NEW STANDARD SHEETS OF RAILWAY TUNNEL CLEARANCE CROSS-SECTIONS

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ABSTRACT: This article presents a new Standard Sheets of Railway Tunnel Clearance Cross-sections prepared for the Správa železnic (Czech Railway Agency). The standard sheets define cross-sections of tunnel structures on conventional and high-speed railway lines up to 350 km/h. The standard covers single-track and double-track tunnels and includes cross-sections for conventionally excavated tunnels, tunnels excavated by tunnel boring machines (TBM), and cut-and-cover frame structures. Upon completion, the standard sheets will replace the documents Clear Tunnel Cross-Section for Single-Track and Double-Track Tunnels issued in 2010–2011. The article presents key input parameters for the proposed tunnel cross-sections and, above all, the aerodynamic assessment, which is essential for cross-section sizing at higher speeds.

1. INTRODUCTION

Extensive preparation of modernization of existing conventional lines and especially intensive planning of high-speed rail throughout the territory leads to the design of a large number of tunnel structures in the conditions of the Czech Republic. For this reason, Správa železnic commissioned the processing of an update of the existing Standard Sheets of Railway Tunnel Clearance Cross-sections in 2024, which is intended to simplify and unify the design of tunnel structures. One of the main requirements was to perform an aerodynamic assessment of the designed cross-sections, which proves to be a crucial parameter at higher speeds.

2. RESEARCH OF FOREIGN REGULATIONS

The first part of the task of updating the model sheets was review of comparable foreign standards. As part of this work, regulations were searched for among railway infrastructure managers in England, Poland and France, but according to available information, these managers have not developed any similar model sheets. On the contrary, regulations dealing with the design of tunnel structures were obtained from Spain, Austria, Switzerland and Germany.

2.1 SPAIN

The Spanish regulation for railway tunnels *, ADIF PLATAFORMA NAP 2-3-1.0 Túneles,* prescribes the basic requirements for railway tunnels, from the cross-section, through the basic requirements for construction, specific geological problems and fire safety (evacuation, rescue areas, water supply, etc.) to the most commonly used standard cross-sections of tunnels, assuming their adaptation according to the conditions of the specific construction. The designer is based on these cross-sections and is obliged to submit a complete cross-section with an explanation of the deviations for assessment before starting further work.

2.2 GERMANY

German Railways Regulation *Richtlinie 853 Eisenbahntunnel plan, build and in-house halten* (Planning, construction and maintenance of railway tunnels) is a very extensive document that deals with tunnel construction on the railway network up to a speed of 300 km/h. The regulation contains typical cross-sections of tunnels, which are mandatory to use. Where adaptation is necessary for project conditions, the designer must submit a complete cross-section with a statement of reasons for approval before further work.

2.3 SWITZERLAND

In Switzerland, *SIA 197/1:2003 Projektierung Tunnel – Bahntunnel* (Tunnel design – Railway tunnels) applies. It does not include any typical railway tunnel cross-sections and clearance size are required via general guidance and reference *to UIC Code 779-11 Determination of railway tunnel cross-sectional areas on the basis of aerodynamic considerations*.

2.4 AUSTRIA

The Austrian guideline *Richtlinien für das Entwerfen von Bahnanlagen Hochleistungsstrecken* (Guidelines for the Design of High-Performance Railway Systems) deals with the complete design of railway lines that are of particular importance for efficient international or local transport. Its validity is limited to a design speed of 200 km/h (maximum operating speed 250 km/h). Appendix 3 of this regulation contains 16 drawing attachments of standard cross-sections of both bored and cut-and-cover tunnels.

2.5 OUTPUTS

A search of these regulations revealed that a similar comprehensive regulation such as the model sheets has been developed, based on available data, partly in Austria and mainly in Germany, from where the development of the existing model sheets was inspired. At the same time, it is evident that in all countries emphasis is placed on the influence of aerodynamic effects and it is necessary to deal with them in detail when designing tunnel structures.

3. AERODYNAMIC ASSESSMENT

3.1 AERODYNAMIC EFFECTS

As part of the research into foreign regulations, but also in the case of tunnel constructions implemented in our country and abroad, it is necessary to assess the aerodynamic effects of a train set passing through a tunnel. It is necessary to verify the effect on the passing train, on the tunnel equipment (e.g. doors to escape routes) and, above all, on the passengers themselves.

Depending on the speed, cross-section and length of the train and the length and clearance of the tunnel, air pressure changes during the train's journey through the tunnel. For a specific location in the tunnel, see Figure 1: First, there is a sharp increase of the static pressure caused by the entry of the train nose into the tunnel (Δp_N), then a gradual increase in pressure continues due to the entire train's journey (Δp_{fr}), when the end of the train enters the tunnel, there is a sharp decrease (Δp_T) and when the front of the train passes the considered location, there is a sharp decrease in pressure (Δp_{Hp}).

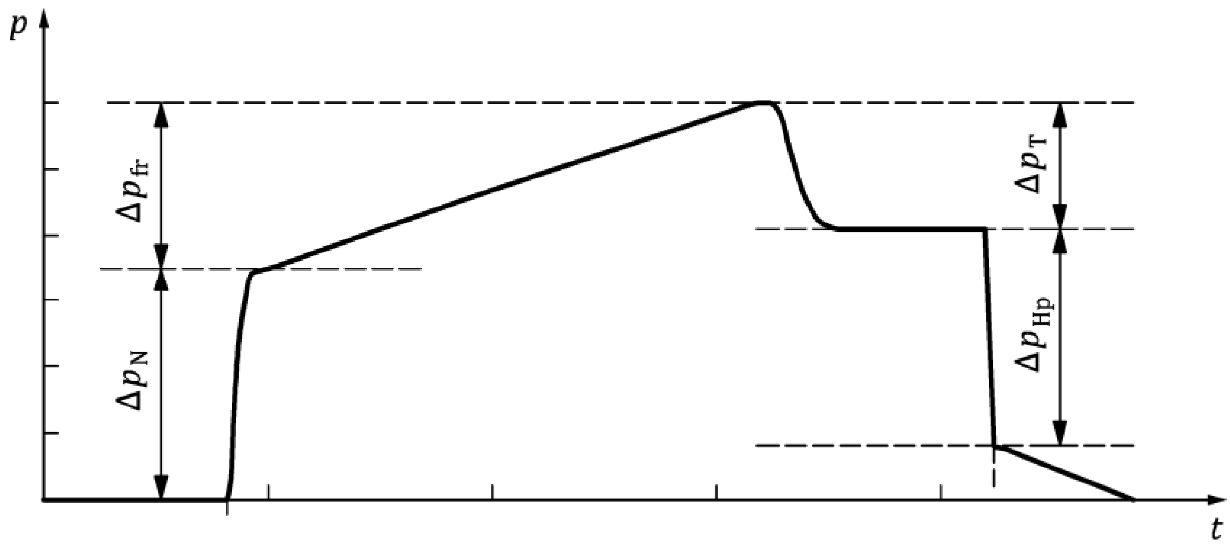

Figure 1: Pressure changes at a specific location in the tunnel (ČSN EN 14067-5).

These pressure changes then propagate from the train to the tunnel portals, returning as waves and their stacking (amplification and attenuation) occurs. In a double-track tunnel, these changes are caused by two oncoming trains, so it is necessary to gradually investigate all the relative positions of the trains in the tunnel depending on the time of their entry. The stacking of the waves caused by them must then be assessed for each case.

3.2 PRESSURE TIGHTNESS OF THE ROLLING STOCK

The effects of pressure changes inside a train depend on the pressure tightness of the train. Pressure tightness indicates how long it takes for an external pressure change to be reflected inside the train. In a non-pressure-tight train, pressure changes in the external environment of the train are reflected almost immediately in the interior of the train, while in a pressure-tight train, there is a delay depending on the degree of sealing of the train, thereby reducing significant short-term pressure fluctuations.

3.3 IMPACT ON PASSENGERS

The impact on passengers when passing through a tunnel is part of the assessment of pressure changes over time. The basic parameter is the health criterion for the maximum pressure fluctuation caused by the passage of a train running in a tunnel at the maximum permitted speed, which is given by *the Commission Regulation (EU) on the technical specifications for the interoperability of the infrastructure subsystem of the rail system in the European Union (TSI INF).* The pressure change must not exceed 10 kPa during the passage of the train through the tunnel.

Furthermore, the so-called passenger comfort criteria are assessed, which are not strictly required by regulations and their specification is up to the infrastructure administrator.

3.4 MICRO-PRESSURE WAVES

Another aerodynamic effect of a train passing through a tunnel is micro-pressure waves. This is a compression wave that is created when the front of the train enters the tunnel and propagates through the tunnel at the speed of sound. At the second portal, pressure equalization occurs, but a smaller part of this wave emerges from the tunnel and propagates from the portal in the form of an impulse micro-pressure wave. The micro-pressure wave acts as an aerodynamic (sonic) bang, which can cause noise pollution (thunderous noise) and lead to rattling of structures around the tunnel portal.

3.5 DRIVING RESISTANCE

From the perspective of the energy intensity of driving through a tunnel, the driving resistance in the tunnel is very important. When a train set drives through a tunnel, compared to driving through open countryside, the driving resistance increases due to the piston effect of the confined space. This effect is expressed by the so-called tunnel factor, which is the ratio between the resistance in the tunnel and the resistance on the open railway.

4. EXISTING STANDARD SHEETS

The existing Standard Sheets of Single-track Tunnel Clearances Cross-sections were issued in 2010 and Sheets of double-track tunnel Clearances Cross-sections in 2011. Both of these regulations were prepared according to the then valid version of the German regulation *Richtlinie 853 - Planning, construction and maintenance of railway tunnels.* This regulation contains standard sheets from which the speed ranges were taken and at the same time similar dimensions of the clearance envelope were used in order to meet the requirements for aerodynamic effects when the train passes through the tunnel, so that it is not necessary to process very time-consuming aerodynamic calculations.

In addition to the basic splitting into single-track and double-track tunnels, the existing standard sheets are divided into three speed intervals, in which the track-centre distance also changes in the case of a double-track tunnel, see Table 1. For these speed zones, one cross-section with a ballast track and one with a ballast-less track is always prepared. In the case of single-track tunnels, variants of tunnel construction by mechanized excavation (TBM) are also given.

Table 1: Summary of existing standard sheets

Speed range [km/h]	Single-track tunnel		Double-track tunnel	
	Construction method	*Cross-sectional area above TK [m²]*	*Cross-sectional area above TK [m²]*	*Track-centre distance [mm]*
0 - 160	Conventional exc.	47.32	73.92	4000
	Mechanized exc.	50.56		
161 - 230	Conventional exc.	52.44	78.68	4200
	Mechanized exc.	53.56		
231 - 300	Conventional exc.	60.38	89.95	4500
	Mechanized exc.	61.20		

5. BASIC REQUIREMENTS FOR STANDARD SHEETS

The new standard sheets include single-track and double-track tunnels within one regulation and contain cross-sections of tunnel structures on conventional and high-speed rail up to 350 km/h. The sheets are divided into several speed zones and there are in each zone cross-sections for conventionally excavated tunnels (with vault), for cut-and-cover tunnels (frame construction) and in the case of single-track tunnels also for tunnels bored by TBM. Each cross-section is prepared for both the ballast track and ballast-less track. An aerodynamic assessment was carried out for all clear tunnel cross-sections to meet the health criterion of 10 kPa according to the TSI INF and the passenger pressure comfort criteria were also checked.

6. PARAMETERS AND INITIAL ASSUMPTIONS FOR NEW STANDARD SHEETS

6.1 TUNNEL LENGTH

At the time of preparation of this article, it is assumed that the validity of the standard sheets will be limited to tunnels up to 10 km in length. Above this length, it is a specific technical solution that requires an individual assessment not only from the point of view of aerodynamics. The length of the tunnels was one of the most discussed topics throughout the creation of the standard sheets. It is one of the direct parameters for pressure changes. Indirectly, the length affects the overall solution of the tunnel from the point of view of fire safety (escape routes), ventilation, traction power supply, etc.

6.2 TRACK-CENTRE DISTANCES

Cross-sections of double-track tunnels are based on the track-centre distances specified in *ČSN 73 6320 - Amendment Z1 (2021) Spatial throughput on national, regional and local railways and standard gauge sidings - National requirements*, see Table 2.

Table 2: Normal track-centre distances according to ČSN 73 6320-Z1

Maximum permitted speed [km/h]	*Normal track-centre distance [m]*
V ≤ 200	4.00
V = 200	4.20
200 < V ≤ 360	4.50

6.3 CROSS-SECTION GAUGE

For all cross-sections, the basic kinematic gauge derived from the international reference profile GC according to *ČSN 73 6320 - Amendment Z1* is used, which is applied in new construction and reconstruction of national and regional railways. The profile is supplemented by an extension of the gauge for electrified railways, which was adjusted to the following parameters based on discussions with the relevant department of Správa železnic, see Figure 2:

- The height of the overhead contact line is 5.3 m above the rail head;
- Assembly height 1.1 m;
- Assembly width 0.8 m;
- Isolation distance 0.3 m.

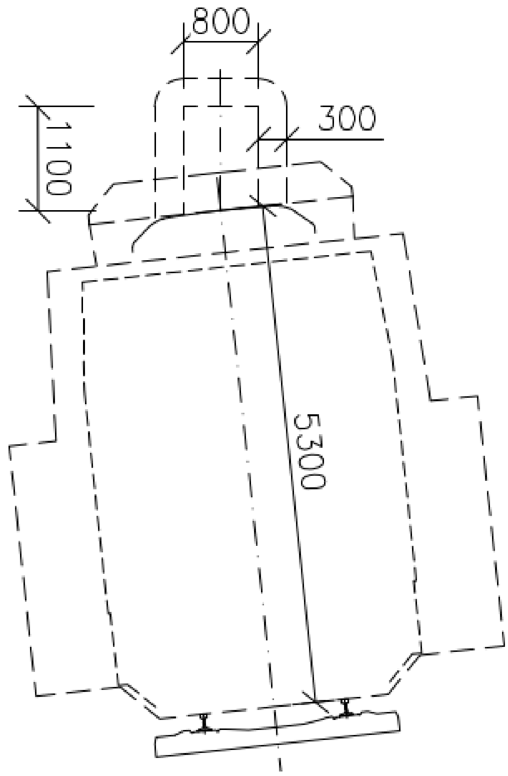

Figure 2: Overhead contact line assembly

In tunnels exceeding 1 km in length, electrical and mechanical traction sectioning occurs, which requires more space above the clearance profile. Due to the possible impact on the clearance profile of the tunnel, the traction sectioning solution was examined for all proposed tunnel profiles.

6.4 CLEAR WALKING AND WORKING SPACE

The clear walking and working space in tunnels is governed, in accordance with ČSN 73 6320 – Z1, by ČSN 73 7508. This standard specifies the requirement for an escape route along a stationary train with a minimum width of 1.2 m and a minimum height of 2.2 m. Since the Commission Regulation (EU) on the Technical Specification for Interoperability relating to "Safety in Railway Tunnels" (TSI SRT) requires a minimum free space of 2.25 m above the escape walkway, all standard-sheet cross-sections have therefore been designed with a clear passage space of 1.2 m in width and 2.25 m in height.

6.5 SPEED ZONES

The standard sheets are again prepared for several speed zones, in which aerodynamic assessments were also carried out. The zones have the following limit values:

- 160 km/h – Minimum rated speed.
- 200 km/h – Basic limit value primarily for double-track tunnels determining the track-centre distances according to ČSN 73 6320 - Z1 (2021). This limit is also based on ČSN EN 14067-5, where for speeds above 200 km/h an assessment of the formation of a micro-pressure wave in the tunnel is required.

- 230 km/h – This is the limit value from the point of view of the aerodynamic characteristics of train sets.
- 250 km/h – At this speed, the INF TSI already requires addressing the flying of ballast from the track superstructure caused by aerodynamic effects when the train passes.
- 270 km/h – This is the speed at which problems with ballast flying off the track superstructure were monitored.
- 300 km/h – Commonly used limit value.
- 350 km/h – Maximum rated speed.

6.6 TRACK SUPERSTRUCTURE

The design of the track superstructure has a minimal impact on the aerodynamic calculations. The standard sheets therefore consider the same clear cross-section for both variants of the track superstructure design - both for structures with a ballast track and for ballast-less track. The choice of the size of the tunnel cross-section is therefore not influenced by the design of the track superstructure, which may change during the development of the project.

On the other hand, the design of the track superstructure has a significant influence on the occurrence of micro-pressure-wave boom, as the solid track reflects micro-pressure waves and the rail bed absorbs them, thereby reducing their effect on the tunnel portals.

6.7 SAFETY CLEARANCE

The requirement for the tunnel safety clearance is based on *ČSN 73 7508 Railway Tunnels* (the standard is valid up to a speed of 160 km/h), where the minimum width of the safety clearance is set to 300 mm. This value has been adopted into the existing standard sheets for all speed ranges and construction methods. In addition, it is stated here that this is a reserve space for additional installation of structures during tunnel repairs, for deformation of the lining and deviations during construction.

When preparing the new standard sheets, it was decided, based on current technological possibilities, that the safety clearance for additional repairs could be reduced. It was clearly specified which part of the safety clearance was intended for deviations during the construction of the tunnel. The safety clearance was therefore set at a total value of 150 mm and consists of 50 mm for construction tolerances and 100 mm for possible future renovations.

The tunnel's clearance profile, which has a direct impact on aerodynamic calculations, only includes space for possible future renovations, with the proviso that if this space is filled in the future, a new aerodynamic assessment of the tunnel must be performed. On the other hand, the space for construction tolerances is not included in the aerodynamic assessment - it can be filled during construction.

6.8 COMFORT CRITERIA

To assess the passenger comfort criterion, the values resulting from EN 14067-5 were considered, as required by the Správa železnic where the following informative values are given in Annex B:

- Pressure changes for a passenger in a non-sealed train should not exceed the values:
    - Pressure changes of 4500 Pa in 4 s in double-track tunnels.
    - Pressure changes of 3000 Pa in 4 s in single-track tunnels.
- Pressure changes for a passenger in a sealed train should not exceed the values:
    - Pressure changes of 1000 Pa in 1 s.
    - Pressure changes of 1600 Pa in 4 s.
    - Pressure changes of 2000 Pa in 10 s.

7. SELECTION OF CROSS-SECTIONS

When preparing the standard sheets, the so-called minimum profiles were first created, which were designed to include the actual vehicle clearance cross-section, including the extension for electrified railways, the track-centre distance in the case of a double-track tunnel, and the clear walking and working space

In order to provide space for the traction sectioning, the height of the frame excavation structure had to be slightly corrected. In the case of the single-track TBM, the tunnel cross-section was minimally increased. In contrast, in the case of the bored tunnel, the vault in both single-track and double-track tunnels allows the implementation of traction sectioning without increasing the profile.

These profiles were then compared with the results of aerodynamic calculations, which, in accordance with the relevant European legislation (TSI INF, ČSN EN 14067-5), primarily checked the fulfillment of the health criterion. Furthermore, the fulfillment of the required pressure comfort values, the pressure load on the vehicles and on the tunnel equipment itself when the train passes through the tunnel were assessed. The result is that for lower speeds (up to 200 km/h) the minimum profile is sufficient. Above 200 km/h, the tunnel profile is increased based on aerodynamic assessment.

Subsequently, optimization was carried out from the perspective of real operation, where in the case of speeds up to 200 km/h, the operation of non-sealed trainsets is assumed, where passenger comfort must be ensured by the size of the tunnel profile. On the contrary, for higher speeds, there would be a significant increase in the required clear area of the tunnel profile. For speeds from 200 km/h to 270 km/h, modern sets are considered, which ensure passenger pressure comfort precisely by the pressure tightness of the cars.

At high speeds of 270 to 350 km/h, aerodynamic calculations result in extremely large clear tunnel areas, which would be unfeasible from the perspective of investment costs. It should be noted here that the calculations are made for a standard train set, which has a cross-sectional area of 12 m^2. Currently operated high-speed trains have a smaller area and therefore generate smaller pressure changes when passing through the tunnel. For these speeds, the cross-sections in the standard sheets will be for information only and the tunnel cross-section should be designed on the basis of an aerodynamic assessment, taking into account the specific length of the tunnel and, in particular, the expected operated trains.

8. CONCLUSION

The preparation of standard sheets of clear tunnel cross-sections is a very complex multidisciplinary issue. The whole process showed how significant the aerodynamic effects in the tunnel have not only on passengers but also on the tunnel equipment and on the trains themselves and their operation. During the processing, it was necessary to assess a large number of variants and input parameters, so at the time of processing this contribution, the debate over the resulting cross-sections is still ongoing. The result will be standard sheets that will not only simplify the preparation of railway tunnel structures, but above all contribute to reducing costs both for the preparatory phase of the project and, above all, for the actual implementation of the tunnel structure.

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