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Aerodynamic Phenomena Caused by the Passage of a Train. Part 1: Pressure Interaction With Objects

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Summary

The series of articles describing aerodynamic phenomena caused by train passage characterise the interaction of a train travelling at high speed with the moving train itself, on other trains, on trackside objects and on people. This interaction can be of two types – generated pressure and slipstream. Apart from the literature analysis, the author's research was also taken into account. The first part presents the general classification of aerodynamic phenomena, the pressure change waveform in open space caused by the passage of a train and the pressure interaction with trackside objects. Conclusions are presented on the construction of a high-speed rail vehicle and the strength and location of structures on high-speed lines.

Keywords: rolling stock, high-speed railways, aerodynamic phenomena

1. Introduction

The movement of a train causes various phenomena in both the track and the subgrade that can then be emitted to the ground and also leads to the formation of phenomena in the surrounding air. The former is due to the wheel-rail contact, the latter to the movement of the vehicle body in a viscoelastic medium, such as air. The subject of this article is the second type of phenomenon, excluding noise, which is a phenomenon composed of both of these types of interactions, i.e. derived from the movement of wheels on rails and the movement of vehicles in relation to the air, and also from mechanical devices (compressors, air conditioners and others) operating on a vehicle. As these are phenomena associated with vehicle motion, they can be treated as dynamic interactions or, more precisely, because of the medium in which the motion takes place, as aerodynamic interactions. Intuitively, it is predictable that the higher the vehicle speed, the greater the interaction. In relation to rolling stock, this is a relatively new field of research. It only began to be comprehensively addressed after vehicle speeds increased above 200 km/h, although vehicles travelling at speeds above 160 km/h were also covered.

A passing train produces two aerodynamic effects. One is connected with the pressure pulsations during passage – the other is the displacement of air masses along the train and also behind the train. The direction of air mass movement follows the direction of the train, although it may be subject to some deviations due to ambient wind resulting from atmospheric phenomena. Moreover, the airflow behind the train is accompanied by turbulence. Both of these aerodynamic effects can act as aerodynamic forces on people and objects. Based on the type of interaction, aerodynamic phenomena can be divided into:

- pressure changes / impacts,
- slipstream.

Based on the object of interaction, aerodynamic phenomena can be divided into:

- the interaction with a moving train,
- the interaction of a moving train with other trains,
- the interaction of a moving train with trackside objects,
- the interaction with people.

Based on the place of interaction, aerodynamic phenomena can be divided into:

- the interaction in an open space,
- the interaction in a space with various objects (buildings, noise barriers, canopies, protective walls, trackside structures, etc.),
- the interaction in tunnels, which can significantly increase the interaction of pressure and slipstream changes (not analysed in this paper).

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There is literature on train drag calculation, such as the paper titled „Aerodynamika pociągu" (Aerodynamics of a train) published by the Research and Development Center for Rail Vehicles in Poznań. However, in this literature it is difficult to find formulas that are easy to apply, allowing the calculation of pressure or of interaction forces caused by the passage of a train. One source for calculating the amplitude of a pressure wave caused by a train passage is UIC 779-1 Leaflet [5].

A rich source of information regarding the description of aerodynamic phenomena is the work [6] "Studies of the air flow velocity distribution in blasts caused by train running and the interaction of passing trains on changes in static pressure acting on the walls of carriages and on the front surface of the locomotive" [6], written 40 years ago by the Central Centre for Research and Development of Railway Technology (the present Railway Research Institute), commissioned by the then Minister. Aerodynamic issues were also addressed in the US Department of Transportation report from 1999 [1].

In parallel with the development of the provisions of the Technical Specifications for Interoperability (TSIs) and their adoption of the provisions governing the railway requirements of the UIC leaflets, the European standards applicable to railways have also been developed. Such standards in relation to aerodynamic phenomena are the series of European EN 14067 standards, in particular EN 14067-4 and its Polish version PN-EN 14067-4 [8], which in practice replaced the aforementioned Leaflet 779-1 [5], although it has not been withdrawn. Some of the provisions defining the requirements for aerodynamic issues have been included in the Loc&Pas TSI [10], but at many points this specification refers to the PN-EN 14067-4 standard, which contains a complete set of provisions for these issues.

In addition, work is being conducted to take into account the effect of crosswind. The phenomenon of crosswind or longitudinal winds with direction either in the same or the opposite direction of train movement, which can have a significant effect on aerodynamic interactions, has been reported by many authors. However, no methods are given in the literature to estimate the interaction of this wind (no calculation formulas).

2. Pressure interaction with objects

As stated in the introduction, one of the two main interactions of a train is the pressure interaction. One paper [1] identifies five parameters that affect the pressure wave magnitude due to the passage of the train front. These are: train speed, train cross-sectional area, distance from a passing train or clearance between trains, elevation above the ground and nose length.

2.1. Pressure fluctuations in the trackside open space

A passing train generates pressure changes affecting trackside objects. EN 14067-4 [8] gives an example of a pressure waveform on a vertical wall caused by a train passage (Fig. 1).

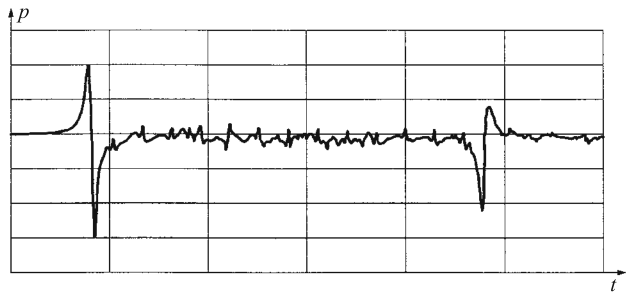

Fig. 1. Pressure-time curve on a flat vertical surface [8]

A positive pressure peak appears on the vehicle front and rapidly changes to a negative peak. The pressure drops to almost zero after the front of the locomotive has passed and fluctuates continuously along the entire rolling stock. Then a negative peak appears near the end of the train, which rapidly turns into a positive peak. The pressure change at the end of the train is lower than the change at the front of the train. In a two-vehicle situation (e.g. two coupled multiple units) there will be an additional pressure peak at the coupling point of the two multiple units (Figure 2).

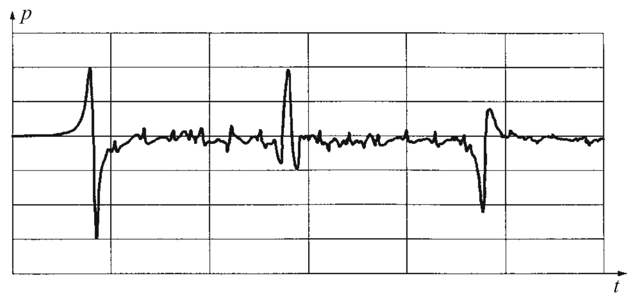

Fig. 2. Pressure-time curve for a two-vehicle train [8]

In the absence of any obstacles or objects, the pressure in the open space will vary along the trainset and, for a stationary trackside point, the pressure variation over time will reflect the pressure variation along the trainset and will show qualitatively similar behaviour to that on a flat vertical surface.

The greatest pressure changes usually occur at the train front. These are shown in Figure 3. Significant pressure variations may also occur at the end of the rolling stock or at couplers of successive vehicles and it is these pressure variations at the train front which are considered to be the most characteristic of all places in the rolling stock (front, couplers, and end of train). The most significant parameter is Δp – the change in peak pressure (peak to peak). It is a reflection of the nose shape (train front) and is smaller for an elongated, more streamlined nose and larger for a flat front. A short nose not only causes a greater change in peak pressure, but is also associated with a shorter duration of the change, making it more abrupt. The combination of the change in peak pressure and its duration will result in a milder or more impulsive (impact) effect on objects.

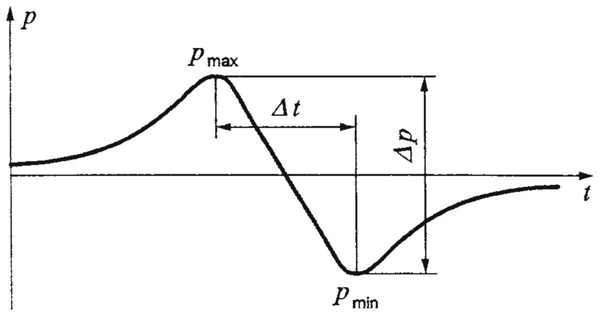

Fig. 3. Change in peak pressure (peak to peak) [8]

The time Δt between the positive and negative peak is related to the nose length L_n and the train speed and can be represented by formula (1) according to [8]:

$$\Delta t \approx L_n : V \quad (1)$$

where:
- Δt – the time between the positive and negative peak,
- L_n – the nose length,
- V – the train speed.

According to the requirements of the standard [8], a series of at least 10 runs should be conducted to properly assess the vehicle. The mean value Δp_m for all Δp_i (from all passages) and the standard deviation σ are then calculated. The characteristic numerical value of the peak pressure change is taken as the mean value plus 2σ, the upper value of the 95% confidence interval:

$$\Delta p_{95\%} = \Delta p_m + 2\sigma \quad (2)$$

and only on this basis can it be determined whether the vehicle meets the requirements of the standard.

The change in pressure is directly proportional to the square of the velocity. For the maximum speed $V > 160$ km/h, for a single vehicle fitted with a driver's cab and for fixed and predefined rolling stock, the maximum permissible pressure variation at a distance of 2.5 m from the track axis is set at 800 Pa with a confidence interval of 95% ($\Delta p_{95\%}$), whereby for rolling stock with a maximum speed between 160 km/h and 250 km/h, the measurement is performed at the maximum speed, and for maximum speed of the rolling stock $V \geq 250$ km/h, the measurement is performed at a reference speed of 250 km/h. No requirements are specified for the speeds $V \leq 160$ km/h.

Figure 4 shows an example of the actual curve of pressure changes for a train with a locomotive and two Z1 passenger wagons, travelling at a speed of 200 km/h (for the needs of the tests performed at that time, the pressure was measured at a slightly greater distance and on the basis of the results obtained its value was converted to a distance of 2.5 m from the track axis). The time axis was shifted so that the pressure peak, corresponding to the moment when the locomotive front (body) passes the pressure sensor,

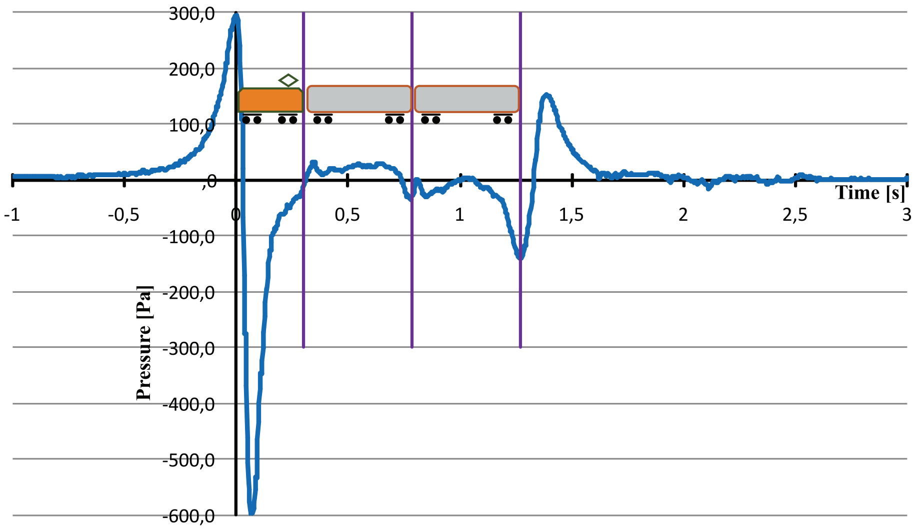

Fig. 4. The actual course of pressure variations at $V = 200$ km/h [author's study]

falls at zero time. In addition, vertical purple lines mark the connection (coupling) of the locomotive and wagons.

The peak pressure change (peak to peak) Δp for this locomotive at a distance of 2.5 m from the track axis was approx. 890 Pa, so the 800 Pa level allowed by the standard was exceeded by approx. 90 Pa (~11%). This result is not surprising as it was an old-style locomotive with a flat front, specially adapted to run at an increased speed of 200 km/h. The measuring train is shown in Figure 5. It should be noted that this is an example result obtained from a single run. On the other hand, as already mentioned above, a series of at least 10 runs is required to properly assess a vehicle and only on the basis of these runs can a vehicle be classified as compliant or non-compliant with the standard.

Fig. 5. Measuring train for pressure tests [photo by A. Zbieć]

The example given also shows that the construction of a new rail vehicle should be based on a comprehensive design of its parameters, including the shape of its front. It must not be reduced to selectively changing certain parameters only, such as maximum speed, without other related parameters. The designers of high-speed trains pay a lot of attention to the train nose shape which, on the one hand, must ensure the smoothest possible pressure variations within permissible limits, and, on the other hand, its length is related to the rail vehicle body shape and the need for the vehicle to enter the gauge (including in track curves) and the maximum distance of the train front to the nearest axis required by other regulations [2], which, in trains running on newly-built high-speed lines, cannot exceed 5.0 m.

A report [1] cites the results of full-scale tests (on real objects) on interaction of the train front shape with the generated pressure. The pressures were compared between slender nose locomotives with nose proportions of 0.8 to 1.25 (nose length-to-width ratio) with flat nose locomotives for which the nose shape ratios ranged from 0.1 to 0.5. The tests found that trains with slender noses produced pressure effects half that of trains with flat noses. So a train with a slender nose can move at 40% more speed, producing the same pressure change effect as a train with a flat nose. In contrast, tests conducted on container trains generated pressure pulses that were up to 20% higher than on flat nose trains.

In addition to the aforementioned parameter Δp, according to [8] a dimensionless coefficient of pressure change ΔC_p determined from formula (3) is also defined:

$$\Delta C_p = 2\,(p_{max} - p_{min}) : (\rho\ V^2) = 2\Delta p : (\rho\ V^2) \qquad (3)$$

where:
- ΔC_p – dimensionless coefficient of pressure change,
- p_{max} – maximum pressure (in the positive peak),
- p_{min} – minimum pressure (in the negative peak),
- ρ = 1.225 kg/m^3 – standard air density,
- V – train speed,
- Δp – pressure change in the peak (peak to peak).

The ΔC_p coefficient is a fundamental characteristic for a specific rail vehicle. It depends on the elevation above ground level and the lateral distance from the track axis. The greater the distance, the smaller the ΔC_p. For the locomotive in question, a factor of ΔC_p = 0.48 was obtained in this run. Example waveforms of ΔC_p are shown in Figure 6. Curve 1 corresponds to vehicles with a long, streamlined nose, curve 2 to vehicles with a flat front.

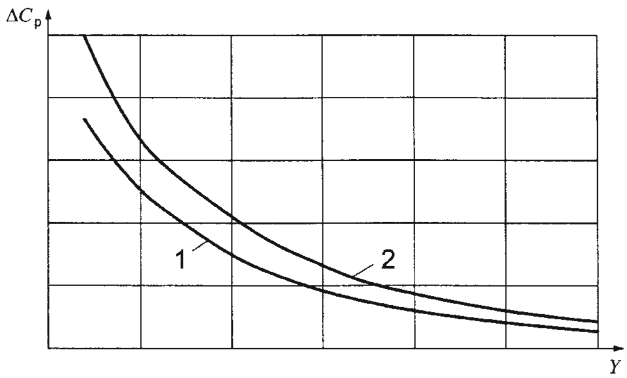

Fig. 6. Example waveforms of ΔC_p [8]

2.2. Pressure interaction with vertical structures

Figures 1 and 2 give an example of the pressure waveform on a vertical wall caused by a passing train, and Figure 7 shows how this pressure interacts with a vertical wall. PN-EN 14067 4 [8] provides formulas for estimating pressure when the results of measurements, calculations or simulations are not available. The method of such pressure estimation has already been included in UIC 779 1 (5), but computational

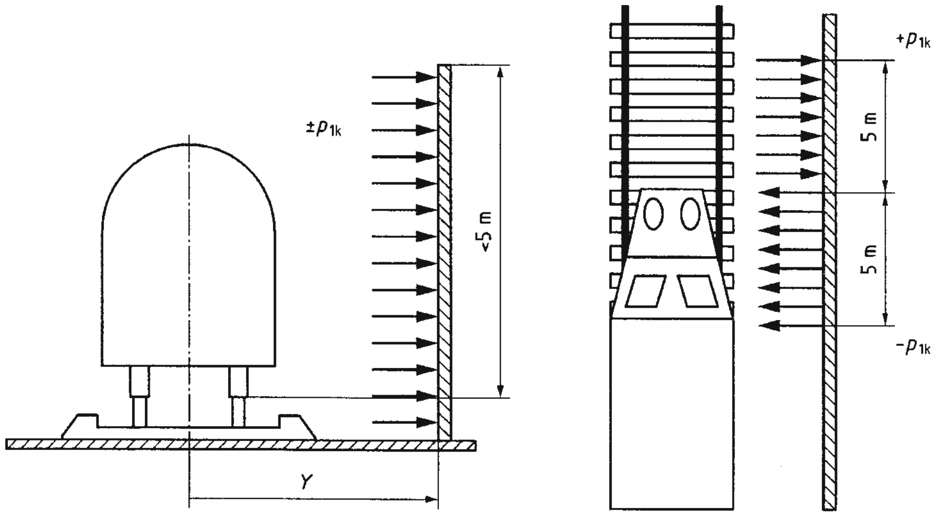

Fig. 7. Pressure interaction with flat vertical surfaces [8]

formulas have been modified as the knowledge in this field develops.

The objects most exposed to the pressure caused by a train passage are mainly flat vertical structures, such as:

- facades of buildings in the vicinity of the track,
- noise barriers,
- protective walls, etc.

According to [8], the pressure changes can be calculated by formulas (4) and (5):

$$p_{1k} = 0.5 \cdot \rho \cdot V^2 \cdot k_1 \cdot C_{p1} \tag{4}$$

and

$$C_{p1} = 2.5 : (Y + 0.25)^2 + 0.02 \tag{5}$$

where:

$\rho = 1.225$ kg/m^3 – standard air density,
V – train speed,
k_1 – shape factor for the train:
$k_1 = 1.0$ for freight trains,
$k_1 = 0.85$ for passenger trains,
$k_1 = 0.6$ for high-speed trains $V \geq 250$ km/h, with good aerodynamic design,
C_{p1} – aerodynamic coefficient, depending on the distance from the track ($Y \geq 2.3$ m),
Y – distance from the track axis.

For elements less than 1 m in height or less than 2.5 m in length, the calculated pressure shall be increased by a coefficient of 1.3. The pressure calculated according to the presented formula for several selected speeds and at different distances from the track axis for high-speed trains ($k_1 = 0.6$) is shown in Table 1.

Table 1

Pressure for different speeds at different distances from the track axis

Speed [km/h]	Pressure [Pa] at object distance from track axis [m]					
	2.3	3	4	5	6	7
160	293.6	186.3	115.0	80.4	61.0	49.0
180	371.6	235.8	145.5	101.7	77.2	62.1
200	458.8	291.1	179.7	125.6	95.3	76.6
220	555.1	352.3	217.4	151.9	115.3	92.7
240	660.6	419.3	258.7	180.8	137.2	110.4
260	775.3	492.0	303.7	212.2	161.0	129.5
280	899.2	570.7	352.2	246.1	186.7	150.2
300	1032.2	655.1	404.3	282.5	214.4	172.4
320	1174.5	745.3	460.0	321.4	243.9	196.2
340	1325.8	841.4	519.3	362.9	275.4	221.5
350	1405.0	891.6	550.3	384.5	291.8	234.7

[Author's study].

The calculated values and the graph confirm the intuitively perceptible relationship that the greater the distance from the track axis for a given running speed, the lower the pressure interacting with the surface. For example, at a speed of 300 km/h, at a distance of 2.3 m from the track axis (the minimum distance at which the formula is applicable), the pressure is 1032.2 Pa and at a distance of 5 m from the track axis, it is only 282.5 Pa, i.e. 3.65 times less. The pressure waveform as a function of distance from the track axis for different speeds is shown in Figure 8. In order to better illustrate the pressure distribution in the vicinity of the rail vehicle wall, and more precisely the kinematic gauge of the rolling stock, this figure shows a fragment of the kinematic gauge outline of the rolling stock according to UIC Leaflet 505-1 [4].

At a constant distance from the track axis, the higher the running speed, the higher the pressure, e.g. for a distance of 5 m from the track axis and a speed of 160 km/h, the pressure is 80.4 Pa, at twice the speed of 320 km/h, the pressure is about 321.4 Pa, so four times more. At 350 km/h, the pressure is already 384.5 Pa, almost five times more. The pressure waveform as a function of speed for different distances from the track axis is shown in Figure 9.

These pressure values must be taken into account when designing trackside structures, such as noise barriers, especially on high-speed lines. Until now, maximum train speeds of 160 km/h have not posed any risk in this respect. The subsequent revisions of the PN-B-02011 standard [7], in force until 2008, were replaced by the European standard PN-EN 1991-1-4:2008 [9]. According to the PN-B-02011:1977 standard [7], the value of the characteristic speed pressure was 250 Pa (in Zone I – with the lowest specific wind speed of 20 m/s) for the prevailing part of the Polish territory. These values had to be taken into account when designing all structures and only the pressures caused by the train passage, higher than those specified in the construction standard, had to be taken into account in trackside structures.

The new EN 1991-1-4 standard [9] slightly changes the wind load zones. The former Zone I, which covered most of Poland without the two mountain zones in the south and the Swietokrzyskie Mountains and

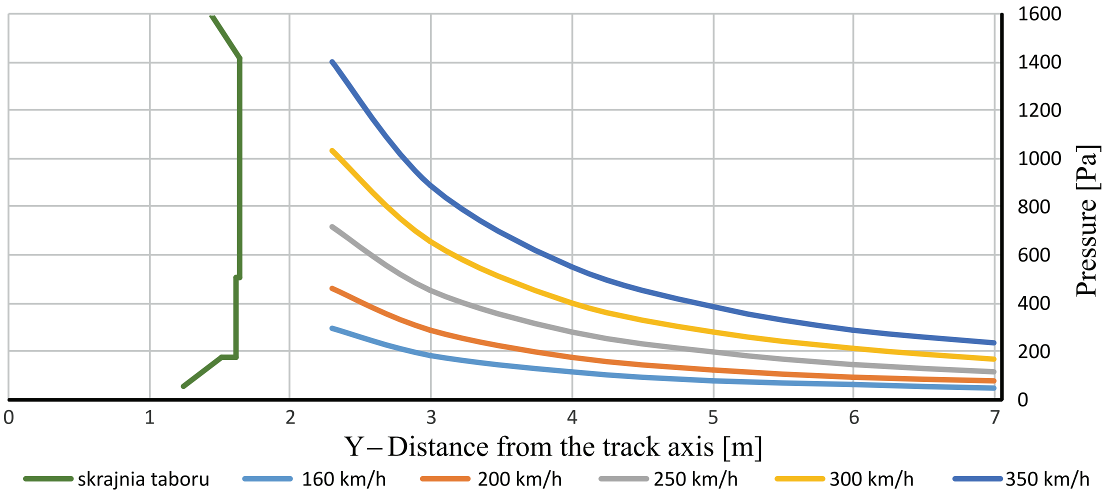

Fig. 8. Pressure as a function of distance from the track axis for different speeds [author's study]

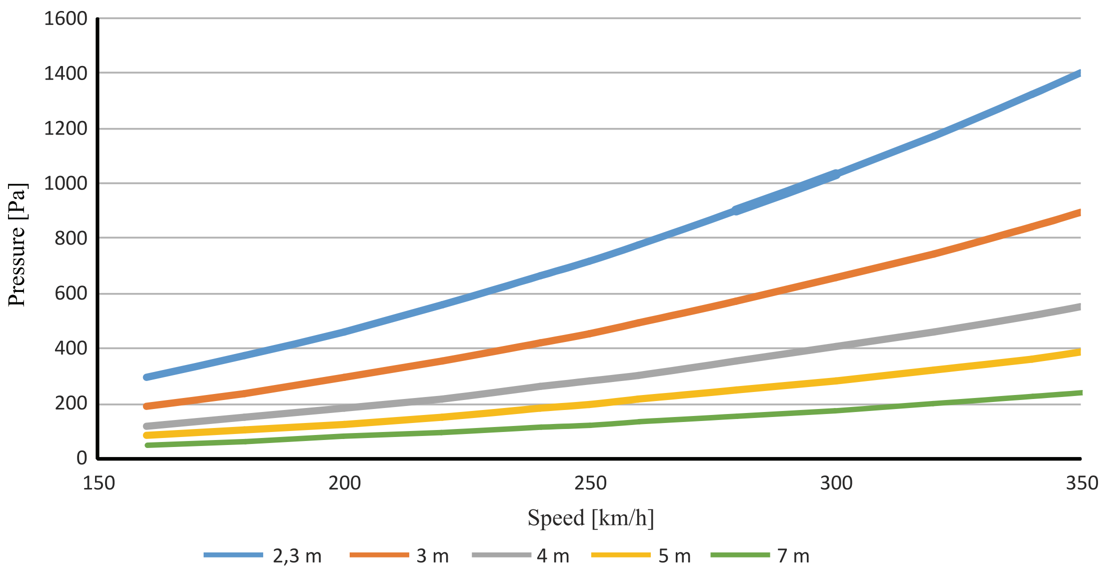

Fig. 9. Pressure as a function of speed for different distances from the track axis [author's study]

the coastal part, was enlarged to include the Swietokrzyskie Mountains and part of the coastal belt, which became "narrower". The previous Zone II, comprising the Swietokrzyskie Mountains and the coastal belt, was restricted to a narrowed coastal belt, and Zone III, comprising two mountain zones in southern Poland, remained unchanged. At the same time, the wind speed value recommended for the calculations and the corresponding characteristic speed pressure value were changed from 20 m/s to 22 m/s and from 250 to 300 Pa and the air density ρ = 1.25 kg/m^3. The EN 14067-4 railway standard [8] recommends the standard air density value to be ρ = 1.225 kg/m^3.

For a standard passenger train (consisting of a locomotive and attached wagons) and a speed of 160 km/h, a pressure of 300 Pa occurs at a distance of 2.78 m from the track axis, i.e. just over 1.1 m from the vehicle gauge and for high-speed trains this distance decreases to 2.27 m (approx. 0.6 m from the vehicle gauge). Thus, at 160 km/h, for properly designed and constructed trackside structures located at a distance of about 2.8 m from the track axis, there is no danger from the aerodynamic interaction of the train.

At speeds of 250 km/h and above, this safe distance definitely increases. According to the currently valid PN-EN 1991-1-4 standard [9], a pressure of 300 Pa occurs at distances from the track axis given in Table 2.

The conducted analyses show that flat, vertical objects, located at a shorter distance from the track axis than the distance indicated in Table 2, at a given train speed, should be designed to withstand a pressure greater than that specified in the standard [9].

2.3. Pressure interaction with horizontal structures above the track

Similarly to the interaction with vertical trackside surfaces, the air pressure caused by the passage of a train interacts with the flat horizontal surfaces above the track (Fig. 10). Such objects include:

- structures to protect the overhead contact line (e.g. gantry structures),
- piers and footbridges.

Based on [8], pressure changes can be calculated according to the formulas (6) and (7):

$$p_{2k} = 0.5 \cdot \rho \cdot V^2 \cdot k_2 \cdot C_{p2} \qquad (6)$$

and

$$C_{p2} = 2 : (h - 3.1)^2 + 0.015 \qquad (7)$$

where:

ρ = 1.225 kg/m^3 – standard air density,

Table 2

300 Pa pressure range for different speeds

***V* [km/h]**	**160**	**180**	**200**	**220**	**240**	**250**	**260**	**280**	**300**	**320**	**340**	**350**
p = 300 Pa for passenger trains (standard)												
***Y* [m]**	2.78	3.20	3.62	4.06								
p = 300 Pa for high-speed trains												
***Y* [m]**	2.27	2.61	2.95	3.30	3.66	3.84	4.03	4.41	4.81	5.23	5.66	5.89

[Author's study].

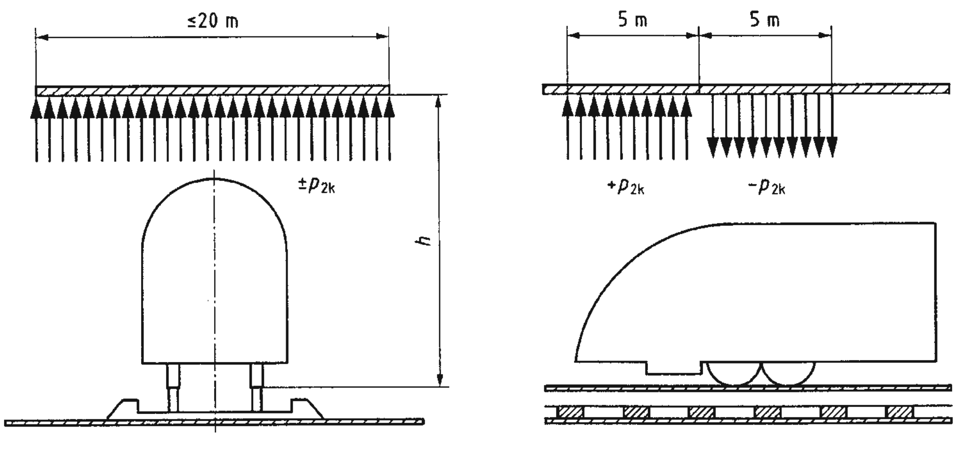

Fig. 10. Pressure interaction with flat horizontal surfaces above the track [8]

V – train speed,
k_2 – shape factor for the train:
$k_2 = 1.0$ for freight trains,
$k_2 = 0.85$ for passenger trains,
$k_2 = 0.6$ for high-speed trains $V \geq 250$ km/h, with good aerodynamic design,
C_{p2} – coefficient, depending on the height above the track,
h – height of the bottom surface of the structure in question above the rail head.

A similar interaction caused by a train passing can be observed on flat horizontal surfaces located at a certain height on the side of the track (Fig. 11). This is the case for the roofing of platforms with a minimum height of 3.8 m above the rail head, supported on poles, without side walls (parallel to the platform) and without a wall formed by another train standing on the track on the other side of the platform.

The pressure for a certain distance from the track axis can be calculated according to [8] from the formulas (8) and (9):

$$p_{3k} = 0.5 \cdot \rho \cdot V^2 \cdot k_3 \cdot C_{p3} \tag{8}$$

and

$$C_{p3} = 1.5 : (Y + 0.25)^2 + 0.015 \tag{9}$$

where:
$\rho = 1.225$ kg/m^3 – standard density,
V – train speed,
k_3 – coefficient dependent on height h:
$k_3 = (7.5 - h) : 3.7$ for 3.8 m $\leq h <$ 7.5 m,
$k_3 = 0$ for $h \geq 7.5$ m;
C_{p3} – coefficient dependent on the height above the track,
Y – distance from the track axis,
h – height of the bottom surface of the structure in question above the rail head.

2.4. Pressure interaction with mixed structures

In a similar way, it is possible to calculate the interaction of air pressure caused by the passage of a train on flat mixed trackside surfaces: vertical and horizontal or inclined (Figure 12). Such objects include:

- noise barriers consisting of a vertical part and an inclined or horizontal part,
- platform canopies comprising a roof and side walls parallel to the platform, which may be either a roof support structure or a wall filling the space between supports),
- platform canopies providing cover for a waiting room or other structure at the same time,
- pole-based platform canopies between two tracks when there is another train on the track on the other side of the platform.

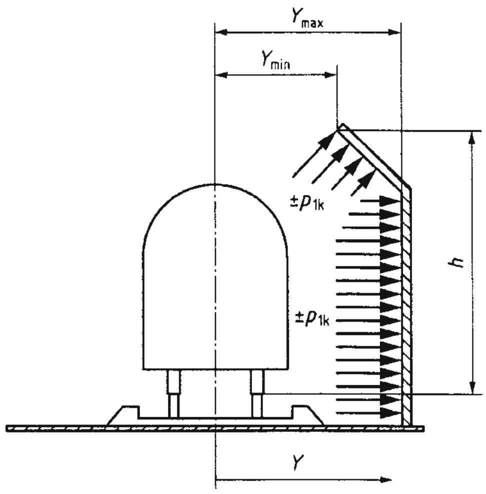

Fig. 12. Pressure interaction with mixed structures [8]

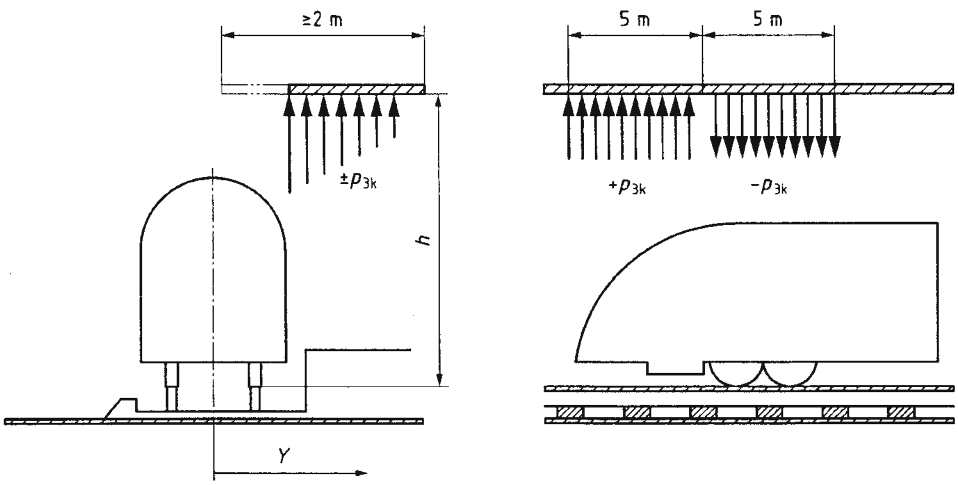

Fig. 11. Interaction of pressure on the side of the track with surfaces at a certain height [8]

The equivalent pressure in this case is greater than the pressure acting solely on a vertical or horizontal surface. This pressure can be calculated using formulas (10) and (11) as for vertical surfaces [8]:

$$p_{1k} = 0.5 \cdot \rho \cdot V^2 \cdot k_1 \cdot C_{p1} \quad (10)$$

and

$$C_{p1} = 2.5 : (Y + 0.25)^2 + 0.02 \quad (11)$$

with $Y = 0.6 \cdot Y_{min} + 0.4 \cdot Y_{max}$
where:

Y_{min} – minimum distance of the surface in question from the track axis,
Y_{max} – maximum distance of the surface in question from the track axis,
If $Y_{max} > 6$ m, then $Y_{max} = 6$ m is used for the calculation.

2.5. Pressure interaction with enclosed structures

Other types of structures are enclosed structures that surround the tracks for a length limited to 20 m (Figure 13), such as:

- structures with a horizontal surface above the tracks and at least one vertical surface,
- formwork (e.g. used in bridge construction),
- temporary structures (e.g. service walkways/bridges),
- structures to protect the overhead contact line (e.g. gantry structures).

Structures longer than 20 m give rise to effects similar to those in tunnels, but with much larger pressure amplitudes and are not covered by the formulas given.

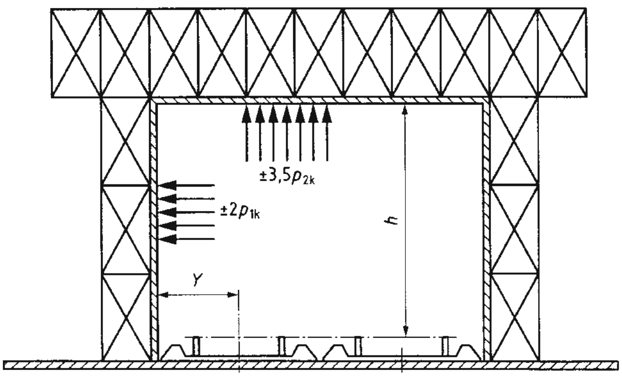

Fig. 13. Pressure interaction with enclosed structures [8]

The interaction of air pressure caused by the passage of a train with such structures can be calculated according to the formulas given in EN 14067-4 [8]:

- point 2.1 – pressure p_{1k} for vertical surfaces along the track,
- point 2.2 – pressure p_{2k} for horizontal trackside surfaces.

The values of these pressures should be multiplied by the following multipliers:

- ×2 – for pressures p_{1k} interacting with flat trackside vertical surfaces,
- ×2.5 – for pressures p_{2k} interacting with flat horizontal surfaces above the track if the structure encloses one track,
- ×3.5 – for pressures p_{2k} interacting with flat horizontal surfaces above the track if the structure encloses two tracks (as in Fig. 13).

3. Conclusions

Increasing the train speed results in a significant increase in aerodynamic interactions, including those in the pressure wave generated when the train passes. Regardless of the distance from the track axis, the pressure at 350 km/h is nearly 5 times greater than at 160 km/h. Therefore, when designing structures, such as:

- noise barriers,
- bridges and footbridges,
- structures to protect the overhead contact line,
- platform canopies,
- waiting rooms or other structures,
- enclosed structures surrounding the tracks,

which may be located in close proximity to the track on which high-speed trains will run, it is necessary to take into account higher pressures interacting with these structures than those arising directly from PN-EN-1991-1-4 [9]. In order to avoid the construction of structures with increased strength, there should be a sufficiently large distance from the track axis.

When designing a new high-speed rail vehicle, it should be provided with an appropriate aerodynamic shape, in particular the shape of the nose, which is decisive for the magnitude of pressure changes generated in the environment. A short nose causes a greater change in peak pressure and makes it more abrupt. A long nose provides smoother pressure variations that are within acceptable limits, thus allowing higher travel speeds. At the same time, the distance of 5.0 m from the front of the vehicle to the nearest axis must not be exceeded, which is related to the shape of the vehicle front and the ability of the vehicle to fit into the gauge (including track curves) and the fouling point.

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