

Open-source one-dimensional modelling of piston-effect pressure waves in high-speed railway tunnels: verification, benchmarking against 3D CFD and single-train design-load screening

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Abstract

Purpose – The piston effect of a high-speed train passing through a tunnel produces pressure transients that drive tunnel cross-section design and impose loads on rolling stock and equipment. This paper verifies an open-source one-dimensional solver for these transients and defines the limits of its predictive capability.

Design/methodology/approach – The train is represented as a moving cross-sectional-area blockage in the quasi-one-dimensional compressible Euler equations, discretised with a second-order MacCormack scheme. The solver is verified against the analytical entry-wave solution, validated against a published full-scale measurement of the piston-wind field, benchmarked against published three-dimensional computational fluid dynamics (CFD), subjected to a five-level grid-refinement study with dissipation and nose-ramp sensitivity tests and applied to a single-train design case.

Findings – The compression-wave amplitude agrees closely with both the analytical solution and the published three-dimensional CFD results. The principal result concerns the localised suction peak beneath the train nose, commonly assumed to lie beyond the reach of area-averaged one-dimensional models: once the cell size resolves the nose ramp, it is grid-convergent, with a Richardson value within a few per cent of the three-dimensional CFD result. What had appeared to be non-convergence was due to under-resolution. Coupling to a cabin-sealing model shows that a narrower tunnel is viable only if the rolling stock carries a more demanding sealing specification.

Originality/value – The solver is, to the author's knowledge, the first permissively licensed one-dimensional tool for high-speed compression-wave transients released with a reproducible verification-and-validation suite, providing a common baseline for benchmarking new closures. The grid study also corrects a limitation commonly attributed to this class of model.

Keywords Piston effect, High-speed railway tunnel, Compression wave, MacCormack scheme, Grid convergence index, Cabin sealing

Paper type Research article

Nomenclature

Symbol	Definition
A, A_0	free/undisturbed tunnel cross-sectional area (m^2)
A_{tr}	train cross-sectional area (m^2)

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RS	c_0	ambient speed of sound (m/s)
	GCI	grid-convergence index (%)
	L, L_{tr}	tunnel/train length (m)
	p, p_0	pressure/ambient pressure (Pa)
	P_f	initial compression-wave amplitude (Pa)
	pobs	observed order of grid convergence (–)
	u, V	air/train velocity (m/s)
	$\beta = A_{tr}/A_0$	blockage ratio
	λ_t, λ_{tr}	Darcy friction factors (tunnel/train)
	Δp_{pp}	exterior peak-to-peak pressure change (kPa)
	E	specific total energy (J/kg)
	k_2, k_4	Jameson artificial-dissipation coefficients (–)
	γ	ratio of specific heats (–)
	Δx	grid spacing (m)
	τ	dynamic sealing time constant of the rolling stock (s)

1. Introduction

When a train enters a tunnel at high speed, the displaced air generates a compression wave that propagates at the speed of sound; the tail generates an expansion wave, and both reflect at the open portals with a change of sign. The superposition of these waves and of the quasi-steady pressure field around the train produces the unsteady pressure environment known as the piston effect. Its consequences are well documented: alternating loads relevant to the fatigue design of car bodies and tunnel equipment; aural discomfort and, in the limit, medical risk; the micro-pressure wave emitted at the exit portal; and a dominant influence on the required free cross-sectional area of the tunnel, one of the most expensive geometric parameters of a high-speed line (Baron, Mossi, & Sibilla, 2001; Gawthorpe, 2000; Hara, 1961; Howe, 1998; Niu, Sui, Yu, Cao, & Yuan, 2020; Vardy, n.d.; William-Louis & Tournier, 2005; Woods & Pope, 1981).

Train–tunnel aerodynamics has been dominated in the last two decades by three-dimensional CFD with moving-mesh techniques, used to study surface pressures for different tunnel lengths (Luo, Zhang, Zhang, & Zhang, 2017), unsteady subway flows (Xue, You, Chao, & Ye, 2014), car-body fatigue loading during crossings (Lu *et al.*, 2019), slipstreams in double-track tunnels (Fu, Li, & Liang, 2017; Meng, Meng, Wu, Li, & Zhou, 2021) and aerodynamic comfort during passages (Yan, Yang, & Zhang, 2011). The Chinese high-speed programme has driven much of this activity, reviewed by Ma, Zhang, and Liu (2012), and the fluctuating pressure loading of trains in tunnels had been characterised experimentally and numerically before it (Seo, Park, & Min, 2006). These studies resolve the flow in detail but require meshes of tens of millions of cells and days of computing time per configuration, which makes them poorly suited to the repeated multi-case scans – over tunnel length, cross-section, blockage ratio and speed – needed early in the design of a new line.

One-dimensional unsteady compressible models occupy the opposite end of the cost–fidelity spectrum. Since early analytical and flow-prediction methods (Hara, 1961; Woods & Pope, 1981), 1D methods have been refined continuously (Baron *et al.*, 2001; Howe, 1998; William-Louis & Tournier, 2005) and remain the workhorse of practical tunnel aerodynamics, as implemented in software such as ThermoTun (Vardy, n.d.); network models of the same family reproduce measured air-exchange rates in extra-long tunnels within about 7% (Krasnyuk, Lugin, Irgibayev, & Alferova, 2023), and 1D formulations remain an active research topic (López González, Galdo Vega, Fernández Oro, & Blanco Marigorta, 2014; Vorobyev & Bogdanov, 2025). Openly available 1D tools do exist, but not for this physics. The Subway Environment Simulation program (SES) (U.S. Department of Transportation, 2002), whose

version 4.1 was released from distribution restriction in 2021 and forked as the open-source OpenSES ([OpenSES Project, 2022](#)), has been used for decades and is arguably the reference open tool for underground aerodynamics. It is, however, an incompressible, quasi-steady network model developed for subway ventilation, thermal and fire analysis, and it therefore does not represent the sonic-speed propagation, portal reflection and superposition of compression waves that govern loads at 350 km/h. The compressible 1D codes that do represent them – ThermoTun ([Vardy, n.d.](#)), and the TETUN and TRUNS codes developed for European certification work and validated against full-scale campaigns ([Somaschini, Rocchi, Tomasini, & Schito, 2020](#)) – are proprietary or otherwise not openly distributed. Academic method-of-characteristics implementations are widespread but are generally described rather than released.

The scope of this paper is deliberately restricted to a single train. Both the exterior wave-system loads and, through a first-order cabin-sealing model, the interior pressure relevant to passenger comfort are treated. Two-train crossings in double-track tunnels, which govern the comfort-based sizing of such lines, are the subject of a companion study and are not claimed here. A central methodological point, established by the grid-convergence study of [Section 3](#), is that the area-averaged 1D formulation resolves the localised suction peak beneath the train nose as well as the wave-system quantities, but only on grids an order of magnitude finer in cell size, and some two orders of magnitude more expensive, than wave-system work requires. The parametric study of [Section 4](#) is therefore run at wave-system resolution, and its quantitative claims are confined to the quantities convergent there – the exterior peak-to-peak load and the sealing-filtered interior comfort metrics.

The contributions are: (1) an open-source quasi-1D solver, with derivation and released V&V suite ([Section 2](#), [Appendix A](#)); (2) verification against analytical references over a range of blockage ratios, validation of the piston-wind field against a published full-scale measurement, and an independent benchmark of the compression-wave amplitude against published 3D CFD at 250–400 km/h, together with a grid-convergence analysis delimiting the model's valid output ([Section 3](#)); and (3) application to the planned 350 km/h North–South railway in Vietnam, reporting grid-convergent single-train exterior loads and, via a cabin-sealing model, interior comfort metrics ([Section 4](#)). [Section 5](#) discusses limitations and [Section 6](#) concludes.

1.1 What is and is not claimed as new

Because the physical and numerical formulation used here follows established one-dimensional practice, it is worth stating precisely what this paper claims. The governing equations, the moving-blockage representation of the train and the MacCormack discretisation are not new: they follow ([William-Louis & Tournier, 2005](#); [Woods & Pope, 1981](#)) and the wider 1D literature, and no new closure, boundary treatment or numerical method is introduced. Nor is a capability claimed that the proprietary compressible codes lack. What is offered is, firstly, an implementation gap: an openly licensed, documented and extensible compressible solver for high-speed tunnel transients, released with a verification-and-validation suite that reproduces every figure and table of this paper from the published scripts. The open tools in this field are incompressible network models that cannot address this physics, and the tools that can are closed, so a practitioner or researcher wishing to test a new friction law, portal treatment or sealing model against a documented compressible baseline currently has nowhere to start. Secondly, and independently of the software, the paper contributes a methodological result: the grid study of [Section 3.4](#) shows that the localised suction peak beneath the train nose, commonly assumed to lie beyond the reach of area-averaged 1D models, is in fact grid-convergent and quantifies the resolution at which it becomes so. That result corrects a limitation commonly attributed to this class of model – one the present author had also assumed before carrying out the refinement study reported here.

2. Mathematical model and numerical method

2.1 Governing equations

The flow is one-dimensional, compressible and unsteady, with the train represented as a prescribed reduction of the free area $A(x,t)$. With ρ , u , p and E the density, velocity, pressure and specific total energy, conservation of mass, momentum and energy over the free area reads

$$\partial(\rho A)/\partial t + \partial(\rho u A)/\partial x = 0 \quad (1)$$

$$\partial(\rho u A)/\partial t + \partial[(\rho u^2 + p)A]/\partial x = p \partial A/\partial x + f_t + f_{tr} \quad (2)$$

$$\partial(\rho E A)/\partial t + \partial[(\rho E + p)u A]/\partial x = -p \partial A/\partial t + f_{tr} V \quad (3)$$

closed by $p = (\gamma - 1)\rho(E - u^2/2)$, $\gamma = 1.4$. The geometric term $p \partial A/\partial x$ is the axial projection of the pressure force exerted by the train nose and tail on the air; $-p \partial A/\partial t$ is the moving-surface work, with $\partial A/\partial t = -V \partial A/\partial x$ for a rigid train. Wall and train-skin friction use Darcy closures, $f_t = -(\lambda_t/8)\rho|u|u P_t$ and $f_{tr} = -(\lambda_{tr}/8)\rho|u-V|(u-V)P_{tr}$, with $\lambda_t = 0.02$ and $\lambda_{tr} = 0.012$ (William-Louis & Tournier, 2005; Woods & Pope, 1981). A formal derivation of (1)–(3), the treatment of the moving blockage and its equivalence to the formulation of Woods and Pope (Woods & Pope, 1981), together with a global energy-balance check, are given in Appendix A. The model contains no local (form) loss coefficients at the nose, tail or portals; the consequences of this choice are quantified in Section 3.4 and discussed in Section 5.

2.2 Train representation

The blockage $b(x,t)$ rises from zero to A_{tr} over the streamlined nose length and falls symmetrically at the tail using cosine ramps; $A(x,t) = A_0 - b(x,t)$ (Figure 1). The train position is prescribed kinematically, so portal entry and exit are handled by clipping the blockage to the domain.

2.3 Numerical scheme

Equations (1)–(3) are integrated with the explicit predictor–corrector MacCormack scheme (MacCormack, 1969), formally second-order in space and time. Because the waves are weak ($\Delta p/p_0$ of order 10^{-2}), shock-capturing is unnecessary; grid-scale oscillations near the area ramps are damped by Jameson-type artificial dissipation with a pressure-based sensor scaling the second-difference term ($k_2 = 0.8$) and a background fourth-difference term ($k_4 = 0.008$) (Jameson, Schmidt, & Turkel, 1981); these coefficients are held fixed for every result in this paper, and their influence is quantified in the sensitivity study of Section 3.4. The time step is not fixed: it is recomputed at every step from a Courant condition on the local wave speeds, with a Courant number of 0.60 for the application cases and 0.85 for the benchmark case of Section 3.4, both well inside the explicit stability limit. The formulation carries a general area field $A(x, t)$, so a tunnel of varying cross-section – enlargements, transition zones or shafts represented as area changes – is admissible without modification, although every case presented here uses a prismatic tunnel. At the portals, characteristic-type open-boundary conditions are imposed on two ghost cells at each end: the incoming characteristic is prescribed from the ambient state (ambient stagnation conditions for inflow, ambient static pressure for outflow) while the outgoing characteristics are extrapolated from the interior, which reproduces the sign-inverting reflection at open ends. As is typical of dissipative schemes on a near-discontinuous front, the leading edge of the compression wave carries a small dispersive overshoot; the physically meaningful quantity is the post-front plateau amplitude, which is the value used throughout (the overshoot is examined in Section 3.4). Wherever a wave amplitude is reported, it is extracted as the median pressure in a fixed window from 0.2 to 0.7 s after the front arrival at the probe, which excludes the overshoot by

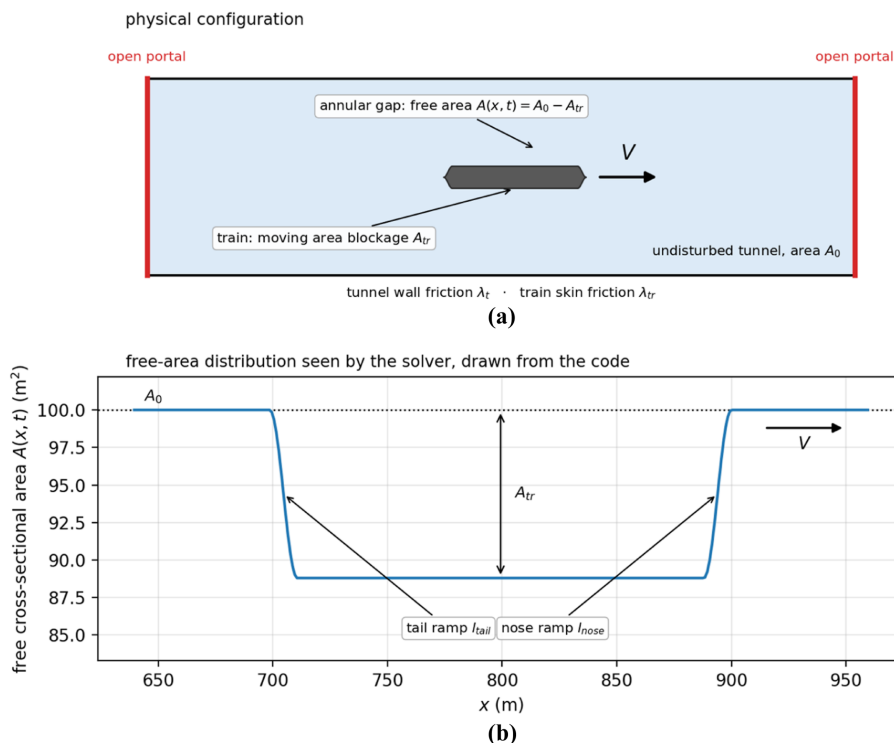


Figure 1. Quasi-1D representation of the train–tunnel system. (a) Physical configuration: the train is a moving cross-sectional-area blockage in a tunnel with open portals and friction acts both on the tunnel wall and on the train skin in the annular gap. (b) Corresponding free-area distribution $A(x, t)$ actually seen by the solver, plotted from the code, with the cosine nose and tail ramps resolved. Source: Author’s own work

construction; peak-to-peak values, by contrast, are formed from the raw recorded pressure history at a probe moving with the train at mid-train length, as the difference between its maximum and minimum over the transit, without this front treatment; the definition and its consequences are discussed in [Section 5](#). A global energy-budget check on a closed test duct shows the total energy drift to remain within the artificial-dissipation truncation over a full transit time (the quantitative result is reported in [Appendix A](#)).

2.4 Cabin pressure (sealing) model

The interior (cabin) pressure p_c is obtained from the computed exterior signature p_e by the standard first-order pressure-sealing relation $dp_c/dt = (p_e - p_c)/\tau$, integrated exactly over each time step, where τ is the dynamic sealing time constant of the rolling stock ($\tau = 0$ for an unsealed vehicle; τ of order 6–18 s for modern sealed high-speed stock). Passenger comfort is assessed from the largest interior pressure change within moving 1 s, 3 s and 10 s windows, compared with the UIC comfort limits of 0.5, 0.8 and 1.0 kPa respectively ([CEN, 2021](#)).

3. Verification, benchmarking and grid convergence

3.1 Verification: compression-wave amplitude (analytical)

Terminology follows ASME practice: comparison against the analytical entry-wave solution is verification, since it tests the discretisation against an exact solution of the same

model, whereas comparison against published 3D CFD is benchmarking rather than validation, because the reference is itself a computation and not a measurement; the comparison against full-scale measurement in Section 3.2 is validation in the strict sense. Table 1 and Figure 2 compares the computed plateau amplitude of the initial compression wave with the analytical entry-wave solution (Hara, 1961), with friction removed to match the analytical assumptions, for two blockage ratios spanning the practical range: $\beta = 0.112$ ($A_0 = 100 \text{ m}^2$) across 200–350 km/h, and $\beta = 0.160$ ($A_0 = 70 \text{ m}^2$) at 350 km/h. Agreement is within 1% throughout, and the amplitude is grid-insensitive (below 0.5% for $\Delta x \leq 2.5 \text{ m}$); the computed front-arrival time at mid-tunnel matches the acoustic time x/c_0 within 0.3%. The verification therefore holds over the whole blockage range used in the application, not at a single β .

3.2 Validation of the piston-wind field against full-scale measurement

The one quantity for which an independent full-scale measurement could be obtained with all of its parameters documented is the piston-wind field. Fu, Li, and Liang (2017) report a full-scale test on the Beijing–Shanghai high-speed line in which an ultrasonic anemometer

Table 1. Verification of the compression-wave plateau amplitude against the analytical solution

Speed (km/h)	β	Solver (Pa)	Analytical (Pa)	Deviation
200	0.112	504	502	+0.4%
250	0.112	794	791	+0.3%
300	0.112	1,156	1,153	+0.3%
350	0.112	1,599	1,595	+0.2%
350	0.160	2,415	2,408	+0.3%

Source(s): Author’s own work

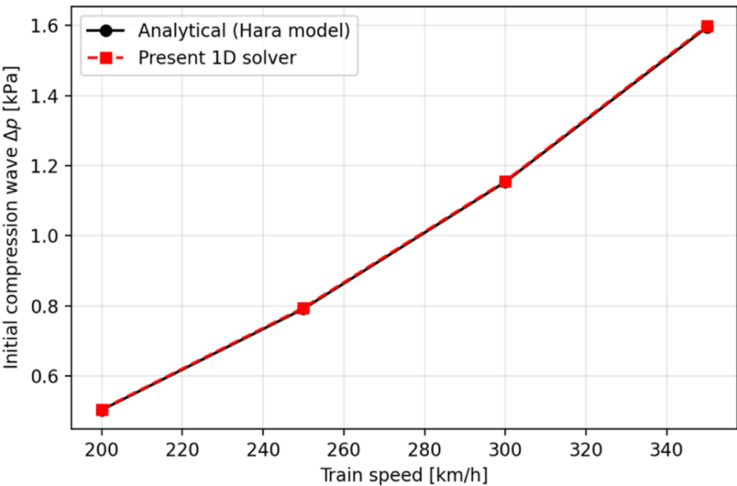


Figure 2. Verification of the initial compression-wave plateau amplitude against the analytical (Hara) solution, frictionless ($A_0 = 100 \text{ m}^2$, $\beta = 0.112$). Source: Author’s own work

recorded the longitudinal air velocity 500 m from the entrance of a 1,005 m tunnel of 100 m² free cross-section carrying two tracks, as an eight-coach trainset passed at 250 km/h, the probe being 1 m from the car body and 1.5 m above rail level. The configuration matches the baseline of Section 4 in free cross-section, track arrangement and trainset and differs in speed. Running the present solver at that configuration and sampling the area-averaged velocity at the same station gives Figure 3.

What is being compared needs care, because the measured and computed quantities coincide over part of the record and not over the rest. Ahead of the train nose, the air column in the tunnel is driven forward essentially as a plug, so a point measurement and the area average are the same quantity; over that interval the computed piston wind is 0.044 V against a measured 0.049 V, low by 11%, and the two traces follow the same rise. The nose-passage transient is reproduced closely: the computed minimum is -0.100 V against a measured -0.099 V, and it occurs within 0.06 s of the measured one; the arrival times of nose and tail follow from the tunnel kinematics. Once the nose has passed, the probe lies inside the annular gap 1 m from the car body and records a near-body boundary-layer velocity, which reaches 0.36 V at tail passage; an area-averaged formulation does not represent that quantity and returns 0.03 V, so the two curves separate by construction rather than by error. The comparison therefore validates the piston-wind field and the wave kinematics against measurement and illustrates directly where area averaging ceases to apply, but it establishes nothing about the interior structure of the annular flow. It is grid-independent: the computed piston wind changes by 0.3% across $\Delta x = 2, 1$ and 0.5 m.

As an internal consistency check on the same quantity, the quasi-steady piston wind was also compared with a momentum balance written with exactly the same closures as the solver, which isolates numerical error: for a 1 km train ($A_{tr} = 10 \text{ m}^2$, $A_0 = 60 \text{ m}^2$) in a 12 km tunnel at 120 km/h the mid-tunnel velocity approaches 5.695 m/s against 5.533 m/s from the balance, a 2.9% difference attributable to finite development time. Because both sides share the friction closure that makes the test sensitive to λ , it is reported only as a consistency check; the comparison with the measurement above is the substantive one.

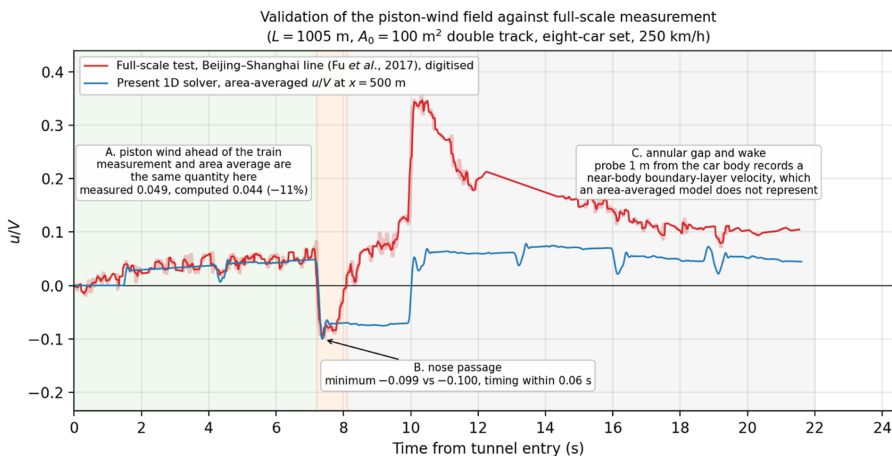


Figure 3. Validation of the piston-wind field against the full-scale measurement of Fu *et al.* (2017) (1,005 m tunnel, $A_0 = 100 \text{ m}^2$ double track, eight-coach trainset, 250 km/h, probe 500 m from the entrance). Region A, ahead of the train nose, compares like with like; Region B is the nose-passage transient; in Region C, the probe records a near-body boundary-layer velocity that an area-averaged formulation does not represent. The measured trace is digitised from the published figure, the shaded band being the vertical extent of the plotted line. Source: Author's own work

3.3 Benchmarking against 3D CFD

The grid-convergent output of the solver is benchmarked against an independent 3D-CFD dataset that is not used elsewhere in its construction. An independent 3D-CFD study (Liu, Liu, Yao, Chen, & Yang, 2023) reports, for a high-speed train in a single-track tunnel of $A_0 = 70 \text{ m}^2$ (train area 11.8 m^2), the initial compression-wave amplitude P_f as a function of speed from 250 to 400 km/h. Running the present solver at that configuration reproduces P_f to within 4.4% across the whole speed range, the deviation falling from +4.4% at 250 km/h to +2.1% at 400 km/h (Table 2, Figure 4) and captures the near-quadratic dependence on speed. This is an independent, high-speed benchmark on a configuration (single track, 70 m^2) distinct from both the verification of Section 3.1 and the application of Section 4. It establishes the accuracy of the initial compression-wave amplitude only. The peak-to-peak load used in Section 4 is built on the same wave physics but additionally involves portal reflections, wave superposition, the tail expansion wave and friction over a full transit, none of which this comparison tests; that distinction is developed in Section 5, and no claim of equivalent accuracy for the complete pressure history is made here.

Table 2. Benchmark of the compression-wave amplitude P_f against the 3D-CFD data of Liu et al. (2023) (single-track tunnel, $A_0 = 70 \text{ m}^2$, $A_{tr} = 11.8 \text{ m}^2$)

Speed (km/h)	Solver (Pa)	3D CFD (Liu et al., 2023) (Pa)	Deviation
250	1,295	1,240	+4.4%
300	1,876	1,830	+2.5%
350	2,580	2,510	+2.8%
400	3,420	3,350	+2.1%

Source(s): Author’s own work

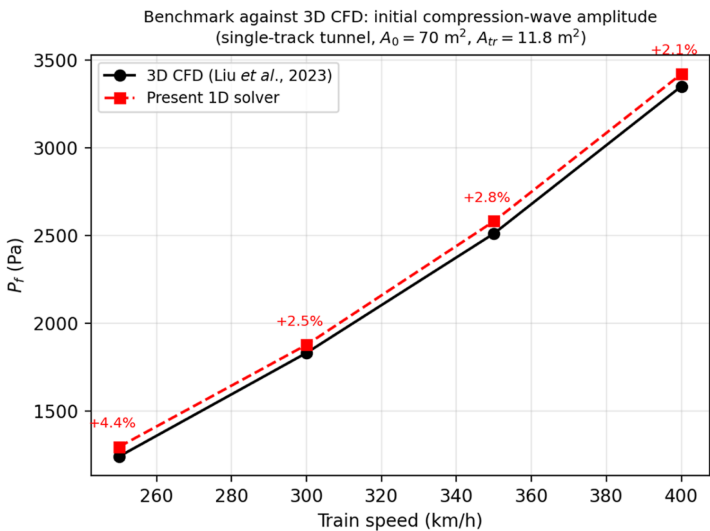


Figure 4. Benchmark against 3D CFD: initial compression-wave amplitude versus train speed, present solver against the 3D-CFD data of Liu et al. (2023). Source: Author’s own work

3.4 Grid convergence, resolution requirements and the limits of the model

A formal grid-convergence study was performed following Roache's grid-convergence index (GCI, factor of safety 1.25) on systematically refined grids with refinement ratio 2. Two quantities are examined: the exterior peak-to-peak load used in [Section 4](#), and the localised minimum (suction) pressure beneath the train nose in a benchmark configuration, which is the quantity most often used for point-value comparison with 3D CFD. The benchmark configuration is that of the moving-mesh 3D-CFD study of [Luo et al. \(2017\)](#): an eight-car train of length 200.68 m, maximum cross-sectional area 11.43 m² and streamlined head of 3.73 m, running at 200 km/h through a 500 m double-track tunnel of 80 m² free cross-section, with the pressure sampled 15 m behind the nose. It is distinct from the configurations of [Sections 3.1 and 3.3](#) and from the application of [Section 4](#). The raw values on every grid level are listed in [Table 3](#), and the refinement behaviour is plotted in [Figure 5](#), so that convergence can be inspected directly rather than through a single index.

The central result is that the nose suction peak is grid-convergent, but only on grids substantially finer than those normally used for wave-system work. The prescribed nose ramp of this benchmark is 3.73 m long, so grids of 1 and 0.5 m place only a few cells across the ramp; the triplet (1, 0.5, 0.25 m) accordingly lies in the pre-asymptotic range, returning an observed order of 0.63 and an apparent GCI above 70%. Refining further, the successive changes fall from 37% to 32%, 11% and, finally, 3.1%, the observed order rises to 1.70 and then 1.83 – approaching the formal second order of the scheme – and the fine-grid GCI falls to 6.0% and then 1.5%. The Richardson-extrapolated value, 1,084–1,091 Pa on the two finest triplets, lies within 3.5% of the 3D-CFD reference value of 1,054 Pa for the same configuration ([Luo et al., 2017](#)). A large GCI on a coarse triplet therefore indicates under-resolution, not the absence of a finite limiting solution; an earlier assessment based only on the (1, 0.5, 0.25 m) triplet reached the opposite conclusion and is corrected here.

Two checks separate numerical under-resolution from artefacts of the discretisation itself. Doubling or halving each Jameson dissipation coefficient (k_2 between 0.4 and 1.6, k_4 between 0.004 and 0.016) changes the peak by less than 0.7%, so the grid trend is not a dissipation artefact. Replacing the cosine nose ramp with a linear ramp of the same length changes the peak by 2.0% at $\Delta x = 0.25$ m and 1.2% at $\Delta x = 0.125$ m, a difference that itself diminishes under refinement, so the trend is not an artefact of the ramp representation either. A third check addresses the suggestion that only a spatially averaged peak might converge: averaging the pressure over windows of 1 m and 5 m centred on the probe changes the peak by less than 0.5%

Table 3. Grid-refinement results. Raw values on every level and the Roache GCI for each consecutive triplet (refinement ratio 2, factor of safety 1.25)

Quantity/grid triplet	Δx (m)	Value	Observed order p	GCI (fine)
Head-car suction peak (benchmark)	1.0	2,288 Pa	–	–
	0.5	1,666 Pa	–	–
	0.25	1,263 Pa	0.63 (pre-asymptotic)	73.3%
	0.125	1,139 Pa	1.70	6.0%
	0.0625	1,105 Pa	1.83	1.5%
Richardson value/3D CFD (Luo et al., 2017)	–	1,091/1,054 Pa	–	deviation +3.5%
Exterior peak-to-peak (baseline)	4.0	4.426 kPa	–	–
	2.0	3.885 kPa	–	–
	1.0	3.639 kPa	1.14	7.0%
Exterior peak-to-peak ($A_0 = 70$ m ²)	4/2/1	6.064/5.571/	0.85	8.0%
		5.298 kPa		
Exterior peak-to-peak ($L = 0.5$ km)	4/2/1/	5.132/4.731/3.580/	–1.52 (4/2/1); 2.88	not defined;
	0.5	3.423 kPa	(2/1/0.5)	0.9%

Source(s): Author's own work

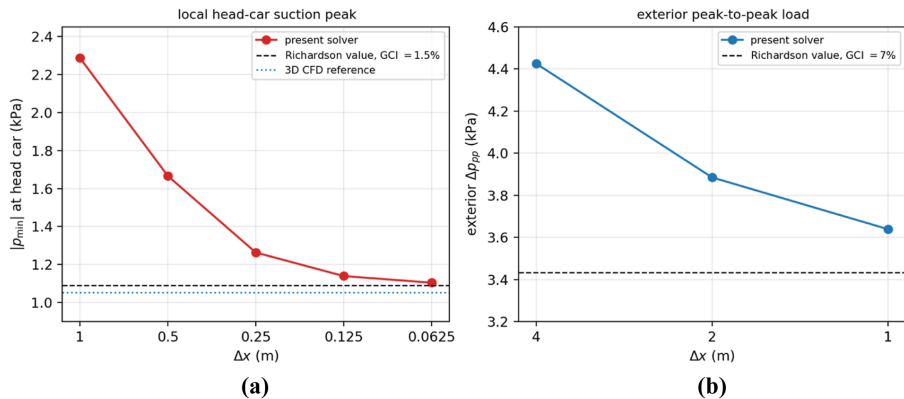


Figure 5. Grid-refinement behaviour: (a) the local head-car suction peak converges towards the Richardson value and the 3D-CFD reference once the nose ramp is resolved (five grid levels, $\Delta x = 1$ to 0.0625 m); (b) the exterior peak-to-peak load of the application case ($\Delta x = 4$ to 1 m). Source: Author's own work

and leaves the GCI unchanged because in an area-averaged formulation the suction peak is a smooth feature distributed over the nose ramp rather than a singular spike. Spatial filtering is therefore unnecessary once the ramp itself is resolved. For the application train of Section 4, whose nose ramp is 12 m, the equivalent requirement is Δx of order 0.2 – 0.4 m; no point-value suction peak is reported for that configuration, and none of the results of Section 4 depends on one.

The convergence study was repeated at the edges of the design sweep, because the shortest tunnel and the largest blockage ratio need not share the resolution requirement of the baseline. At $A_0 = 70 \text{ m}^2$, the behaviour matches the baseline (GCI 8.0% at $\Delta x = 1$ m). The shortest tunnel does not: for $L = 0.5$ km the triplet $(4, 2, 1 \text{ m})$ returns a negative observed order ($p = -1.52$), so no meaningful index can be formed from it, and grids of $\Delta x \leq 1$ m are required before convergence is attained, at which point the observed order is 2.88 , and the load settles at 3.42 kPa with a GCI below 1% . All four grid levels for this case are listed in Table 3. The short-tunnel entries of the design sweep are therefore computed and reported at $\Delta x = 0.5$ m in Section 4.3, and the coarser resolution acceptable at 2 km is not sufficient there.

The resolution needed to converge the nose peak, Δx of order 130 th to 160 th of the nose ramp length, is roughly an order of magnitude finer in cell size than that needed for the wave-system load, and, because both the cell count and the number of explicit time steps scale with it, the corresponding cost is roughly two orders of magnitude higher. The practical consequence is a division of labour rather than a limitation of principle: the solver is used at $\Delta x \approx 1$ m for the parametric work of Section 4, where only wave-system quantities are required and refined locally when a point-value peak is of interest. The remaining physical restriction is separate from resolution – the formulation carries no local (form) loss coefficients at the nose, tail or portals, so the converged peak is the inviscid area-averaged value, which the comparison above indicates is about 3.5% conservative relative to 3D CFD for this configuration.

For completeness, a moving-mesh 3D-CFD dataset (Luo *et al.*, 2017) (head-car minimum pressure versus tunnel length at 200 km/h) is retained as a trend-level cross-check. That comparison is computed at $\Delta x = 0.25$ m, at which this quantity is not yet grid-converged (Table 3), so it is trend-level only: the 1D values exceed the 3D ones by between 4% and 20% , with the largest excess at the shortest tunnel. The 1D and 3D curves are nevertheless of the same order, and both exhibit an unfavourable-length plateau, though they place the shallow maximum at different lengths; the unfavourable length is determined directly in Section 4.3 instead of being inferred from this quantity.

4. Application to the 350 km/h North–South railway in Vietnam

4.1 Configuration and scope

The planned line is designed for 350 km/h with about 10% of its 1,541 km alignment in tunnels (National Assembly of Vietnam, 2024). The rolling stock is an eight-car CR400AF-type trainset (length 201.4 m, cross-section 11.2 m², perimeter 13.3 m, 12 m nose), and the baseline is a double-track tunnel of 100 m² free cross-section, with 70–100 m² examined for the cost–load trade-off (Table 4). All results are for a single train and, following Section 3, are reported as the grid-convergent exterior peak-to-peak pressure at $\Delta x = 1$ m (fine-grid GCI $\approx 7\%$ at the baseline). Two-train crossings, which on a double-track line approximately double the loads and govern the comfort-based sizing, are outside this single-train scope and are treated in companion work; the conclusions below are conditioned accordingly.

4.2 Baseline case and design criteria

For the baseline (2 km, 100 m², 350 km/h), Figure 6 shows the pressure histories at a fixed mid-tunnel point and on the train body, and Figure 7 the corresponding x – t wave diagram. The grid-convergent exterior peak-to-peak load is 3.64 kPa at $\Delta x = 1$ m (Richardson value 3.43 kPa, fine-grid GCI 7.0%), formed as defined in Section 2.3 from the raw moving-probe history. The relevant design criteria are collected in Table 5. The exterior peak-to-peak value maps to the medical (health) limit; the interior comfort limits are reached by the cabin pressure, which depends on rolling-stock sealing and is assessed in Section 4.5 through a first-order sealing model.

4.3 Influence of tunnel length and the unfavourable length

Figure 8 shows the exterior peak-to-peak load against tunnel length. Following Section 3.4, the short-tunnel range is computed at $\Delta x = 0.5$ m, where the load is grid-converged, while the full range to 3 km is shown at $\Delta x = 1$ m with error bars given by the fine-grid GCI. For a single train, the load is remarkably insensitive to length: across 0.4–3 km it stays within about 5% of 3.6 kPa and across the refined range 0.7–1.2 km it varies by only 0.5%. Every value lies far below the 10 kPa medical limit.

Because the solver is available, the unfavourable (most severe) tunnel length is determined numerically rather than taken from the closed-form relation alone. On the refined grid the load rises monotonically from 3.40 kPa at 0.4 km to a shallow maximum of 3.59 kPa near 0.7–0.8 km and then decays slowly, which brackets the closed-form estimate $L_{cr} \approx (L_{tr}/4)(c_0/V)(1 + c_0/V) = 793$ m adopted in the EN 14067–5 framework (CEN, 2021). The closed-form relation is thus confirmed by the solver for this configuration. Two qualifications matter for practice. The maximum is a broad plateau rather than a sharp peak – the metric changes by less than 1% between 0.7 and 1.2 km – so the unfavourable length is not a critical design threshold for the single-train exterior load. And on the coarser $\Delta x = 1$ m grid, the sweep shows an

Table 4. Parameters of the application study

Parameter	Value
Train speed V	350 km/h (97.2 m/s)
Train length/area/perimeter	201.4 m/11.2 m ² /13.3 m
Nose and tail ramp length	12 m
Tunnel free cross-section A_0	70–100 m ²
Tunnel length L	0.5–3 km
Friction factors λ_t/λ_{tr}	0.02/0.012
Ambient p_0, T_0	101.325 kPa, 15 °C
Grid spacing Δx	1 m (GCI $\approx 7\%$)
Source(s): Author's own work	

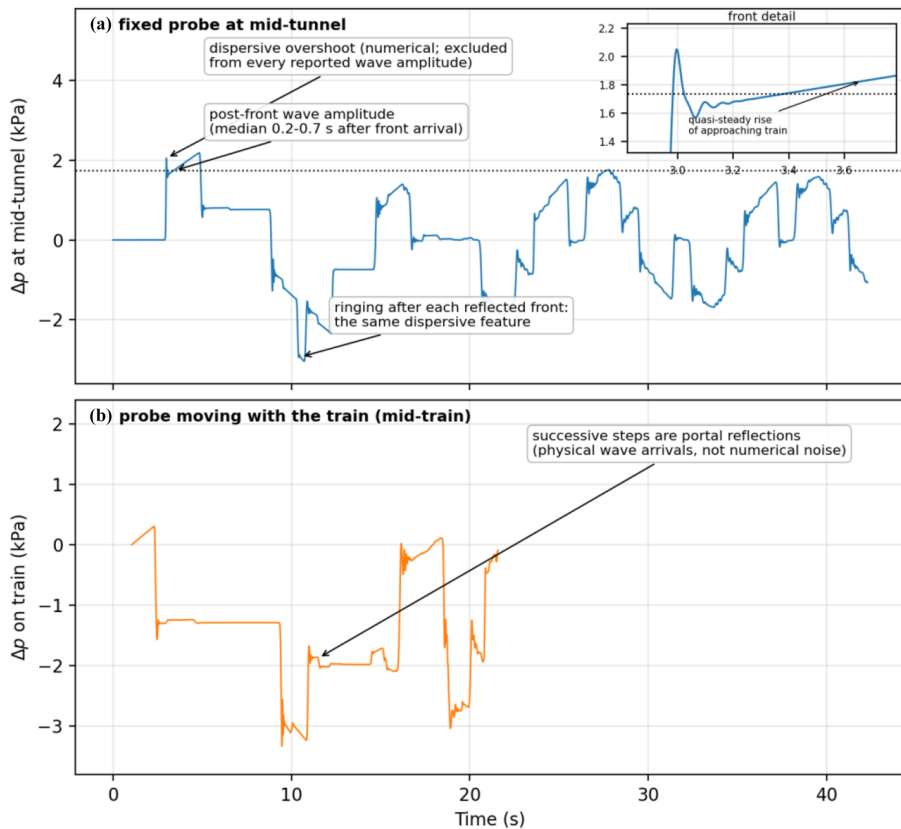


Figure 6. Baseline case (2 km, $A_0 = 100 \text{ m}^2$, 350 km/h): exterior pressure histories (a) at a fixed mid-tunnel probe and (b) at a probe moving with the train. The inset resolves the wave front: the dispersive overshoot is a numerical feature and is excluded from every reported wave amplitude, whereas the dotted line is the physical post-front amplitude, taken as the median over 0.2–0.7 s after arrival; the slow rise that follows it is the quasi-steady field of the approaching train, not part of the front. The smaller ringing after each reflected front is the same dispersive feature. The successive steps in both panels are portal reflections, that is, physical wave arrivals, not numerical noise. Source: Author's own work

apparent maximum at 0.4 km, which the refined calculation removes; the variation across lengths is of the same order as the discretisation error at that resolution, which is why the refined grid is necessary for this particular question.

4.4 Influence of tunnel cross-section and the design trade-off

Figure 9 and Table 6 show what happens when the free cross-section is reduced from 100 m^2 ($\beta = 0.112$) to 70 m^2 ($\beta = 0.160$) for the 2 km tunnel. The exterior peak-to-peak load rises from 3.64 to 5.30 kPa, an increase of about 46%, reflecting the strong dependence of wave amplitude on blockage ratio; all three sections remain below the medical limit for a single train. Comparing the two sweeps, cross-section changes the load by an order of magnitude more than length does over the ranges examined, so among the parameters varied in this single-train study the cross-section is the stronger driver. This ranking is conditional on the parameters held fixed – speed, nose geometry, friction closure, portal configuration and single-train operation – and is not a general statement about all design variables.

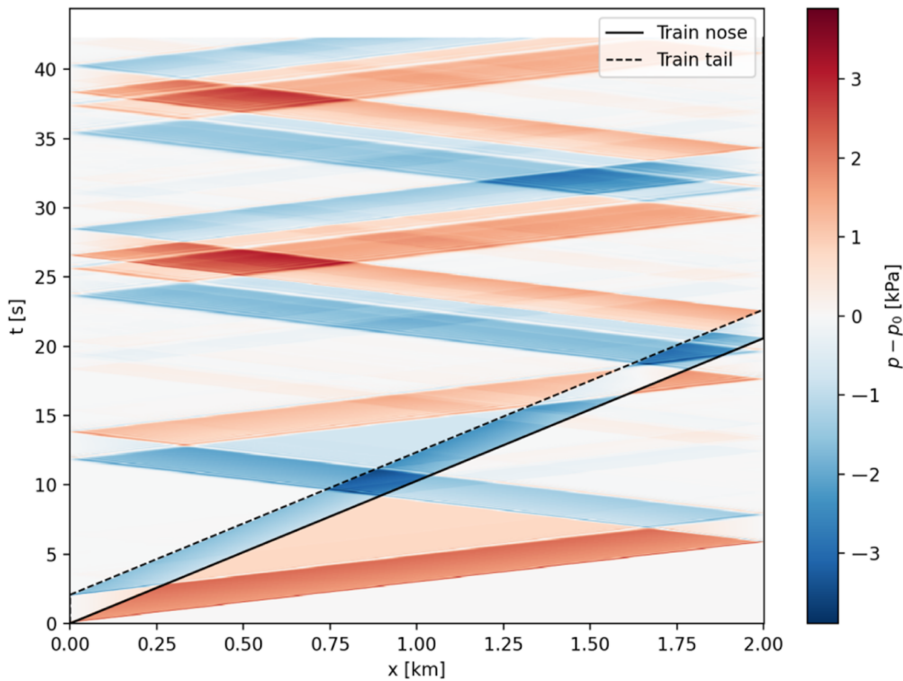


Figure 7. x - t diagram of the pressure field for the baseline case; solid and dashed lines mark the train nose and tail trajectories. Source: Author's own work

Table 5. Design criteria for tunnel pressure loads referenced in this study

Criterion	Limit	Applies to
UIC 779–11 medical/health (UIC, 2005)	10 kPa (worst transit)	Exterior-connected pressure
UIC/EN 14067–5 comfort (CEN, 2021)	0.5/0.8/1.0 kPa in 1/3/10 s	Interior (cabin) pressure
China TB 10621 comfort (National Railway Administration of China, 2014)	4 kPa in 3 s	Interior (cabin) pressure

Source(s): Author's own work

The load alone does not express the trade-off a designer faces because the exterior load is not itself a comfort criterion: what the passenger experiences is the cabin pressure, which depends on how well the rolling stock is sealed. Table 6 therefore couples the three quantities that actually trade against one another. Reducing the section from 100 to 70 m² saves about 30% of the excavated volume, but raises the exterior load by 46% and, more demanding, raises the sealing time constant required to meet the UIC comfort criteria from 12.0 to 20.6 s, an increase of 72%. The intermediate section of 85 m² saves 15% of excavation for a 28% increase in the sealing requirement. Since the sealing performance of the rolling stock is fixed by procurement rather than by the tunnel designer, this coupling is the practically binding constraint: a narrower tunnel is affordable in civil terms only if the fleet specification can carry

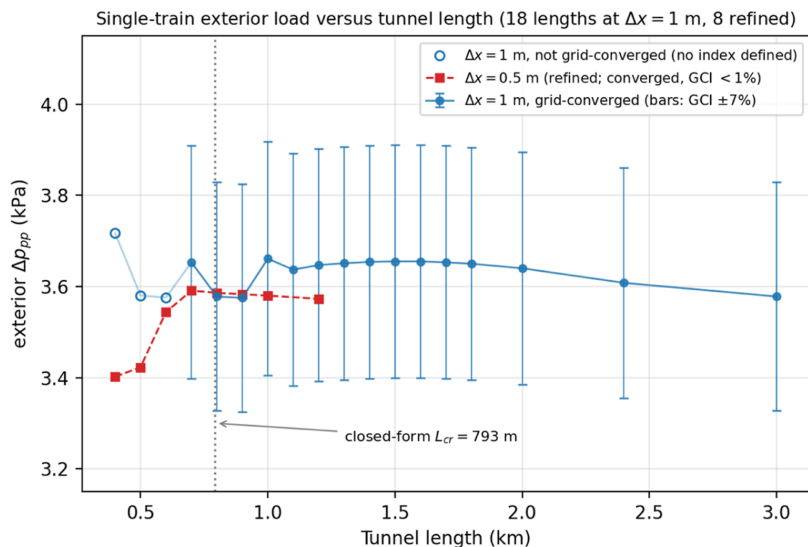


Figure 8. Single-train exterior peak-to-peak load versus tunnel length ($A_0 = 100$ m², 350 km/h). Circles: $\Delta x = 1$ m with GCI error bars; squares: $\Delta x = 0.5$ m over the short-tunnel range; the dotted line marks the closed-form unfavourable length. Source: Author's own work

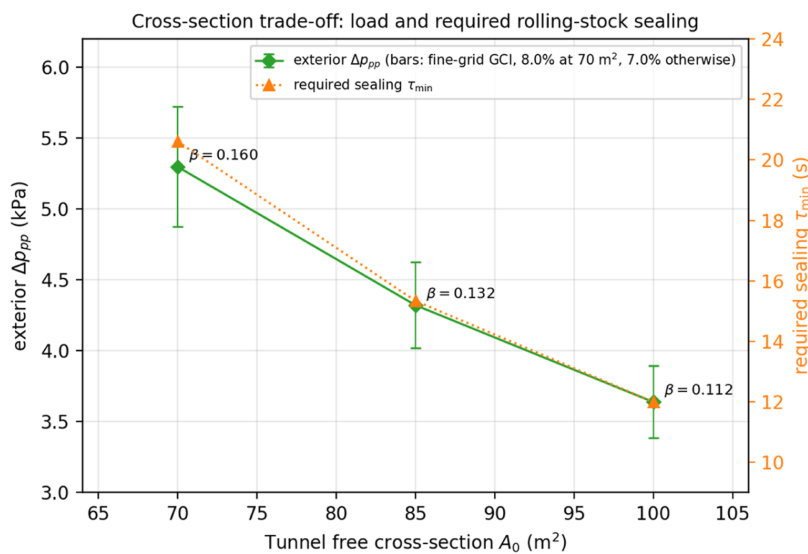


Figure 9. Cross-section trade-off ($L = 2$ km, 350 km/h, single train): exterior peak-to-peak load with GCI error bars (left axis) and the sealing time constant required to meet the UIC comfort criteria (right axis). Source: Author's own work

the corresponding sealing requirement. The excavation figures are an order-of-magnitude proxy (free cross-section multiplied by length, excluding overbreak, lining and portal works) and are intended for relative comparison, not for costing.

Table 6. Cross-section trade-off for the 2 km baseline tunnel at 350 km/h, single train: exterior load, sealing time constant required to satisfy all UIC comfort criteria and excavation-volume proxy

A_0 (m ²)	β	Exterior Δp_{pp} (kPa)	Required τ_{min} (s)	Excavation proxy (10 ³ m ³ /km)	Change vs 100 m ² (excav./load/sealing)
70	0.160	5.30	20.6	70	−30%/+46%/+72%
85	0.132	4.32	15.3	85	−15%/+19%/+28%
100	0.112	3.64	12.0	100	reference

Source(s): Author's own work

4.5 Interior comfort and rolling-stock sealing

Passenger comfort is governed by the cabin pressure rather than the exterior pressure. The cabin pressure is obtained from the baseline exterior signature through the first-order sealing model of Section 2.4, and Table 7 and Figure 10 give the largest interior pressure change in the 1 s, 3 s and 10 s windows as a function of the sealing time constant τ .

Grid convergence was examined for each window separately rather than for the 3 s window alone, because the three windows weight the exterior transient differently. The unsealed case requires particular care: at $\tau = 0$ the cabin pressure is identical to the exterior pressure and receives no filtering at all, and it is correspondingly not grid-convergent – between $\Delta x = 2$ and 1 m the three window metrics still change by 12.2%, 15.7% and 6.8%. Every sealed case is convergent: for $\tau \geq 3$ s, all three windows agree to within 0.4% across $\Delta x = 4, 2$ and 1 m. The first-order filter is a low-pass that attenuates precisely the sharp, grid-sensitive part of the exterior signal, so the interior metrics are a reliable model output in the sealed regime even where the raw exterior short-window metric is not. The results below are reported only for the sealed regime.

For the single-train baseline, the UIC criteria are met only by well-sealed stock. An unsealed vehicle fails by a wide margin; $\tau = 6$ s satisfies the 1 s and 3 s limits but not the 10 s limit; and the 10 s criterion remains binding throughout the sealed range. The minimum sealing time constant satisfying all three criteria was located by bisection rather than read from a coarse sweep, giving $\tau_{min} = 12.05, 12.00$ and 11.97 s at $\Delta x = 2, 1$ and 0.5 m respectively – that is, $\tau_{min} \approx 12.0$ s with a grid-related spread below ± 0.05 s. The value of exactly 1.00 kPa in the 10 s column of Table 7 is not a coincidence: at the threshold, the binding criterion is met with equality by construction. Modern high-speed rolling stock lies within this range, so the baseline section is compatible with commercially available sealing performance. These conclusions are conditional on the first-order sealing model, which is the standard engineering representation but is not itself validated against measured interior pressure here (Section 5).

Table 7. Interior (cabin) comfort metrics for the baseline case (2 km, 100 m², 350 km/h, single train) versus sealing time constant τ , at $\Delta x = 1$ m, against the UIC comfort limits (0.5/0.8/1.0 kPa in 1/3/10 s)

τ (s)	Δp 1 s (kPa)	Δp 3 s (kPa)	Δp 10 s (kPa)	UIC comfort	Grid- convergent?
0 (unsealed)	3.15	3.15	3.64	fail	no (6–16%)
3	0.53	1.04	1.99	fail	yes (<0.4%)
6	0.33	0.62	1.52	fail (10 s)	yes (<0.4%)
12.0 (τ_{min})	0.20	0.42	1.00	pass (10 s binding)	yes (<0.4%)
18	0.14	0.32	0.74	pass	yes (<0.4%)

Source(s): Author's own work

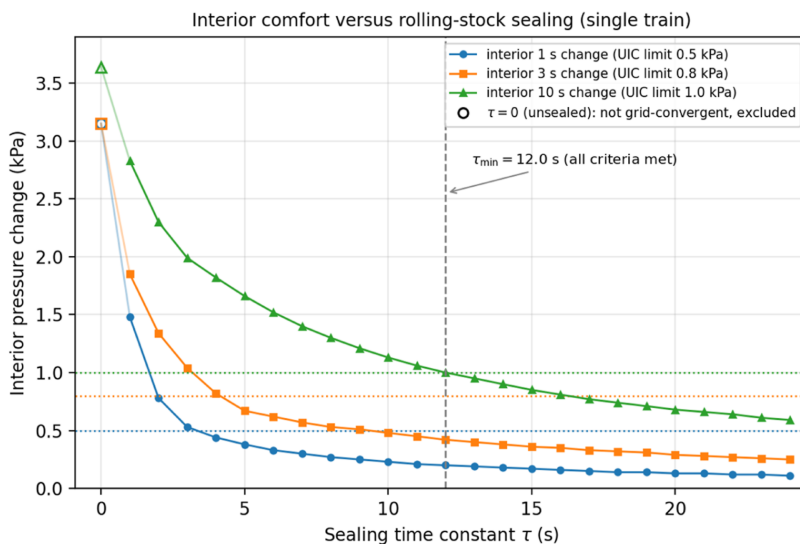


Figure 10. Interior comfort metrics for the baseline case versus rolling-stock sealing time constant τ . Dotted lines mark the UIC comfort limits, given in the legend for each window; the dashed vertical line marks $\tau_{\min} = 12.0$ s, at which all three criteria are satisfied. Source: Author's own work

5. Discussion and limitations

The evidence in this paper is of two different strengths, and it is worth stating which is which. The compression-wave amplitude – the quantity generated as the train enters the tunnel – is the best supported: it is verified against the analytical solution to within 1% over the blockage range used here, and it agrees with published 3D CFD to within 4.4% between 250 and 400 km/h. The piston-wind field is validated against a full-scale measurement on an operating high-speed line, the nose-passage transient being reproduced to within 2% in amplitude and 0.06 s in timing. The piston-wind field is supported by comparison with full-scale measurement (Section 3.2): the computed wind ahead of the train is low by 11%, the nose-passage minimum is reproduced to within 2% and the wave kinematics to within 0.06 s. The exterior peak-to-peak load used in Section 4 is a weaker claim. It is grid-convergent, and it is built from the same wave physics, but it also depends on portal reflections, wave superposition, the tail expansion wave, friction and the sampling trajectory, none of which is separately validated here. Agreement for the initial wave does not by itself establish equivalent accuracy for the complete pressure history, and the peak-to-peak results are therefore presented as a screening quantity with a stated numerical uncertainty rather than as a validated design value. Comparison against a measured pressure history – as distinct from the measured velocity history used in Section 3.2 – remains the most valuable next validation step.

Because the definition of the peak-to-peak metric affects both the convergence study and the comparison with design criteria, it is stated explicitly. It is formed from the pressure history at a probe moving with the train at mid-train length, over the interval from tunnel entry until the train has fully left the tunnel, as the difference between the maximum and minimum of that single history. It is not maximised over several probe positions. Wave amplitudes quoted elsewhere are plateau values, extracted as the median over 0.2–0.7 s after front arrival, which excludes the dispersive overshoot at the wave front (Figure 6). The peak-to-peak metric does not inherit that treatment: it is taken from the raw history, so the dispersive ringing that accompanies each front is included in it. This is deliberate, since a design load should not be reduced by a smoothing operation applied after the fact, and it makes the reported values

conservative; but it is also the principal reason why this metric converges more slowly than the plateau amplitude, a fine-grid GCI of 7.0% against below 0.5% (Sections 3.1 and 3.4).

The remaining limitations bound the model rather than invalidate the results above. The formulation carries no local (form) loss coefficients at the train nose and tail or at the portals. Section 3.4 shows that this does not prevent the nose suction peak from converging – the converged value is about 3.5% conservative relative to 3D CFD for the benchmark configuration – but it does mean the model returns the inviscid area-averaged peak, and three-dimensional portal-relief effects are absent. The latter matters most for the shortest tunnels, where the portal region occupies the largest fraction of the domain; the 0.4–0.5 km results carry the largest physical uncertainty in Figure 8 for that reason, over and above the numerical uncertainty shown by the error bars. Adding calibrated loss-coefficient junctions, following established 1D practice (Vardy, n.d.; Woods & Pope, 1981), is the natural next development.

The study is single-train throughout. Two-train crossings approximately double the loads on a double-track line and govern both the structural sizing and the comfort assessment in practice; they require the two-blockage extension and are treated separately. No conclusion here should be transferred to a crossing scenario. Interior comfort is included through the first-order sealing model, whose output is grid-convergent in the sealed regime (Section 4.5), but which is not compared with measured cabin pressure in this work; the sealing conclusions are conditional on that model. The friction closures use constant Darcy coefficients; the piston-wind check of Section 3.2 is the only quantity materially sensitive to them and is not used in the application. The pressure-gradient output also provides the source term for micro-pressure-wave estimates (Baron *et al.*, 2001; Howe, 1998), which are not pursued here.

On computational cost, the screening metric of Section 4 is converged at $\Delta x \approx 1$ m, at which a single tunnel transit runs in tens of seconds on one processor core; resolving the local nose peak takes roughly two orders of magnitude longer but remains a matter of minutes. An equivalent moving-mesh 3D-CFD case of the kind used for the comparisons here requires multi-million-cell meshes and wall-clock times of the order of days on a cluster (Liu *et al.*, 2023; Luo *et al.*, 2017). A controlled like-for-like benchmark was not run, so the comparison is quoted as the difference in practical turnaround reported for such cases rather than as a measured speed-up factor; the point is simply that the 1D solver makes multi-case parameter studies routine, which is its intended role.

6. Conclusions

An open-source, MIT-licensed quasi-one-dimensional solver for piston-effect pressure waves in high-speed railway tunnels has been developed and released together with a reproducible verification-and-validation suite. The compression-wave amplitude is verified against the analytical solution to within 1% over a range of blockage ratios and agrees with published 3D CFD to within 4.4% between 250 and 400 km/h.

The grid study yields the principal methodological result. The localised head-car suction peak, commonly assumed to lie beyond the reach of area-averaged 1D models, is in fact grid-convergent: refined to a cell size of order 130th to 160th of the nose ramp length, it attains an observed order approaching the formal second order of the scheme, a fine-grid GCI of 1.5%, and a Richardson value within 3.5% of 3D CFD. What had appeared to be non-convergence was under-resolution of the nose ramp. Sensitivity tests on the artificial dissipation, the ramp representation and spatial filtering exclude the alternative explanations. The resolution requirement, however, is roughly an order of magnitude finer in cell size – and some two orders of magnitude more expensive – than that needed for wave-system loads, which sets a practical division of labour: coarse grids for parametric screening, local refinement for point-value peaks.

Applied to the planned 350 km/h North–South railway in Vietnam for a single train, the exterior peak-to-peak load varies by only a few per cent across tunnel lengths from 0.4 to 3 km, with a broad and shallow unfavourable-length plateau near 0.7–0.8 km that confirms the

closed-form EN 14067–5 estimate of 793 m. Cross-section is the stronger of the two drivers examined: reducing the free section from 100 to 70 m² raises the load by about 46%. Coupled to a first-order sealing model, the design trade-off is sharper than the load figures alone suggest – that 30% saving in excavated volume raises the sealing time constant required for UIC comfort compliance from 12.0 to 20.6 s, so the narrower tunnel is viable only if the fleet specification can carry it.

It is equally important to state what this work does not provide. It is not a validated tool for train-crossing scenarios, which govern the design of double-track lines and lie outside the present single-train scope. Its evidence base covers the initial compression-wave amplitude and the piston-wind field; the complete-transit peak-to-peak load is grid-convergent and physically consistent but has not been compared with a measured full pressure history and is offered as a screening quantity. Local suction peaks are convergent but are returned without local loss mechanisms, so they should be read as inviscid area-averaged values, and short-tunnel results carry additional physical uncertainty from unmodelled portal relief. The sealing conclusions are conditional on a first-order cabin model that is not validated against measured interior pressure. Readers requiring point-value structural loads, crossing scenarios or portal-region detail should couple this solver with 3D CFD or measurement rather than substitute it for them.

The solver, its verification-and-validation suite and every application case are released openly so that the loss-coefficient, crossing and sealing extensions identified above can be developed and benchmarked by others on a common, reproducible baseline. That baseline, rather than any single numerical result, is the contribution this paper is intended to make.

Data availability

The solver source code (Python), the verification and validation suites, and all case and figure input files are openly available under the MIT license in a public repository that is permanently archived on Zenodo with a citable DOI; the repository README maps each figure and table to its reproduction script. The repository URL and DOI identify the author and are therefore withheld from this anonymised manuscript in accordance with the double-anonymous review policy; they have been supplied to the editorial office and will be inserted on acceptance.

Declaration of generative AI use

During the preparation of this work, the author used an AI to assist with language editing and figure preparation. The author reviewed and edited all output and takes full responsibility for the content of the publication.

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Supplementary material

The supplementary material for this article can be found online

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