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Aerodynamic Phenomena Caused by the Passage of a Train. Part 4: Pressure Influence on People

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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 characterised. 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 forth part presents the influence of pressure on people.

Keywords: rolling stock, high speed railways, aerodynamic phenomena

1. Introduction

The first part [1] of the series of articles discussed a general classification of aerodynamic phenomena, divided into pressure changes and slipstream by the type of influence. 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 influence 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. In the third part [3] the phenomenon of a slipstream was described, which is the second, in addition to pressure, main type of aerodynamic influence caused by a train passing at high speed. The characteristic features of the slipstream and its influence on the environment (in the form of forces acting on objects) and railway infrastructure were described. From a comparison of the slipstream caused by a standard train (made up of a locomotive and carriages) and high-speed multiple units, it is clear that multiple units create a much smaller slipstream and can run at higher speeds due to this type of influence. Mixed aerodynamic influence (i.e. the combined, simultaneous influence of pressure and slipstream) that can cause the breakstone to be picked up by the "suction" of the pressure and the entrainment of the breakstone by the slipstream wave are also discussed and illustrated with pictures.

The fourth part describes the influence of pressure on people – both on railway employees and passengers waiting on platforms and standing in open windows or sitting right next to the window in passing trains.

2. Influence of aerodynamic effects on people

As with the impact of a train on objects close to the track, the following types of aerodynamic influence on people can be distinguished:

- pressure changes / impacts,
- slipstream,
- mixed influence.

An additional type of influence, not directly related to the influence of those mentioned, but one that is

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worth mentioning on this occasion, is the psychological influence. The pressure influence is discussed in this section, while the other types of influence will be presented in later sections of the series.

3. Pressure influence on passengers or workers in the open air

In the case of the former, no cases of harmful influence on the human body of pressure caused by the passage of a train have been reported. The only organ that can react negatively to such pressure changes is the organ of hearing. The pressure wave generated by the passage of a train, often felt as a pressure hit on the eardrum, can cause adverse effects. Similar provisions are included in the report [4] "One aspect of pressure change related to the aerodynamics of high-speed train operations is that the people on station platforms situated too close to a passing train can experience the effects of pressure transients as sensation in their ear passages".

While there is no disagreement that the presence of significant positive pressure can cause damage to the auditory organ, there is no clear data concerning the harmful effects of reduced pressure, or even vacuum, on the organ of hearing. According to some sources [5, 6], analogous to positive pressure, damage to the eardrum can also occur in a vacuum: "Rapid decompression can rupture eardrums and sinuses, bruising and blood seep can occur in soft tissues, and shock can cause an increase in oxygen consumption that leads to hypoxia". Also according to the report [4], among the posted ear symptoms caused by pressure changes of 13,332÷66,661 Pa (for both positive and negative pressure), rupture of the tympanic membrane is listed – table 1.

According to other sources [7, 8, 9] vacuum leads to almost immediate unconsciousness (within 9÷11 seconds) due to rapid loss of oxygen from the body, and attempting to hold one's breath can cause lung damage. Cardiovascular collapse is also possible. However, vacuum does not cause damage to the eardrum, and only a too rapid return from vacuum to normal pressure may be harmful in this case. The article [8] cites an incident from 1966 when, during testing in the vacuum chamber of a prototype space suit, the air supply hose became detached from the suit and the pressure inside dropped rapidly to about 0.007 atmospheres (= 709 Pa). This means that the pressure differential was around 100,600 Pa, which was considerably higher than the one given in the Table 1. There was no rupture of the eardrum and the only negative effect was ear pain, which was considered to be the result of the rapid compression (return to normal pressure). Therefore, there is no clear confirmation of the harmful effects of the vacuum on the organ of hearing.

Furthermore, it should be noted that, according to the physical division, several types of vacuum are distinguished (Table 2 [10]), and the pressure during the described accident (7 hPa) was at the lower limit of

Table 1

Ear symptoms at different levels of pressure changes [4]

Pressure [Pa]	Symptoms
Higher relative pressure in the middle ear (decrease in ambient pressure)	
400÷667	Palpable sensation of ear filling.
1,333÷2,000	Distinct sensation of ear filling. Reduced intensity of sound hearing.
2,000÷4,000	Increasing discomfort associated with ringing in the ears (tinnitus) of a hissing, roaring, cracking or snapping nature; may manifest as pain and mild dizziness. (If there is no pathology, a pressure of 2,000 Pa is usually sufficient to force the Eustachian tube to work and equalise the pressure – causing an annoying „click" that can be felt in the ear).
> 4,000	Increasing pain, tinnitus and dizziness.
13,332÷66,6611	Rupture of the eardrum if the ear trumpet is completely blocked.
Relative pressure in the middle ear lower (increase in ambient pressure)	
400÷667	(as for the pressure drop),
1,333÷2,000	(as for the pressure drop),
2,000÷4,000	(as for the pressure drop).
7999	Severe ear pain, pronounced tinnitus and onset of nausea.
7,999÷10,666	Severe ear pain radiating to the temporal region, parotid gland and cheek; deafness; dizziness and tinnitus usually worsen, but tinnitus may resolve.
13,332÷66,661	Rupture of the eardrum.

Table 2

Types of vacuum [10]

Types of pressure	Pressure in hPa (mbar)	Number of molecules per cm^3	Average free path of a molecule	Number of strokes per surface ($cm^{-2} \cdot s^{-1}$)
Atmospheric pressure	1,013.25	2.7×1,019	68 nm	1,023
Low vacuum	300÷1	1,019÷1,016	0.1÷100 µm	1,023÷1,020
Medium vacuum	$1 \div 10^{-3}$	1,016÷1,013	0.1÷100 mm	1,020÷1,017
High vacuum (HV)	$10^{-3} \div 10^{-7}$	1,013÷109	10 cm÷1 km	1,017÷1,013
Ultra high vacuum (UHV)	$10^{-7} \div 10^{-12}$	109÷104	1 km÷105 km	1,013÷108
Extreme high vacuum (XHV)	$10^{-12} \div 10^{-14}$	104÷102	105÷107 km	108÷106
Outer space	$10^{-7} \div 10^{-16}$	109÷1	1÷109 km	1,013÷104
Absolute vacuum (perfect)	0	0	∞	0

"low vacuum", close to the border with the next range of "medium vacuum".

As the pressure variation during train passage is of the order of 1,000 Pa, this means that the pressure range under consideration is permanently in the first range – i.e. we are dealing with "atmospheric pressure". For a standard atmospheric pressure of 1,013 hPa, a pressure reduction of 1,000 Pa (= 10 hPa) gives a pressure of 1,003 hPa. This is in the range of atmospheric pressures occurring throughout the year and very far from the nearest vacuum range – "low vacuum". Therefore, in further considerations, the pressure reduction (negative pressure) associated with the passage of a train and affecting the human ear will not be taken into account. Only positive pressure will be considered.

According to the waveform, shown in part one [1] in Figure 3, the time Δt between the positive and negative peaks will correspond to half the T period of the pressure wave. Thus, the frequency f of the resulting pressure wave:

$$f = \frac{1}{T} = \frac{1}{2\Delta t}. \tag{1}$$

For the actual waveform recorded at 200 km/h, shown in part one [1] in Figure 4, the time Δt is 0.0627 s, corresponding to a frequency of about 8 Hz. The resulting noise must therefore be classified as infrasonic noise.

The current 2018 version of the regulation on harmful factors in the working environment [11] does not contain limit values for infrasonic noise. It was removed in the 2002 regulation [12] on the basis of the 2009 [13] amending regulation. However, in 2010, the PN-Z-01338:2010 [14] standard for infrasonic noise appeared, but any assessment methods contained therein only apply to corrected values related to long exposure. In addition, there is the PN-ISO 10843 [15] standard, which presents recommended methods for describing and measuring single impulses and short series of impulses arising from explosions, artillery fire, bomb blasts and similar phenomena, shock waves, gunshots and the operation of machinery and equipment stimulated by explosive charges. No limit values are presented in this standard, so there is no normative document on the basis of which it can be assessed whether the noise resulting from the pressure peak is harmful to peoples or not. However, the physical phenomenon itself remains. For an estimate, we will use the 2002 version of the regulation [12], which is no longer in force. According to this, the peak uncorrected sound pressure level must not exceed 145 dB.

Similar observations and values are included in the report [4]: "Pressure variations below a frequency of 20 Hz, which is below the audible range of the human ear, are referred to as infrasonic. There are no standards established for human exposure limits because there is insufficient understanding about human exposure to infrasound and its effect on hearing loss [16]. A suggested maximum sound pressure level for infrasound exposure is 150 dB, regardless of how short the exposure time [17]. This maximum pressure level is lowered for an exposure of longer duration."

Based on the formula in section 1.3.4 of PN-N-01307 [18], the sound pressure level L is:

$$L = 10\lg\left(\frac{p}{p_0}\right)^2 \text{ [dB]}, \tag{2}$$

where:

p – sound pressure [Pa],

p_0 – reference pressure = 20 µPa.

Thus, a peak uncorrected sound pressure level of 145 dB corresponds to 355 Pa (for the maximum sound pressure level of 150 dB suggested in the report [4], this would already be 632.46 Pa).

Two approaches can be adopted to estimate the safe distance from a passing train (from the track axis):

- if the passenger or employee is in an open area or on a platform without any fixed elements – such as shelters, waiting rooms, booths, noise barriers or fences – it may be assumed, as described in part one [1] in section 2.1. that any rail vehicle authorised to run meets the maximum peak pressure variation of 800 Pa (peak to peak) at a distance of 2,5 m from the track axis at 250 km/h, or
- if a passenger or staff member is in an area or on a platform that contains any fixed elements – such as shelters, waiting areas, booths, noise barriers or fences – the formulae for pressure variation at a given distance from the track axis, as set out in part one [1] in section 2.2. may be used.

In the first case, it is necessary to estimate what proportion of the total 800 Pa pressure variation is accounted for by the positive part of the peak, since, according to the previous analyses, it is the one responsible for the possible harmful effects on the organ of hearing. In the studies carried out by the author, cited in part one [1] in section 2.1, the ratio of peak to peak (positive to negative) was approximately like 1:2. Thus, out of the permissible value of 800 Pa, the value of the positive part of the peak is about 267 Pa and the negative part is about 533 Pa.

These tests were carried out on one type of train and at a limited range of speeds. In further analysis of the detrimental effects of positive pressure on the eardrums, in order to maintain an additional safety zone, a more unfavourable assumption can be made that the ratio of positive to negative peak values is as 1:1 (rather than 1:2 – as in the cited studies). Thus, the positive part of the peak will be half of the total allowable pressure variation of 800 Pa, i.e. 400 Pa at a distance of 2.5 m from the track axis, as noted in part one [1], section 2.1, at a reference speed of 250 km/h (or at maximum speed if lower). Since the peak uncorrected sound pressure level is 145 dB, which corresponds to 355 Pa, then by modifying the formula from the first part [1], section 2.2., (and arranging the ratio with the elimination of the factors $0.5{\cdot}\rho{\cdot}V^2{\cdot}k_1$, and leaving the aerodynamic coefficient C_{p1}, which depends on the distance from the track) it is possible to calculate the distance from the track axis for which this pressure will decrease from a value of 400 Pa to a value of 355 Pa. The calculated distance is 2.68 m from the track axis, i.e. slightly more than 1 m from the rail vehicle wall (or more precisely from the kinematic gauge of the rolling stock) and almost exactly 1 m from the edge of the platform (according to PKP PLK Technical Standards [19]). Such situation is shown in Figure 1.

To clarify: there is a 55 mm difference between the kinematic gauge of the rolling stock at platform height, i.e. 760 mm above the top of the rail [20], and the edge of the platform, but more relevant here is the horizontal difference in distance between the edge of the platform and the kinematic gauge of the rolling stock at the height of the passenger's torso – i.e. its upper part, i.e. above 1,170 mm from the rail head (= 410 mm above the plane of the platform), and this is only 30 mm.

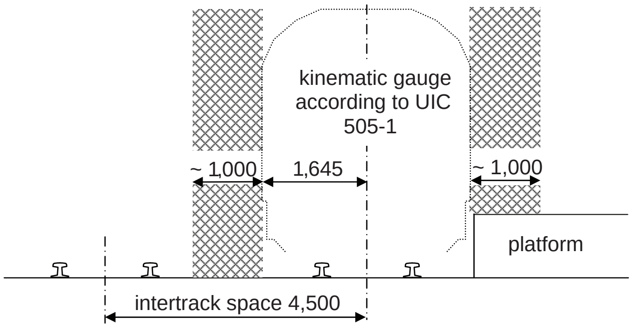

Fig. 1. Hearing danger zone in open space at V = 250 km/h [author's own elaboration].

The report [4] presents interesting findings by showing the magnitudes of the pressures acting on a person in an open space just 1 m away from the side wall of the carriage (Figure 2). Pressures were presented as a function of train speed and as a function of the shape of the train's nose ("Slender-Nose"; "Bluff-Nose"). For a speed of 250 km/h, the pressure at a distance of 1 m from the sidewall of the train, for a train with a Slender-Nose (curve ΔC_p = 0.1), is about 291 Pa, and for an intermediate nose (curve ΔC_p = 0.2) is 582 Pa. The value of 355 Pa at a distance of 1 m obtained from the analyses is between the values for the Slender-Nose and intermediate nose from the US report.

In the second case considered, i.e. when a passenger or employee is in an area or on a platform containing some fixed elements, then using the formula in part one [1], section 2.2., the distance (from the track axis) for which a pressure of 355 Pa will occur can be calculated. The results for different trains and different speeds are shown in Table 3 and Figure 3.

For comparison – in the first case, a pressure of 400 Pa (assumed half of 800 Pa) was obtained at a distance of 2.5 m from the track axis, at a speed of 250 km/h. This situation applies to the pressure in an open space. On the other hand, for a space containing some fixed elements, for the same speed of 250 km/h and at a distance of 2.5 m from the track axis, the pressure calculated using the formula from part one [1], section 2.2, will be 621 Pa. The reduction of these pressures to the permissible pressure of 355 Pa will occur: in the first case (open space) at a distance of 2.68 m from the track axis (i.e. about 1 m from the rolling stock kinematic gauge), and in the second case (space containing some fixed elements) only at a distance of

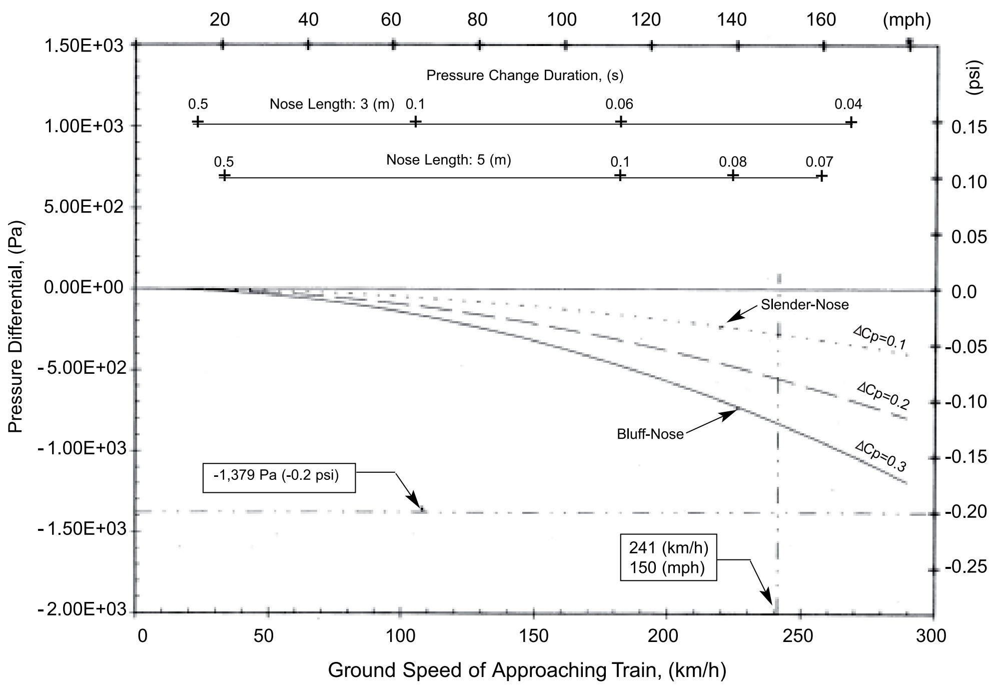

Fig. 2. Pressure at a distance of 1 metre from the train in open space [4]

Table 3

Pressure incidence distance 355 Pa for different speeds

V [km/h]	160	180	200	220	240	250	260	280	300	320	340	350
p = 355 Pa for passenger trains (standard)												
Y [m]	2.52	2.90	3.28	3.67	–	–	–	–	–	–	–	–
p = 355 Pa for high-speed trains												
Y [m]	2.06	2.36	2.67	2.99	3.31	3.47	3.64	3.98	4.33	4.69	5.07	5.26

[Authors' own elaboration].

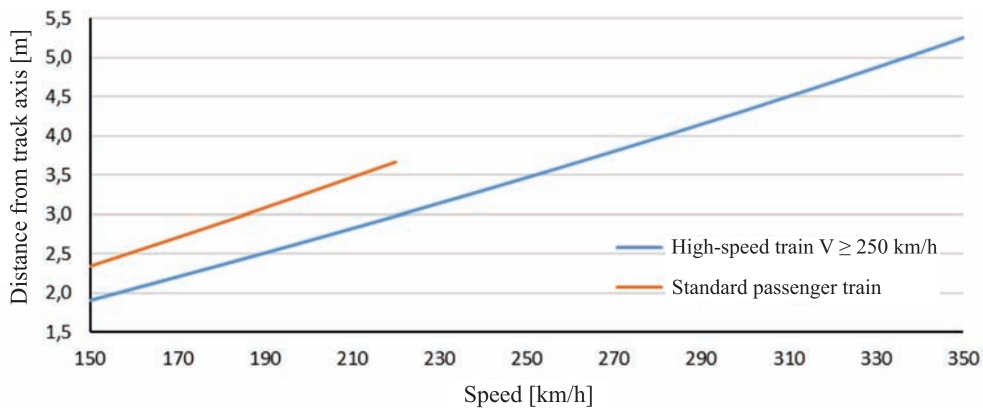

Fig. 3. Occurrence of 355 Pa pressure for fast and standard train [author's own elaboration]

3.47 m from the track axis (i.e. about 1.8 m from the rolling stock kinematic gauge).

On the basis of the analyses, it can be concluded that the more critical (dangerous) effects on the hearing organ arise when a passenger or worker is in an area or on a platform containing some fixed elements. Then – due to the action of the impulsive pressure wave – the expected pressures are more detrimental to the eardrum. In such a case, calculations should be carried out according to the formula in section 2.2 of part one [1] when determining hazardous areas for human occupancy.

For speeds of 300 km/h or 350 km/h and the presence of fixed elements, the safe distance from the track axis on which the high-speed train is running is about 4.33 m or 5.26 m respectively. Figure 4 shows the danger zones where there is exposure to possible hearing damage to passengers and staff, for a high-speed train speed of 350 km/h. It should be borne in mind that the values obtained were determined by theoretical formulae and not by measurements. Therefore, the actual values for specific types of railway vehicles may differ. In addition, in the absence of normative regulations, a value of 145 dB (≈ 355 Pa) from the now repealed version of the regulation on harmful factors in the working environment was used as a criterion for the peak uncorrected sound pressure level.

Figure 4 shows that in order for passengers or staff to be able to stay between a train travelling at 350 km/h and the wall of a fixed object, the distance from the side of the train to this object, should be a minimum of 4 m (3.6 m for a pressure drop to an acceptable value plus at least a small area for people).

4. Pressure influence on passengers in a train

Another issue to be analysed is the effect of the pressure generated by the high-speed train on the passengers in the conventional train. Part two [2] Table 3 and Figure 3 show the pressure values on the sidewall of a passing train, depending on the speed V_1 of the high-speed train and the width of the intertrack space. When a high-speed train passes another train on lines with 4.5 m intertrack space (designed for speeds above 300 km/h), a pressure of 355 Pa will be reached on the wall of the latter train already at a speed of around 212 km/h of the high-speed train. This means that people sitting or standing in the train right next to an open window (in a standard train with older-type carriages or older-generation EMUs), when passing a high-speed train travelling at a speed higher than 212 km/h, will be exposed to an impulse pressure wave significantly exceeding 355 Pa. For a 4.2 m wide intertrack space (designed for speeds above 250 km/h to 300 km/h), the estimated sound pressure limit will already be reached at just over 190 km/h, and for a 4.0 m wide intertrack (designed for speeds above 200 km/h to 250 km/h), the estimated sound pressure limit will already be reached at around 180 km/h.

The report [4] presents the results of a pressure impact study carried out on a track with an intertrack space of 3.96 m (13ft) and using 3.035 m wide electric multiple unit "Silverliners". In one run, a train with pressure sensors was travelling at approximately 160 km/h (100 mph) and passed a train travelling at approximately 220 km/h (138 mph). Pressure peaks of +352/−469 Pa were then recorded. These values are lower than those obtained using the calculations for 220 km/h and 4 m intertrack space from Table 3 and Figure 3 in the second part of the series of articles [2]. However, it should be recalled that these are results obtained from a single ride, whereas, as mentioned in part one [1], section 2.1, a series of at least 10 runs is required to correctly determine the pressure and to calculate the mean value Δp_m and the standard deviation σ, from which the mean value plus 2σ is determined ($\Delta p_{95\%} = \Delta p_m + 2\sigma$). One should remember that calculations according to EN 14067-4 [21] were carried out up to the kinematic gauge of the rolling stock (1,645 mm from the track axis), and the average actual width of Polish passenger carriage is up to 2.88 m. That is, the actual distances between trains will be slightly greater and the interaction pressures slightly lower. Only actual tests on the track will be able to verify the theoretical values obtained, while the US tests presented here clearly show that already at 220 km/h a positive pressure peak value of 352 Pa has been reached, which is almost equal to the permissible value of 355 Pa. This means that for a 4.0 m wide intertrack space, designed for traffic with a maximum speed of up to 250 km/h, the sound pressure value will already be exceeded for speeds above 220 km/h.

Taking into account the presented calculation results according to PN-EN 14067-4 [21] and the results of the US tests according to the report [4], countermeasures must be taken to ensure that passengers on

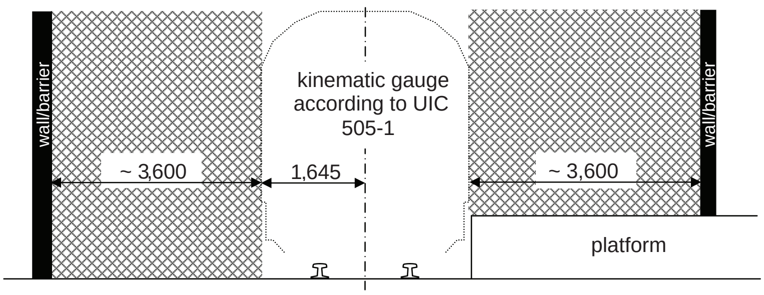

Fig. 4. Hearing danger zone in the vicinity of fixed objects at V = 350 km/h [author's own elaboration]

older conventional trains – with openable windows – are protected from the development of pressure waves with a higher than permissible amplitude. This can be achieved by:

- the use of clear signage prohibiting standing in the open window;
- arranging the timetable appropriately so that when a high-speed train is passing, conventional rolling stock is stopped at stations on tracks not adjacent to the track on which the high-speed train is passing;
- limiting the speed of a high-speed train to around 180÷210 km/h (depending on the width of the intertrack space) when passing conventional trains.

However, the best and safest solution seems to be the use of modern air-conditioned carriages with fixed windows on the same route as high-speed trains.

Similar conclusions were found in paper [22] although 200 km/h was then considered as the speed of high-speed trains:

- "…in cases where high-speed trains have to pass passenger trains developing conventional speed (up to 120 km/h) and also standing on the adjacent track with carriages not adapted to high speed, the high-speed train has to slow down so as to pass the conventional train at a slowed speed of up to 120 km/h.";
- "Carriage windows and the carriages themselves on trains passing high-speed trains should be sealed. Opening windows on a train that passes a train travelling at high speed (160–200 km/h) should be prevented."

5. Conclusions

The only organ that can be adversely affected by the pressure effects caused by the passage of a train is the organ of hearing. The pressure wave generated can be felt as a pressure impact on the eardrum and can cause adverse effects. Of the pressure changes generated, primarily positive pressures should be considered, as there is insufficient evidence of the detrimental effects of negative pressure associated with the passage of a train.

For the actual waveform recorded at 200 km/h, the resulting pressure waveform had a frequency of approximately 8 Hz. Thus, it is infrasonic noise. As there are no limit values for infrasonic noise, the considerations in this article are informative and can only serve as guidelines and recommendations.

The analyses carried out indicate that the danger of harmful pressure effects on the organ of hearing is greater when a passenger or worker is in the vicinity of fixed vertical buildings (shelters, waiting rooms, booths, noise barriers, fences, etc.) than in a space without any buildings. At a high-speed train running speed of 250 km/h and for the maximum value of peak uncorrected sound pressure level of 145 dB (equivalent to 355 Pa) assumed in the study as the permissible value, the danger zone for human presence in an area without any buildings is 2.68 m from the track axis, i.e. 1 m from the edge of the platform, and in the vicinity of fixed vertical buildings – 3.47 m from the track axis, i.e. 1.8 m from the edge of the platform. For speeds of 350 km/h these distances will obviously be greater. For vertical buildings, the safe distance will be 5.26 m from the track axis, i.e. about 3.6 m from the edge of the platform (as in Figure 4), and taking into account the passenger space, the distance from the edge of the platform to this object should be at least 4 m. The danger zone on the platform where high-speed trains will pass without stopping should be suitably marked, e.g. with a yellow line or even barriers, and supplemented with information boards.

In order to ensure the protection of passengers travelling on trains with openable windows (conventional trains of the older type) which may pass high-speed trains, the appropriate measures mentioned above should be applied. However, the best solution should be to introduce a rule that only trains with fixed windows, equipped with air conditioning, may run on the same route as high-speed trains.

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