Management Summary

Investigation of variants for the traction power supply of the Erzgebirgstunnel on the planned high-speed railway line Dresden – Prague using simulation methods

Short title:	**Investigation of traction power supply variants for the Erzgebirgstunnel**
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1 Motivation and objectives

As part of the creation of Trans-European railway corridors in the so-called TEN network, a high-performance high-speed line is currently being planned between Dresden, the state capital of Saxony, and the Czech capital Prague (see Figure 1).

The new railway line is intended to relieve the existing double-track main line through the Elbe Valley via Bad Schandau (D) and Děčín (CZ). The new line also intends to connect to the planned high-speed line from Ústí nad Labem to Prague in the Czech Republic to considerably increase the transport capacity of the railway on this important European route in the future and significantly shorten journey times.

Part of the new high-capacity line will be an approximately 30 km long tunnel through the Ore Mountains (also referred to as “Erzgebirgstunnel”), around two-thirds of which will run through German territory and one-third through Czech territory. There is a joint Germany/Czech Republic planning area for the tunnel.

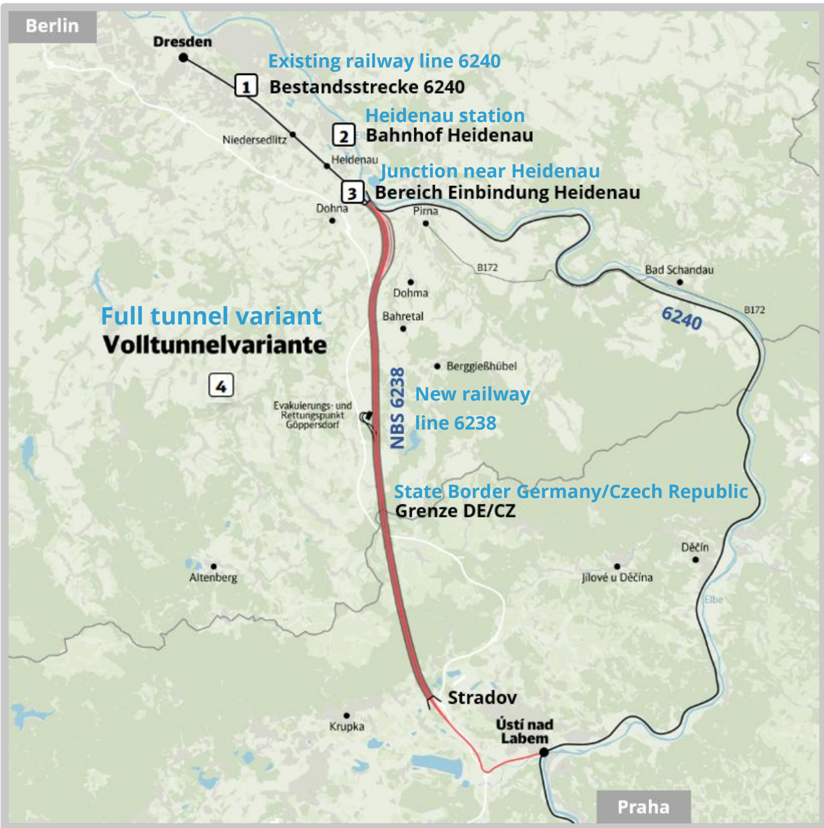


Figure 1: Route of the planned high-speed railway line Dresden – Prague (section between Dresden and Ústí nad Labem), full tunnel variant

An overview longitudinal section of the route including the mountain and track gradient profile is shown in Figure 2.

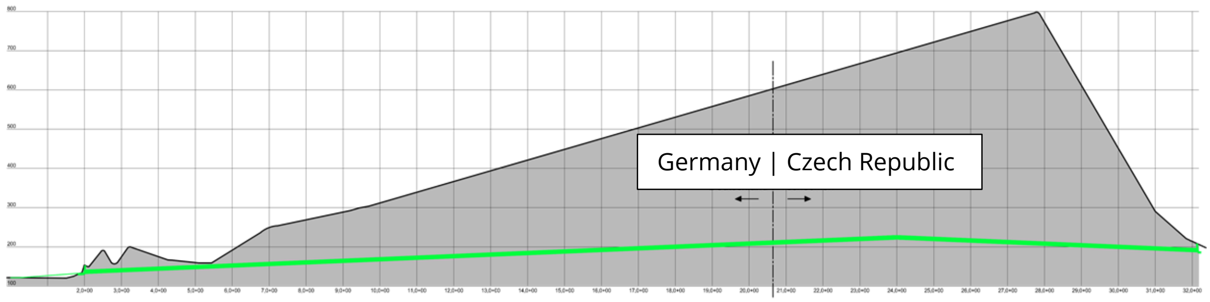


Figure 2: Overview longitudinal section of the tunnel in the Ore Mountains (Erzgebirgstunnel), [1] (edited)

For the new line with the cross-border Erzgebirgstunnel through the Ore Mountains, multiple traction power supply variants were developed and evaluated regarding their technical feasibility and advantages as part of a scientific study [2]. Basis for the investigations was a planned railway schedule for normal and peak hour operation.

In particular, the location of the system separation point (German: “Systemtrennstelle”, abbreviated with SST) between the existing German AC 15 kV 16.7 Hz and the planned AC 25 kV 50 Hz traction power supply system (previously: DC 3 kV) in the Czech Republic, the design of the feeders and the choice of contact line construction in the tunnel were analysed using modern simulation tools.

in addition to the investigated electrotechnical parameters, aspects of railway operation, availability, tunnel safety and maintenance must be considered in particular for a future detailed design of the feeder structure for the Erzgebirgstunnel.

Based on the scientific study [2], an in-depth system study of the feeder concept [7] was carried out and a further variant of the railway energy supply was simulated and analysed. All investigation variants are assessed and compared technically and energetically in terms of voltage stability, exploitation of the current carrying capacity and energy loss of the catenary system.

2 Simulation variants and methodology

2.1 Simulation variants

The new railway line connects to the existing traction power supplies with their respective national electrification systems on both sides of the Erzgebirgstunnel. While the AC 15 kV 16.7 Hz system with powerful 16.7 Hz generators is already in place on the German side, the AC 25 kV 50 Hz system is planned to replace the DC 3 kV traction power supply in the Ústí nad Labem area.

When establishing a connection between both electrification systems, interconnection or bridging of the overhead line sections with different voltages and frequencies is impossible. For this reason, a system separation point in the overhead contact line is mandatory on the new line for the transition of the voltage systems.

The development of variants for the traction energy supply of the Erzgebirgstunnel is based on the following structural and operational investigation criteria:

1. System structure and feeding concept
   a. Position of the system separation point
   b. Design of the feeders

2. Overhead contact line system in the tunnel
   a. Catenary
   b. Overhead conductor rail

3. Railway Operation Concept
   a. Day timetable
   b. Night timetable

   each for normal and worst-case operation

The analysed variants are formed based on the possible locations of the system separation point as follows:

Variant 1	STS near national border	(tunnel apex)
Variant 2	STS in CZ	(tunnel portal, outside the tunnel)
Variant 3	STS in DE	(tunnel portal, outside the tunnel)

The necessary integration into the high voltage power supply systems in Germany and the Czech Republic is technically feasible for all the presented options.

For **variant 1** (shown in Figure 3), it is only possible to longitudinally separate the feeding sections within the tunnel and feed the separated tunnel sections from the 16.7 Hz and 50 Hz traction power network from each side. At the tunnel apex, a coupling point (cross-coupling) is provided on the end of both feeding sections between the two separately fed tunnel tubes to improve the voltage stability.

In the current planning phase, many uncertainties are present, such as the undefined location of the proposed 50 Hz substation in the Czech Republic. A new substation may be built or instead one of the existing grid connection points in either Koštov or Světec could be used. Therefore, multiple feeder lengths in the Czech territory were analysed. This results in three different designs for variant 1:

1A	New substation in the immediate vicinity of the tunnel portal in CZ
1B	Existing substation site in Koštov (previously DC 3 kV), approx. 10 km from the tunnel portal in CZ
1C	Existing substation site in Světec (previously DC 3 kV), approx. 30 km from the tunnel portal in CZ

In variants 1B and 1C, an autotransformer system from the substation to the tunnel portal on the Czech side is envisioned for reasons of voltage stability (two autotransformers are installed every 10 km). No autotransformers will be installed inside the tunnel.

The existing rectifier substation in Koštov is connected to the 22 kV grid. There is a direct connection to the 110 kV grid for the rectifier substation in Světec. The substation site in Světec therefore has a significantly higher short-circuit capacity than the site in Koštov which is closer to the tunnel portal.

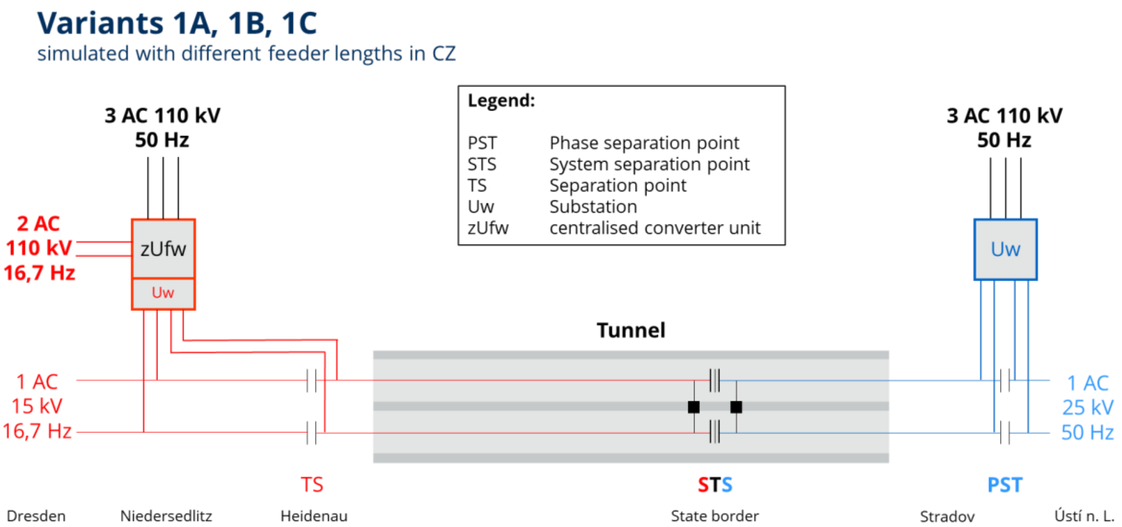


Figure 3: Variant 1, system separation point inside the tunnel apex, one-sided supply of the tunnel on both sides with AC 15 kV 16.7 Hz and AC 25 kV 50 Hz respectively

For variants 2 and 3 a distinction is made between a one-sided (A) and a two-sided (B) supply of the Erzgebirgstunnel's feeding sections.

Based on the simulation results from variant 1, **variant 2A** (STS in CZ, one-sided supply of the tunnel from DE with AC 15 kV 16.7 Hz) can be ruled out due to the poor voltage stability values. An autotransformer system with 2AC 2x15 kV 16.7 Hz, which is technically conceivable but particularly expensive inside the tunnel, is ruled out.

For the railway energy supply of the Erzgebirgstunnel's feeding sections with a system separation point planned in the Czech Republic, only the two-sided supply with the AC 15 kV 16.7 Hz system (**variant 2B,** Figure 4) is considered. The tunnel sections are supplied from the existing substation in Dresden-Niedersedlitz and a new decentralized 16.7 Hz converter station near the tunnel portal in the Czech Republic. For the parallel operation of the substation and the converter station, voltage pilot signal control is planned, for which long-term positive operating experience has been gained in Germany for comparable feeder configurations.

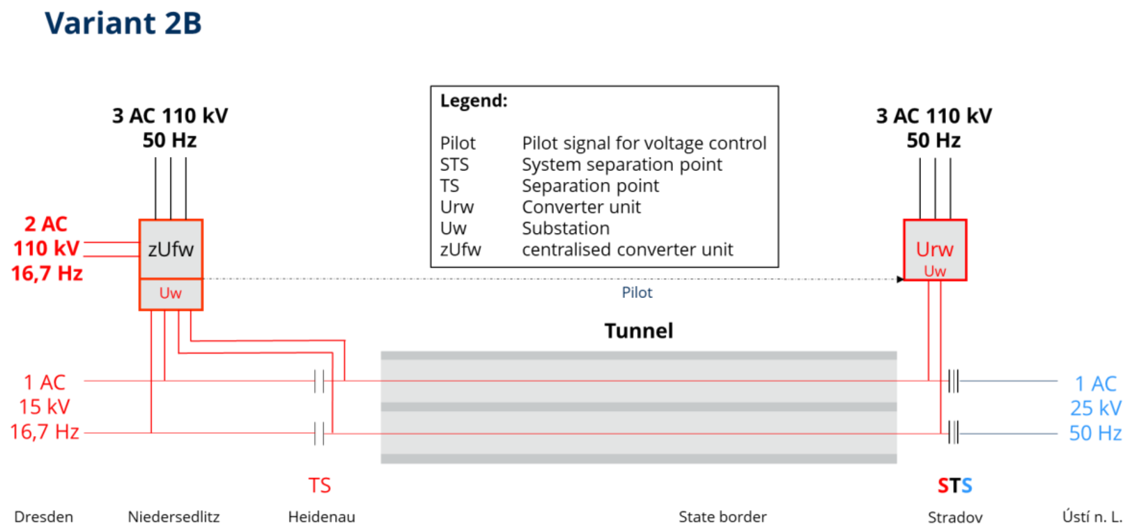


Figure 4: Variant 2B, system separation point in the Czech Republic, two-sided supply of the tunnel with AC 15 kV 16.7 Hz

The **variant 3A** (STS in Germany, one-sided supply from a substation in the Czech Republic, tunnel section fed with AC 25 kV 50 Hz) can be ruled out due to insufficient voltage stability. An autotransformer system with 2AC 2x25 kV 50 Hz, which is technically feasible but too costly, especially in tunnels, is ruled out.

There are several technically possible sub-variants for **variant 3B** with system separation point in DE, which feed the Erzgebirgstunnel's feeding sections either on one or both sides with AC 25 kV 50 Hz.

In the simplest case, conventional 50 Hz substations are provided on both sides of the tunnel. These substations in Germany and the Czech Republic are connected to two different 110 kV grids that are located far apart from each other, which means that the same phase angle cannot be guaranteed. For this reason, in addition to the system separation point in Germany, this variant also requires a phase separation point in the tunnel (**variant 3B-1**), which results in the operational disadvantage of a double system separation section structure. In addition, only one-sided supply can be realised on both sides, which was already ruled out as a disadvantage in variant 1. This subvariant is therefore not pursued further.

Without a phase separation point in the tunnel, there would be a permanent coupling of the 110 kV/50 Hz supply networks via the 25 kV overhead line, which could lead to undesirable transfer power. This would require the use of special transformers in the substations (**variant 3B-2**), for which there are no references or experience in the railway sector. This subvariant is therefore also ruled out as unfavourable.

The use of a 50 Hz converter in Germany (**variant 3B-3**, see Figure 5) coupled to the 50 Hz substation in the Czech Republic by means of voltage pilot signal control eliminates the problem of the direct grid connection at the 110 kV level via the 25 kV feeder. Furthermore, there is no need for a phase separation point at the tunnel apex, which results in an advantageous two-sided supply of the tunnel. In Germany, there are many years of experience with pilot signal control from the 16.7 Hz grid, which can be directly transferred to the 50 Hz supply.

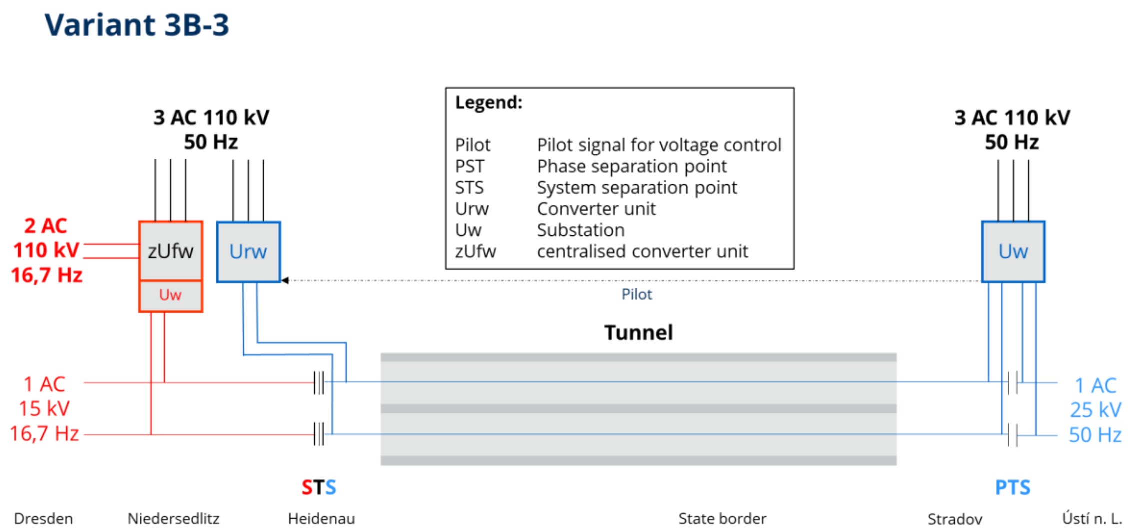


Figure 5: Variant 3B, system separation point in Germany, two-sided supply of the Erzgebirgstunnel's feeding sections with AC 25 kV 50 Hz

2.2 Methodology

Based on the traffic task definition (VAst) [3] and the railway operations study (EBWU) [4] operating concepts were created for the tunnel. These concepts were modelled in regard to railway operations and driving dynamics using the commercial software OpenTrack [2] in a time step procedure. Both a day and a night timetable as well as a normal and a worst-case operating scenario (period of maximum utilisation) were investigated using typical train, vehicle and driving data, and the highest electrical loads were determined.

Table 1 illustrates the operating programmes examined in the model.

Table 1: Number of trains per direction

Train category	Normal operation, day timetable	Worst-Case operation, night timetable
SPFV (Long-distance passenger trains)	1 per 60 minutes	-
SPNV (Regional passenger trains)	1 per 120 minutes	-
SGV (Freight trains)	4 per 60 minutes	12 per 60 minutes

The Erzgebirgstunnel shall be used exclusively by freight traffic at night. The night timetable in worst-case operation with a dense cycle of 5 minutes results in the highest traffic load. It characterises the total amount of total energy in the network and thus determines the necessary system design. The daytime timetable in normal operation is dominated by the high performance of the individual vehicles and is energetically representative for the continuous operation.

In conjunction with the railway operation simulation in OpenTrack [5], the network of the electrical railway energy supply was modelled through co-simulation with the commercial software OpenPowerNet [6] and the resulting electrical load flows in the electrical energy systems were calculated as quasi-stationary values.

As a result of the coupled simulations, the driving diagrams of all trains are available for validation of the operating programmes as well as all voltage, current and power curves over time and location, including the respective energies and loss balances for evaluation of the variants that were investigated. The simulation results allow a qualitative and quantitative comparison of the operating scenarios and the analysed energy supply concepts. For the subsequent evaluation from an electrotechnical point of view, technical and economic criteria were considered.

3 Evaluation criteria and results

3.1 Evaluation criteria

The study of variants to assess the technical feasibility, performance, energy efficiency and availability of the future railway energy supply is based on the following normative and economic evaluation criteria:

1. Voltage maintenance
    a. Minimum voltage at the current collector according to DIN EN 50163
    b. Average usable voltage at the current collector according to DIN EN 50388-1
2. Load capacity and actual load of critical equipment (overhead line and cables)
3. Loss energy and efficiency of the overhead contact line system as seen from the substation

Due to the early stage of the project (preliminary planning), no railway substation design and component dimensioning were carried out when analysing the railway energy supply of the Erzgebirgstunnel. In addition to the structural and operational consideration of the railway energy supply, the focus of the technical feasibility of the cross-border route section is primarily on the requirements for the overhead line equipment of the Erzgebirgstunnel, which must be determined at an early planning stage.

3.2 Results

To assess the **voltage stability** in the overhead contact line network in accordance with the applicable standards DIN EN 50163 and DIN EN 50388-1, a location-dependent evaluation of the temporal voltage curves of all vehicles was carried out for all overhead contact line sections.

The minimum voltages occurring at the current collector are within their normative limits for all analysed variants in normal and worst-case operation. The two-sided supply leads to significantly better voltage stability in the tunnel in all operating cases, either with a catenary system or with an overhead conductor rail.

With regard to the average usable voltage $U_{mean\ useful}$ according to EN 50388, the variant-specific system dimensioning and design are sufficiently rated. In **variant 1A** with catenary system in worst-case operation, the value of the average usable voltage is 3 V below the normative specification value, but this is negligible due to the selected restrictive input parameters. In all other scenarios, the value is above the normative default value.

The voltage stability requirements are fulfilled best for **variant 3B-3** (STS in Germany, two-sided supply at 25 kV 50 Hz AC) both in normal operation and in worst-case operation.

Figure 6 shows the location-dependent minimum voltage curves at the pantographs of all vehicles in each direction over the entire 2-hour simulation period.

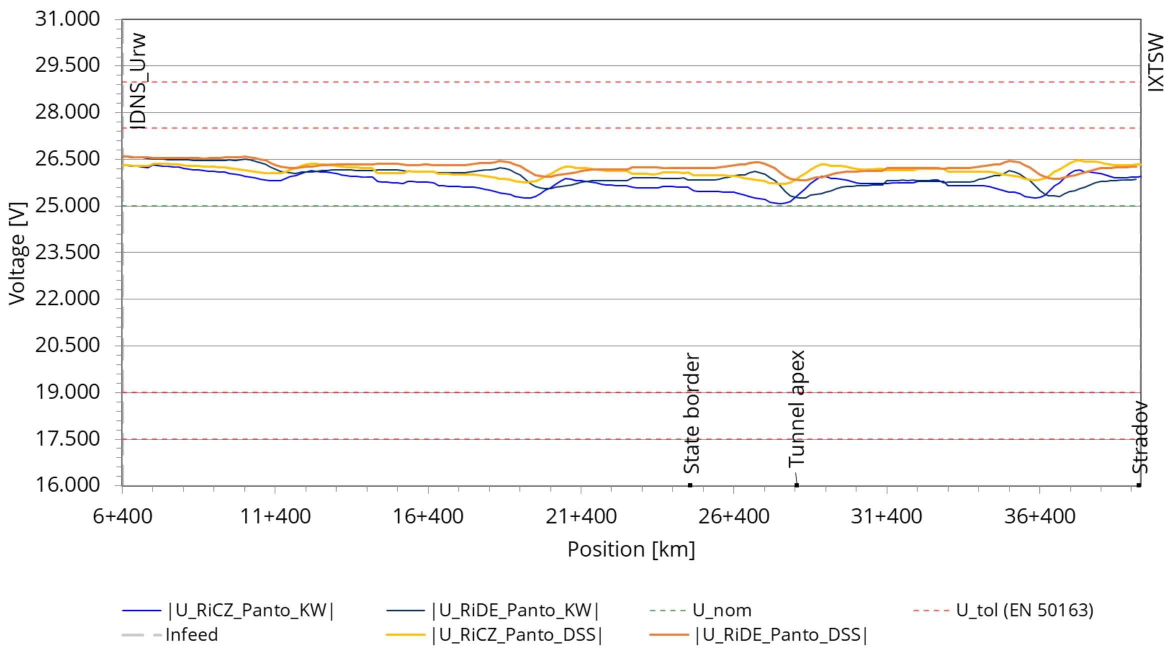


Figure 6: Comparison of voltage stability of catenary vs. overhead conductor rail, variant 3B-3 in worst-case operation, 25 kV grid component, legend: KW – catenary system, DSS – overhead conductor rail, RiDE – track direction to Germany, RiCZ – track direction to Czech Republic

To assess the **load on the overhead contact line system**, the maximum currents occurring in the electrical conductors were determined for the time periods 1 s, 300 s and 900 s on a variant-specific basis and summarised in relation to time, see an exemplary representation in Figure 7.

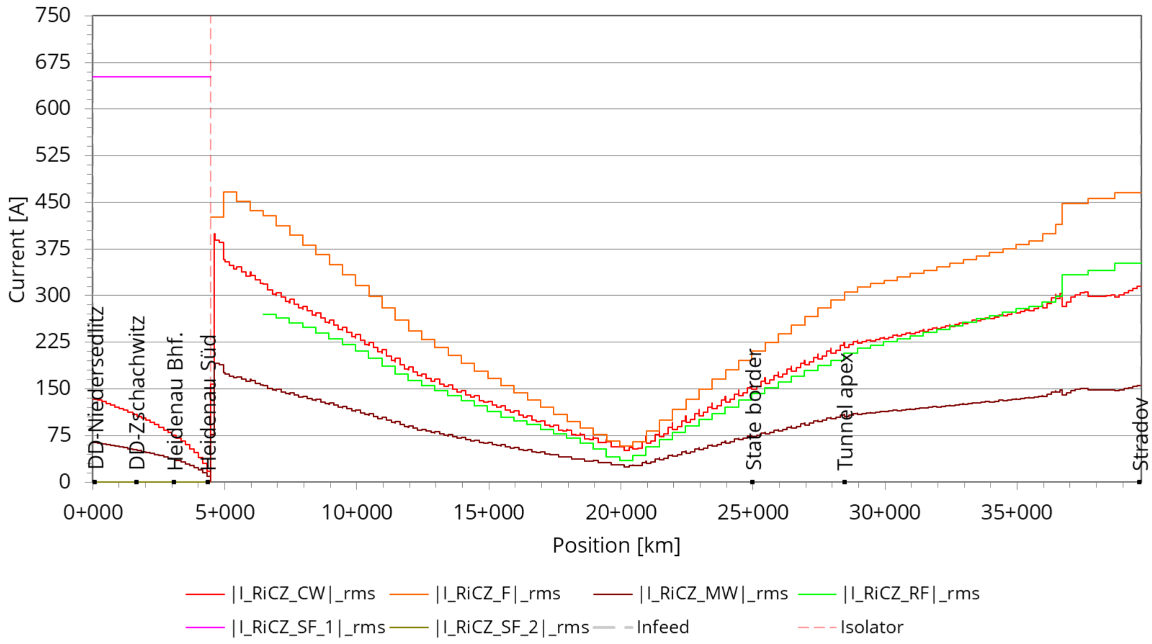


Figure 7: Maximum load currents (overhead contact line and feeder lines) in variant 2B with overhead catenary system, legend: CW – contact line, MW – messenger wire, RF – return conductor, SF – substation feeder line, F - reinforcement line (parallel to the track), RiDE – track direction to Germany, RiCZ – track direction to Czech Republic

The quotient of the respective maximum current value to the current carrying capacity was then calculated. The utilisation factors for all investigated variants are stated and visualised in colour in Table 3.

The value determined for 900 s was compared with the value of the continuous current carrying capacity (see Table 2). The 300-s value was roughly evaluated in comparison with the 1.3-fold continuous value and the 1-s peak value in comparison with the 2-fold continuous value. Especially in the 1 s short-term range, the current-carrying capacity values are actually orders of magnitude higher than twice the continuous current-carrying capacity. This simplified approach was chosen in the current planning phase, as there was no need for complex calculations of the current-carrying capacity with thermodynamic input parameters, which are also still unknown.

The estimated current-carrying capacity values apply to 16.7 Hz. At 50 Hz, the values are reduced slightly. However, due to the higher rated voltage in the 50 Hz system, the currents are disproportionately lower for the same power, so that the same current-carrying capacity values as for 16.7 Hz were used as a rough estimate.

Table 2: Continuous current carrying capacity for some conductors

	Maximum continuous current in A
Catenary type “Re 250” with parallel feeder line	1.230
Overhead conductor rail type “Sicat SR” with contact wire type “AC-120”	3.446
2xAl 240 substation feeder line conductor	1.378

Table 3: Utilisation of the current-carrying capacity of the overhead contact line and substation feeder line (SL 1). RE250+VL – Catenary system type RE250 with parallel feeder line, DSS – overhead conductor rail, RiDE – track direction to Germany, RiCZ – track direction to Czech Republic

0% 80% 95%

					15 kV								25 kV			
Utilisation of the current-carrying capacity in %					Re250+VL		SL 1		DSS		SL 1		Re250+VL		DSS	
		Fahrplan	Variante	Zeitbereich	RiCZ	RiDE	RiCZ	RiDE	RiCZ	RiDE	RiCZ	RiDE	RiCZ	RiDE	RiCZ	RiDE
STS TSP	Day	Normal operation	1A	1 s	84%	76%	51%	54%	26%	25%	56%	59%	29%	36%	7%	10%
				300 s	88%	81%	67%	71%	29%	26%	66%	69%	18%	25%	6%	8%
				900 s	75%	69%	57%	60%	25%	21%	56%	59%	19%	22%	6%	7%
	Night	Worst-Case operation		1 s	78%	64%	53%	57%	26%	21%	57%	61%	25%	27%	7%	7%
				300 s	89%	75%	63%	67%	28%	20%	61%	65%	17%	21%	5%	5%
				900 s	116%	98%	82%	87%	37%	25%	80%	84%	22%	28%	7%	7%
STS DE	Day	Normal operation	3B-3	1 s	66%	30%							43%	34%	13%	10%
				300 s	20%	16%							52%	40%	17%	13%
				900 s	17%	17%							45%	37%	15%	12%
	Night	Worst-Case operation		1 s	30%	22%							52%	29%	16%	9%
				300 s	13%	16%							58%	35%	19%	11%
				900 s	17%	21%							75%	46%	25%	15%
STS CZ	Day	Normal operation	2B	1 s	62%	55%	24%	25%	16%	17%	24%	25%				
				300 s	57%	44%	34%	36%	18%	20%	34%	35%				
				900 s	48%	39%	32%	34%	16%	17%	32%	33%				
	Night	Worst-Case operation		1 s	59%	34%	27%	29%	20%	13%	27%	29%				
				300 s	65%	44%	37%	39%	20%	15%	37%	39%				
				900 s	83%	57%	48%	50%	26%	20%	47%	50%				

The results show that the **current-carrying capacity** of the catenary contact line with one-sided supply at the German nominal voltage level (**variant 1A**) is borderline to inadequate. In variant 1A, the loads in worst-case operation at night are unacceptably high in the catenary design. Even in normal operation, the utilisation of the current carrying capacity is at its highest in this scenario.

In **variant 3B-3**, the overhead contact lines analysed in the tunnel area (catenary system and overhead conductor rail) have sufficient current carrying capacity compared to the currents occurring during operation.

The aim of the **energy analysis** is the variant-specific assessment of the total energy requirement and the determination of the energy loss of the overhead contact line system. For this purpose, the losses of the overhead contact line system were determined from the simulations for a 2-hour simulation period and normal operation according to the EBWU (see [4]). These are compared in Figure 8. The total losses in the 15 kV and 25 kV network sections are different between the individual variants due to the variant-specific section lengths in the 15 kV and 25 kV grid.

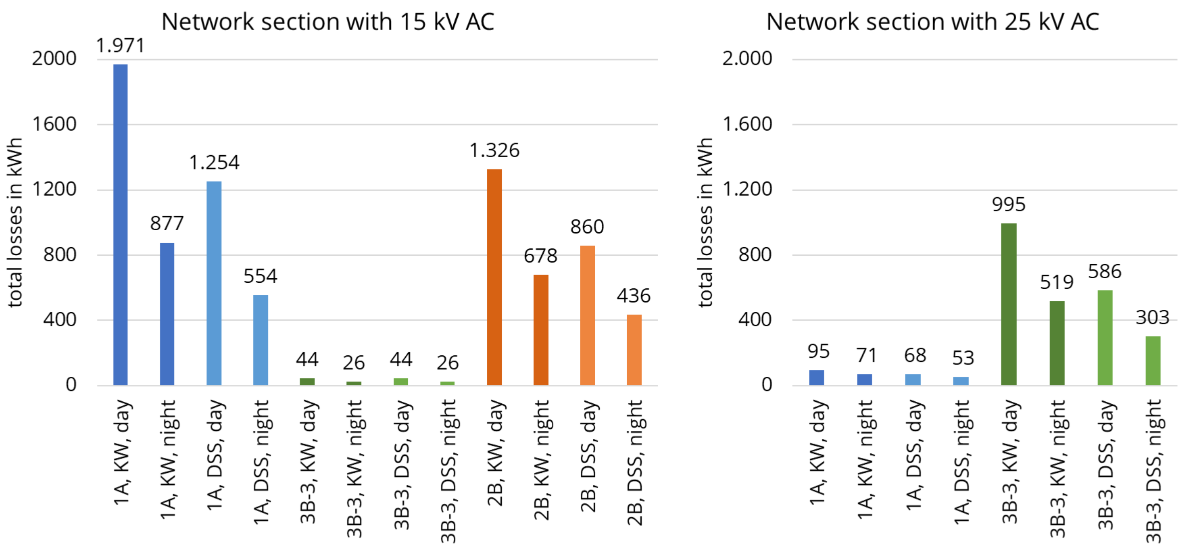


Figure 8: Total losses of the overhead contact line system (2 h simulation period, normal operation according to EBWU), legend: Variant (1A, 2B, 3B-3) according to chapter 2.1, KW – catenary system, DSS – overhead conductor rail

In order to ensure direct comparability of the energy loss in 24-hour operation, the same daily transport performance must be used as a basis for comparison. Based on the daily timetables from the EBWU, the number of trains per train class was determined for each direction. For each train class (SPFV – long distance passenger trains, SPNV – local passenger trains, SGV – freight trains), the traffic work in tonne-kilometres and the energy consumed at the pantograph from the normal operating scenarios day and night were determined for each specific variant for each network and direction. From the energy absorbed at the pantograph and the losses in the overhead contact line, a ratio was formed and used to determine the total energy loss. The resulting error due to specifically lower losses due to better voltage stability compared to the simulated peak hour is on the safe side and is neglected in the analysis. The individual results are then compiled in relation to the values for 24-hour operation for the total losses of the overhead contact line system, the daily transport load and the total energy requirement of the energy consumed at the pantograph.

In normal operation, an operational transport performance of approx. 14,143,940 tkm is achieved within 24 hours. The modelled train journeys consume an absolute energy of approx. 426,101 kWh at the pantograph.

Based on the simulated results, the total energy requirement seen from the substation output terminals (Table 4) and the loss energy at the overhead contact line system for the operating programme of one day according to the EBWU (Table 5) can be determined and compared between the types of overhead contact line. The maxima and minima of the respective values are highlighted in colour.

Table 4: Total energy demand from the substation output terminals per 24 h

Variant	E_{KW}	E_{DSS}	E_{KW} - E_{DSS}	(E_{KW} - E_{DSS}) / E_{KW}
1A	442.312 kWh	436.375 kWh	5.937 kWh	1,34%
2B	438.054 kWh	434.033 kWh	4.021 kWh	0,92%
3B-3	434.089 kWh	430.826 kWh	3.263 kWh	0,75%
	Max	**Min**	**Max-Min**	**(Max-Min)/Max**
Extreme values	*442.312 kWh*	*430.826 kWh*	*11.486 kWh*	*2,60%*

Table 5: Loss energy at the overhead contact line system per 24 h

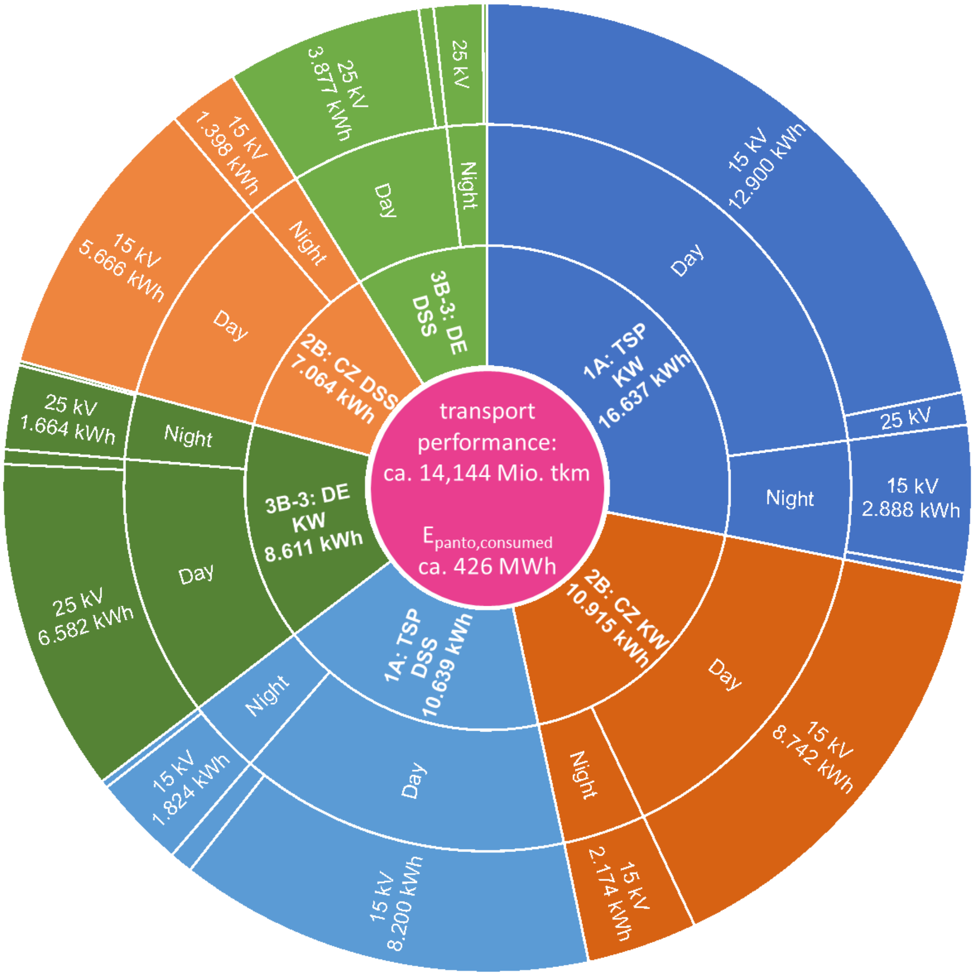
Variant	$E_{KW,V}$	$E_{DSS,V}$	$E_{KW,V}$ - $E_{DSS,V}$	($E_{KW,V}$ - $E_{DSS,V}$) / $E_{KW,V}$
1A	16.637 kWh	10.639 kWh	5.998 kWh	36,05%
2B	10.915 kWh	7.064 kWh	3.851 kWh	35,28%
3B-3	8.611 kWh	5.213 kWh	3.398 kWh	39,46%
	Max	**Min**	**Max-Min**	**(Max-Min)/Max**
Extreme values	*16.637 kWh*	*5.213 kWh*	*11.424 kWh*	*68,67%*

The sunburst diagram in Figure 9 shows the hierarchical comparison of the variant-specific energy loss of the overhead contact line system for 24-hour operation with time-of-day and grid-specific components. The transport work and the energy absorbed at the pantograph are plotted inside the circle. As a result of the operating programme, it is the same for all variants and thus allows a direct comparison of the variants investigated. The variants are shown in clockwise order, starting with the variant with the highest energy loss of the catenary system (variant 1A catenary system) and ending with the variant with the lowest energy loss of the catenary system (variant 3B-3 overhead conductor rail).

The following statements can be derived after analysing the simulation results:

- Variant-specific energy losses are always lower when overhead conductor rails are used than with the catenary configuration.
- The variants with double-sided supply always have lower losses than the single-sided supplied variants when using the same overhead contact line design.
- The variants that have larger network components with a higher nominal voltage (25 kV) always have the lowest losses.
- The use of the overhead conductor rail reduces the loss level compared to the catenary system by approx. 35 to 39 %, depending on the variant.
- The total energy requirement is reduced by a maximum of 1.34 % (single-sided supply) or 0.92 % (double-sided supply) with overhead conductor rails compared to catenary systems.
- The minimum-loss variant (3B-3, double-sided, ceiling conductor rail) reduces the loss level by 68.67 % and the total energy requirement by 2.60 % compared to the initial variant (1A, single-sided, chain system).

The most energy-efficient configuration of all the variants analysed is variant 3B-3 with overhead conductor rail. This variant has the lowest total losses of the overhead contact line system and therefore also the lowest absolute total energy requirement compared to all the variants analysed. **From an electrical engineering point of view, variant 3B-3 with overhead conductor rail is therefore the preferred variant.**



day	25 kV	637 kWh
night	25 kV	212 kWh
day	25 kV	457 kWh
night	25 kV	158 kWh
day	15 kV	281 kWh
night	15 kV	83 kWh
day	15 kV	281 kWh
night	15 kV	83 kWh
	25 kV	971 kWh

Figure 9: Hierarchical comparison of the variant-specific energy loss of the overhead contact line system (24-hour operation with daytime-specific and grid-specific components)

4 Recommendation and further need for investigation

Due to the improved voltage stability, the higher current carrying capacity and the lower loss level (assuming the same tunnel cross-section), the use of an overhead conductor rail is recommended in the Erzgebirgstunnel.

The simulations carried out have shown that variant 3B-3 with two-sided supply with AC 25 kV 50 Hz from a substation in the Czech Republic and a converter in Germany (system separation point at the German tunnel portal) is recommended as the preferred electrical engineering variant. Due to the location of the system separation point in Germany, further criteria (e.g. the ability to accelerate a freight train on the gradient in front of the tunnel portal or the length of the system separation point considering manual operation of the main vehicle switch) must be taken into account when deciding on the variant.

Due to the significantly better voltage stability and the considerably lower line losses, the two-sided supply of the Erzgebirgstunnel's feeding sections is fundamentally recommended from an electrotechnical point of view. However, a two-sided supply of the Erzgebirgstunnel poses challenges because the power is supplied on different national territories and by two different operators (DB AG and Správa Zěleznic). For example, issues related to the ownership of the electrotechnical systems would have to be clarified on both national territories (including access and switching authorisations for a 50 Hz converter in Germany or a 16.7 Hz converter in the Czech Republic). Due to the different regulations of the two operators, interfaces, areas of application, and responsibilities must be harmonised and agreed. Furthermore, a joint electricity price model or a division of energy billing is necessary due to the country-specific energy tariffs and tax billing.

In addition to the possible problems related to this interface management, the economic efficiency of a two-sided supply should be analysed over the system life cycle because:

- only a slight reduction in the loss level is expected and
- the return on the system investment is presumably insufficient compared to the savings from lower energy losses over the system life cycle.

The following technical analyses are also recommended for the upcoming planning phases:

- Detailed consideration of failure modes, in particular with regard to tunnel safety / rescue concept, maintenance and operation with reduced performance

- Design and detailed consideration of the railway power supply on the Czech side, in particular for the Ústí nad Labem junction and the new Ústí - Praha line, taking into account the changeover from DC 3 kV to AC 25 kV 50 Hz, the integration of the more powerful substations to be built into the national grid (possibly with asymmetry) and the possible types of supply (conventional supply with transformers and phase separators versus supply by converters).

List of sources

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