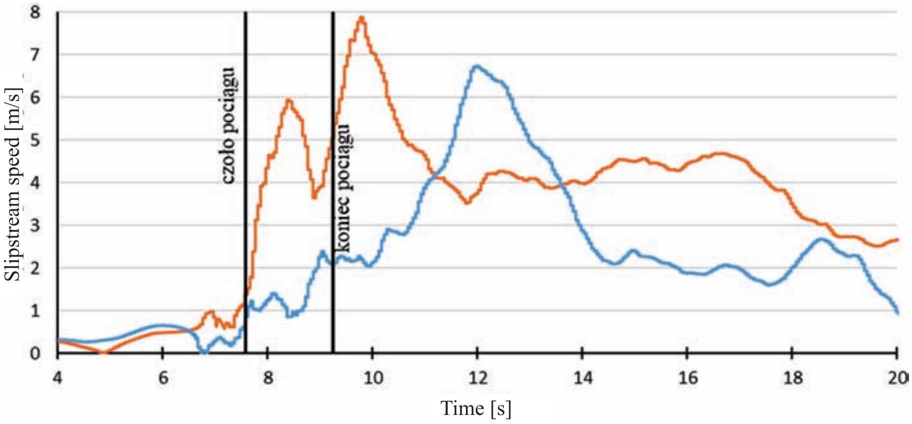

Fig. 1. Slipstream at a height of 1.4 m for two runs at the same speed [author's study]

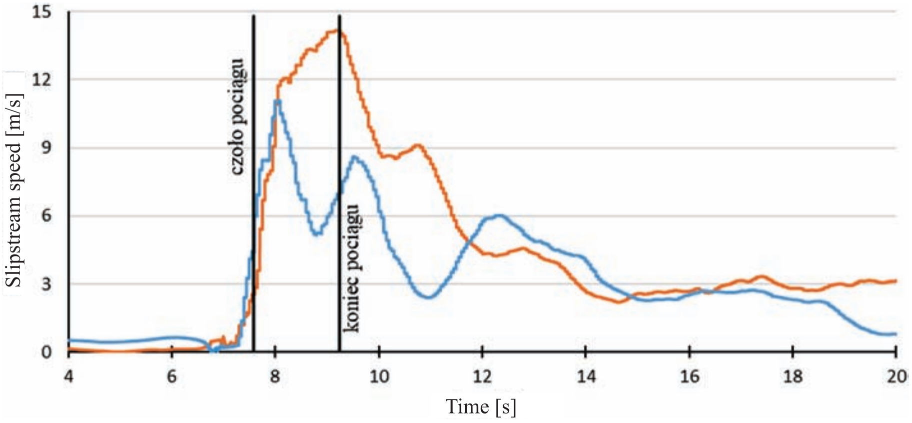

Fig. 2. Slipstream at a height of 0.2 m for two runs at the same speed [author's study]

a relatively long time before the train enters the station. A clear increase in the slipstream curve corresponds to the passage of the train head next to the slipstream sensors, while its further course is different. At a height of 1.4 m above the top of rail, for both passages the observed peak of the slipstream curve is – proportionally to the passage time – quite a long time after the passage of a train. The runs are slightly different at 0.2 m above the top of rail. In one of the passages, the observed peak in the slipstream curve occurs during the train's passage itself, and at the other, at the end of the passage. Therefore, in the case of slipstream, it cannot be spoken of such repeatability of results – at least with regard to the nature of the curves – as in the case of pressure measurements, and the maximum value of the slipstream may occur during the passage of a train or at different times after its passage.

For this reason, the standard PN-EN 14067-4 [3] requires that the recording begins min. 4 seconds before the passage of the train head, and that the recording ends min. 10 seconds after the passage of the train. And just as in the case of pressure measurements it was required to carry out a series of at least 10 runs, in order to correctly assess the vehicle, a series of at least 20 runs is required for the slipstream measurements. The recording should be carried out at a frequency of min. 10 Hz, and the recorded data are averaged over one second (Fig. 3), which results in a clear attenuation of the peaks, especially those of short duration. The recorded maximum values should then be statistically analysed.

The standard PN-EN 14067-4 [3] specifies the maximum slipstream values for the obtained measurement results, within the confidence interval 95% – $U_{95\%\ \mathrm{max}}$, at a distance of 3 m from the track axis. Measurements are performed for two heights above the top of rail: 0.2 m – slipstream related to large air turbulences at the height of the running gear and the chassis of the vehicle, and at a height of 1.4 m – slipstream related to the movement of the vehicle body.

The maximum permissible slipstream values are:

- at a height of 1.4 m above the top of rail – 15.5 m/s, measured at a maximum speed or at a speed of 200 km/h, if the vehicle speed exceeds 200 km/h;
- at a height of 0.2 m above the top of rail – 20 m/s, measured at a maximum speed below 250 km/h, or 22 m/s, measured at a maximum speed of the

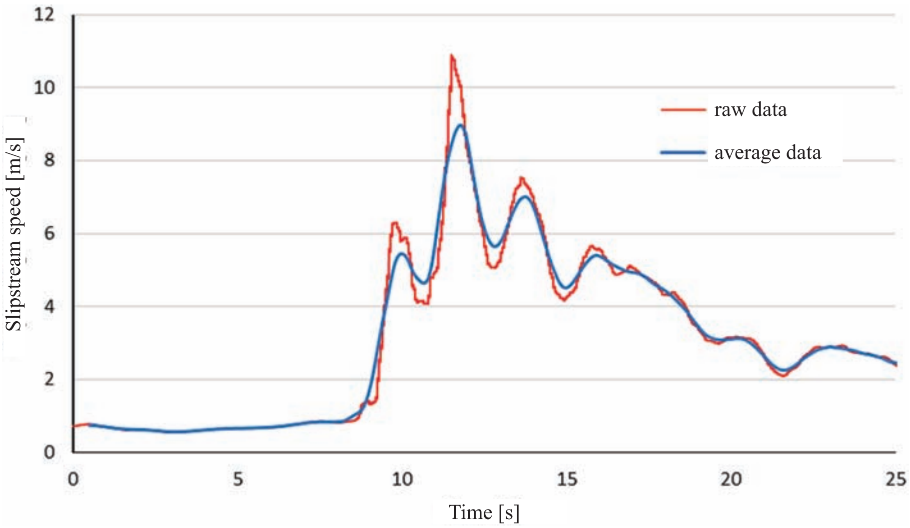

Fig. 3. Averaging of recorded data over one second [author's study]

vehicle from the range 250 km/h ≤ V < 300 km/h or measured at 300 km/h, if the vehicle speed exceeds 300 km/h.

No requirements are specified for speeds $V \leq 160$ km/h.

Figures 4 and 5 present the maximum slipstream values averaged over one second for a conventional train and a high-speed electric multiple unit (EMU), recorded at heights of 1.4 m and 0.2 m above the top of rail. The results from tests other than the approval for entry into service of a specific type of railway vehicle were used for the graphs. This gives a much wider range of test speeds than the approval tests (in which case slipstreams are tested at a speed close to the maximum speed of the test vehicle or at the above speed stated by the standard [3]). The resulting additional effect is the ability to show the increase in average slipstream value (dotted lines of the trend) as the speed increases.

The obtained slipstream numerical values from the individual runs were statistically analysed, i.e. they were calculated to the value corresponding to the reference speed, as follows:

$$U_{i,\mathrm{ref}} = U_i \cdot V_{\mathrm{ref}} : V_{\mathrm{i}}, \qquad (1)$$

where:

$U_{i,\mathrm{ref}}$ – i-th speed of slipstream for the reference speed [m/s],
U_i – i-th speed of slipstream for the recorded speed [m/s],
V_{ref} – reference speed,
V_i – recorded speed.

For a conventional train, the value of 190 km/h was assumed as the reference speed, and the value of 250 km/h for the EMU. The average value U_{av} for all U_i and the standard deviation σ were then calculated. The characteristic numerical value of the slipstream is assumed to be the average value increased by 2σ – i.e. a value within the confidence interval 95%:

$$U_{95\%} = U_{av} + 2\sigma. \qquad (2)$$

The values $U_{95\%}$ are marked on both graphs (diamond-shaped signs). Moreover, horizontal lines indicate the (maximum) limit values of the slipstream specified by the standard [3].

The characteristic numerical values of the slipstream $U_{95\%}$ for conventional and high-speed (EMU) rolling stock show that despite the significant difference in speed (here: 60 km/h), the rolling stock designed for high-speed has only a slightly higher value $U_{95\%}$ at a height of 1.4 m above the top of rail (corresponding to the slipstream caused by the vehicle body) than the conventional rolling stock. However, at a height of 0.2 m above the top of rail (corresponding to the slipstream caused by the running gear and vehicle chassis), despite the higher speed, the high-speed rolling stock (EMU) has a lower characteristic numerical value of the slipstream $U_{95\%}$ than the conventional rolling stock. This indicates a much better aerodynamic shape of the high-speed vehicle, which has the chassis and bogies as well shielded as possible, in contrast to the conventional rolling stock, which has no such shield or only to a limited extent, setting in motion greater air masses and also causing greater turbulences.

For trains configured from fixed and predefined rolling stocks, the whole rolling stock is assessed, and for trains composed of several connected train units, it is sufficient to check a train composed of two units, provided that the minimum train length is 120 m.

For single traction vehicles equipped with a train driver's cab, the tested vehicle in a trainset is checked

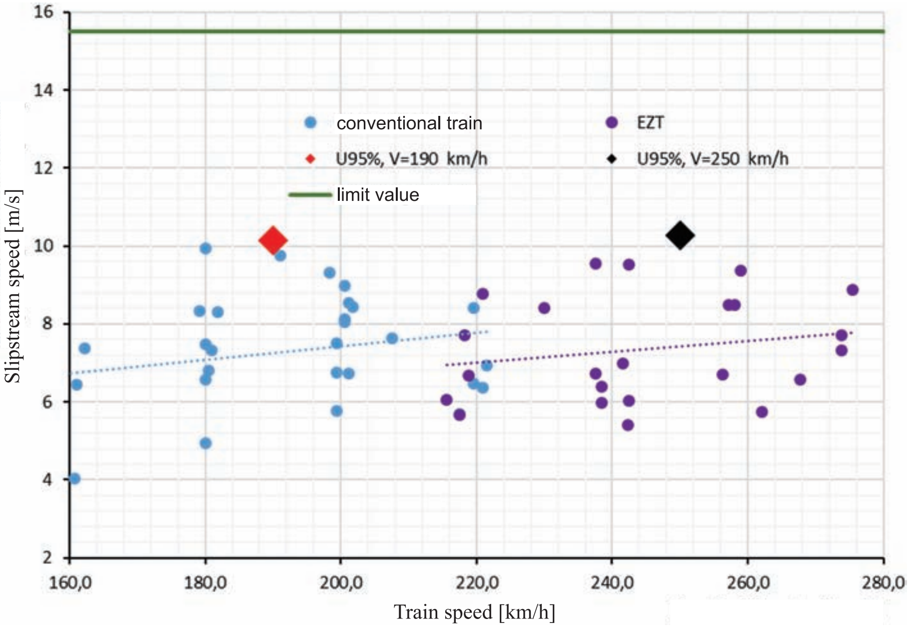

Fig. 4. Slipstream at a height of 1.4 m for a conventional train and EMU [author's study]

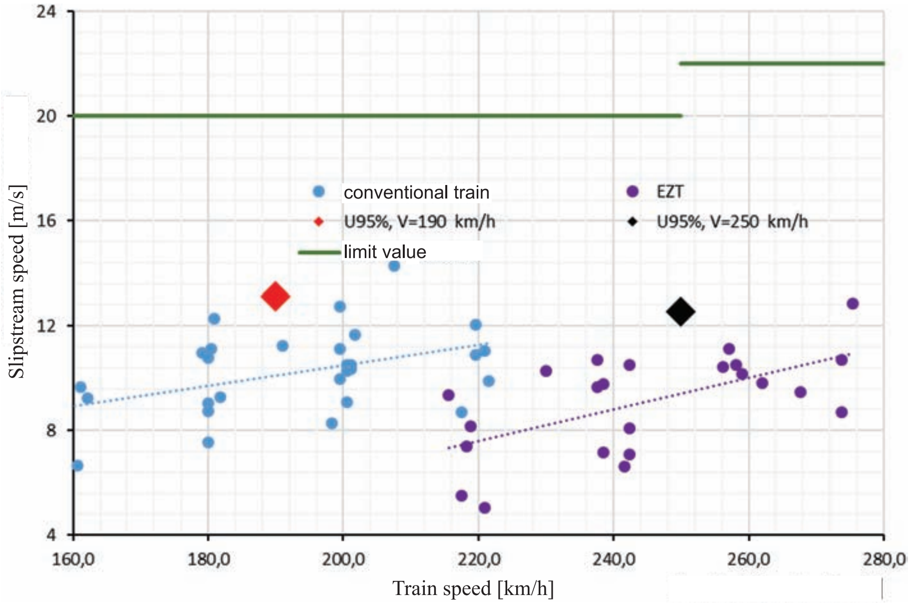

Fig. 5. Slipstream at a height of 0.2 m for a conventional train and EMU [author's study]

together with passenger wagons with a minimum total length of 100 m. The check has to be done both for a traction vehicle placed at the beginning and at the end of the rolling stock, as well as with two traction vehicles, one at the beginning and one at the end of the rolling stock.

For individual passenger wagons, there are two possibilities to confirm that the conditions required by the standard are met. The first possibility is to confirm similarity to existing wagons or those for which positive test results have been obtained, taking into account:

- maximum speed (not exceeding the speed of the reference vehicle);
- location of the end bogies (arrangement, recesses and outline of the bogie);
- changes in train envelope (i.e. width and height of the body) above the bogies by less than 10 cm.

The second possibility is to carry out tests and check that the slipstream values measured at a distance of 3 m from the track axis, at a height of 0.2 m and 1.4 m above the top of rail, within the confidence interval 95% – $U_{95\%}$, do not exceed the permissible values $U_{95\%max}$. In this case, the wagon should be tested in two configurations of placement in the rolling stock: directly behind a locomotive, which complies with the requirements in a rake of wagons with a minimum total length of 100 m and at the end of a rake of wagons with a minimum total length of 100 m behind a locomotive, which complies with the requirements. If it is a special-purpose wagon, such as a restaurant wagon, which is always in the middle of a rolling stock, it should only be tested in the middle of a rake of wagons with a minimum total length of 100 m.

When test or simulation results are not available, the graph in Figure 6 can be used to roughly estimate the maximum slipstream value based on the standard PN-EN 14067-4 [3]. It shows the quotient of the maximum slipstream to the train speed U_{max}/v_{tr} as a function of the quotient of the distance from the track axis to half of the train width 2Y/b (the horizontal axis value 1 corresponds to the train sidewall). Curve 1 corresponds to high-speed trains and curve 2 to conventional trains.

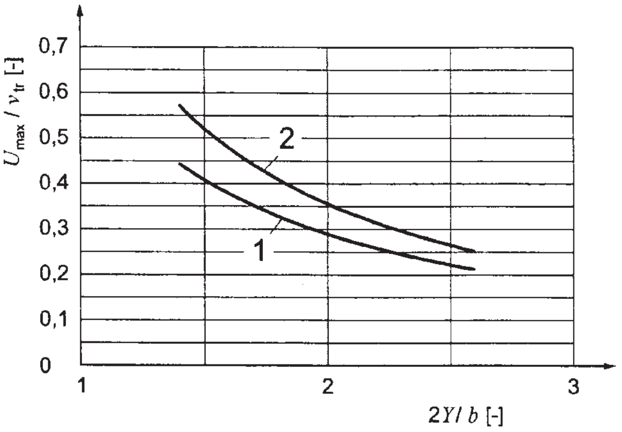

Fig. 6. Graph for rough estimation of maximum slipstream [3]: 1) high-speed trains, 2) conventional trains

Similar results are found in the report [4]. Figure 7 shows the airflow velocities obtained on the basis of theoretical calculations. As in Figure 6, the vertical axis contains the dimensionless value of the quotient of the slipstream to the train speed U/v_{tr}, while the horizontal axis presents the dimensionless value of the quotient of the distance from the vehicle to the width of that vehicle (i.e. the values 1, 2 and 3 of the horizontal axis in Figure 6 correspond to the values 0, 0.5 and 1 of the horizontal axis in Figure 7). There is a fairly good compliance between the results for high-speed trains (curve 1 in Figure 6 and the curve "low induced airflow" in Figure 7).

Figure 8, also derived from the report [4], presents the induced airflow velocities obtained from real tests for different vehicles. For comparison purposes, the same values as in Figure 7 obtained from theoretical calculations (three continuous lines marked as "high/medium/low induced airflow" in the graph) are also included in Figure 8. As in Figures 6 and 7, the vertical axis contains the dimensionless value of the quotient of the slipstream to the train speed U/v_{tr}, while the horizontal axis presents the distance from the vehicle, given in metres. For railways associated with the UIC, due to the use of the same vehicle gauge, the maximum vehicle width is approximately 2.9 m. This means that the distance values of 0 m, 1.5 m and 3 m in Figure 8 correspond approximately to the dimensionless abscissa values of 0, 0.5 and 1 from Figure 7, and the abscissa values of 1, 2 and 3 from Figure 6. In the range up to approximately 1.5 m from the train wall, a very good compliance between the results for the TGV train and the curve "low induced airflow" is noticeable.

Based on the knowledge of the slipstream values, the force acting on nearby objects, which is the physical realisation of the slipstream, can be calculated. It can be calculated using the formula (3) [3]:

$$F = 0.5 \cdot C_F \cdot S \cdot \rho \cdot U_{max}^2, \tag{3}$$

where:

F – maximum force acting on the object;
C_F – aerodynamic coefficient (measured in a tunnel or taken from the standard [7]);
S – characteristic surface;
ρ = 1.225 kg/m^3 – air density;
U_{max} – maximum value of the slipstream generated during the passage of a train.

3. Mixed aerodynamic effects

Similarly as pressure changes arise, which can be observed from the trackside (described in section 2.1 of the first part [1]), there are also pressure changes under the train that affect the ballast. A positive pressure will be generated in the train head area, which will then become a negative pressure. Depending on the value, this negative pressure may cause the crushed stone ballast to be picked up ("sucked out"), and then the slipstream wave may carry the crushed stone ballast away with it. There is, therefore, a combined effect of pressure and slipstream – in other words, a mixed effect. This phenomenon has not been sufficiently tested and the standard PN-EN 14067-4 [3] leaves the issue of aerodynamic effects on the track open.

Based on the research, it can be concluded that apart from the speed of the train itself and its aerodynamic shape, the size of the stones and the height of their arrangement will have a large impact on the possible pick-up of the crushed stone ballast. At the same train speeds, crushed stone ballast pick-up will be more frequent in the case of a conventional train (locomotive + wagons) than in the case of a uniform structure, such as that of multiple-unit trains. In

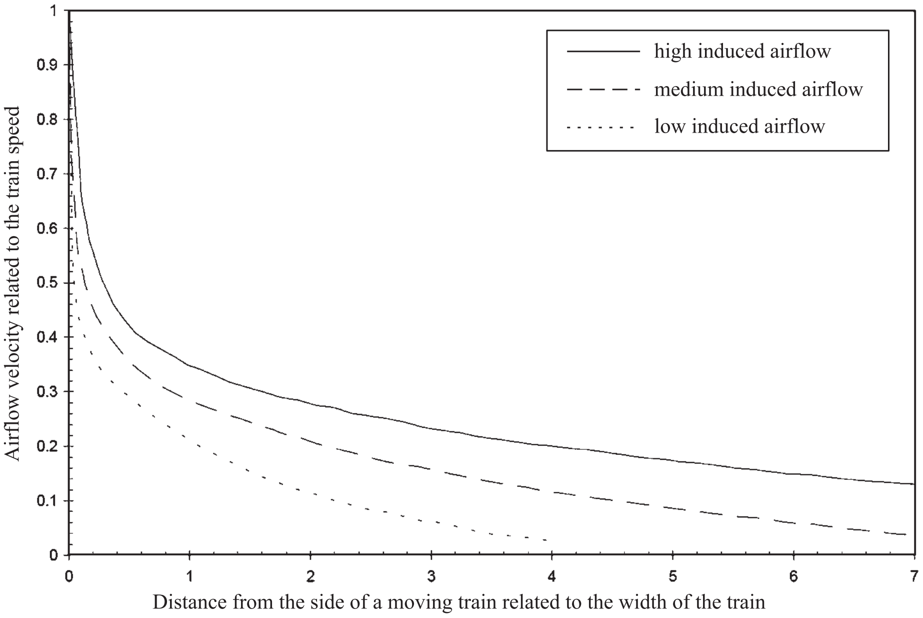

Fig. 7. Slipstream values obtained from theoretical calculations [4, 5]

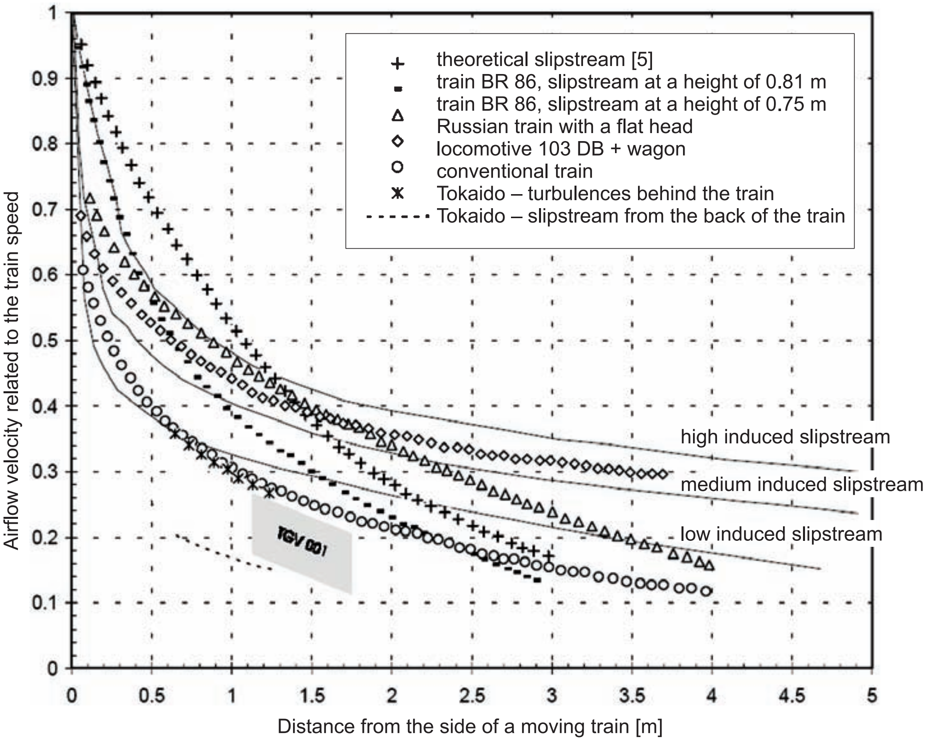

Fig. 8. Slipstream graph obtained from calculations and tests on different vehicles [4, 6]

contrast, the greater the height of the crushed stone ballast placement and the smaller the grain size, the greater the possibility of stones being picked up and dragged behind the train. In some cases, the crushed stone ballast may strike or bounce against the elements of the railway surface or steel parts of the vehicle bogie and strike other, impact-sensitive parts on the vehicle's chassis, causing their damage.

Figures 9 and 10 illustrate this phenomenon. Figure 9 shows a stone lifted by a train and dashing underneath it as it passes. On the other hand, Figure 10 shows a stone lifted by the rear end of the train and still dashing behind the train after it has passed.

In extremely adverse situations due to a combination of speed, the aerodynamic shape of the train, the size and placement of the crushed stone ballast

Fig. 9. A stone lifted and dashing under the train [photo by A. Zbieć]

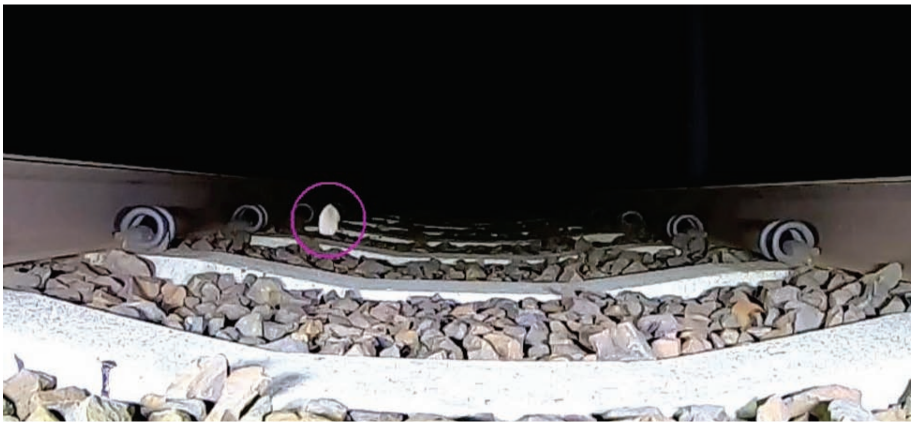

Fig. 10. A stone lifted and dashing still after the train passage [photo by A. Zbieć]

and the presence of infrastructure elements (which change both the magnitude of the pressure impact and the airflow generated by the passage of a train), the crushed stone ballast may also be picked up outside the track. This phenomenon is fortunately much rarer than the picking up of crushed stone under a passing train, moreover, it rather concerns crushed stone of small size and takes place in very close vicinity of a passing train (up to approximately 0.5 m from the train wall).

A similar danger related to the picking up of objects from the track and their possible bouncing against the train, but in the context of the impact on people, will be discussed in more detail in the further part of the cycle.

4. Conclusions

The presented results show that the aerodynamic shape of the body is crucial for the generated slipstream. In this respect, the bodies of unit trains are much better shaped and have a smoother impact than conventional trains, consisting of a locomotive and wagons. This refers both to the generation of the slipstream itself in the form of „wind" and to the forces it generates. The combined effects of both, i.e. pressure and slipstream, generated by the passage of a train at high speed, may cause the crushed stone ballast to be picked up and pulled along with the train. The worse the shape of the railway vehicle body in terms of aerodynamics and the smaller the crushed stone ballast combined with the greater height of the ballast placement, the greater the risk of the crushed stone being picked up. For high train speeds (above 200 km/h), it may seem necessary to use special agents protecting against lifting the ballast (such as special ballast binder resins) or slab track.

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