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Double Degree Master Thesis project on:

CFD ANALYSIS OF PRESSURE WAVES AND LOADS ON NON-TIGHT TRAINS PASSING TUNNELS

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February 2016
Preface

This thesis is the conclusion of a double master degree in aerospace engineering between the Royal Institute of Technology (KTH, Stockholm) and the Polytechnic University of Turin (Politecnico di Torino).

The work was performed at Bombardier Transportation in Västerås (Sweden) from August 2015 to February 2016, inside the Aero- and Thermodynamics department, under the supervision of Mikael Sima.
Abstract

Computing the loads for a train passing a tunnel requires to predict both the external and the internal pressure variations in time, both of which are strong and quick for a non-pressure tight train.

The key achievement of this work has been the development of 3D CFD Star-CCM+ overset mesh simulations capable of simulating the single train tunnel entry and tunnel passage as well as the two trains crossing inside the tunnel. Unfortunately it is not affordable to execute a 3D CFD study for the tunnel passage of each new train model, so 1D CFD codes have been employed, simplified predictive models have been developed and both have been compared to the 3D CFD results.

An important result has been identifying the influence of several parameters on the loads caused both by the travelling pressure waves generated when the train enters the tunnel and by the pressure disturbances due to train crossing inside the tunnel, using Star-CCM+ parameters sweeps simulations over train speed and train and tunnel geometrical parameters.

The main conclusion is that the internal pressure variation is particularly important to compute the loads, especially for non-tight trains. For this reason it is necessary to take into account both the carriage free length and the position along the carriage on which the loads are needed.
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1. Introduction

The velocities reached by modern high speed trains make aerodynamics a key step in the development of a new train in terms of safety, energy consumption and passenger comfort. For high speed trains one important aspect is drag, especially considering that a high speed train nominal power is of the order of magnitude of 10 MW [35], but drag is not the only goal of the train aerodynamic design process. Very important safety factors are cross wind stability and trackside effects, as a train must not fall off the rails for any reasonable wind speed and it must not damage people or object standing near the track.

Another important part of train aerodynamics is tunnel aerodynamics. For example, it is interesting to note that the reason why high speed trains have longer noses is not only to reduce drag, but also to fulfil requirements on the tunnel passage phase. The main goals of tunnel aerodynamics are to ensure passenger comfort and to compute loads on the train structure during tunnel passage, and the main phenomena which have to be modelled are the origin, propagation and interaction with the train of pressure waves travelling in the tunnel.

For non-tight trains, which are the subject of this work, the internal pressure variations can be very quick, thus potentially impacting passenger comfort at higher train speeds. For this reason most high speed trains have a complex and expensive pressurisation system which helps keeping the pressure variations inside the carriage at an acceptable level. They also have to fulfil stringent regulations on the amount pressure change in case of a sealing system failure [6]. Another critical aspect for tunnel passage can be the emission of strong pressure oscillations (Micro Pressure Waves) from the tunnel ends which might disturb the environment near the tunnel end, especially for small cross section area tunnel located in densely populated areas. This is a serious problem in Japan, and because of that Japanese high speed train are famous for their very long noses.

The main scenarios usually addressed in tunnel aerodynamics are either the entry and passage of a single train in the tunnel or a two trains crossing inside the tunnel.

With regards to the single train entry scenario, when the nose of the train enters the tunnel, it generates a compression wave which travels in the tunnel at the speed of sound. In the same way, when the tail of the train enters the tunnel it generates an expansion wave, which also travels in the tunnel at the speed of sound. The time history of pressure as recorded by a stationary probe in the tunnel is named pressure signature of the train, and it must fulfil regulations as in the European norm [6]. When the pressure disturbances arrive at the tunnel end they reflect changing sign (from compression to expansion and vice-versa) and emitting MPWs in the outer environment. After a while the rearward travelling pressure disturbances meet the train with a very high relative velocity. In order to quantify the phenomenon, these pressure disturbances can be of the order of 1000 Pa and with a time scale of about 0.1 s (corresponding to 34 m length) for a high speed train.

When the pressure waves meet the train they generate loads on the train structure, so the maximum expansion and compression loads have to be quantified for maximum strength calculation, and also the cyclic load variation is needed for fatigue calculations. Furthermore, in order to compute the loads on the train structure, both the external and the internal pressure time histories are needed, so the internal pressure has to be computed from the external one, taking into account both the length of the carriage and the location along the carriage on which one needs to compute the load. Taking these two factors into account when computing the loads is extremely important for a non-tight train, as in that case the internal pressure variation follows the external one very quickly.

With regards to the train crossing scenario, the pressure in the portion of tunnel where the two trains are crossing is lower than around one single train: for this reason the pressure time history on one train wall shows a quick reduction in pressure when the opposing train nose passes, and an increase in pressure when the opposing train tail passes. Furthermore, that pressure time history will be very different depending on the side of the train considered. For the wall on the side of the train closest to the opposing train the pressure variations will be very quick and with peaks, while at the train side closest to the tunnel wall the variation will be much
slower and without peaks. Also the disturbance from the head passing is stronger than the one from the tail passing, due to the wake.

These pressure changes at the train wall generate considerable loads. Given that the amplitudes of the pressure waves are proportional to the square of the velocity of the train which generated it, high speed trains are built to withstand much stronger pressure loads. This is why tunnels for high speed trains must be separated by the ones for regional trains which are not certified to withstand such loads. When this rule is broken incidents can happen, as on the 20/07/2015, when one of the two panel of a brand-new regional train carriage door separated inside a tunnel in the Firenze-Arezzo line in Tuscany, most probably due to the encounter of a high speed train [36].

Another reason why high speed trains are built to withstand stronger pressure loads is because they usually feature a pressurisation system which delays the internal pressure variations in order to grant passenger comfort, thus also increasing pressure loads. On the other hand, this work addresses pressure loads on non-tight trains (with velocities up to about 200 km/h), in which case the internal pressure variations are much quicker, thus requiring different models to compute the pressure loads.

In this work both the single train entry and train crossing scenarios have been simulated and different models for load computation have been implemented; the main goal was not to precisely compute the load for a single case, but to assess the influence of the several factors which play a role and to evaluate the effectiveness of different models for load computation. The inputs for these analyses have been the results of CFD simulations on simplified 3D train geometries, in order to be able to perform simulations for many different cases. Well-validated results for a benchmark case with the same simplified geometry were available to confirm the simulation set-up, so this work does not include comparisons with experimental results.

In order to simulate the train entry and the train crossing scenarios, both 3D and 1D CFD codes have been employed. The 3D CFD code was Star-CCM+, while the 1D code was NUMSTA. The 3D CFD simulations will be referred to as Star simulations, while the 1D simulations will be referred to as NUMSTA ones.
2. Theoretical Background

In this section the basic theories needed to correctly estimate and predict the behaviour of the train when crossing a tunnel will be recalled. To begin with some topics of fluid mechanics will be exposed, mainly to justify the models and approximations used in the following chapters. So the focus of this part will be on basics of compressible flow and unsteady wave motion. After that, a brief introduction will be given to tunnel aerodynamics and pressure tightness of the train.

2.1. Topics of Compressible Flow

In this chapter some basics of compressible flow and unsteady wave motion will be recalled, as even just using basic relations some important predictions can already be made about the properties of the head compression wave generated in the tunnel entrance phase. The whole Section 2.1 mainly follows the Anderson book “Modern compressible flow” [4].

2.1.1. One dimensional conservation equations

The most basic form of conservation equations is the steady one-dimensional inviscid adiabatic formulation. From the basic principles of conservation of mass, momentum (Newton law) and energy (First Principle of Thermodynamics), the three scalar equations Eq. (2.1) can be obtained which determine the changes in flow quantities when the fluid flows from the entrance to the exit of the constant cross section 1D control volume.

\[
\begin{align*}
\rho u &= \text{const.} \\
p + \rho u^2 &= \text{const.} \\
h + \frac{u^2}{2} &= \text{const.}
\end{align*}
\] (2.1)

Looking at Eq. (2.1), \( \rho \) is the density \( [\text{kg/m}^3] \), \( u \) is the flow velocity \( [\text{m/s}] \), \( p \) is the static pressure \( [\text{N/m}^2] \), and \( h \) is the static enthalpy \( [\text{J/kg}] \).

In order to close the system, two further equations describing the behaviour of the fluid itself are needed, for air one can generally use the perfect gas equation and the definition of static enthalpy for the constant \( c_p \) case as in Eq. (2.2).

\[
\begin{align*}
p &= \rho RT \\
h &= c_p T
\end{align*}
\] (2.2)

In Eq. (2.2), \( R \) is the perfect gas constant, equal to \( 287 \frac{J}{Kg \cdot K} \) for air, and \( c_p \) is the heat transfer coefficient at constant pressure, equal to \( 1005 \frac{J}{Kg \cdot K} \) for air at standard conditions.

By knowing the conditions at the entrance of the control volume one can use these two sets of equations to close the system of five equations in five unknowns, thus obtaining the conditions at the exit of the control volume. This fundamental set of equations will be useful both to find simple expressions to model the compression wave generated by the head of the train entering a tunnel in the following part of this chapter, and to be extended to the full 3D unsteady RANS equations (Reynolds Averaged Navier-Stokes, Eq. (3.8)), which are used in an integral finite volume formulation in the CFD simulations. Given that the extension of the Euler equations to the unsteady RANS is needed in this work only for the CFD simulations, the RANS equation will be described in the CFD background chapter (Chapter 3).
2.1.2. Basics of compressible flow and sound propagation

A compressible flow is a variable density flow. All the flows are compressible to an extent, but some can be treated as incompressible as long as the variations of density are negligible, as an example if their relative magnitude is less than 5% when compared to an imposed pressure variation magnitude. In which situations this condition can be verified depends on both the fluid and the flow considered.

The isothermal compressibility \( \tau \) is defined by Eq. (2.3).

\[
\frac{d\rho}{\rho} = \frac{p\tau}{\rho} \frac{dp}{p}
\]  

(2.3)

It models the amount of variation of density caused by an imposed variation of pressure for an isothermal process, and it is a property of a fluid. Water has an isothermal compressibility of \( 5 \times 10^{-10} \frac{m^2}{N} \) while it is \( 10^{-5} \frac{m^2}{N} \) for air. The imposed variation of pressure on the other hand depends on the flow. Given the Mach number of a flow, defined as the ratio of local flow speed over local speed of sound, the maximum pressure increase is obtainable by isentropically getting the flow to rest; this pressure is defined as total pressure (or stagnation pressure). The ratio between total to static pressure is a function of the Mach number, and when the Mach number is 0.3 (about 360 km/h for air at standard conditions) the relative variation of density is 4.6% for air and a negligible quantity for water. For practical applications, 0.3 can be taken as a limit of Mach number below which the flow of air can be considered incompressible, while the flow of a liquid can be considered incompressible for any Mach number.

Compressibility is strongly related to sound propagation. In fact, the propagation of sound is the propagation of small amplitude isentropic disturbances, so the density has to change slightly for the sound to propagate. A first analysis of a sound wave which gives the definition of the speed of sound is as follows. Placing a frame of reference on a weak wave (i.e. the propagation in space of a small amplitude disturbance) travelling through fluid at rest, one can define the speed of the flow incoming into the wave as \( a \). Downstream the wave, the conditions will be different in terms of all the flow quantities, and the velocity will be \( a + da \). If the increment \( da \) is considered small, Eq. (2.1) can be applied to a volume of fluid containing the wave and differentiated to get the following relation.

\[
a^2 = \frac{dp}{d\rho}
\]  

(2.4)

The hypothesis of small disturbances implies that the transformation is isentropic, so:

\[
a = \sqrt{\left(\frac{d\rho}{dp}\right)_s} = \sqrt{\frac{1}{\rho_s}} = \sqrt{\gamma RT} = 341 \frac{m}{s}
\]  

(2.5)

In Eq. (2.5) \( \tau_s \) is the isentropic compressibility, and the numerical value is computed at standard sea level conditions. From Eq. (2.5) one can realize that the speed of sound is inversely proportional to the compressibility, so an incompressible gas would have an infinite speed of sound. Furthermore the speed of sound is proportional to temperature, and this comes from the fact that the small disturbances in the gas propagate through molecular collisions, so their velocity is proportional to the thermal agitation velocity of the molecules in the gas. It is important to note that while the wave propagates at the speed of sound, the velocity of the fluid upstream and downstream of the wave is zero. This is a key difference which distinguishes a weak wave (small disturbance, isentropic) from a nonlinear one (finite disturbance, non-isentropic).

2.1.3. Moving normal shock waves

One of the most important findings in compressible flow are the normal shock governing equations, which come directly from an application of the Euler equations Eq. (2.1) to a control volume containing a stationary shock wave. A stationary shock wave is an adiabatic compression process, in which an incoming supersonic flow is slowed to subsonic conditions in an extremely thin region (a few molecular mean free paths), thus increasing its pressure and temperature with high associated viscous losses in the shock region.
The most important relation for a normal shock is the Prandtl relation, which comes directly from the Eulerian conservations Eq. (2.1).

\[ M_1^* M_2^* = 1 \]  

(2.6)

In Eq. (2.6) subscript 1 stands for upstream the wave, 2 stands for downstream, and \( M^* \) is the characteristic Mach number. This relation implies that the flow downstream of a normal shock must be subsonic if the upstream one is supersonic, furthermore the latter condition must always hold for a shock because of the second principle of thermodynamics.

Starting from the Prandtl relation, the governing equation for a steady normal shock wave can be derived, which is not useful to do in this context.

Looking instead at the motion of an unsteady shock wave, such as the one in Fig. 2.1, one can depict the differences among the two problems.

![Diagram](image)

**Fig. 2.1 Stationary and moving normal shock waves [4].**

The gas ahead of the moving shock wave is assumed stagnant, the velocity of the moving shock wave is denoted with \( W \) and the velocity downstream of it is \( u_p \). The Euler conservation equations Eq. (2.1) assume the form of Eq. (2.7).

\[
\begin{align*}
\rho_1 W &= \rho_2 (W - u_p) \\
p_1 + \rho_1 W^2 &= p_2 + \rho_2 (W - u_p)^2 \\
h_1 + \frac{W^2}{2} &= h_2 + \frac{(W - u_p)^2}{2}
\end{align*}
\]  

(2.7)

From Eq. (2.7) the governing equations for a moving shock wave can be derived. It is convenient to refer all the quantities to the static pressure ratio \( \frac{p_2}{p_1} \) across the moving wave, which defines its intensity. It must be underlined that the condition \( \frac{p_2}{p_1} > 1 \) must hold, as if the wave were an expansion one it would follow different constitutive equations. The density and temperature drop can be explicitly expressed as a complicated function of the pressure drop. More interesting is the expression of the moving shock velocity in Eq. (2.8).

\[ W = a_1 \sqrt{\frac{y+1}{2y} \left( \frac{p_2}{p_1} - 1 \right) + 1} \]  

(2.8)
In Eq. (2.8) $a_1$ is the expression of the speed of sound upstream of the wave. One can see in Eq. (2.8) that the shock wave moves faster than sound. This is readily explained when recalling that the sound wave (which travels at the speed of sound) is a weak wave, so the pressure drop across it is infinitesimal, while a moving shock wave has a finite pressure drop, so it moves faster than sound (Eq. (2.8)). Besides, the governing equation for the sound wave are the one for the moving shock wave in the limit $\frac{p_2}{p_1} \to 1$.

Another important difference between a moving shock wave and a stationary one is that the velocity $u_p$ downstream of the wave is always positive, and it can even get supersonic, while the velocity downstream of a sound wave is zero.

Furthermore, another difference between a moving shock wave and a stationary one is that, even though both flows are adiabatic, while in the latter the total enthalpy is conserved Eq. (2.1), the moving shock wave is not iso-enthalpic. This is can be seen in the third equation in Eq. (2.7), as the total enthalpies by definition are computed using $h_1, h_2, u_1, u_2$.

These properties of the propagation of a moving shock wave are directly applicable to the propagation inside the tunnel of the head compression wave generated by the tunnel entry of the train. It must be kept in mind anyway that the nose entry compression wave is much weaker than a shock wave, as its amplitude is in the order of magnitude of 1000 Pa; this causes its width in space to be about 100 m (much more than the few mean free paths width of a shock wave), so it should be treated as a finite compression wave (Section 2.1.7).

### 2.1.4. Reflection of moving waves at a boundary

It is useful to also look at the phenomena happening when the nose entry compression wave reaches a boundary, as an example the tunnel exit. What determines the behaviour of the reflected wave is the kind of boundary condition. If there were a wall at the end of the tunnel, the boundary condition to be satisfied would be a wall normal velocity equal to zero, as shown in Fig. 2.2.

![Reflection of shock wave on a wall](image)

**Fig. 2.2 Reflection of shock wave on a wall.** Above: before reflection. Below: after reflection [4].

The velocity coming into the reflected shockwave would be the $u_p$ the wave had before hitting the wall, and the velocity downstream of the reflected shockwave would be zero to satisfy the boundary condition. This means that the reflected wave is another shock wave, as the relative speed across it decreases.

On the other hand, with an open-air tunnel end, the boundary condition to be satisfied at the exit is for the pressure at the exit of the tunnel to be ideally equal to ambient pressure. This means that the reflected wave would see an incoming flow pressure equal to the $p_2$ before the reflection. Furthermore $p_2$ is higher than the
ambient pressure, as the pressure must have increased across the compression wave before the reflection. So the reflected wave is an expansion wave, as the pressure decreases across it. So when a compression wave arrives at an open air tunnel end it reflects as an expansion wave.

It must be highlighted that in reality the exit of a tunnel would not impose a pressure constantly equal to the ambient one at each instant and regardless of the incoming disturbances. Due to this, in a real tunnel exit, the incoming head compression wave will not immediately be reflected as an expansion wave. While the compression wave is bouncing back in the tunnel as an expansion one it also emits a less intense secondary compression wave which propagates in space outside the tunnel, thus the incoming compression wave gets slightly delayed and weakened at the reflection. The secondary wave is call Micro-pressure wave (MPW) and it will be treated in the following sections. It is important to keep in mind this phenomenon when shaping the domain and choosing the boundary conditions for the CFD simulations. Furthermore this wave reflection process can be very well visualised with animated results from the simulations.

2.1.5. Elements of acoustic waves propagation

It is useful to examine the behaviour of a weak sound wave, which can be a first approximation of the finite compression wave generated by the train entrance. One can imagine a sound wave as the propagation in space of a small disturbance \( \Delta \rho \), which is linked to a \( \Delta u \), \( \Delta p \), and so for each thermodynamic quantity. Given the initial distribution of one of these quantities in space, which is uniform except for the disturbance, the conservations of mass, momentum and energy can predict the propagation of the wave. It is convenient to express the inviscid adiabatic conservations in a differential formulation, using entropy in the energy equation:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \mathbf{V} \cdot (\rho \mathbf{V}) &= 0 \\
\rho \frac{\partial \mathbf{V}}{\partial t} &= -\nabla p \\
\frac{\partial s}{\partial t} &= 0 
\end{align*}
\]  

(2.9)

This system of nonlinear PDEs can be linearized in the hypothesis of small disturbances. The 1D linearized formulation becomes

\[
\begin{align*}
\frac{\partial \Delta \rho}{\partial t} + \rho_\infty \frac{\partial \Delta u}{\partial x} &= 0 \\
\rho_\infty \frac{\partial \Delta u}{\partial t} &= -a_\infty \frac{\partial \Delta \rho}{\partial x} 
\end{align*}
\]  

(2.10)

These are the acoustics equations, they are linearized in the approximation of small disturbances, and they describe the propagation of sound waves in one dimension. Being them linear, they can be solved in closed form.

The solution consists in the propagation of the undeformed (due to linearity) initial profile at the velocity \( a_\infty \) (the speed of sound is constant due to small disturbances) in either the positive (right running) or the negative (left running) direction. If for example the initial disturbance is given in terms \( \Delta \rho \), then it will propagate at the speed of sound, and the magnitude of the associated variations of \( \Delta u \) and \( \Delta p \) are given by Eq. (2.11), which is found by manipulating the system of Eq. (2.10).

\[
\Delta u = \pm \frac{a_\infty}{\rho_\infty} \Delta \rho = \pm \frac{1}{a_\infty \rho_\infty} \Delta p 
\]  

(2.11)

The plus sign in Eq. (2.11) holds for right-running waves and the minus sign for the left running ones. It must be stressed again that these disturbances are limited to the wavefront region in space. Indeed, after the passage of the wave, velocity density and pressure are nearly equal to the upstream undisturbed ones, as the propagation sound waves is an isentropic process (\( \Delta \rho, \Delta p, \Delta u \sim 0 \)). It is also interesting to note that the mass motion induced by \( \Delta u \) is in the same direction of the propagation of the wave for compression disturbances (positive \( \Delta \rho, \Delta p \)) while it is in the opposite one for expansion disturbances (negative \( \Delta \rho, \Delta p \)). This is coherent with the direction of the mass motion induced by a finite compression or expansion wave, such as the ones generated by the entrance of either the head or the tail of the train in the tunnel.
Furthermore, if a generic 1400 Pa train nose entry compression wave is considered weak, so close to isentropic, the flow velocity displaced by that wave will be about 3.4 m/s. It is interesting to note that this is a first approximation of the difference in velocity between the two ends of the train nose finite compression wave exposed in the following section.

### 2.1.6. Finite waves propagation

A finite wave is the propagation of a disturbance which is not assumed small in space. This kind of wave is also called non-linear wave, and it can be either a compression or an expansion wave. The main difference between a weak wave and a finite one is that in the latter the propagating disturbance, as an example in terms of \( \Delta \rho \), is not small. So the disturbance in density will generate a disturbance in temperature, so makes this a non-linear problem. The main effect of the nonlinearity is the deformation of the profile of the initial disturbance as the wave propagates. This kind of waves is still isentropic.

The governing equation are still the inviscid adiabatic ones Eq. (2.9), which can be manipulated and expressed in 1D formulation using velocity and pressure as variables, as in Eq. (2.12).

\[
\begin{align*}
\frac{1}{a} \left( \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} \right) + \rho \frac{\partial u}{\partial x} &= 0 \\
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} &= 0 
\end{align*}
\]  

(2.12)

The solution of this system of PDE appears not straightforward, but the method of characteristics can help a lot in understanding the results of it.

By expressing this system in matrix form, one can retrieve the eigenvalues which represent the characteristic velocities of the problem. By integrating the velocities one can represent the two characteristic curves in the \( x-t \) (space-time) diagram. Expressing the system Eq. (2.12) along the two characteristic lines gives two compatibility equations in Eq. (2.13), one for each characteristic line.

\[
\begin{align*}
C_- \text{ line: } \frac{dx}{dt} &= u - a \\
\text{comp. along } C_- & : du - \frac{1}{\rho a} dp = 0 \\
C_+ \text{ line: } \frac{dx}{dt} &= u + a \\
\text{comp. along } C_+ & : du + \frac{1}{\rho a} dp = 0
\end{align*}
\]  

(2.13)

The reason why the system has been represented onto the characteristic lines is that along these lines the compatibilities equations are ODE, not anymore PDE, so they can be easily solved by integrating along the characteristic lines. This integration gives the two Riemann invariants \( J_- \) and \( J_+ \) in Eq. (2.14) and Eq. (2.15), one for each characteristic line.

\[
\begin{align*}
J_- &= u - \int_{C_+ \rho a} \frac{1}{\rho a} dp = u - \frac{2a}{\gamma - 1} = \text{ cost along } C_- \\
J_+ &= u + \int_{C_+ \rho a} \frac{1}{\rho a} dp = u + \frac{2a}{\gamma - 1} = \text{ cost along } C_+ \\
\Rightarrow \begin{cases} 
\frac{1}{2} (J_+ + J_-) \\
\frac{\gamma - 1}{4} (J_+ - J_-)
\end{cases}
\end{align*}
\]  

(2.14)

(2.15)

Each invariant comes from the integration of Eq. (2.13), so it is constant along the associated characteristic line. The algebraic system of algebraic equations Eq. (2.14) gives the solution of the problem along the characteristic lines, expressed in Eq. (2.15). The method of characteristics for the solution of this problem consists in computing the Riemann invariants along the domain from the initial condition, then draw the characteristic lines (for a time step as their inclination is not constant), then propagate each Riemann invariant across the associated characteristic, and use Eq. (2.15) to get the solution at the instant considered.
But even without solving the problem with the characteristic method, from these equations one can still take important considerations on the motion of such a wave, which will be useful when looking at the propagation of the wave generated in the tunnel entrance phase.

First, each point of the wave profile moves at a velocity $u + \alpha$ (right running wave). This is easy to understand by thinking about the propagation process of the disturbance, which moves due to molecular collision. The motion of the disturbance has a velocity $\alpha$, but if the gas through which the disturbance propagates travels at a speed $u$, the two phenomena are superposed, so the velocities are summed. This property is extremely important, as any disturbance in $\rho$, as an example an increase in $\rho$ (compression), causes both an increase in $u$ (induced mass flow), and an increase in temperature, which in turn increases $\alpha$. These two effects both cause an increase in the wave propagation velocity, so the tail of a finite compression wave travels faster than its head, so the density profile gets steeper while the wave travels, and the same happens to the pressure profile. This phenomenon is named non-linear steepening of the wave, and it is a well-known effect in shock tubes and in tunnels. If a tunnel is long and smooth enough, the finite compression wave caused by the entrance of the head of the train might even steepen itself into a shockwave. The opposite happens to the expansion wave caused by the entrance of the train tail, so its profile gets more flat instead of steeper.

Looking again at the 1400 Pa train nose entry compression wave, it has been found in Section 2.1.6 that the velocity downstream of it is 3.4 m/s. Neglecting the variation of temperature (and so speed of sound) across the wave and given that the length of this wave in space is about 50 m, for a 1D isentropic flow it would take 14.7 s for the finite compression wave to become a shockwave: at a speed of 340 m/s this corresponds to 5000 m, which is less than many tunnels length. If one considered also the influence of the increase in temperature across the shockwave this distance would be even shorter. In real tunnels with a real fluid there are anyway other factors which prevent the non-linear steepening to turn the finite compression wave into a shockwave, as described in Section 2.2.

It is important to note that a finite wave, either a compression or an expansion one, is still isentropic, as opposed to a moving shock wave.
2.1.7. Finite compression and expansion waves

To better clarify the behaviour of a finite wave, in the Fig. 2.3 the propagation of a finite compression wave generated in a shock tube is represented.

Fig. 2.3 Characteristics representation of a finite compression wave in a shock tube [4].

The piston in Fig. 2.3 suddenly starts to move at $t = 0$, then accelerates, and then moves at a constant speed. As long as the piston is accelerating, a right-running compression wave and a left running expansion wave originate at the piston. The family of characteristic lines in the region at the right of the piston is associated with the third eigenvalue of the system, so the characteristic velocity is $u+a$ while in the region at the left of the piston that velocity is $u-a$. The third family characteristic lines are converging in the region at the right of the piston, so a right running finite compression wave takes place there, which gets narrower as it travels and turns into a shock after a short while. The fact that the first family characteristic lines are diverging means that an expansion fan (finite expansion wave) is taking place in the region at the left of the piston, and it gets wider as it travels.

Looking at the finite compression wave, its head, which path is coloured green, travels at the speed of sound in the upstream still gas. The tail of the compression wave, which path is red, travels at the speed of sound in its location (which is higher than the upstream speed of sound) plus the velocity induced by the mass flow (which moves in the same direction of the piston). Both these effects increase the velocity of the tail of the compression wave, leading to an increase of the pressure gradient, until the finite compression wave becomes a shock. At that moment the flow ceases to be isentropic, and the moving shock travels at a velocity which is higher than the upstream speed of sound (Eq. (2.8)) and lower than the one of the tail of the compression wave. The shock velocity can be computed using the relations from section 2.1.3, as the velocity downstream of the shock, which is the piston velocity, is a sufficient parameter to determine the pressure drop.

Focusing on the train head entry, the generated finite compression wave travels along the tunnel getting steeper and steeper until it reaches the tunnel end, then reflects back as a compression wave. As the latter travels backward in the tunnel it gets wider again, so when it reaches the starting point it will be about as wide as it was at the beginning. This holds only for an inviscid isentropic (no shocks) 1D flow, with an ideal pressure
outlet. The situation in which the backward travelling wave hits the train again is named pressure wave encounter scenario, and this conclusion suggests that in order to compute the loads on the train one might use as external pressure the time history of the head finite compression wave as it was as soon as it was generated, keeping in mind that it might have a positive or negative sign depending on the number of reflection it has gone through. This conclusion is extremely useful as it allows to neglect the wave propagation phase for this scenario, and the wave propagation is a very complex phenomenon which strongly depends on details of each single tunnel, as shown in the following chapters.
Tunnel aerodynamics

Determining the behaviour of the air inside the tunnel while the train passes is of paramount importance because of many reasons. It is very important to compute the external pressure felt by the train both with regard to the structure, as the external pressure determines the structural load, and with regard to the passenger, as the fluctuations in time of the internal pressure must be reasonably limited.

Some of the most influencing parameters which determines the performance of the train when crossing a tunnel are the velocity of the train, the ratio between the train cross section and the tunnel cross section (named blockage ratio), the nose shape, the presence of ballast in the track, the portal shape and the presence of air shafts to relief the pressure oscillations. The number of parameters involved and the coupling between train and tunnel design make tunnel aerodynamics a complex design task.

In this chapter at first an overview of the propagation pattern of the waves generated at the train entry will be given. Then the focus will shift on the generation of the head compression wave, in order both to give first estimates of its shape and to assess the influence of geometrical parameters such as nose and tunnel portal shape on its intensity. After that, the propagation of the generated head compression wave will be studied, in order to introduce the phenomena which counteract the non-linear steepening. In the end a brief introduction will be given on Micro Pressure Waves, which are the compression wave emitted in the outside environment when a wave reflects at the tunnel end.
2.2.1. Overview of wave propagation pattern and pressure signature

In this section at first the pressure signature of a train entering tunnel will be introduced, then the wave propagation pattern of a full tunnel passage will be exposed and commented. It is of paramount importance for this work to define the pressure signature and the wave propagation pattern, as they are the main phenomenon which determines the structural loads on the train.

The first step is to visualise the train entry phase. In order to do so, one can visualise a train about to enter a tunnel. As the train is moving, it displaces air in front of him, pushing it towards the sides and the roof towards the tail, so from a reference frame stationary to the ground the air is pushed forward in front of the train nose, originating a stagnation region with higher pressure. When the train nose pressure disturbance starts entering the tunnel, the pressure level starts propagating inside the tunnel at the speed of sound. This phenomenon causes the train nose entrance in the tunnel to generate a finite compression wave, just as the one generated by the accelerating piston in Section 2.1.7. If the train were of exactly the same size as the tunnel and the velocity of sound were infinite, the resulting flow field would just be air homogeneously displaced in the whole tunnel at the piston velocity. The opposite happens when the tail enters the tunnel, so a finite expansion wave is generated which then also travels in the tunnel at the speed of sound following the head one. The two waves can be recorded by a stationary probe inside the tunnel, as shown in Fig. 2.4.

The Train-Tunnel Pressure Signature is the pressure time history generated by the train entry in a tunnel recorded at a fixed point inside the tunnel, as shown in Fig. 2.4. The first disturbance is the nose entry compression wave, which is also the strongest one both in terms of amplitude ($\Delta p_N$) and of gradient. In all of this paper the pressure gradient is $\frac{\partial p}{\partial t}$ (and not $\nabla p$), as usual in train aerodynamics. Following the nose entry compression wave there is a slower pressure increase named $\Delta p_{fr}$. It is due to the flow in the train-tunnel annulus area: the pressure is much higher close to the train nose than at the portal and the flow velocity is in the opposite direction than the train one. Given that the pressure at the portal is the ambient pressure, then the pressure ahead of the nose must increase to push air towards the tunnel entrance, as if in a pipe flow in which the developed boundary layers on the walls require a pressure drop to sustain the flow. As the train keeps on entering the tunnel the pipe gets longer, so a higher pressure drop is required. The duration and magnitude of the friction rise strongly depends on the train length, on the roughness of the train and tunnel walls, and on the cross sectional area of the flow channel between train and tunnel walls. A more detailed explanation and visualisation of the friction rise can be found in Section 4.2.6.

![Fig. 2.4 Train-tunnel pressure signature, fixed position in the tunnel](image-url)
After the friction rise the expansion wave due to the train tail entry comes to the probe, its magnitude is considerably smaller than the nose entry wave one due to the wake influence, and it is named $\Delta p_T$. The sudden pressure drop $\Delta p_H$ is due to head passing the probe location.

In order to assess the propagation pattern of the pressure waves recorded in the pressure signature during a whole tunnel passage, one can look at Fig. 2.5.

![Wave propagation pattern](image)

**Fig. 2.5**

Plot A) External pressure felt on the train during whole tunnel passage. Also plotted internal pres., load.

Plot B) Pressure felt by a stationary probe in the tunnel during the whole tunnel passage.

Plot C) Wave propagation pattern (space-time), shows position of train and waves for each time instant

Fig. 2.5 Shows CFD results of a whole tunnel passage in case of a 50 m long train, 500 m long tunnel and train speed of 250 km/h. Plot A shows the external pressure felt by a probe on the train wall. It also shows the internal pressure and the structural load computed using a time constant $\tau = 0.5$ s, but now the focus is only on the external pressure, so this will be introduced in the following sections. Plot B shows the pressure felt at a stationary point probe 100 m inside the tunnel, so it records the pressure signature in the same way as in Fig. 2.4. Plot C shows the wave propagation pattern, so it shows the position of the train (for nose, probe and tail) and the one of the two waves for each time instant. It should be underlined that the black lines show compression waves, while the green ones show expansion waves, and the line style distinguish between head and tail entry waves.

Following a chronological exposition, the first event is the generation of the head compression wave, which then travels inside the tunnel at the speed of sound and gets recorded by the tunnel probe at about 2 s (marked with black oblique cross). While the train is entering the tunnel, the pressure in front of the nose keeps on rising due to the friction rise, but this is barely noticeable in Fig. 2.5 as the train is very short and smooth, with a simplified geometry. The main goal of this simulation was to estimate the head compression...
wave. After the friction rise, the tail enter the tunnel, and the tail wave gets recorded first by the train probe and then by the tunnel probe at about 2.2 s (marked with green straight crosses). Between 3 s (red circle) and 3.75 s (blue circle) the train is passing the tunnel probe, so both probes record a similar pressure in this phase. Shortly after that an expansion wave comes to the train (green oblique cross) from the train front: it comes from the reflection of the head compression wave at the tunnel far end, and its amplitude in absolute value is close to the one recorded in the pressure signature. That expansion head-wave then reflects at the tunnel entrance, and hits again the train but this time from the tail, again as a compression head-wave (black oblique cross). So pressure waves travelling in both directions can be seen by the train, and the same wave will each time present itself as a compression or expansion wave, without weakening too much at each reflection and propagation (depending also on the tunnel features), and the strongest wave is always the head one. These conclusions will be of paramount importance when deciding which cases to look at for load computation.

2.2.2. Generation of the head compression wave

The head compression wave is generated by the interaction of the moving non-uniform pressure field around the train nose with the ground-fixed tunnel entry, so it is an unsteady problem. The low speed of the train (when compared to the speed of sound), makes the head compression wave very wide in the tunnel axis direction. For a train travelling at 250 km/h in a 75 m² cross section tunnel, the magnitude of the head compression wave will be in the order of 1000 Pa (150 dB), while its width can be approximately 5 times the tunnel diameter [5]; this corresponds to about 50 m, as confirmed by CFD result for such cases.

The magnitude of the pressure increase across the head compression wave can be approximated using Eq. (2.16), [7].

\[
\Delta p_N = \frac{\rho v_{tr}^2}{2} \frac{1 - (1 - B)^2}{(1 - M)(M + (1 - B)^2)};
\]

(2.16)

In Eq. (2.16) \( M \) is the train Mach number calculated using the train speed \( V_{tr} \) and the undisturbed field sound speed, and \( B \) is the blockage ratio, defined as the ratio of the train cross sectional area over the tunnel cross sectional area. This formula is valid for the inviscid compressible flow around a snub-nosed train (a horizontal cylinder head shape) and shows that the two most important parameters which influence the pressure drop are the train velocity and the blockage ratio, and that an increase in both parameters results in a stronger head compression wave. It must be underlined that comparing the \( \Delta p_N \) computed using Eq. (2.16) with the one from Star simulations, a difference will arise due to the boundary layers developing both on the train nose and on the ground, as the boundary layer displaces flow and so it acts as an increase of train cross sectional area.

A more complex formula for \( \Delta p_N \) is Eq. (2.17) by Sockel [30], which also includes pressure loss coefficients for the head of the train.

\[
\begin{align*}
0 &= X_h + \frac{(M_a - X_h)^2(1 + X_h)}{2} \left(1 - \frac{1 + X_h}{(1 - B)^2}\right) - \zeta_h \frac{(M_a - X_h)^2(1 + X_h)^2}{2(1 - B)^2} \\
\Delta p_N &= \left(1 + \frac{\kappa - 1}{2} X_h \right) \frac{\zeta_h}{\gamma - 1} - p_0
\end{align*}
\]

(2.17)

In order to employ Eq. (2.17) one has to recursively solve the first part for \( X_h \), an unknown in the form of a Mach number, and then apply it to the adiabatic isentropic relation, as shown in the second line. \( \zeta_h \) is the loss coefficient of the train head, \( p_0 \) is the ambient pressure, \( \kappa \) is the ratio of specific heats, \( M_a \) is the Mach number, \( B \) is the blockage ratio. The level of flow assumptions in the Sockel equation is comparable to the one of NUMSTA, but the latter does not include head and tail loss coefficients.
A third way to compute $\Delta p_N$ for a generic case is to measure it from a benchmark Star simulation ($\Delta p^b_N$) and then correct it for different velocities or blockage ratios as in Eq. (2.18).

$$
\begin{align*}
    f^b_B & = \frac{1 - (1 - B)^2}{(1 - M)[M + (1 - B)^2]} \\
    \Delta p_N & = \Delta p^b_N \left(1 - \frac{V}{V^b}\right) \frac{f^b_B}{f^b_B}
\end{align*}
$$

(2.18)

In Eq. (2.18) the superscript $b$ stands for benchmark, $f^b_B$ models the influence of a different train or tunnel cross sectional area from the benchmark case and the ratio of squared velocities does the same for different velocities. The formulation of Eq. (2.18) gives the advantage of starting from a benchmark pressure increase $\Delta p^b_N$ which is more accurate than either the Eq. (2.16) or the Eq. (2.17) one, thus predicting a $\Delta p_N$ closer to the one predicted by Star.

For predicting both the magnitude of generated micro pressure waves at the end of the tunnel and the load generated on the train by the head entry compression wave, a very important parameter is the maximum pressure gradient of the head entry compression wave, especially for non-tight trains. The maximum pressure gradient basically depends on the magnitude of the pressure wave $\Delta p_N$ and on the pressure rise time, which is approximately the time it takes for the pressure field around the nose of the train to enter the tunnel. The maximum pressure gradient can be approximated using Eq. (2.19), [5].

$$
\frac{\partial p}{\partial t}_{\text{max}} = \frac{\rho v^2}{R} \frac{B}{R} \frac{0.64 + 1.3 M^6}{1 - M^2}
$$

(2.19)

In Eq. (2.19) $R$ is the tunnel radius. This formula holds for a snub-nosed train and a simple sharp-edged tunnel entry, so it does not take into account the influence of the nose length and of the entrance hood, which are both strong. It anyway allows to understand that the velocity counts with the third power, and this is because the magnitude of the pressure difference is influenced by the velocity squared (16), while the velocity still influences the time it takes for the nose of the train to enter the tunnel, which determines the pressure rise time, and so the maximum gradient of pressure. Compressibility also affects the maximum pressure gradient, as Eq. (2.16) and Eq. (2.19) show that a higher Mach number corresponds to both a higher pressure drop and a higher pressure gradient.

A more flexible way to compute the maximum pressure gradient is to divide $\Delta p_N$ by a time scale characteristic of the compression wave. This time scale can be expressed as the ratio between a characteristic length of the compression wave (of the same order of magnitude as the nose length), and the train velocity, as expressed in Eq. (2.20), [8].

$$
\frac{\partial p}{\partial t}_{\text{max}} = \frac{\Delta p_N}{\Delta t}; \quad \Delta t = \frac{L}{V_{tr}}
$$

(2.20)

The procedure expressed in Eq. (2.20) is more flexible than the Eq. (2.19) one, as the characteristic length might be chosen according to the desired output, as an example in order to fit the Star results. The paper [8] advises to use $L$ which is directly proportional to the tunnel hydraulic diameter.

Then by using Eq. (2.18) to compute $\Delta p_N$ together with Eq. (2.20) to compute $\frac{\partial p}{\partial t}_{\text{max}}$ one can define the head entry compression wave for cases with different train speed and tunnel cross section than the benchmark one; this is the main concept behind the fitting of the Star results which has been performed for both the single train entry and train crossing scenario and will be exposed in Chapter 4. Another important result of that fitting procedure is the expression of $L$ as a function of tunnel cross section, train cross section, nose length and track spacing, which is useful not only to compute the maximum gradient from Eq. (2.20), but also to improve NUMSTA accuracy in terms of time scale of the generated head compression wave, as will be exposed in Chapter 4.
All of these ways to compute the pressure increase $\Delta p_N$ and $\frac{\partial p}{\partial t}_{\text{max}}$ will be compared in Chapter 4.

Velocity of the train and blockage ratio are not the only factors which determine the head compression wave. To begin with, the front shape and in particular its length and distribution of cross sectional areas have a great influence on the maximum pressure gradient. A first approximation of the influence of the nose shape can be taken considering an axisymmetric train entering an axisymmetric tunnel. This approximation is sufficient to model the features of the compression wave sufficiently downstream of the tunnel entrance, so that the wave has had time to become planar.

![Fig. 2.6 Influence of nose shape on maximum pressure gradient [9].](image)

Looking at the results in Fig. 2.6, one realizes that the most important parameter is the slenderness of the nose, represented by the ratio of nose length over nose width ($a/b$). Comparing bodies with the same slenderness, the best results are obtained with a nose resembling a paraboloid of revolution, with about a 10% advantage over an ellipsoid. In order to reproduce these advantages on a realistic train nose, which is not axisymmetric, one can try to follow the area distribution of these basic shapes. Furthermore, numerical optimization procedures can be set-up in order to derive the best nose shape to reduce the pressure gradient in a very effective way.

Another way to reduce the pressure gradient generated at the tunnel entrance is to build a hood at the tunnel entrance, because the pressure gradient is determined by the pressure drop across the head compression wave and the rise time, which in turn is influenced by the nose and hood lengths. The most basic tunnel entrance hood is the “half penne pasta” kind, shown in Fig. 2.7 together with a Shinkansen 700 train.
For sure the combination of a long and slender nose such as the Shinkansen one and a flared portal such as the one in Fig. 2.7 would increase the rise time of the head compression wave, thus granting a lower maximum pressure gradient. More complicated portals can be designed, with holes on the lateral wall to reduce the head pressure wave magnitude, as shown in Fig. 2.8.

From the charts in Fig. 2.8 it is possible to understand the influence of the entrance hood and of the holes. First of all, the pressure history without portal is the one which shows both the maximum pressure amplitude of the compression wave and the minimum pressure rise time and so the highest gradient. Adding the portal without holes the rise time heavily increases while the pressure amplitude remains unchanged, thus lowering the maximum gradient. In this case it is possible to note two peaks in the pressure gradient time history, the first lower one caused by the train entrance in the portal, and the second higher one caused by the train entrance in the tunnel. Adding the holes allows to smoothen the two peaks in the gradient time history and to slightly lower the maximum amplitude of the head compression wave.
To sum up, different kinds of extension of the tunnel entrance are beneficial, as shown in Fig. 2.9.

![Fig. 2.9 a) flared entrance, b) ventilated entrance [23].](image)

The decreasing cross section of a flared entrance such as the one in Fig. 2.9a makes the transition to the lower cross sectional area more gradual, while the ventilated one in Fig. 2.9b allows the fluid in the higher pressure area to flow out from the openings.

Generally the worst shape for a tunnel entry in terms of maximum gradient of the generated head compression wave is the simplest sharp edged perpendicular tunnel portal, which is also the most common in many countries, so in the following of this work the tunnel portal will be assumed of that kind.

Another aspect of the generated compression wave is its three-dimensional character. During the tunnel entrance phase, while the wave is being generated, its character is strongly three dimensional due to the difference in shape between the train and the tunnel. Therefore in this phase a quasi-1D flow approximation would not be able to predict the time scale of the compression wave, as that time scale roughly corresponds to the time it takes for the 3D nose and 3D pressure field around it to enter the tunnel and a 1D code clearly cannot simulate the 3D pressure field.

After the entrance phase the wave propagates inside the tunnel, quickly becoming a planar wave: in this phase the flow could well be approximated with 1D theories with the addition of friction loss coefficients, such as in the NUMSTA code. What can be done to bring NUMSTA predicted head compression wave closer to the Star one is to choose a nose length for the NUMSTA train which is proportional to the \( L \) used in Eq. (2.20), in order to match the NUMSTA time scale to the Star one. This procedure has been implemented and it will be described in Chapter 4.

### 2.2.3. Propagation of the head compression wave

If the tunnel were smooth and axisymmetric and the flow were inviscid, the propagation of the head compression wave would precisely follow the finite wave propagation equations in Section 2.1.6. Basically in that case, if the tunnel were long enough (about 5000 m for a 1400 Pa, 50 m wide wave in a 75 \( m^2 \) tunnel), the non-linear steepening effect would turn the head compression wave in an unsteady shockwave Eq. (2.11). In reality, instead, there are many factors which weaken the non-linear steepening effect. The impact of friction, ballast and cross-section variation will be assessed in this section.

Friction is divided in two kinds, quasi-steady and unsteady friction. The quasi-steady wall shear stress is equal to the one which would arise in a steady flow with the same velocity (Eq. (2.21)) and it is the one modelled in NUMSTA. The unsteady friction instead is the component due to the transients happening as the moving compression wave travels. For example, considering a pipe flow, one can define two steady states with different pressure drops and velocity distributions. While passing from a state to the other, even if the two steady states are qualitatively similar one another, the velocity and pressure distribution during the transient may be very different from the steady states. What determines the speed at which the flow reacts to the imposed disturbance is turbulent diffusion. This effect depends on the time history of the rate of change of
mean velocity (Eq. (2.22)), and it is not modelled in NUMSTA. An overview of these two effects is given in Fig. 2.10.

![Diagrams showing effects of steady and unsteady friction on wave propagation](image)

**Fig. 2.10 Effects of steady and unsteady friction on wave propagation [11].**

Top: step initial pressure profile. Bottom: linear initial pressure profile.

Looking at the upper left plot of Fig. 2.10, one can see the propagation of a step wave with Quasi-steady friction only. The distance is meant as relative to a fictitious wavefront travelling at the speed of sound. Given that the finite compression wave travels faster than sound (Section 2.1), the step wave front after 10 seconds is 25 meters in front of the fictitious one. The effect of quasi-steady friction is given by the dotted lines: it causes a reduction in amplitude. In the left-lower plot, one can see the propagation of a ramp wave, which steepens in time due to the non-linear steepening effect. The quasi-steady friction still reduces the amplitude of the wave. The unsteady friction, as in the two right plots, not only reduces the amplitude of the wave, but also the pressure gradient, directly counteracting the non-linear steepening effect.

The two kinds of friction can be modelled in 1D flow solvers using friction coefficients. The quasi-steady friction is modelled in the steady flow usual way, as in Eq. (2.21).

$$\tau_{w\, steady} = c_f \frac{1}{2} \rho U^2$$

(2.21)

While the unsteady friction can be modelled using Eq. (2.22), from [11].

$$\tau_{w\, unsteady}(t) = \frac{2\mu}{R} \int_0^t W(t-\eta) \left( \frac{\partial u}{\partial t} \right)_\eta d\eta$$

(2.22)

The unsteady friction is dependent on the time-history of the variation in time of velocity. W is an approximate weighting function that determines the influence of previous time instants, µ is the dynamic viscosity and R is the pipe radius. η is the time index on which the integration is performed. Eq. (2.22) has been found for smooth walled turbulent hydraulics flow [11]. By adjusting the $c_f$ and the $W$ coefficients, the 1D results can be adjusted to closely match experimental ones.
Star automatically models both kinds of friction, while NUMSTA only model the quasi-steady one through a friction coefficient chosen by the user. The friction coefficient can be slightly increased taking into account that NUMSTA does not model the unsteady friction.

The dissipative influence of ballast is caused by the high pressure air behind the wave front flowing into the ballast. This causes a reduction in the pressure behind the wave front, and the reduction is inversely proportional to the distance from the wave front, because behind the wave front the pressure increase inside the ballast reduces the pressure drop across the ballast. Thus ballast does not influence the magnitude of pressure increase across the compression wave, but it does influence the shape of the compression wave and so the maximum gradient, and its influence is much stronger than the friction one, as shown in Fig. 2.11.

Looking at the left plot of Fig. 2.11 one realizes that ballast not only heavily influences the shape of the wave front, but also its velocity of propagation. Looking at the right plot of Fig. 2.11, it is clear that ballast alone prevents the ramp wave from steepening into a step wave.

Given that the ballast dissipative effect depends on the pressure difference across the region behind the wavefront and the ballast, after a sufficiently long propagation time there will be an asymptotic state in which the ballast dissipative effect is precisely balanced with the non-linear steepening effect. The asymptotic wave shape is shown in Fig. 2.12 and compared with experimental results.

\[ w_0(t) = \frac{3e}{\zeta \rho h} \int_0^t W(t - \eta) \left( \frac{\partial p}{\partial t} \right)_\eta d\eta \]  

In Eq. (2.23) \( w_0 \) is the velocity of the flow into the ballast, \( e, \zeta \) and \( h \) are the porosity, mass ratio and thickness of the ballast, and \( W \) is a weighting function derived assuming that the ballast can be modelled as a Helmholtz
resonator and includes other parameters of the ballast. Overall, ballast is a very effective way to reduce the maximum pressure gradient of the travelling compression wave. Even only putting ballast in a limited portion of the tunnel (near the tunnel exit, [13]) can reduce the maximum gradient.

Modelling ballast is not possible in NUMSTA, while one could set-up a porous jump in Star in order to account for the pressure flow into the ballast. Anyway this would be difficult to validate, and neglecting ballast is always conservative in terms both of maximum gradient and amplitude of the generated head compression wave, so ballast has not been modelled in this work. Strongly increasing the surface roughness of the tunnel floor might at a first impression at least partially account for the presence of ballast, discussed in Chapter 4.

The last kind of influence on the wave propagation listed in this section is the one from side branches. A side branch is an opening in the tunnel wall from which air can flow out from the tunnel, so it acts like an outlet, as described in Section 2.1.4. The incoming wave front will propagate in both the tunnel and the side branch, so the wave front in the tunnel downstream the side branch will be weaker than the incoming one. The instantaneous reduction in pressure increase across the compression wave is a disturbance which propagates upstream in the main tunnel as an expansion wave, such as the one reflected from the tunnel open end.

Acoustic theory can be applied to deduce the magnitude of pressure drop across the transmitted wave in the tunnel downstream of the side branch as a function of the incoming one, as in Eq. (2.24) from [12]. What is described by the equation is what happens to the travelling pressure wave when it meets a change in flow cross sectional area (a side branch is an increase in flow cross sectional area). A decrease in flow cross sectional area is what happens instead when the travelling pressure wave meets the train, and it corresponds to a negative $\Delta A$ in Eq. (2.24). In that case, the transmitted pressure wave is the one felt by the train, and the reflected one travels back into the tunnel in the opposite direction of the incoming one.

$$h(\tau) = \frac{2A_{tu}}{2A_{tu}+\Delta A} f(\tau)$$

(2.24)

where $f(\tau)$ is the amplitude of the incoming compression wave and $h(\tau)$ is the amplitude of the transmitted wave in the tunnel downstream the side branch. $A_{tu}$ is the tunnel cross sectional area, while $\Delta A$ is the change in flow cross sectional area. From Eq. (2.24), with a tunnel area of 81 m$^2$ and a branch area of 10 m$^2$, the magnitude of the compression wave would decrease by 6%. This means that the maximum pressure gradient (meant as time derivative of pressure in a fixed point in space, as in the literature on the subject) would decrease of the same amount, as the rise-time is not influenced by the side branch. The reduction of pressure in the area between the wave front and the nose of the train is beneficial for drag too [1], as a portion of air does not need to be pushed until the tunnel end anymore. For these reasons, adding pressure relief ducts between two parallel single track tunnels can be worth the price. An example is the Channel tunnel, in Fig. 2.13.

![Fig. 2.13 Pressure relief ducts in the Channel tunnel.](image-url)
Another useful application of Eq. (2.24) is to the pressure wave encounter scenario (when a train travelling in the tunnel encounters a travelling pressure wave). If a compression wave with a magnitude of 1400 Pa is travelling in a 63 m$^2$ cross section tunnel towards a 11 m$^2$ train, then the train walls will not see a pressure increase of 1400 Pa when the wave passes them. Instead, they would feel a 1533 Pa pressure increase, as can be found by Eq. (2.24) with $\Delta A = -11$ m$^2$. This difference is relevant, so one should always record the pressure time history at the train wall, and he should not use a pressure recorded by a stationary probe in the tunnel. Besides, the pressure time history felt at the train wall has different time scales when compared to the one felt by a stationary probe, due to the relative velocity between the train and the wave, so one really should always record the pressure time history at the train wall.

On the other hand to record the head entry wave at the train wall, the wave must have propagated forth and back into the tunnel, so the recorded time history at the train wall would depend on modelling both propagation and reflection of the wave, which can only be done for a specific tunnel, it is affected by numerical dissipation and it takes much computational power as the domain is long and the characteristic velocity to be used to determine the time step is the speed of sound. In the end, as described in Chapter 4, the pressure disturbance as recorded by a stationary probe in the tunnel has been used to compute the loads for the wave encounter scenario. If modelling wave encounter for a specific train-tunnel combination is needed, the pressure can anyway be scaled by the $\frac{2A_{tu}}{2A_{tu} + \Delta A}$ factor in order to better represent the pressure felt at the train wall, and the time axis can be scaled in such a way to take into account the relative velocity between the train and the wave. Both these factors would have a strong impact on the pressure load, especially for a non-tight train.

Concluding, the three main factors which influence wave propagation in the tunnels are friction, ballast, and Tunnel cross sectional area changes: all of them counteract the non-linear steepening of the wave, and their relative importance might lead to different situations, depending also on the tunnel length. An asymptotic wave shape can be reached, the wave can be damped or it can steepen into a shock wave depending on these factors, so their influence must be assessed for each train and each tunnel.

### 2.2.4. Generation of the Micro Pressure Wave

When the compression wave generated by the train nose reaches the tunnel exit, it is reflected inside the tunnel as an expansion wave and at the same time it originates a Micro Pressure Wave outside the tunnel exit. The expansion wave generated by the train tail entering the tunnel also generates a MPW when it reflects on the end of the tunnel, but usually the strongest MPW is the one due to the tunnel entry wave. Actually also the waves due to the train nose and tail exiting the tunnel create very weak MPW at the tunnel entrance after having travelled backwards through the tunnel.

If the tunnel exit were a perfect pressure outlet, imposing $p = 0$ (where $p$ clearly is the differential pressure) at every instant, then there would be no MPW emission, and the tunnel entry wave would be completely reflected as an expansion wave. With a real tunnel exit, instead, when the compression wave arrives at the tunnel exit it originates an acoustic wave, which intensity is related to the time derivative of mass flow at the tunnel exit. Expressing the mass flow at the tunnel exit as a function of the overall pressure drop across the compression wave just before it reaches the tunnel end Eq. (2.16), one gets the relation between incoming pressure time derivative and MPW intensity in Eq. (2.25).

$$\Delta p_{\text{MPW,max}} = \frac{A_{tu}}{\pi ra} \left( \frac{\partial p}{\partial t} \right)_{\text{compr}}$$  \hspace{1cm} (2.25)

In Eq. (2.25) $\left( \frac{\partial p}{\partial t} \right)_{\text{compr}}$ is the maximum pressure gradient of the incoming compression wave, $\Delta p_{\text{MPW,max}}$ is the amplitude of the originated MPW, $a$ is the speed of sound and $r$ is the distance from the tunnel exit. It is interesting to note that the amplitude of the incoming compression wave does not have a direct influence on the originated MPW, while it is the maximum pressure gradient (meant as time derivative) which determines its amplitude. This means that the MPW amplitude is roughly proportional to the third power of the train
speed Eq. (2.19). The MPW issue can be serious for a wide range of tunnel lengths, but it is more concerning for high blockage ratio average-length (about 9 km) slab track tunnel, where the compression wave has enough time to steepen but has not enough time to get dissipated by unsteady friction.

MPW are infrasonic waves, which spectrum can usually barely reach audible frequency, but they can cause problems such as window rattling. An average limit of MPW amplitude above which they become hazardous can be taken at around 20 $Pa$ at 25 m from the tunnel portal [14] (115 dB for European norm). This value of intensity of the acoustic wave can be translated into a value of sound pressure level, measured in $dB$, using the following formula:

$$SpL_{dB} = 20\log_{10}\left(\frac{\Delta P}{2 \times 10^5 Pa}\right)$$

(2.26)

A value of 20 $Pa$ correspond to 120 $dB$, which can be translated into common experience using the examples in Tab. 2.1.

<table>
<thead>
<tr>
<th>Sound Pressure (N/m$^2$)</th>
<th>Sound Level (dB)</th>
<th>Typical source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>160</td>
<td>Peak level at ear of 0.303 caliber rifle</td>
</tr>
<tr>
<td>200</td>
<td>140</td>
<td>Jet aircraft taking off at 25 m</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
<td>Human pain threshold</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>Very noisy factory</td>
</tr>
<tr>
<td>0.2</td>
<td>80</td>
<td>Ringing alarm clock at 1m</td>
</tr>
<tr>
<td>0.02</td>
<td>60</td>
<td>Ordinary conversation at 1m</td>
</tr>
<tr>
<td>0.002</td>
<td>40</td>
<td>Quiet office</td>
</tr>
</tbody>
</table>

The problem of MPW has long been known in Japan, where tunnels usually have a smaller cross section and residential areas are closer to the tracks when comparing to Europe. The shape of the nose of the Shinkansen 700 train in Fig. 2.7 shows the extent of the problem. MPWs are recently becoming a problem in Europe too. In December 2005, in a newly built tunnel in Germany, loud booming noises could be heard from the tunnel exit [14]. Their intensity was enough for them to be classified as a sonic boom from a high altitude supersonic aircraft. The reason for the incident was a last moment change in the tunnel design, shifting from a ballasted tunnel to a slab-track tunnel, thus reducing the damping of the maximum pressure gradient of the head compression wave. The installation of acoustic absorbers solved the problem.

### 2.3. Pressure Transients Effects

The pressure transients a high speed train creates when passing through a tunnel have been introduced and exposed (Fig. 2.4, Fig. 2.5) in the previous section. When shifting the observation point from a fixed point in the tunnel to a fixed point just behind the nose of the train (Fig. 2.14), one can see the impact of the pressure waves on the train.
In Fig. 2.14 the origin of the time axis corresponds to the instant in which the train enters the tunnel. Initially the pressure rises as a direct result of the friction rise. This is because the air flows in the opposite direction with respect to the train, and the pressure at the portal is the ambient one, so the pressure at a fixed position along the train increases in time while the train enters the portal. Then the tail entrance into the tunnel originates the expansion wave which travels forward and causes the $\Delta p_T$ in Fig. 2.14 when it reaches the probe.

Another transient occurring on the train is the reflected backward travelling expansion wave arriving at the train head (generated by the nose entrance, $\Delta p_N$ in Fig. 2.14).

All of these changes in the external pressure on the train wall also cause changes in the internal pressure. In particular, the internal pressure will follow the external one with a delay proportional to the degree of pressure tightness of the carriage, as will be shown in section 2.3.2. The internal pressure variations will impact on the passenger comfort, and the local difference between external and internal pressure will put a load on the train structures and components. The degree of pressure sealing of the train determines both the level of passenger comfort and the behaviour of the local pressure difference which cause the structural loads.

The external pressure time history in Fig. 2.14 can be compared with the one in Fig. 2.5-a: they represent the same phenomenon but for different combinations of train and tunnel lengths, so they look different especially in terms of friction rise and timings of the pressure changes.

### 2.3.1. Pressure loads

The loads caused by pressure transient on the train structure are given by the local pressure difference between the internal and external surface of the structure, so their behaviour will be totally different when comparing a sealed train to an unsealed one.

Referring to a sealed train, if the train were perfectly sealed then the time history of pressure load on the structure would be perfectly coincident with the external pressure one. In the real world the train has a defined level of tightness, quantified by coefficients introduced in the next section. With a model of the pressure equation and a tightness value, given the time history of the external pressure, one can calculate the time history of the internal one, and the difference among the two is the load. A typical time history of such a load is presented in Fig. 2.15.
In this situation the high level of pressure sealing is able to limit the variation of pressure in time inside the train. The value of pressure difference is close to the external pressure one, as the internal pressure is nearly constant. Anyway it might happen that the magnitude of pressure difference is higher than the external pressure one; in this situation the value of external and internal pressures have opposite signs. The pressure time history in region 1 of Fig. 2.15 is due to the pressure transient caused by the passing of a single train inside the tunnel, while the one in region 2 is due to a train crossing inside the tunnel. It is immediate to note that the latter situation is more critical, and that is because first the higher pressure regions in front of both trains noses and then the lower pressure regions around both trains bodies sum up, resulting in quick high amplitude external pressure changes on both trains walls.

A perfectly unsealed train would present the opposite situation, the external pressure would be precisely equal to the internal one everywhere, so no load would result. This is not the situation in a real unsealed train, where the carriage will present a small level of sealing, variable along its length. Considering the situation of a train crossing inside the tunnel (the most demanding in Fig. 2.15) and fixing probes in three locations along the length of the first carriage of one train, the resulting pressure time history is depicted in Fig. 2.16.
The pressure drop arrives outside the nose of the first carriage (location 1) and then propagates inside. In the train frame of reference the outside pressure drop travels at the relative velocity between the two trains, while the pressure signal inside a single carriage travels at the speed of sound. For this region in locations 2 and 3 the internal pressure is lower than the external one already before the external pressure drop arrives at those locations. Thus at location 1 the load on the structures is towards the outside of the carriage, while in location 2 and 3 it is towards the inside of the carriage. The magnitude of the load is minimum in location 2 and maximum in location 3, where it reaches the magnitude of the external pressure drop. It is important to note that the internal pressure is very close to constant for the three axial positions along the carriage length, so when modelling the load on the carriage the internal pressure can be approximated as homogeneous.

The main conclusion from this section is that it is very important to take into account both the position along the carriage length in which one wants to compute the load and the so called Free Length of the carriage, which is the length of the internal area in which the pressure waves travel freely and so the internal pressure can be assumed homogeneous. Also there is an increasing trend to have easy access between the carriages, i.e. a Free Length that extend to several carriages and possibly a whole, which lead to increased loads, especially for non-tight trains.

These conclusion will be confirmed by the analysis of the results for both the wave encounter scenario and the train crossing ones, in Chapters 4 and 5.
2.3.2. Pressure tightness

As expressed in the previous sections, the external pressure felt by the train walls strongly varies in time both due to travelling pressure waves originated by the train entrance into the tunnel and by train crossing inside the tunnel. Depending on the intensity of these pressure variations, the train might need a sealing system that closes most of the openings between the internal carriage environment and the external one in order to keep the variations of the internal pressure to an acceptable level, thus granting passenger comfort and safety. The structural pressure load on a point of the carriage structure is given by the difference between internal and external pressure, so the pressurisation system has a huge influence on the loads too, as the internal pressure variations in a pressure-tight train are reduced in magnitude and delayed when compared to a non-tight train.

When designing a high speed train it is very important to reach a good level of air tightness, as newly designed high speed trains can be certified for top speed in the order of 380 km/h, so the pressure transients induced by such a train entering a tunnel can be harmful for passengers. It is also challenging to design an effective sealing system, as a flow of only 0.15 m$^3$ of air through a carriage can change the internal pressure of 100 Pa [29]. The sealing design must cover all possible leakages, from the most evident such as ventilation intakes and exhaust, doors and windows to tolerances on the production and maladjustment.

The pressure history inside the train depends mainly on the external pressure time history, the pressure tightness level of the cars, the internal volume (a higher volume with the same leakage mass flow gives less variation of internal pressure) and the elastic deflection of the structure.

Nowadays two ways of measuring the pressure tightness of a carriage are in use. The simplest one is the leakage area model, which consist in assigning to all the possible leakages a value of area which corresponds to the one needed by a sharp orifice to cause the same pressure drop. In this case the values of area of each leakage can be summed in order to get an overall leakage flow. Furthermore with this approach, being the velocity across the fictitious orifice proportional to the square root of the pressure drop, the mass flow across the leakage is also proportional to the square root of the pressure drop across the leakage.

The other model is the time constant one. The time constant is taken as the time the pressure difference between the inside and the outside of the carriage takes to reduce by 63%. This approach is useful to describe the leakages of the whole car or train, particularly on track, as time constants of multiple leakages do not sum. Furthermore, as shown by Eq. (2.27), this model assumes that the leakage mass flow is proportional to the pressure difference between interior and exterior, so the two models are in contrast one another, in the sense that they model different kind of leakages. In other words, if those approaches were used in a measurement to determine the time constant and the leakage area of a carriage, then the values obtained would be valid only for that pressure difference across inside and outside. If the coefficients were used to predict the internal pressure time history for a different pressure difference they would give different values.

In reality both the kinds of leakages described exist in a real carriage. Representing the leakage as a pipe flow, the pressure losses at the pipe edges would be proportional to the velocity of the flow squared (as they are mainly due to separation-induced cross sectional changes). The pressure losses due to the developed flow inside the pipe would be proportional to the velocity for a laminar flow, and to a power of the velocity from 1.75 to 2 for a turbulent one. Leakage flows are anyway usually laminar, due low Reynolds number associated to the small velocity and small dimensions of the leakages. For this reason, a complete model of losses would have to comprise two coefficients, one for each kind of loss, modelling the two leakage flows in parallel.

Realistic values of time constants for are shown in Tab. 2.2.
Tab. 2.1 Realistic Values for Time Constant [20].

<table>
<thead>
<tr>
<th>Train type</th>
<th>Time constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsealed train (Regional train)</td>
<td>( \tau &lt; 1s )</td>
</tr>
<tr>
<td>Minimum sealed train (Eurocity)</td>
<td>( 1s &lt; \tau &lt; 6s )</td>
</tr>
<tr>
<td>Well sealed train (TGV)</td>
<td>( 6s &lt; \tau &lt; 10s )</td>
</tr>
<tr>
<td>Excellently sealed trains (ICE3, Transrapid)</td>
<td>( \tau &gt; 10s )</td>
</tr>
</tbody>
</table>

The high-time constant sealing system required by higher travelling velocities increases not only the initial price of a train but also its maintenance costs. Furthermore, the structures of a pressure sealed carriage have to withstand a higher pressure load when compared to an unsealed one, thus lowering its fatigue-life.

Another phenomenon which influences the internal pressure time history is the car body deformation. When the external pressure changes rapidly it causes an elastic deformation of the car body, which immediately changes the volume occupied by internal air, thus changing the internal pressure. The car body deformation effect is represented using a coefficient \( k \) obtainable by experiments.

The differential equations which give the time history of the internal pressure as a function of the external one for each leakage model are Eq. (2.27) and Eq. (2.28).

\[
\frac{dp_i}{dt}_{\text{Time Constant}} = \frac{k}{1+k} \frac{dp_e}{dt} + \frac{1}{\tau(1+k)} \Delta p(t) \tag{2.27}
\]

\[
\frac{dp_i}{dt}_{\text{Leakage area}} = \frac{k}{1+k} \frac{dp_e}{dt} + sgn(\Delta p(t)) \frac{a^2 S_{eq}}{V(1+k)} \sqrt{2p|\Delta p(t)|} \tag{2.28}
\]

In these equations \( p_e \) is the external pressure, \( p_i \) is the internal pressure and \( \Delta p \) is the pressure difference between outside and inside. \( \tau \) is the time constant, \( S_{eq} \) is the equivalent leakage area and \( k \) is the coefficient of elastic car body deformation. The first term of the two equations is identical as it represents the amount of pressure change due to the body deformation. Looking at the dependence on the pressure difference among inside and outside, the time constant model depends linearly on it, while the leakage area model depends on its square root, as already explained.

In this work the model used for load computation is the time constant one, as it is the most appropriate for a whole generic train. The value of \( k \) used is 0.1.

It is important to underline that Eq. (2.27) has been employed to compute the internal pressure in two different ways. The most straightforward one is to take the external pressure time history from a point probe on the train wall and apply Eq. (2.27) to compute the internal pressure time history. With the internal pressure time history one can compute the loads by just subtracting it to the external one. By doing this one neglects the influence of the carriage free length on the internal pressure and on the loads, which can be very strong. This first way to compute the internal pressure will be recalled as “Point \( \tau \) model” in the following of this work, as it would be valid if the carriage were small. A more accurate way to compute the internal pressure taking into account the carriage free length is to give as input to Eq. (2.27) the average external pressure along the car external surface and use Eq. (2.27) to compute the internal pressure assuming it to be homogeneous inside the carriage. Then, in order to compute the loads on the carriage wall for each location along the carriage one has to subtract the internal pressure time history to the external one from a point probe placed in the required location.
location along the carriage wall. Employing this more accurate method, which will be recalled as “Free Length model”, one can assess the influence of the carriage free length on the internal pressure and loads. Both the point probe and the Free Length models have been used in this work.

### 2.3.3. Pressure comfort

Pressure comfort criteria aim to grant a desirable or acceptable comfort for the passengers on trains. Such criteria have always been fundamental also for the design of aircraft pressurization systems. While criteria for pressure comfort in airplanes are the same worldwide, the criteria for trains are different from country to country.

There are several ways to impose a pressure comfort criterion. In order to estimate an acceptable degree of pressure change in time, one has to take into account both the magnitude of the pressure change and its duration in time. So a limit can be put on the maximum pressure gradient (instantaneous rate of change of pressure with time, left column of Tab. 2.2), or on the overall variation of pressure in a time interval (right column of Tab. 2.2). In particular, the maximum variation specified over a time interval is cumulative, so if the pressure first increases of 1000 Pa and then decreases of 3000 Pa this counts as 4000 Pa.

Some pressure criteria are listed in Tab. 2.2.

<table>
<thead>
<tr>
<th>State</th>
<th>Max gradient [Pa/s]</th>
<th>Max variation [Pa] (time period [s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>300</td>
<td>1000 Pa</td>
</tr>
<tr>
<td>USA</td>
<td>410</td>
<td>700 Pa (1.7s)</td>
</tr>
<tr>
<td>EN14067-5:2011-unsealed, double track</td>
<td></td>
<td>4500 Pa (4s)</td>
</tr>
<tr>
<td>EN14067-5:2011-unsealed, single track</td>
<td></td>
<td>3000 Pa (4s)</td>
</tr>
<tr>
<td>EN14067-5:2011 sealed train</td>
<td></td>
<td>1000 Pa (1s) 1600 Pa (4s) 2000 Pa (10s)</td>
</tr>
<tr>
<td>Passenger aircrafts-usual operations (worldwide)</td>
<td>25</td>
<td>/</td>
</tr>
</tbody>
</table>

Looking at the criteria for the EN 14067-5:2011 norm for unsealed trains, different limits are given depending on whether the tunnel is a single track or a double track one. The limit for double track tunnels is less stringent because in that case the worst condition is a superposition of the entrance waves with the train crossing, which is statistically very rare. On the contrary, for a single track tunnel the worst case is the encounter of the generated waves, which happens several times for each tunnel crossing, so the limit is more stringent for this scenario.

While the pressure criteria in Tab. 2.2 regard the comfort of the passenger, the TSI criterion (Technical Specification for Interoperability) from the European Union concerns the safety of the passenger, and it has the level of law. TSI states that the maximum peak-to-peak external pressure variation during the whole tunnel
passage should not exceed 10000 Pa, thus granting passenger safety also in case the sealing system fails, so it is a medical criterion and it has nothing to do with comfort.

Limit values of pressure variations for comfort are different from country to country. Furthermore, a comfort criterion is subjective, and changes much from person to person. The huge difference in allowed pressure variation between trains and airplanes is due to the fact that the pressurization system of the airplane is much more powerful than the train one, and that the change of external pressure around an aircraft in usual operations is much more gradual than the one around a high speed train crossing another one inside a tunnel. Actually the overall variation of pressure felt inside a civil aircraft from ground level to cruise level is 24 kPa, corresponding to an equivalent altitude inside the cabin close to 2400 m. This variation is stronger in magnitude than the one felt inside a train, even in a tunnel train crossing situation, but it is distributed over a time interval of a few minutes (instead of fractions of second for the train crossing), giving the respiratory system enough time to compensate it.

In general a pressure comfort criterion should also be dependent on the comfort level expected by the train and on the number of tunnels during a usual route. It has been proved that in a sealed train passengers become more susceptible to pressure variations, because of the average higher comfort level [16].
3. CFD background

In this section the fundamentals of Computational Fluid Dynamics will be recalled. CFD is any method which can solve numerically the governing equations for a flow of interest in a discretized form. A few books would be needed to describe in detail all the equations and numerical techniques used in nowadays CFD solvers, so this brief introduction will only at first focus on the very fundamental Navier-Stokes equations, which together with turbulence constitutes the physical model solved by CFD. In the second and third sections the approaches of the STAR-CCM+ and NUMSTA software used in the simulations for this thesis work will be introduced.

3.1. Fluid Dynamics for CFD

In this section the governing equations for fluid flows (the so called Navier-Stokes equations) will first be introduced and then completed with a Turbulence model.

3.1.1. Full Navier-Stokes equations

Starting from the basic principles of conservation of mass, momentum and energy in a flow, one can derive the full system of PDE which describes the flow. The Navier-Stokes equations (NS equations) are the ones which describe the conservation of momentum.

The 3D differential conservative formulation of the conservation equations is Eq. (3.1) from [31].

\[
\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \rho \vec{v} \\ \rho E \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho \vec{v} \\ \rho \vec{v} \otimes \vec{v} + p \vec{I} - \vec{\tau} \\ \rho \vec{v} H - \vec{\tau} \cdot \vec{v} - k \vec{\nabla} T \end{bmatrix} = \begin{bmatrix} 0 \\ -f_c \\ W_T + q_H \end{bmatrix}
\]  

(3.1)

In these equations \( \rho, \vec{v}, E \) are the density, velocity and specific internal energy [\( J/kg \)] of the flow: they are taken as the unknowns of the system. \( \vec{v} \) is the velocity vector, it has a number of components equal to the space dimensions. \( \vec{\tau} \) is the stress tensor, it includes both the viscous laminar and turbulent terms, it can be expressed as in Eq. (3.3), and it is a N by N matrix, with N being the number of space dimensions. The other quantities are \( \vec{I} \), which is the identity tensor, and \( H \) which is the specific enthalpy. \( k \) is the thermal conductivity and it is assumed as a known function of temperature and pressure. The \( \vec{v} \times \vec{v} \) product is a vector product, \( \vec{\tau} \cdot \vec{v} \) is a scalar product, \( \nabla \) is the Nabla operator (\( \nabla T \) is the gradient of temperature, \( \nabla \cdot \vec{v} \) is the divergence of velocity).

This system when expressed in three dimensions is made of five nonlinear PDEs, so it needs all the quantities to be expressed as function of the aforementioned five ones (\( \rho, \vec{v}, E \)) in order to be closed. The knowns of the system are on the right hand side, they are the external forces, work and heat flux.

These equations are directly deduced from the basic conservations Eq. (2.1), so they are precise and hold for any flow (as long as the continuum hypothesis is fulfilled) of any fluid. Of course errors will arise in the physical modelling of all the aforementioned other quantities, especially for the turbulent part of the viscous stresses. Furthermore these equations are differential, so they hold for any infinitesimal fluid particle, but to be solved they first need to be discretized (as no known close solution exists for a generic case), so errors will arise in the numerical discretization too. Further errors will arise from the solution of the discretized system.

For the flow of air at low temperatures, one can use the ideal gas with constant coefficients approximation, Eq. (3.2).
In Eq. (3.2) \( R \) is the ideal gas constant per unit mass \([J/kgK]\), so it depends on the molecular weight of the gas, and \( c_p, c_v, \gamma \) are respectively the specific heat transfer coefficients at constant pressure and temperature and their ratio. These equations hold for low temperature flows of air, and they introduce a very low error.

Air can be assumed as a Newtonian fluid, which is a fluid in which the viscous stresses are linearly proportional with the strain rate of the fluid element. In this approximation the viscous stress tensor can be expressed as in Eq. (3.3) from [31].

\[
\tau_{ij}^V = \mu \left[ \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) - \frac{2}{3} (\nabla \cdot \vec{v}) \delta_{ij} \right]
\]

In Eq. (3.3) \( \mu \) is the dynamic viscosity coefficient of the fluid, \( \nabla \cdot \vec{v} \) is the divergence of velocity, and \( \delta_{ij} \) is the Kronecker delta. Of course both the introduction of the Newtonian fluid approximation and the technical measure of the dynamic viscosity coefficient as a function of pressure and temperature introduce errors, but they are usually small for flows of air. The notation \( \tau_{ij}^V \) indicates that Eq. (3.3) only takes into account the viscous shear stresses and not the turbulent ones (Eq. (2.4)).

Using the ideal gas relations Eq. (3.2) and the constitutive equations Eq. (3.3) the system of conservations equations Eq. (3.1) is closed, so once discretized and solved it can predict any flow fulfilling the various hypothesis listed above.

The most usual way to discretise the NS system for CFD is the finite volume method (FV method), which means expressing the system in an integral formulation and applying it to small finite volumes in which the domain has been subdivided into (mesh cells), thus obtaining a system of algebraic equations. Another method which can be employed to solve the Navier-Stokes equations is the finite element method (FEM), in which a weak formulation is used to express the NS equations on the discretised domain. Besides, there is also for example the Lattice Boltzmann method, which is based on a statistical kinetic.

The FV process of course introduces discretization errors, which can be bigger than the ones coming from the flow approximations listed above. But if the cell size is taken small enough for the problem for which the solution is required then this error is still acceptable. Another error comes from the solution of the discretized system of algebraic nonlinear equations, which is never directly solved in a single step, but it can be solved iteratively usually for as many iterations as needed to reach an acceptable degree of error.

CFD solvers take care of all the steps needed to solve the system, and the algorithm they use usually reaches convergence, but it is not straightforward to estimate the magnitude of each of the error described above. When comparing the CFD results to experimental ones, if the mesh is fine enough and the simulation has converged, the match can be quite good for laminar flows.

When addressing turbulent flows, instead, one realizes that in order to resolve the smallest scales of turbulence the require cell and time step size would be too small. Simulations on such a mesh (Direct Numerical Simulations) have been carried out on super computers for very simple problems, but they are still not useful for industrial applications. In this contest of course turbulence cannot be resolved directly, so it has to be modelled. Turbulence modelling is usually a very important source of error, as described in the following section.

### 3.1.2. Turbulence modelling

Turbulence is a chaotic, random and time dependent state of motion which arises at high Reynolds numbers [32]. When a flow presents a high Reynolds number, its inertial forces are much higher than the viscous ones,
so it is more unstable and this instability can cause the transition from a laminar flow to a turbulent one. In order to find governing equations for turbulence a Reynolds decomposition is usually employed, thus decomposing each flow quantity in a mean (in time) component plus a fluctuating one, indexed with an ′. The fluctuations are due to three dimensional rotational flow structures, called turbulent eddies. The eddies present a huge variety of length and time scales, simulating which requires a very fine mesh and a very small time step, as previously explained. The eddies boost mixing very effectively, dramatic increasing the exchange of fluid particles between adjacent volumes of control, which results in an increase of mass diffusivity (for chemical reactions), momentum diffusivity (so viscosity increases), and thermal diffusivity. The mechanism which transfers kinetic energy from the mean flow to the bigger eddies is the vortex stretching, which is a direct consequence of the velocity gradients which deform the bigger eddies. Once the bigger eddies have taken energy from the mean flow they transfer it to smaller eddies. This process is called energy cascade, and the larger eddies are the ones with the highest kinetic energy. The smallest eddies are dissipated by viscous effect, and their scale for usual engineering flows is in the order of 0.01 mm [32].

The ways to introduce turbulence into CFD calculations are various. Conceptually, the most straightforward one is the DNS (Direct Numerical Simulations), in which all the turbulent scales are resolved. This means that the cells are small enough to resolve the smallest viscous scales, and that the time step is small enough to resolve the fastest turbulent fluctuations (clearly the simulation has to be unsteady in order to compute the time dependent turbulent fluctuations). The combination of these two factors makes DNS still beyond reach. The most common turbulence approach is to solve the RANS (Reynolds Averaged Navier Stokes, Eq. (3.8)) equations for the mean flow, thus modelling all the turbulence at any scale. These equations are directly deduced by the NS equations Eq. (3.1) applying the Reynolds decomposition and time averaging all the components. The extra terms which appear at the end of this process represent the interaction between turbulent fluctuations, and they can be estimated (introducing errors) from mean flow quantities, thus allowing to model the effect of turbulence on the mean flow quantities.

Another kind of turbulent calculation is the LES (Large Eddied Simulation), which consists in resolving both the mean flow and the largest Eddie scales, which are the most anisotropic and energetic ones, while the smaller scale turbulence is still modelled. LES is nowadays used for engineering calculations, but it is more difficult to set-up than RANS.

Focusing on solving the RANS equations, a model is needed which can link the extra terms in the RANS equations to mean flow quantities. These extra terms are the Reynolds stress tensor and the scalar transport terms. The strong dependence of turbulence on velocity gradients suggests to take the Reynolds stresses as proportional to the strain rate of the flow; this is the Boussinesq approximation [32].

\[
\tau_{ij}^R = -\rho \overline{u_i u_j} = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \tag{3.4}
\]

The terms \( \tau_{ij}^R \) are the Reynolds stresses, so they are due to turbulence as opposed to the \( \tau_{ij}^V \) ones in Eq. (3.3), which are due to viscosity. The over bar in Eq. (3.4) indicates a time average, the ′ terms are the fluctuating components while the capital ones are the mean ones. \( \mu_t \) is the turbulent viscosity and \( k \) is the turbulent kinetic energy per unit mass, defined as

\[
k = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{3.5}
\]

A similar relation is used for the scalar transport terms.

Comparing Eq. (3.4) to Eq. (3.3) it is immediate to realize that applying the Boussinesq approximation corresponds to treating turbulence as additional viscosity. A turbulence model is needed to link the turbulent viscosity \( \mu_t \) and kinetic energy \( k \) to the mean flow quantities in order to close the RANS system of equations through the Boussinesq approximation.

The most basic model is the mixing length one, in which essentially the user specifies the turbulent viscosity and kinetic energy through a free parameter, the mixing length. The mixing length is specified at each point in
the domain, so the user controls where to put turbulence. Of course this model is both the most simple, as no additional PDEs are added to the five (in 3D) conservation equations, but it is also the less accurate.

The most widely used and validated model is the $k - \epsilon$ one. In this model two PDEs are used to describe the convective-diffusive transport, production and destruction of the two quantities $k$ and $\epsilon$, which is the rate of dissipation of turbulent kinetic energy per unit mass $[m^2/s^2]$. These two PDEs, when solved, give the values of $k$ and $\epsilon$ at each point. From these two quantities the turbulent viscosity can be computed via dimensional analysis, as in Eq. (3.6).

$$\begin{cases}
\frac{\partial}{\partial t} \theta - \nu \nabla \cdot \theta = 0 \\
\frac{\partial}{\partial t} l - \epsilon \frac{k^+}{\epsilon} = 0 \\
\mu_t = C_{\mu} \rho k^2 / \epsilon
\end{cases} \tag{3.6}$$

In Eq. (3.6) $\theta$ is the turbulent velocity scale and $l$ is the turbulent length scale. From Eq. (3.6), the expression for the turbulent viscosity in Eq. (3.7) can be obtained.

$$\mu_t = C_{\mu} \rho k^2 / \epsilon \tag{3.7}$$

The coefficient $C_{\mu}$ in Eq. (3.7) is equal to 0.09 for the $K-\epsilon$ model.

Solving the two PDEs for $k$ and $\epsilon$ and applying Eq. (3.7) the system of the 5 transport equations plus the two turbulence equations is closed. But still it cannot be solved, as particular care has to be given to the Boundary Conditions for the turbulence equations. The main problem is that the two equations for $k$ and $\epsilon$ as well as Eq. (3.7) become ill-conditioned as either $k$ or $\epsilon$ approach zero.

More recent turbulent models will be introduced at the end of the following section, after recalling the velocity profiles in turbulent boundary layers.

Concluding, the whole RANS compressible equations system is Eq. (3.8).

$$\begin{cases}
\frac{\partial}{\partial t} \rho + \nabla \cdot \rho \vec{v} = 0 \\
\frac{\partial}{\partial t} \rho \vec{v} + \rho \nabla \vec{v} + \rho \vec{I} - \vec{t} = \nabla \cdot \vec{f}_c \\
\tau_{ij} = \tau_{ij}^V + \tau_{ij}^R
\end{cases} \tag{3.8}$$

The shear stress tensor $\vec{t} \equiv \tau_{ij}$ is made of the viscous component $\tau_{ij}^V$ from Eq. (3.3) and the turbulent component modelled by the Reynolds stresses $\tau_{ij}^R$ which comes from Eq. (3.4), the Boussinesq approximation. Depending on the turbulence model chosen, additional equations might be required to express the Reynolds stresses as a function of the system unknowns $\rho, \vec{v}, E$. The first line in Eq. (3.8) is the continuity equation, the second line includes the momentum equations (which are as many as the space dimensions), and the third line is the energy conservation equation.

### 3.1.3. Boundary Conditions and Wall treatment

The most basic BC needed for turbulence modelling is the freestream one. For a laminar freestream one would like to impose both $k$ and $\epsilon$ equal to zero, but this would make the two equations for $k$ and $\epsilon$ as well as Eq. (3.7) become ill-conditioned, so very small mainly arbitrary values must be specified.

A more complex BC to be imposed is the wall one. Before describing the approaches which can be used, a description of the velocity profile in a turbulent boundary layer is needed. The velocity distribution in a turbulent boundary layer in a pipe will be shown in order to introduce the influence of roughness. Taking as reference velocity the friction velocity $V_*$, equal to the square root of the wall shear stress over the density,
one can plot the adimensional velocity distribution against the adimensional wall distance $\eta$ (usually named $y^+$) in a semi logarithmic plot, as in Fig. 3.1.

First considering a hydraulically smooth wall one can describe the velocity distribution for increasing distance from the wall, basing on the description in [33]. For $y^+$ lower than 1, the velocity distribution of the viscous sublayer holds, in which $U^+ = y^+$. In this region the viscosity has damped the turbulent eddies, and the flow is laminar. If the Reynolds number of the external flow is high enough, a region called logarithmic layer takes place outside the laminar sublayer, but still well inside the boundary layer thickness. This region shows a local production and destruction of turbulence, from which one can compute the velocity distribution. The distribution is called log-law, and for hydraulically smooth pipes it is as in Eq. (3.9).

$$\phi = \frac{U}{V_c} = 5,75 \log_{10} y^+ + 5,5$$  \hspace{1cm} (3.9)

With $y^+ = yV^*/v$. This profile is represented by the red line in Fig. 3.1, and it is valid approximately for a range of $y^+$ such as: $30 < y^+ < 1000$. Between the laminar sublayer and the log layer, a transition region takes place in which both the laminar sublayer law $U^+ = y^+$ and the log law (Eq. (3.9)) predict similar values of $U^+$. This region is also often called buffer region.

If the wall is rough, one has to distinguish between different regimes. If the roughness is contained in the viscous sublayer then its effect is negligible, so the wall is hydraulically smooth. If the roughness level is higher, then it can be modelled by changing the velocity distribution inside the log layer, as shown in Fig. 3.1. The losses due to roughness depend both on roughness height and density. For this reason a parameter called “equivalent sand-grain roughness”, $K_s$, is used to compare the actual case to the roughness height causing an equivalent velocity distribution on a sand-grain rough pipe. The modified log-law for fully rough walls (so for $K_s^+ = K_s V^*/v \geq 70$) is Eq. (3.10) and it is represented in Fig. 3.1 Universal velocity profile for turbulent flow through pipes, [33] for different values of $K_s$, expressed as $K_s^+$.

$$\phi = \frac{U}{V_c} = 5,75 \log_{10} \frac{y}{K_s} + 8,5$$  \hspace{1cm} (3.10)
Getting back to the approaches needed to model the wall BC for turbulence, there are basically two approaches which can be followed. The first one is named “low Re” approach: in this case the first cell height is low enough to be able to integrate the turbulent PDEs down to the wall, so again one would like to impose both a k and ε equal to zero at the wall. Being this not possible, damping functions can be applied on a k and ε as an artifact in order to be able to obtain the wanted BCs.

If the Reynolds number of the flow is high enough to allow for a logarithmic layer, then the “High Re” approach can be used. In this case the first cell centroid is imposed a value of velocity taken from the log law distribution (Eq. (3.9) or Eq. (3.10)). In this case the first cell centroid needs to fulfill the conditions 30<y+<1000, otherwise it is inconsistent to use the log layer velocity distribution. With the log-law velocity distribution one can directly implement the roughness of the wall too (Eq. (3.10)).

Clearly the low-Re approach will be more precise, as the portion of boundary layer which is resolved is higher than for the High-Re approach. However, the y+ < 1 requirement can be too computationally expensive, especially for very high Re number flows, such as the ones around high speed trains. In these cases the High-Re approach is usually preferable, unless a very high accuracy in modelling the boundary layer is required, which might be the case for drag computations but usually not for tunnel aerodynamics. All y+ models are also available in which the two laws for the low-Re approach and high-Re approach are smoothly connected. This is particularly useful if the first cell falls inside the buffer region.

A turbulence model which has no need for wall damping function in Low Re approaches is the Wilcox k − ω one. As the name states, the two turbulent variables in this model are the turbulent kinetic energy per unit mass and the turbulence frequency ω = ε/k (also named “Specific dissipation rate”). In this model the two turbulence transport equations are reformulated, and at the wall the value of k can be set to zero, while the ω can be given a very high value without compromising the well-posedness of the turbulence equations. This is done in the Star-CCM+ software by a wall treatment which contains empirical relations such as the log-law but for the turbulent quantities. A problem of this model is the definition of the free-stream turbulence BCs, as the model is found to heavily depend on those values.

The solution to the latter problem is the Menter k − ω SST model [32], which blends both the K − ε model and the Wilcox k − ω ones, using the first one in the turbulent region far from the wall and the latter in the near wall region. Blending functions are used to avoid instabilities in the region of transition between the two models, and limiters on the turbulent viscosity and on the production of k are used to improve performance in the stagnation region, which are usually poorly modelled by K − ε approaches. These features make the SST k − ω model the most general model in the field of external aerodynamics ([32], [34]), so it has also been preferred for this work.

3.1.4. Basic discretisation schemes

The RANS system of non-linear PDEs (3.8) does not allow for a direct solution except for very specific cases, so numerical solutions must be found. The most common method used to solve Eq. (3.8) is to discretise them both in space and time using the finite volume (FV) approach, and the basis of the FV approach can be described looking at the very simple 1D advection equation, discretised using finite differences.

The most basic discretisation techniques can be introduced looking at the advection equation on a 1D domain Eq. (3.11).

$$\frac{\partial u}{\partial t} + a \frac{\partial u}{\partial x} = 0$$  \hspace{1cm} (3.11)

In Eq. (3.11) u is the unknown of the problem, while a is the advection velocity. This equation models the advection in space of an intial spatial distribution of u, so the analytical solution of the problem is straightforward. The problem can anyway also be solved numerically using the finite difference (FD) method, which corresponds to the FV method in one dimension. The 1D domain is then divided in many segments with a fixed length Δx, which represent the mesh for this simple 1D case. The time also needs to be discretised, so a time step Δt needs to be chosen.
If first order finite differences are used to discretise both time and space, then the discretised equation is Eq. (3.12).

\[ u_j^{n+1} = u_j^n - \frac{a\Delta t}{\Delta x} (u_j^n - u_{j-1}^n) \]  

(3.12)

This discretisation method is usually called forward time-backward space (or first order explicit Euler). In Eq. (3.12) the \( j \) index indicates the cell and the \( n \) index indicates the time instant. The fact that this scheme is explicit means that no system has to be solved to perform the timestep, so the algebraic Eq. (3.12) already gives the solution at the following time step.

The stability requirement of the explicit Euler scheme is Eq. (3.13).

\[ CFL \equiv \frac{a\Delta t}{\Delta x} < 1 \]  

(3.13)

Eq. (3.13) states that the stability requirement of the explicit Euler scheme is a CFL number lower than 1. This condition corresponds to constraining the initial \( u \) profile in space not to move more than one cell in each timestep, so the maximum allowable timestep is proportional to the mesh size and inversely proportional to the advection velocity. If the time step is chosen in such a way to give a CFL higher than 1 the solution diverges, i.e. if one applies Eq. (3.12) for several time steps then the solution grows indefinitely.

The accuracy of the explicit Euler scheme is given by its truncation error \( TE \) in Eq. (3.14).

\[ TE_{\text{Expl Euler}} = \frac{1}{2} a\Delta x (1 - CFL) u_{xx} + O(\Delta x^2, \Delta t^2) \]  

(3.14)

In Eq. (3.14) \( u_{xx} \) is the second derivative of \( u \) with respect to \( x \). The most important conclusion one can take from Eq. (3.14) is that the scheme is consistent, as if \( \Delta x \) and \( \Delta t \) tend to zero the truncation error also tends to zero, so the numerical solution tends to the analytical one. The fact that the leading error term in Eq. (3.14) is proportional to \( \Delta x \) makes the numerical scheme first order accurate, so, for example, if the mesh size is halved the truncation error is also halved. Besides, it is proportional to \( u_{xx} \), so the error is of a diffusive kind. This means that gradients in the advected \( u \) profile (such as discontinuities) are damped by the numerical error. It is important to note that for a lower CFL the stability requirement is more easily met, but the damping of the solution due to the diffusive error increases.

In order to get rid of the stability requirement Eq. (3.13) one can use and implicit time integration, so for example the implicit Euler scheme in Eq. (3.15).

\[ u_j^{n+1} (1 + \frac{a\Delta t}{\Delta x}) - \frac{a\Delta t}{\Delta x} u_{j-1}^{n+1} = u_j^n \]  

(3.15)

One can realise that in order to perform a time step using the implicit Euler method one has to solve the linear system in Eq. (3.15). This increases the computational cost, but it allows to get rid of the CFL<1 stability requirement, which can be prohibitive to fulfil for 3D unsteady CFD simulations.

In order to increase the order of accuracy in space for this 1D case, one can use the Lax-Wendroff scheme. This scheme is second order accurate in space, so if one halves the cell size the truncation error decreases with a factor of four. It is still an explicit scheme, so the CFL<1 requirement for stability still holds.

Even if the 1D advection equation is much simpler than the RANS ones, it allows to introduce very important concepts in CFD which then remain valid for 3D CFD commercial software as well. For example, the numerical scheme chosen in Star for this work is second order accurate in terms of space discretisation (where the mesh has a sufficient quality), and it is implicit in terms of time discretisation. This means that there is no CFL<1 stability requirement, but still the CFL number can give an indication on the accuracy of the time integration, as if a too high time step is chosen then the accuracy of the time integration strongly reduces. These concepts will be recalled in Section 3.2, where the discretisation used by Star will be introduced.

Of course the RANS system of equations Eq. (3.8) is much more complex than the 1D advection equation so further concepts needs to be introduced in order to understand how can they be discretised.
One important concept is the **Finite volumes** discretisation, which is the basis for the space discretisation used by most CFD softwares. While in 1D the FV method corresponds to the FD one, in 2D or 3D meshes the FV method performs much better. The main steps needed to implement the space discretisation using the FV approach are the following:

1. To cast the RANS Eq. (3.8) in an integral continous formulation which can be applied to the mesh cells.
2. To convert the continuous integral formulation into a discrete integral one (Finite Volumes method).
3. To express all the terms contained in the integral continuos formulation as a function of a combination of the values of the seven unknowns of the system \((\rho, u, v, w, E, k, \omega)\) at the cell center.

This process allows to discretise the RANS equations into a very big algebraic system, which can then be solved iteratively. The details of the FV space discretisation will be described in Section 3.2.2, referring in particular to the formulation used in Star. It must be kept in mind anyway that the FV is extremely general, and it is not Star-specific. The choice to use the Star formulation in Section 3.2.2 to describe more general aspects as the FV discretisation and the Coupled and Segregated flow models has been taken in order to consistently analyse and compare the details of those aspects on the same level. In order to address their most general aspects, those concepts have also been briefly introduced already in this section.

The FV discretisation of a real-world problem usually leads to a very big linear system, finding the close solution to which would not be feasible. For this reason iterative methods are used. But iterations can also be used in a so-called **transient approach**, in which one solves a steady flow starting from a generic initial condition and then using the unsteady flow equations to get to a steady solution.

A very important choice to define the kind of iterations performed is the choice of flow model.

The **coupled flow** model works on the full unsteady RANS system of equations at each iteration. In case of a steady flow, for each iteration the finite volume approach is used to discretise both the continuity, momentum and energy equations all at once, and the iteration happens on a pseudo time step. So even if the simulation is steady, a pseudo time is generated to perform the iteration. On the other hand, if the simulation is unsteady the physical time is divided into time steps, each of which includes a few inner iteration in pseudo time. The pseudo time has nothing to do with the physical time, it is only a numerical tool to perform the iteration.

The **segregated flow** model, instead, uses a predictor-corrector approach to perform the iterations. Each iteration is performed following the SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm, which is briefly introduced here as described in [39]; the version of simple algorithm used by Star will instead be introduced in Section 3.2.4. The SIMPLE algorithm iteration for the 3D case starts taking as predicted pressure \(p^*\) the pressure field at the end of the previous iteration, then it continues with the following steps:

1. Solve the momentum equations using \(p^*\) to obtain the predicted velocity components \(u^*, v^*, w^*\).
2. Solve the pressure correction equation, which is a reformulation of the continuity equation aimed at computing the correction needed for the pressure to fulfill continuity. The pressure correction equation uses the predicted velocity components \(u^*, v^*, w^*\) to compute the pressure correction \(p'\).
3. Get the final pressure field by adding the pressure correction \(p'\) to the predicted pressure \(p^*\).
4. Use \(p'\) to correct the predicted velocity components \(u^*, v^*, w^*\) in order to take into account the change in pressure due to the correction, thus getting the final velocity field \(u, v, w\).
5. Solve the discretisation equation for other scalars, such as the temperature for the energy equation, and the turbulent kinetic energy and dissipation for the \(k - \epsilon\) turbulence equations.

The main advantage of the segregated flow model as opposed to the coupled one is that it does not attempt to solve the five NS equations all at once, but it solves the continuity and the momentum equations separately, so it requires much less memory and computational resources to perform the iteration. For this reason it is usually the most common choice in commercial CFD tools. On the other hand the coupled flow model is more robust, as it solves the whole RANS system all at once, so it might be a better choice for example for highly compressible flow where the variations in density are very strong.
3.2. Star-CCM+ software

In this section the steps needed to set-up a simulation and compute a solution will be exposed, basing on the approach used in the Star-CCM+ software employed in this thesis work. Of course this is only to be meant as a quick introduction to these concepts, it has to be underlined that the Star-CCM+ user guide is made of no less than 12993 pages, and it still only gives a hint about what the software actually does. The main goal of this section is to introduce the basic features and parameters present in Star-CCM+ which will be used in the following sections.

Star-CCM+ is a commercial multi-purpose CFD software. It is capable to handle any phase of the simulation from CAD modelling to post processing. In this work it has generally been used for 3D time dependent compressible flow simulations, solving the RANS equation employing the Menter $K - \omega$ SST model and also employing RBM (Rigid Body Motion) techniques together with overset mesh to handle the train motion both for the single train entry and double crossing scenarios.

3.2.1. Workflow

A very useful feature of Star is that it allows to perform all of the phases of the simulation inside the same GUI window, without having to exchange, convert and import geometry files, mesh file, simulation files or results files.

Given that the geometry used in this work was quite simple, the train and the domain geometry have been easily modelled in the Star CAD editor, without requiring the assistance of a CAD operator. When defining the train and domain geometry, the shape of the overset mesh regions and also the car surfaces on which to probe the pressure were defined too.

Before setting the boundary condition one should choose the flow formulation (coupled or segregated), and set-up the simulation numerical parameters. The next step was to define the various regions, initial and boundary conditions, together with the mesh parameters. At this point mesh generation could be performed.

With the mesh, one can then develop a macro to define the motion settings, start the simulation, possibly stop it to change the motion and time integration settings and continue the simulation, then finally stopping it at the desired instant. This was key as it allowed to automatically run dozens of simulations during nights and weekends on the cluster, making the parametric studies in Chapters 4 and 5 realizable in a reasonable time.

Then the simulation results can first be visualized in Star, in order to check whether the simulation has had problems or it has run properly. After also assuring the monotonical reduction of residual inside each time step, at least for the non-turbulent equations, the results from the interesting pressure probes could be exported to Matlab in order to be more extensively post-processed, as described in chapters 4 and 5.

3.2.2. Meshing and space discretisation

The meshing phase allows to divide the 3D computational domain into a high number of very small finite volumes on which the RANS equations Eq. (3.8) can be discretized.

Star most common meshing technique for 3D domains is a polyhedral unstructured one, as shown in Fig. 3.2 for a generic benchmark problem found in the Star User Guide.
Polyhedral cells have on average 14 faces, but that number is not fixed. This kind of cells improve the overall computational time and improves convergence when compared with hexaedral cells (trimmed mesh in Star, six face per cell) or tetrahedral ones (4 faces per cell), as having less cell with more faces (less equations and unknowns with more terms inside each equation) grants a faster convergence.

Anyway in this work a trimmed mesh has been preferred, as shown in Fig. 3.3 for the same benchmark problem.

The trimmed mesh offered two key advantages for tunnel entry and passage simulations:

1. One source of error in this work simulations is the overset mesh overlap region (Fig. 3.6). This is because the overset mesh interface (the overlap region) is made of superposed cells, and it is not a clean interface.
But if the cells that are superposed in the overset mesh interface have the same cubic shape, as for a trimmed mesh, the interpolation is then much easier.

2. The flow inside the tunnel is always nearly one dimensional, so having all the cell faces aligned with the main flow should reduce the numerical dissipation, especially for the travelling pressure waves, which might be very sensitive to numerical dissipation as their timescales are very short.

A drawback of the trimmed mesh model is that the cell size variations are very abrupt, as the refinement are only implemented with a factor of 0.5 for the cell size (Fig. 3.3).

In Star them mesh cell size is defined through a base size, which is the coarsest size in the region which is being meshed and a few refinements, which can be either on the surface mesh or on the volume one. Also one can of course introduce prismatic layers on the walls.

More complex to set-up is the overset mesh. Overset mesh is a technique which allows to simulate objects moving in the domain for cases in which an in-place interface is not feasible. In order to do so, two separated mesh regions are defined, a background and an overset regions. Those regions can be completely or partially superposed, and they can exchange fluxes only at the overset boundary. Also multiple overset regions can intersect each other. A generic overset mesh set-up is shown in Fig. 3.4, from the Star user guide.

![Fig. 3.4 Generic overset mesh set-up. Overset and background regions are superposed but completely distinct, they can exchange fluxes only at the Overset Mesh Boundaries [34].](image)

So in case of an overset mesh approach the domain is made of background and overset regions. In order to perform the spatial discretization, one mesh continuum has to be computed from the separated and superposed background and overset region, in a process called hole cutting.
Fig. 3.5 Hole cutting procedure and regions definition: Moving Region is the overset one, Stationary region is background one, Overlap region is the only one made by a superposition of active cells from both layers, and it is used to interpolate the solution between the other two regions.

In Fig. 3.5 one can see that before the hole cutting the two mesh regions are superposed, while after it a single mesh continuum is generated on which space discretization can be performed.

In order to explain how overset mesh works, one can name active cells the one which are included in the computational domain for the current iterations, and inactive cells those which are not. For an iteration in which the overset region does not move, the active cells will be the one of the background mesh outside the overset region and the ones of the overset mesh inside the overset boundary. The inactive cells will be, for example, the background ones which fall inside the overset region. The overset boundary must always be shared by both mesh levels, so for example overset mesh cells could fall outside the overset boundary if for example the overset region intersects a background wall. So the set of active cell forms a continuum on which the spatial discretization can be applied and the iteration performed.

When the overset region moves, as an example when one of the cars in Fig. 3.4 moves forward, a few background cell which were inactive in the previous iteration will become active (at the back of the car); for these cells a problem arises as they do not have values for the variables as they were inactive. This means that they (acceptor cells) must be given those values from the overset cells which occupied their position at the previous iteration (donor cells). Also, a few background cell which were active at the previous iteration will become inactive (at the front of the car): they are the donor for the overset mesh cells which take their place at the current iteration. If Star for any reason is not able to find a donor the simulation stops, complaining that “no active donor cells have been found” for acceptors in the considered region. For this reason the overset boundary is usually not a line, but a set of superposed cells from both layers named Overlap Region, as shown in Fig. 3.5. In this region where active cells from both layers are superposed the solution is interpolated from one layer to the other, so for example continuity cannot be fulfilled there. A higher number of cells in this
region results in a higher robustness, as a donor can be found more easily, but one has to keep in mind first that the accuracy of the interpolation goes with the coarsest cell size among the two layers at the interface, and then that if the interpolation region grows bigger the interpolation error also increases. Keeping a constant cell size, a lower number of cells in the interpolation region is better for accuracy, but this might lead the simulation to crash if no donors are found. This region were active cells are superposed can also be appreciated in Fig. 3.6 from the single train entry simulation.

Fig. 3.6 Overlap region-intersection between Moving overset region and Stationary background region wall. Horizontal section plane shows only the cells belonging to the Moving overset region.

In Fig. 3.6 one can appreciate the versatility of the overset mesh, as the overset region can intersect other regions cells or walls without major problems. Looking at the horizontal section plane, one can see that the moving region cells lying in the front-right part of the domain fall outside the computational domain (outside the tunnel wall), so they are inactive so they are not shown. Looking at the floor wall, one can see that before the tunnel entrance the overlap region is very clean, as it is made by one single layer of cells of the same dimension, thanks to the two regions both employing a trimmed mesh with the same size. Around the tunnel entry corner instead the shape of the overset region is much less neat, and also the active Moving region cells are one quarter of the size of the active Stationary region cells which they are superposed to, so one has to keep in mind that the accuracy in that area is the one associated with the coarsest size.

The overset mesh approach also imposes a requirement on the time step. If the time step were too big, the rear end of the moving region might cover in a time step a distance higher than the overlap region there. This means that a few background cells would become active without having being acceptor, thus giving an error. So the interface should not cover a distance higher than the overlap region in one time step (the suggested maximum distance is one single cell for the User Guide). This requirements effectively correspond to imposing a CFL number equal to 1 computed with the velocity and cell size at the interface.
With a properly implemented overset mesh, at each time step a mesh continuum is generated on which the RANS equations can be discretised.

To discretize (in space) means to formulate each of the continuous RANS Eq. (3.8) over the volume of each single cell, using as free variables a combination of the values of the seven unknowns of the system \((\rho, u, v, w, E, k, \omega)\) at the cell center, so, for a 1 million cell mesh, at the end of the spatial discretization one gets a system of 7 million equations in 7 million unknowns.

If the problem is time dependent, as the one of this work (due to the relative motion between the train wall and the vertical part of the tunnel wall, or between a train and another train), then one also has to discretize in time, which will be described in the following sections.

Referring to the space discretization, a FV approach is employed through the following main steps:

1. To cast the RANS equation in an integral continuous formulation which can be applied to the mesh cells Eq. (3.16).
2. To convert the continuous integral formulation into a discrete integral one (Finite Volumes method) Eq. (3.17).
3. To express all the terms contained in the integral continuous formulation as a function of a combination of the values of the seven unknowns of the system \((\rho, u, v, w, E, k, \omega)\) at the cell center.

In order to show the first two steps one can look at a generic time dependent convection diffusion equation for a scalar \(\phi\), and keep in mind that the full RANS set can be ultimately expressed using 7 such equations for each cell. The continuous integral formulation of the time dependent convection diffusion equation is equations Eq. (3.16), from Star User Guide [34].

\[
\frac{\partial}{\partial t} \int_V \rho \chi \phi \, dV + \int_A \rho \phi (v - v_g) \cdot da = \int_A \Gamma \Delta \phi \cdot da + \int_V S \phi \, dV
\]

In Eq. (3.16) \(\rho\) is the density, \(\chi = 1\) for a single phase flow, \(\phi\) is the scalar, \(V\) is the cell volume, \(v\) is the velocity of the flow, \(v_g\) is the velocity of the grid in the current frame of reference, \(a\) is the cell boundary area over which to integrate, \(\Gamma\) is the diffusion coefficient and \(S\) is the source term.

The first term is the transient term, and it exists only for time dependent simulations. The second term is the convective one, the third term is the diffusive one (\(\Delta\) is \(\nabla^2\), the Laplace operator), and the fourth one is the source term.

It is prohibitive to closely solve the integrals for each face, so it is much better to convert Eq. (3.16) into the discrete integral one in Eq. (3.17).

\[
\frac{\partial}{\partial t} \left( \rho \chi \phi V \right)_0 + \sum_f \left[ \rho \phi (v \cdot a - G) \right]_f = \sum_f \left( \Gamma \Delta \phi \cdot a \right)_f + \left( S \phi V \right)_0
\]

Now each of the terms can be expressed as a function of \(\phi\) at the cell centre. The first term does not need further work, as it already is a function of \(\phi\) at the cell centre. The second term is a function of \(\phi\) at the cell face (\(G\) just contains the grid fluxes due to motion), so the so called reconstruction gradients must be used to compute \(\phi\) at the cell faces from \(\phi\) at the cell center. The third term needs the value of the Laplacian of \(\phi\) at the cell face. Again, reconstruction gradients are used to do so.

Without going deep into the formulation Star uses for those reconstruction gradient, which is also not explicitly reported in the User Guide, they express the gradient of \(\phi\) at the cell center as an algebraic function of \(\phi\) at the cell center of the considered cell and the adjacent ones, so that when they are multiplied by the distance between the cell centre and the cell face and summed to the \(\phi\) value at the cell centre one gets the wanted value of \(\phi\) at the cell face.

In the very end, using the reconstruction gradients one can express Eq. (3.17) as a function of \(\phi\) at the cell center of the considered cell and the adjacent ones. By doing this for each cell one has finally composed the
discretized system. One still has to complete the iteration and then discretize in time, as exposed in the following sections.

These reconstruction gradients are extremely important for accuracy and convergence, and they are the most basic feature of any 3D CFD FV code. In the case of Star they automatically provide both upwinding (thanks to a clever preconditioning matrix they look for the values of variables in the direction the associated characteristic comes from) and an accuracy up to second order. Up to second order means that if the grid quality is high compared to the flow gradients (no skewness, and low cell size variations between adjacent cells) the accuracy is second order, otherwise the reconstruction gradient is limited in order to keep the value of $\phi$ at the cell face between the values of $\phi$ at the cell center of the considered cell and the adjacent one. This limiter can cause problems if the flow field is nearly constant, so it can be deactivated activating the TVB limiters, but this showed poor result for the considered simulations. Furthermore one can also choose to voluntarily reduce the maximum accuracy level of the reconstruction gradient in order to improve robustness.

3.2.3. Coupled flow formulation

Flow model is the way to convert the continuous RANS formulation Eq. (3.8) into an algorithm which can be implemented on a given mesh ultimately employing discretised equations such as Eq. (3.17). This can be done in Star using two completely different approaches, each of which has a different field of application. The choice of flow model is the first step in the numerical parameters set-up, as it defines the solution procedure and so the numerical parameters, such as the under-relaxation factors for the segregated model or the Courant number for pseudo-time stepping integration in the coupled flow model.

Both flow models are capable of discretising the NS equations in order to allow to set-up a solution algorithm. The common steps to both the models are the space discretisation and time discretisation. With regards to the space discretisation, a mesh is used to represent the geometry, so that each primary variable ($\rho$, $u$, $v$, $w$, $E$) can be expressed at the cell centre and an algebraic system can be formulated and solved at each iteration in order to find their values. Regarding the time integration, the physical time is divided into intervals, named time steps, so that at each interval the physical time is increased, and inside each interval the space discretisation is applied to solve the system keeping the unsteady terms constant.

When Coupled is chosen as flow model, then the continuity, momentum and energy equations are solved simultaneously inside each iteration also employing a pseudo-time marching approach and a preconditioning matrix in order to speed up convergence as much as possible.

When Segregated is chosen as flow model, then continuity and momentum are solved one at a time using a predictor-corrector approach and energy equation is solved at a later time: splitting the NS equation set into three sub sets to be solved separately hugely simplifies the solution procedure from a numerical point of view, but the procedure gets much more complicated to understand and explain.

Given that both approaches have been used in this work, and in order to introduce the solver settings, advantages and disadvantages of each approach, an overview of the solution procedure for each of the formulations will be given in the following of this section. Most of the equations are taken from the Star-CCM+ software User Guide [34].

For what concerns the Coupled flow model formulation, one can start from Eq. (3.18), which is the continuous integral formulation of the three NS equations (Eq. (3.1)).

$$\frac{\partial}{\partial t} \left[ \int_V \mathbf{W}_X \, dV \right] + \int_V [\mathbf{F} - \mathbf{G}] \cdot \mathbf{a} \, dV = \int_V \mathbf{H} \, dV; \quad \mathbf{W} = \begin{bmatrix} \rho \\ \rho v \\ \rho E \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho (v - v_g) \\ \rho (v - v_g) \otimes v + p \mathbf{I} \\ \rho (v - v_g) H + pv_g \end{bmatrix}$$

$$\tag{3.18}$$
The notation in Eq. (3.18) is consistent with Eq. (3.1), Eq. (3.16) and Eq. (3.17). \( G \) and \( H \) are not reported for brevity, but they simply contain the viscous terms (including turbulent ones), the heat fluxes and the source terms.

It must first of all be underlined that Eq. (3.18) has had to be corrected from the Star user guide formulation. In the user guide, the Convective \( (F) \) and Viscous \( (G) \) fluxes integral term were included in the time derivative, but they should not, as can be seen when looking for example at the physical dimensions of the terms for the continuity equations (kg/s, first line), so the formulation from the Star user guide seems wrong. Basically in the Star user guide the second integral is included in the squared parenthesis. This looks wrong, also because in case of source terms different from zero, it would always prevent the system reaching a steady state, as the time derivative could never get to zero.

Eq. (3.11) is the whole NS system expressed in a continuous integral formulation. Before expressing it in a discrete formulation in order to get the algebraic system needed for the solution, one really needs to implement two numerical artefacts which heavily improve the conditioning number of the system matrix, thus allowing for the most efficient numerical solution possible.

The first artefact is preconditioning the system matrixes, as shown in Eq. (3.19).

\[
\Gamma \frac{\partial}{\partial t} \left[ \int_{V} Q \, dV \right] + \oint_{S} (F-G) \cdot dA = \int_{V} H \, dV \quad \Gamma = \begin{bmatrix}
\frac{\partial}{\partial t} & 0 & \rho_T \\
\frac{\partial}{\partial t} & \rho I & \rho_T \nu \\
\rho H & \rho T H + \rho C_p & \end{bmatrix}
\]

(3.19)

In Eq. (3.19) \( Q \) is the column vector of the primitive variables \( \rho, \nu, E \), and the other symbols are consistent with the previous equations.

Again, the formulation in the Star user guide seems wrong, as it includes the second integral in the time derivative and preconditioning matrix (square parenthesis), which is both dimensionally wrong for the time derivative, and not consistent for the preconditioning, as the most fundamental property of a preconditioning is that it affects the pseudo-time term, so that for a steady state (transient approach) it tends to zero. If one preconditions the fluxes then the solution after an infinite time (transient approach) is different between the preconditioned and un-preconditioned versions of the system, so the preconditioning system would not be consistent. So it seems that Eq. (3.19) is the correct expression for the preconditioned system.

In Eq. (3.19) \( \Gamma \) is the preconditioning matrix, and the parameters appearing into it are complicated functions of both the primary variables and grid properties. The purpose of preconditioning is to bring the eigenvalues of the algebraic system matrix in Eq. (3.20) much closer one another, thus improving the conditioning number of that matrix, and so speeding up the convergence of the problem. Without preconditioning the convergence would be either much slower or even impossible for the cases analysed in this work.

The discretised version of the preconditioned system of equations is.

\[
V_0 \Gamma_0 \frac{\partial Q_0}{\partial t} + \sum_f (f_f + g_f) \cdot a = hV_0
\]

(3.20)

Eq. (3.20) has to be casted for each cell in order to build the algebraic system corresponding to the space discretisation. The subscript 0 indicates the considered cell centre, while the subscript f indicates the cell face. \( V_0 \) is the cell volume, \( \Gamma_0 \) is the preconditioning matrix computed for the considered cells. The summation term includes all the convective \( (f) \) and viscous \( (g) \) fluxes which can be computed from the considered and neighbouring cells geometries (grouped in \( a \)) and primitive variables.

Now the formulation in the Star user guide looks correct with respect to the convective and viscous fluxes \( f \) and \( g \), which are now correctly not included in the time derivative and not multiplied by the preconditioning matrix.
A key comment on Eq. (3.20) is that preconditioning the time derivative destroys the time accuracy of the numerical scheme. This means that this numerical scheme can only be applied to transient approaches. A transient approach is to be applied to a problem which presents a steady state. When looking for a steady state solution one might try to solve NS Eq. (3.18) without the transient term; this looks the easiest way to solve the problem, but it is definitely not the most numerically efficient. What is preferable is to solve the transient NS equation starting from an initial condition in order to reach a steady state. When a steady state has been reached, then that is the solution. In this approach one does not care about the time evolution of the problem, one only cares about the final steady state. So it is appropriate to multiply the time-evolution term with a preconditioning matrix, thus modifying the time-evolution terms arbitrarily, as one does not care about the time history. So one looses time accuracy, but the preconditioning matrix allows both a more robust and much quicker convergence to the steady state. Given that the time in Eq. (3.20) is not the physical time anymore, it is named pseudo-time. A great advantage of the pseudo-time is that, being it non-physical, the pseudo time-step can also be different from cell to cell depending on the local conditions of the flow. One could also see the transient approach as an iterative procedure for the solution of the NS system Eq. (3.18) without the transient terms.

This so-called transient approach is currently the basis for most of the commercial CFD codes. The convergence to steady state can be checked looking at the residuals. The residuals basically are a norm of the last two terms of Eq. (3.20), so when they are low the transient term time derivative is also low, so the problem is not varying much from an iteration to the following. When the residuals cease to decrease, then that’s the maximum accuracy reachable for that problem on that mesh.

The question then becomes how to address unsteady problems, such as the one in this work. If the time in Eq. (3.20) is a pseudo-time, then one has to go back to the physical time through a technique named dual time stepping.

\[
\frac{\partial}{\partial \tau} \int_V W dV + \Gamma \int_V \frac{\partial}{\partial \tau} Q dV + \int_V [F - G] \cdot \vec{a} = \int_V H dV
\]

\[
\frac{\partial}{\partial \tau} \int_V W dV = \begin{bmatrix} \rho \\ \rho \vec{v} \\ \rho \vec{E} \end{bmatrix}
\]

(3.21)

In Eq. (3.21) \( Q \) is the primitive variables column vector \((\rho, \vec{V}, E)\), \( \Gamma \) is the preconditioning matrix and \( \tau \) is the pseudo-time. Eq. (3.21) is analogous to both Eq. (3.18) and Eq. (3.19), as it contains the same source terms, convective and viscous fluxes term, and pseudo-time preconditioned transient term \( \frac{\partial}{\partial \tau} \sum \int_V W dV \) as Eq. (3.19), but it also contains the physical time term \( \frac{\partial}{\partial \tau} \sum \int_V W dV \) from Eq. (3.18).

In order to solve Eq. (3.21) to get the time accurate evolution of a flow, one divides the physical time into many time steps, and each time step into many inner iterations which proceed in pseudo-time. This approach is called pseudo-time marching (or dual-time stepping). Inside each time-step one should take enough iterations so that the pseudo-time preconditioned term does not vary anymore in time. In order to fulfil this requirement in real simulations, one can look at the residual drop inside each time step, aiming for example for a few orders of magnitude decrease (1-2 for the simulations in this work depending on the equations) inside each time step. Once the inner iteration inside a time step have reached a steady state solution then the time derivative of the pseudo-time transient term in Eq. (3.21) is negligible, so Eq. (3.21) becomes the un-preconditioned time accurate version of the NS system Eq. (3.18).

The inner iterations procedure used in Star follows the implicit time-stepping iterative algorithm in Eq. (3.22).
In order to introduce Eq. (3.22), one can imagine being at a physical time-step \( n \) with size \( \Delta t \), and dividing it into \( m \) inner iterations in pseudo-time \( \tau \) with size \( \Delta \tau \). One begins the time-step knowing \( Q^0 \). Then at the \( i \)-th inner iteration one can compute \( \Delta Q_i = Q_i - Q^0 \), and so \( Q_i \), from \( W \) and \( R \) (the residuals) at the previous inner iteration \( i-1 \) and from \( W \) at the previous and actual time steps \( n-1 \) and \( n \), which are held constant during the actual time step. At the end of the \( m \) inner iterations one gets \( Q^m \), from which one can compute \( W_{n+1} \), thus concluding the time step. This procedure for time integration is implicit, so each inner iteration a system is solved for \( \Delta Q \), taking into account the values of \( Q \) at the following time instant.

At this point the pseudo-time step is concluded, so the unsteady terms can be updated, thus performing the physical time step. The physical time discretisation scheme can be either first or second order explicit or implicit. For simplicity, the first order implicit scheme is reported in Eq. (3.23), which is named Backward Euler time integration scheme. Eq. (3.23) refers to the convection diffusion equation of a generic scalar \( \Phi \), such as Eq. (3.16), so the formulation is consistent with that equation.

\[
\frac{\partial}{\partial \tau} \left( \rho \chi \phi V \right)_0 = \frac{\left( \rho \chi \phi V \right)_{0}^{n+1} - \left( \rho \chi \phi V \right)_{0}^{n}}{\Delta \tau}
\]  

(3.23)

As shown in Eq. (3.23) both the time integration schemes, being implicit, require the solution of a system (\( \phi \) will be \( \rho, u, v, w, E \) once at a time) to update the variables from a physical time step to the other. The time-stepping implicitness allows for much higher time-steps. The user can also choose to perform an explicit time accurate integration with a very small time step fulfilling the CFL<1 requirement in each cell for high-accuracy time-accurate computations.

From Eq. (3.22) and Eq. (3.3) one can realise that the user can specify three parameters for the time integration of an unsteady problem using the coupled flow formulation:

1. \( \Delta t \): it is the physical time-step size. Clearly the smaller it is the more accurate and expensive the scheme is. An indication for the choice of the physical time step can be given by the CFL number, defined as in Eq. (3.24).

\[
CFL = \frac{v \cdot \Delta t}{\Delta x}
\]  

(3.24)

In Eq. (3.24) \( \Delta t \) is the physical time-step, \( \Delta x \) is an indicative mesh size and \( v \) is the characteristic velocity of the phenomenon one is modelling. A lower CFL number indicates higher accuracy in time integration. The optimal CFL number lies around 1. It is not said that a higher CFL automatically leads to instability as the time integration is implicit, so it can handle higher CFL without diverging. One has to keep in mind anyway that for higher physical time-step size the accuracy is of course lower, as the discretisation error increases.

2. \( m \): the number of inner iterations per time-step. It should generally between 5 and 10, not more as it is more accurate to have more physical time-steps with fewer inner-iterations than vice-versa. So there is a balance between how many time-steps and how many inner iterations to perform. One also has to keep in mind for this simulation that for each time step the mesh overset needs to be updated, which is a time consuming process, and also the geometrical parameters of the mesh, such as the spacings between the cells, have to be recomputed.

3. \( Cour \): the user also has to specify a Courant number which then determines the pseudo-time step size, following this relation:

55
In Eq. (3.25) CFL is the user specified Courant number (Cour) which has absolutely nothing to do with the CFL in Eq. (3.24), as they are the same number but the Eq. (3.25) refers to the pseudo-time step, while the one in Eq. (3.24) refers to the physical time step. $\lambda_{\text{max}}$ is the maximum eigenvalue of the inviscid NS system, while $\sigma = \mu \frac{\Delta t}{\Delta x^2} \approx 1$ is the Von Neumann number. The first term fulfills the stability condition for the convection terms, while the second one does so for the diffusion terms, so the software chooses the minimum among the two.

There is no guidelines on how to choose the Cour value. The default is 50, but values between 5 and 100 or even higher can also work, as the User Guide states.

The conclusions drawn from the theory in this section is that a higher Cour can on one hand lead to higher convergence in each time step for the same number of inner iterations, as the inner iterations proceed further into the pseudo-time. On the other hand a too high Cour (Eq. (3.25)) decreases the accuracy of the pseudo-time integration, just as a high CFL (Eq. (3.24)) does for the physical time. The Cour role for the Coupled Flow implicit dual-time stepping is the same one the Under Relaxation Factors play for the Segregated Flow implicit time stepping, but while the URF are usually not brought far from the advised optimal values, the Cour number should be increased to boost the advantage the coupled flow model might have on the segregated one. So one should not only find a balance of CFL (physical time step, 3.24) and inner iterations, but also of Cour (pseudo-time step, 3.25).

The advantages (and disadvantages) of the Coupled Flow model when compared to the Segregated Flow one (next section) claimed by Star User Guide are the following:

1. The coupled flow is more computationally intensive, especially in terms of memory, as the whole NS system has to be stored in the RAM memory at once. This is a direct result of solving the whole NS system at once. Again, for one million cells, the full NS system solved with the Coupled Flow approach is of 5 million equations (without turbulence). For the same problem the segregated flow requires to solve three separate systems, two of them of 1 million equations (pressure correction, energy) and one of 3 million equations (Momentum for velocity prediction).
2. Increased robustness, especially with shocks. In my opinion this is a direct advantage of solving the NS system all at once, as one can handle stronger variations or even discontinuities. On the other hand one should keep in mind that turbulence equations are not solved together with the NS ones, and that very often the first equations to diverge are the turbulence ones.
3. Coupled flow can handle larger CFL, this scenario is analogous to setting all the URFs equal to 1 in a Segregated flow solver. My interpretation of this statement is that setting a higher Cour for the pseudo-time stepping can be done without divergence, and it can lead to the same results one would get when setting all the URFs equal to 1. This means that one would reach a better residual decrease for the same physical time step size and number of inner iterations, or equivalently that one could reduce the number of inner iterations and reach the same residual decrease.
4. Number of iteration needed does not depend on the mesh size.

For this thesis work many runs have been performed with the coupled flow model, but then it has been discarded in favour of the segregated one.

Given the relatively small mesh size of the tunnel entry simulations (2 millions cells), the coupled flow looked an attractive choice as it might have allowed a lower number of inner iterations per time step to reach the same residual drop and an increased robustness thanks to solving the whole system all at once.

But the coupled flow approach turned out to be very sensitive to small problems in the mesh, and it was painful to find the best combination of physical time-step size, number of inner iterations and Cour number.
(pseudo-time step size). As will be described in Chapter 4, in the end a few runs with the Coupled Flow got to a sufficient level of accuracy. When comparing these runs with similar Segregated Flow runs, the same level of accuracy can be reached with time steps up to about 50% higher for the Coupled Flow. But this is at the expense of an increased RAM usage (not a problem for my set-up) and workload, so more computational time per iteration, so in the end the advantage got much less than 50%. In the end, the factor which made me go for the Segregated was the process of tuning of physical time-step size, inner iterations and Cour, which are extremely influent for the Coupled Flow results.

3.2.4. Segregated flow formulation

When the Segregated flow model is chosen, the continuity, momentum and energy equations are solved separately, one at a time, using a predictor-corrector SIMPLE approach on a co-located grid. Predictor-corrector means that one equation (momentum) is solved first, in order to get the predicted velocity ($v^*$) using pressure and density from the previous time step. An equation can then be spelled to find the pressure correction ($p'$) which satisfies continuity using the predicted velocity $v^*$. That pressure correction is then used to correct the predicted velocity. The corrected velocity, pressure and density are the results of the iteration.

The energy equation is solved separately after continuity and momentum. This model is much more complicated to understand and explain but less computationally expensive to solve than the Coupled Flow one, and it is currently the default Flow model in many commercial CFD software.

In order to show the Segregated Flow model set-up one can start from the continuous integral Continuity and Momentum equations Eq. (3.26).

$$\frac{\partial}{\partial t} \int_V \rho \chi V \, dV + \oint_A \rho (v - v_s) \cdot da = \int_V \Delta dV$$

$$\frac{\partial}{\partial t} \int_V \rho \chi V \, dV + \oint_A \rho \nabla \otimes (v - v_s) \cdot da =$$

$$- \oint_A p \cdot da + \oint_A T \cdot da + \int_V (f_r + f_p + f_o + f_i) dV$$

(3.26)

The formulation is consistent with Eq. (3.11): comparing the two formulations, one can first of all notice that in this case the equations are expressed separately, as they are solved separately. In Eq. (3.19) $T$ is the viscous stress tensor and the $S_u$ and $f$ terms on the right hand side are the source terms. Now the convective fluxes are outside the time derivative, as they should be, thus confirming that the Star formulation for the Coupled flow was wrong.

The main steps employed by the Segregated flow algorithm to perform an iteration (for continuity and momentum equations) are the following:

1. The iteration begins by knowing all the pressure and velocity components at the cell centers, and using them together with the reconstruction gradients (Section 3.2.2) to compute the values of velocity and pressure (and respective gradients) at the cell faces.

2. At this stage a discretised version of the momentum equation from Eq. (3.26) can be applied to compute the predicted velocities $v^*$ as in Eq. (3.27).

$$\frac{\partial}{\partial t} \rho \chi V_0 + \sum_f [v \rho (v - v_s) \cdot a]_f = - \sum_f (p \cdot a)_f + \sum_f T \cdot a$$

(3.27)
The formulation of Eq. (3.27) is consistent with Eq. (3.20). \( \chi = 1 \) for single phase flows, \( V \) is cell volume, \( \mathbf{v} \) is velocity vector, \( \mathbf{v}_g \) is grid velocity, \( a \) includes the geometrical aspects of the Finite Volume expression of the various integrals. The first term in Eq. (3.27) is the unsteady term, and it present only if the computation is unsteady, it is never used for transient pseudo-time step problems. The second term are the convective fluxes, the third are pressure stresses and the fourth are viscous stresses.

This discretised set of three equations for each cell can then be linearized and solved using the pressure field from the previous iteration and applying a Finite Volume discretisation with implicit URFs as shown in Eq. (3.28) for a generic scalar.

\[
a_p\phi_p^{k+1} + \sum_n a_n \phi_n^{k+1} = b \quad \Rightarrow \quad \frac{a_p}{\omega} \phi_p^{k+1} + \sum_n a_n \phi_n^{k+1} = b + \frac{a_p}{\omega}(1-\omega)\phi_p^k
\]

(3.28)

The first part of Eq. (3.28) shows a generic algebraic system to discretise the convection-diffusion equation of a generic scalar \( \phi \) for a cell \( p \). \( a \) are the various coefficient for each term, and the summation over \( n \) is the summation over the cell faces of the cell \( p \). The one represented in Eq. (3.28) is the line of a system which will include as many lines as the cell number times the number of unknowns in the system (three in case of the momentum equations). In order to introduce an implicit under relaxation factor \( \omega \) one can use the formulation in the second part of Eq. (3.28). For \( \omega = 1 \) this corresponds to having no under-relaxation, so trusting completely the solution after the time step; this can lead to instability. For \( \omega = 0 \) there is no advance in time for the momentum equation. For an intermediate value of the lower the value of the URF the more stable the numerical scheme is, but also the convergence is slower, as each iteration make the solution change less. In general if a problem is present with the mesh it is difficult to deal with it with the URFs, while reducing the URFs can be very useful for example for the first iterations in order to reduce instability. The under-relaxation in Eq. (3.28) is introduced implicitly as it is included in the coefficient of the algebraic system and it is not applied after the system resolution, as will happen for pressure.

Solving this algebraic system of size 3 times the number of cells (when the solution of a system is referred to actually this means applying a multigrid cycle to smoothen the residuals for that iteration to an acceptable level) gives the three components of predicted velocity \( \mathbf{v}^* \) at the cell centres. \( \mathbf{v}^* \) is the predicted velocity as it has been computed using the pressure field from the previous time step, so it is not the actual velocity field. In order to get the velocity field at the end of the iteration one has to correct \( \mathbf{v}^* \) taking the continuity equation into account as follows.

3. \( \mathbf{v}^* \) does not satisfy continuity. One can define as \( \dot{m}_f \) the mass flow at the cell faces computed using the predicted velocity and the values of pressure and density from the previous time step, then the correction needed to satisfy continuity is the term \( \dot{m}_f \) in Eq. (3.29).

\[
\sum_f \dot{m}_f = \sum_f (m_f^* + \dot{m}_f) = 0
\]

(3.29)

The \( \dot{m}_f \) mass flow correction term can be expressed as function of the predicted velocity and pressure correction term \( p^r \) (which is the correction to be applied to the pressure at the old time step to get the pressure which satisfies continuity), so the algebraic system Eq. (3.29) can be expressed as in terms of \( p^r \) as in Eq. (3.30).

\[
p^r + \sum_n a_n p_n^r = r \quad \Rightarrow \quad p^{n+1} = p^n + \omega p^r
\]

(3.30)

As in Eq. (3.28), Eq. (3.30) has to be expressed for each cell \( p \), and the summation is over the \( n \) faces of the cell \( p \). But now the URFs are applied after the system has been solved, and not implicitly as they had been applied for the momentum system of equations.
After the system for pressure has been solved one has both the pressure field at the end of the iteration and the pressure correction field $p'$ needed to correct the velocity as follows.

4. In the end the predicted velocity $v^*$ can be corrected using the pressure correction field from the algebraic system Eq. (3.30), as shown in Eq. (3.31).

$$v^{n+1} = v^* - \frac{V \Delta p'}{a_{\nabla p}}$$

(3.31)

In Eq. (3.31) $V$ is the cell volume, $\Delta p'$ is the pressure gradient and the denominator is the vector of central coefficients of the system Eq. (3.27), dimensionally it is velocity times density.

At this stage the corrected velocities and pressure are known, so one can solve the energy and turbulence systems to compute the final values of all the variables at the end of the iteration. Each of the set of algebraic systems solves has its own URF chosen by the user.

The SIMPLE algorithm iteration does not include a pseudo time, so if the simulation is transient then as many iterations as needed are performed without referring to a pseudo-time, and the unsteady terms in the NS equations are added only if the problem is unsteady. In the latter case, the physical time is treated just as described for the Coupled flow, so the user can choose the time step size and the number of inner iterations, and at the end of each time step the transient terms in physical time will be updated solving the time integrations method chosen, such as, for example the Eq. (3.23) one.

The advantages (and disadvantages) of the Segregated Flow model when compared to the Coupled Flow one (previous section) are the following:

1. The segregated flow approach requires less memory and it is less computationally intensive, as it solves three separate systems (respectively with size 1, 3 and 1 time the number mesh cells) instead of a single one with size 5 time the mesh cells number. Only just this advantage allows the segregated model to perform better unless there are discontinuities in the flow field such as shockwaves. The travelling compression waves in the tunnel are compressible phenomena, but they are very far from being shockwaves as their width in space is in the order of 50 m and not a few molecular mean free paths.

2. The segregated flow model requires strong under relaxation factors when compared to the coupled flow one, which allows for high Cour numbers, which corresponds to URFs close to 1. For the simulation setups used in this work this advantage materialised only after having spent a lot of time in setting up the right Cour number for the coupled approach, and at the expense of a very high sensitivity to relatively small problems in the mesh so in the end the segregated flow has been preferred.

3. With the segregated flow model the number of iterations needed to reach a defined level of convergence increases linearly with the mesh cells number. This is not a serious problem for most of this work as the mesh cell size is relatively limited (about a couple of millions cells). Anyway this might become a problem for train entry and crossing simulations with real train geometries.

Concluding, the segregated flow approach has been chosen together with a first order implicit time integration for the Star simulations carried on in this thesis, as this was the most robust and easy to use combination, still granting the required accuracy in modelling the interesting phenomena. For other setups such as highly compressible flows or more difficult flow fields the coupled flow approach might be preferable.
3.3. NUMSTA software

NUMSTA is a 1D commercial CFD code developed for tunnel aerodynamics [38]. A 1D code simulates only one component of velocity, assuming it homogeneous along the flow cross sectional area. For this reason it does not simulate viscosity (wake and boundary layers) or turbulence, but one can still add friction coefficients to the code in order to at least give as input the amount of drag and pressure loss due to the boundary layer.

Despite this, when properly tuned, NUMSTA can give accurate enough results with regards to the $\Delta p_N$, pressure increase across the nose entry compression wave (Fig. 2.4), but the results will be worse for $\Delta p_f$, as NUMSTA cannot model the wake. With regards to the train crossing scenario, the value of pressure in the area where the two train cross will be modelled well enough, while the 3D flow field around the trains noses and tails will not be modelled.

The governing equation solved by NUMSTA are the Quasi-1D inviscid unsteady equations Eq. (3.32).

$$\frac{\partial (Ay)}{\partial t} + \frac{\partial (Af)}{\partial x} = S^0 + S^1 + S^0$$

These equations are the equivalent of the 1D Euler equations Eq. (2.1), but they also account for area changes. Eq. (3.32) are made by a set of three scalar equation: continuity, momentum in the tunnel axial direction and energy. The formulation of Eq. (3.32) is the conservative formulation of the 1D Euler equations with area change, so it is expressed through the set of conservative variables $(\rho, \rho u, \rho e_t)$ and not for the primitive variables $(\rho, u, e_t)$, where $u$ is the axial component of velocity in the tunnel and $e_t$ is the specific total internal energy [J/kg]. The fluxes also contain the specific total enthalpy $h_t$. The source term are due to area variations, one can realise that an increase in area along the positive tunnel axial direction leads to a decrease in velocity and to an increase in pressure.

The numerical algorithm chosen to solve Eq. (3.32) is a Flux Difference Splitting second order Roe scheme belonging to the family of the approximate Riemann solvers. An approximate Riemann solver employs the concept of propagating the Riemann invariants along the characteristic lines from a time step to the other for each cell, thus obtaining a linear algebraic system which can be solved for the primitive variables, as quickly described in Section 2.1.6. It has second order accuracy in space, so it has to employ nonlinear limiters to avoid wiggles, so it is a TVD (Total Variation Diminishing) scheme. This means that the scheme is second order accurate where the flow variables are varying smoothly, while its accuracy gets reduced up to first order near flow variables gradients and extrema in order to ensure monotonicity and avoid wiggles.

NUMSTA allows to introduce the effects of friction into the inviscid flow equations Eq. (3.25) through two friction coefficients, $c_{f,TR}$ and $c_{f,TU}$ respectively for the train and tunnel walls. The user can choose whether to directly specify the value of those coefficient or to let the code compute them using the empirical Churchill formula which includes roughness and compressibility effects. Given that NUMSTA does not introduce pressure loss coefficients to model for example the flow separation around the train tail, one usually wants to specify a higher friction coefficient for the train wall to at least partially increase the pressure loss in order for example to account for the unsteady friction, which NUMSTA cannot model (Section 2). How higher a friction co-efficient? More to be added.
coefficient one needs also depends on the train length. The friction coefficients chosen for all the NUMSTA runs in this work are listed in Tab. 3.1.

**Tab. 3.1 Train and tunnel friction coefficients.**

<table>
<thead>
<tr>
<th></th>
<th>( c_f ) Train</th>
<th>( c_f ) Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.001</td>
<td>0.01</td>
</tr>
</tbody>
</table>

These values for the train and tunnel friction coefficients have been chosen to try to fit the friction rise portion of the pressure signature, and represent a very smooth train and quite a smooth tunnel.

The 1D mesh (which is a sequence of cell spacings \( \Delta x \)) is automatically generated by the code, and the user can specify two cell sizes, a fine and a coarse one. The code then generates the mesh using the coarse size everywhere but at the train nose and tail and at the tunnel entrance and exit. Given that the train is moving, the refinement regions around the train nose and tail move with it, so they are unsteady refinement regions.

The iterative solution procedure consists in a sequence of time steps inside each of which the Roe FDS scheme is executed. Thanks to the code being 1D it is a very quick solution even for a train crossing scenario with quite a fine mesh using a single core for the computation.

In NUMSTA the train and tunnel are represented only as a distribution of flow cross sectional areas along the tunnel axis. At the tunnel entrance there is no imposed inflow or outflow, so the only working force on the fluid is the moving area variation which represents the train motion. The interesting part of the simulation starts when the area variation associated with the moving train enters the tunnel. At the precise moment when the beginning of the area variation associated with the nose train enters the tunnel portal, the front of the head compression wave is generated, and it starts travelling in the tunnel at the speed of sound. The tail of the head compression wave is generated when the last point associated with nose area variation enters the tunnel, so the spatial width of the head compression wave will be close to \( L_n \times V_{tr} / c_s \) where \( L_n \) is nose length, \( V_{tr} \) is train speed and \( c_s \) is the speed of sound. On the other hand, the real head compression wave is born because of the complex interaction between the flow field in front of and around the train nose with the tunnel portal, so its spatial width will be much higher than the one computed by NUMSTA. Overall, NUMSTA predicts quite well the \( \Delta P_N \), but it cannot predict the correct rise-time of the head compression wave, as it cannot model the 3D flow field in front of the train nose.

What one can do to work around this problem is to define a nose length to give as input to NUMSTA which fits the rise time of the head compression wave computed by Star. This is what will be done in Chapter 4 with regard to the train entry, and also in Chapter 5 with regard to the train crossing scenario.
4. Single train tunnel entry and passage

The main goal of the single train tunnel entry simulations is to correctly predict the pressure signature of the train, which means to predict the time history of pressure recorded at a stationary point inside the tunnel. The focus is on the head compression wave, as it is the most strong pressure variation in the whole tunnel passage, and how the shape varies with train and tunnel parameters. A further goal is to find an approximate relationship for the head pressure wave shape as a function of the train and tunnel parameters.

In order to characterise the head compression wave one can use the overall pressure drop ($\Delta p_N$) and the maximum gradient (maximum derivative in time of pressure).

Further goals of the single train tunnel entry simulations are to predict the internal pressure and the structural pressure loads. In order to do so, both the time constant $\tau$ and the Free Length of the carriage as well as the position along the carriage on which one wants to compute the pressure load are needed. Furthermore, especially in case of a non-tight train, for a given shape of the head compression wave, the maximum gradient is extremely important to compute the maximum pressure load.

In this chapter at first the various tools available to predict the head compression wave will be introduced and compared. After that, the Star simulation for a benchmark case will be introduced and the results commented. In order to assess the influence of important parameters variations on the pressure loads, parameter sweeps simulations have been executed, and the results of such sweeps have been included into a fitting procedure capable to quickly generate the pressure signature and compute the loads for any given case.

A further part of the single train entry study is to compare the results of the 3D code Star with the 1D code NUMSTA ones. In particular, NUMSTA nose and train lengths have been tuned in order to give closer results to Star in terms of pressure signature using the findings from the fitting procedure.

The last part of the single train entry study is to fix the pressure signature for a case and compute the resulting loads when the train meets the waves it generated in the so-called Wave Encounter scenario. Both the carriage free length and the position along the carriage on which the loads are computed strongly influence the loads for this scenario.

4.1. Comparison of tools for head compression wave prediction

The main goal of head compression wave prediction is to predict the shape of the head compression wave. Given a generic arctan profile for the head compression wave pressure rise, the main parameters to quantify that wave are the overall pressure drop ($\Delta p_N$) and the maximum gradient (maximum derivative in time of pressure), which are shown in Fig. 2.4. Also the rise-time, which is the time the pressure takes to go from zero to $\Delta p_N$, can be useful to compare results, but the main parameters which determine the pressure loads for the given arctan profile are the pressure drop and the maximum gradient. In case of a non-tight train the maximum pressure gradient is what mostly determines the maximum loads, as the compression wave rise-time is close to the time constant $\tau$ of the carriage. For a pressure tight train, instead, the rise-time is much quicker than the time constant tau, so it is $\Delta p_N$ which is most influent for the pressure load.

The available tools to predict the head compression wave overall pressure drop, maximum gradient and rise time have been introduced in the previous chapters. In this section the results of some of those tools will be compared for a benchmark case of an 11 m$^2$ cross section train travelling at 250 km/h into a 63 m$^2$ cross section tunnel at atmospheric standard conditions. The train has a 4m long nose and its geometry is simplified.

The first tool are the equations Eq. (2.16) and Eq. (2.19) from Howe, which give a first estimate of the overall pressure drop and of the maximum gradient and are valid in the hypothesis of a snub-nosed train entering a sharp-edged tunnel with an inviscid flow. Those assumptions implies that neither the nose length nor the boundary layer displacement thickness and possible flow separations can be modelled. On the other hand these relations are extremely simple and general given the limited amount of input needed.
The second tool (in increasing order of accuracy) is NUMSTA, the 1D CFD code. Giving as input to NUMSTA the physical nose length of the train one can simulate the whole tunnel passage and record the pressure time history. Given that NUMSTA is a 1D inviscid CFD code then one needs to also specify friction coefficients for the train and tunnel walls, but these have a limited influence on the head compression wave.

The third tool is Star-CCM+, the 3D CFD code. Once the simulation set-up is validated, Star results are the most accurate. The geometry used for Star simulations is very simplified and features a smooth train without pantographs, wheels and rails. It will be described in Section 4.2.

Also the Sockel Eq. (2.17) can be used to predict the overall pressure drop, and it could be more accurate than the Howe equations thanks to the possibility to specify an head pressure loss coefficient, but given the limited difference between the results for the three tools in terms of overall pressure drop it looks not relevant to add the estimate from the Sockel equation.

The results of these three tools in terms of overall pressure drop $\Delta p_N$, maximum gradient and rise-time are listed in Tab. 4.1.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Howe equations</td>
<td>1336</td>
<td>7555</td>
<td>/</td>
</tr>
<tr>
<td>NUMSTA (physical nose length)</td>
<td>1335</td>
<td>41630</td>
<td>$\sim$0.06</td>
</tr>
<tr>
<td>Star-CCM+</td>
<td>1311</td>
<td>8989</td>
<td>$\sim$0.3</td>
</tr>
</tbody>
</table>

In terms of overall pressure drop $\Delta p_N$ the three tools are very close to each other. This is also thanks to the 3D train geometry used in Star being very simplified, without flow separations and with a very thin boundary layer around the nose, as with a realistic train geometry with flow separations and particulars such as boogies and pantograph the flow would have been displaced not only by the train nose but also by the boundary layer and separated flow regions. One also has to keep in mind that NUMSTA and Star do not give $\Delta p_N$, but the whole pressure signature, so it is to an extent arbitrary to define where the $\Delta p_N$ ends and where the $\Delta p_{fr}$ begins.

When looking at the predicted maximum pressure gradient, it is evident that the NUMSTA one is completely wrong. This is because NUMSTA is a 1D code, so it cannot simulate the 3D pressure field in front of the train nose, so the rise-time of the head compression wave corresponds to the nose length only. Star, instead, allows to model the 3D interaction between the moving pressure field in front of the train nose and the tunnel entry which generates the compression wave, so the Star gradient is the most accurate. It is interesting to note that the Howe equations get much closer (16% error) to the Star results than NUMSTA in terms of gradient even if they have been developed for a snub nosed train in an inviscid flow. This is because they do include into their analytical formulation an axisymmetric approximation of the 3D interaction between the moving pressure field in front of the train nose and the tunnel entry.

The main conclusion from this analysis is that it is necessary to use Star result to compute the loads for non-tight trains. For cases in which Star might be too expensive one can safely use NUMSTA results as they are extremely conservative. Howe equations instead are appropriate only for the prediction of the overall pressure drop, which is not enough to compute the loads for non-tight trains.

It must be underlined that NUMSTA results can be brought very close to the Star one by tuning the nose and train lengths, as will be shown in Section 4.5. By employing that procedure NUMSTA results get accurate enough also in terms of gradient, so they can be used to compute loads on non-tight trains too.
This section has introduced the core of the problem of head compression wave prediction, so in the following sections each of the different approaches to the problem will be further developed, with the final goal of the chapter being to predict the loads generated by the head pressure wave.
4.2. Star simulation for benchmark case

In this chapter the Star-CCM+ simulation set-up for a benchmark case of the single train entry scenario will be described. The benchmark case for the simulation is the AeroTRAIN reference case, which has been developed to allow for the design of interoperable trains in the European rail network. The simulation set-up description starts from the benchmark case description, and continues with computational domain and mesh description. Then the solver and motion settings are introduced to conclude the simulation set-up description. In the end of the chapter the results for the benchmark case are commented and visualised for the most interesting phases of the tunnel entry and passage.

4.2.1. AeroTRAIN Benchmark

AeroTRAIN, a collaborative EU project within railway aerodynamics, defines a benchmark case with which comparing a CFD tunnel entry simulation in order to show its accuracy [37]. Given the case inputs, AeroTRAIN assures that a specific value of maximum pressure gradient of the head compression wave recorded at 100 m inside the tunnel must be reached. If that value is reached then the simulation set-up is acceptable at least for the computation of the maximum pressure gradient of the generated head compression wave. If the maximum pressure gradient is accurate then the whole shape of the head compression wave pressure rise is also accurate, so the simulation is valid for this work. Actually the AeroTRAIN benchmark case has not been developed for load simulations but for MPW, but for both MPW and loads on non-tight trains the most important quantity is the maximum pressure gradient, so the AeroTRAIN benchmark is definitely appropriate for this work.

The AeroTRAIN case inputs feature an 11 m$^2$ cross section train travelling at 250 km/h into a 63 m$^2$ cross section tunnel at atmospheric standard conditions. The train has a 4m long nose and its geometry is simplified, as shown in Fig. 4.1.

$$S_tr = 11m^2, b = 3m, L_n = 4m, r = 0.75m, h_0 = 0.25m, h = (S_tr + (4r^2 - \pi r^2)) / b$$

![Fig. 4.1 AeroTRAIN reference case train geometry, [37].](image)

Clearly the train in Fig. 4.1 has an extremely simplified geometry. No geometry input for particulars such as boogies, pantographs, rails and so on is required. This allows for a much easier simulation setup and for a huge reduction in computational effort, thus allowing to carry out dozens of parameter sweeps simulations. The simplicity of the geometry also allowed to draw all the CAD models used in the simulations using the Star CAD editor, without requiring the assistance of the CAD expert. It has to be underlined that if a more complicated geometry had been chosen not only the parameter sweeps would have been more challenging, but also the simulation of the whole tunnel passage would have been very expensive. In the parameter sweeps performed the train cross section has been changed to 9 and 10 m$^2$ always keeping the same ratio between h and b.

The length of the train is not specified on the AeroTRAIN reference case, as it does not influence the generated head compression wave. For this reason a very short train length of 50 m has been chosen in order to reduce the computational effort as much as possible. The nose length is 4 m and the height from the ground is only
25 cm, which will require a small mesh size there. In the parameter sweeps performed the nose length has been changed between 2 and 8 m always keeping the same train length.

The tunnel geometry is shown in Fig. 4.2.

The tunnel cross section is 63 m$^2$. In the parameter sweeps performed the tunnel cross section has been changed between 22 and 93 m$^2$ always keeping the same ratio between H and R (and so the same angle highlighted in red).

Given these inputs for the AeroTRAIN case, a valid simulation of the train entry must predict a maximum pressure gradient recorded at 100 m inside the tunnel equal to 9000 Pa/s with a tolerance of +500 and -250 Pa/s. The tolerance is not symmetric as a higher gradient is conservative and so preferable. It has to be underlined that this 3% tolerance on the time-derivative of pressure recorded 100m after the portal, once the pressure wave has already travelled a long portion of domain at the speed of sound, is quite a strict requirement.

The developed simulation set-up for this work has reached a maximum pressure gradient recorded at 100 m inside the tunnel for the AeroTRAIN reference scenario of 8989 Pa/s, well inside the tolerance required. This result has allowed the validation of the CFD set-up, thus also making up for the absence of experimental data comparison. Besides, simulations with different Rigid Body Motions treatments (overset and sliding mesh, as described in the next section) and different flow formulations (Coupled and Segregated flow, Sections 3.2.3 and 3.2.4) reached the required accuracy with all combinations, so it was possible to assess which combination is preferable.

4.2.2. Computational Domain

The computational domain developed for the single train-tunnel entry simulation of the benchmark case is shown in Fig. 4.3 together with the boundaries names and boundary conditions. This is the computational domain for the overset mesh simulations, which is the technique used for the final set-up. A computational domain has also been developed for the sliding mesh simulations, and it is shown in Fig. 4.4.
In Fig. 4.3 the computational domain at the beginning of the simulation is shown. The train is included in the red box, which represents the moving region (overset mesh). The background region is made of the external domain outside the tunnel (coloured in blue) together with the tunnel. As explained in Section 3.2.2, the overset mesh region is superposed to the background one, and at each time step the train slides towards the right of the figure remaining fixed to the overset (red) region, so a procedure is required to select the active and inactive cells from both layers.

The train length is 50 m, the tunnel length is 500 m, the external domain length is 120 m and the “Mountain” radius is 50 m. It has been found important to leave an empty region behind the train tail to allow for the wake to be included in the computational domain and so to avoid instabilities.

Another procedure to model the train Rigid Body Motion is to use a sliding mesh, as in Fig. 4.4.

The sliding mesh treats the train Rigid Body Motion using an in-place interface. Basically the moving (yellow) region is still fixed with the train and slides through the whole domain, but its interface remains in the same position. By doing so the interface is clean and there is no superposition of cells as compared to the overset mesh, so the accuracy is higher than with the overset mesh.

This approach has been used for a few simulations at the beginning of this work in order to assess whether it was preferable over the overset approach. In the end the overset mesh approach has been chosen first because it allows for much more flexibility in the train motion, as the overset (red) region can intersect walls.
or other overset region (as an example for train crossing). Furthermore the overset mesh does not require the sliding (yellow) region which extends outside the domain effectively wasting many computational cells. The main problems with the overset mesh approach are its set-up, which has been cumbersome at the beginning because the software needs to be able to find donor cells for each acceptor cell at each time step, and the lower accuracy due to interpolation error in the overlap region, which requires a careful study to assess the impact of this further source of error on the results. For the final set-up developed, this error had a very limited impact on the solution accuracy, as also confirmed by the result reached in terms of maximum pressure gradient. It is interesting to note that the AeroTRAIN reference simulation has been developed using a sliding mesh approach, while the simulations used in this work are based on the overset mesh approach, and both approaches grant a sufficiently accurate maximum pressure gradient.

4.2.3. Mesh

The mesh shown in this section is the one developed for the overset mesh approach simulations.

The mesh requirements for this unsteady case are:

1. To be fine enough to resolve the most important flow features, such as the interaction between the moving flow field in front of the train nose and the tunnel portal and the propagation of the pressure waves.
2. To satisfy the CFL requirement for time integration (Section 3.2.3) and the overset mesh time step requirement (Section 3.2.2). The CFL accuracy requirement for the implicit time integration requires the time step to be small enough to let the flow cross not more than one cell each time step. This requirement is extremely stringent, but it helps with the accuracy (not for stability) of the time integration. The overset mesh time step requirement prevents the overset mesh fore and aft boundaries to cover inside a single time step a distance higher than one cell. This corresponds to imposing a CFL equal to 1 computed with the train velocity and mesh size at the interface.
   Both these requirements mean that if a finer mesh is desired, a proportionally smaller time step is needed. It also means that reducing the cell size leaving the time step unchanged might reduce the overall accuracy instead of increasing it, as shown by the mesh convergence study exposed later in this section. This has to be kept in mind both when developing the mesh and when choosing the time step size.
3. To satisfy the log-law $y+$ requirement at the train and tunnel walls for the high-Re wall treatment employed (Section 3.1.3). The all-$y+$ wall treatment used is aimed at first-cell-$y+$ higher than 30 in order not to apply the log-law region in the buffer region and lower than about 300 in order not to apply the log-law outside the logarithmic layer or even outside the boundary layer. The all-$y+$ wall treatment includes the viscous sub-layer velocity distribution, but the error might increase if the first cell $y+$ falls in the buffer region. In order to predict the head pressure wave this requirement must be strictly satisfied on the fore part of the train (around double the nose length) wall in order to simulate the boundary layer growth properly, but it can be slightly unfulfilled for example at the aft train wall, as that only influences friction rise and wake.
4. To avoid a too strong cell size variation across the overset mesh interface, as this would heavily increase the size of the overlap region, potentially causing convergence problems. This happened especially in the wake region, where the turbulent equations would diverge because of a too sudden cell size variation across the overset interface.

The best mesh which could be generated fulfilling all of these requirements in the benchmark case is a 2.2 million trimmed cells mesh and it is shown in the following figures. The size of the mesh in the tunnel and surroundings was 0.25 m; this size will be taken as reference for comparison, and it is named “general size”. The mesh cell count is very limited when compared to transient drag or sidewind simulations because in this case the most stringent requirement turned out to be the time integration one. In order to properly model the propagation of the pressure waves on the 0.25 m cells one needs a time step of about 0.001 s, and given that the tunnel passage takes about 8 s the inner iterations really need to be as quick as possible. If the general size were 0.125 m, the time step size needed would have been 0.0005 s, so the overall computational time
would heavily increase (by a factor of up to 16). Furthermore the very simple smooth train geometry allowed to use also the 0.25 m cell size on most parts of the train without losing too much accuracy.

The overall mesh containing the various refinement regions is shown in Fig. 4.5.

**Fig. 4.5 Overview of the mesh with the various refinement regions.**

The general size of 0.25 m is the one at the tunnel entrance and around the train. The train is not visible, it is included in the red box in Fig. 4.5 lower plot. It is important to note that it is not sufficient to shape the general size region around the tunnel entry, instead it needs to be extended further downstream inside the tunnel (for 70 m) and further upstream outside the tunnel around the overset region in order to avoid too strong cell size variation across the overset interface. It is evident that the trimmed mesh cell size variation is abrupt, as cells can only double their dimensions from one size to the other, and so their volume changes by a factor of 8. For this reason not more than one single coarsening can be performed inside the tunnel, otherwise the pressure wave gets dissipated by truncation errors, so the maximum gradient decreases, which is not acceptable.
The mesh around the train head, which is the most important area of the simulation, is shown in Fig. 4.6.

Fig. 4.6 Mesh around train nose.

The general size of 0.25m is the one which appears for example in the upper right part of Fig. 4.6. On the upper part of the figure one can appreciate that the overlap region is very clean and it is made of one single cell layer, thus reaching the most accurate configuration there. This is possible because of two main factors, first the mesh is a trimmed cell mesh, so the cells have the same shape across the interface, and second the size is the same across the interface (0.25m). Inside the overset regions the mesh gets refined up to three times (getting to a size of 3.125 cm) near the train nose. This gradual refinement is based both on imposing a size of 50% the general size on the train nose and on a further curvature refinement.

Another feature of the mesh are the prismatic layers, which are designed to model the boundary layers reaching the required $y^+$ values. Their values are listed in Tab. 4.2.

<table>
<thead>
<tr>
<th>Wall:</th>
<th>N</th>
<th>$\delta$(cm)</th>
<th>Stretching</th>
<th>$y^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Nose</td>
<td>8</td>
<td>3</td>
<td>1,4</td>
<td>~50</td>
</tr>
<tr>
<td>Train Transition</td>
<td>8</td>
<td>5</td>
<td>1,45</td>
<td>~200</td>
</tr>
<tr>
<td>Train Body</td>
<td>8</td>
<td>10</td>
<td>1,45</td>
<td>&lt;500</td>
</tr>
<tr>
<td>Ground and Tunnel</td>
<td>3</td>
<td>10</td>
<td>1,5</td>
<td>~30 for wave &lt;500 near train</td>
</tr>
</tbody>
</table>

In the first column of Tab. 4.2 one can read the location of the prismatic layer, which can also be visualised in Fig. 4.7. N is the number of prism layers, $\delta$ is the whole prismatic layers thickness, Stretching is the ratio between successive layers, and $y^+$ is reported as an indicative value overall the considered wall at the instant shown in Fig. 4.7. The $y^+$ is very good for the train nose and for the boundary layer of the propagating head pressure wave on the ground and tunnel walls. It gets higher in the transition and train body walls, as the boundary layer there is thicker and would require more layers, but it still remains reasonable. Also it is not too important to accurately model the boundary layer there. On the other hand it is fundamental to check the
absence of sudden boundary layer growth or separation due to too abrupt cell size variations. This can be checked in Fig. 4.7.

In Fig. 4.7 one can both check the y+ distribution and the axial (component parallel to the tunnel) velocity component on the tunnel symmetry plane. The y+ lies around 50 for the train nose wall, it gets higher to about 200 in the transition train wall (immediately behind the nose), and it further increases on the train body up to about 500. Despite these successive increases, when looking at the boundary layer one can check that it grows steadily without too sudden thickness variations. One can also note that in the flow region between the train and the tunnel the flow goes in the opposite direction with respect to the train. Another interesting aspect is that the boundary layer remains very thin around the train nose and at the beginning of the transition wall, so this should reduce the difference in predicted head compression wave between Star and other inviscid methods such as the Howe equations or NUMSTA. The situation might have been different for a real train geometry with the associated flow separations.
Getting back to the requirement of low cell size variation across the overset mesh interface, one can check the evolution of that interface near the tunnel entry in Fig. 4.8.

Fig. 4.8 Mesh evolution at the tunnel entrance for successive instants.

In the upper plot of Fig. 4.8 one can visualise the overset region thanks to the horizontal cutting plane. The boundary of that moving region is very clean and it is made of a single layer of cells, and the cell shape and size does not vary across the interface. At each time step the moving region slides of a distance corresponding to one cell size. When the train nose comes to the tunnel entrance the absence of cell size variations across the overset interface grants the best accuracy in simulating the head compression wave generation. Then the head compression wave travels inside the tunnel at the speed of sound leaving the moving region behind, and as the train continues to enter the tunnel the mesh size remains always constant across the interface in order to grant accuracy for the whole pressure signature generation.
The overset mesh can also handle extreme and unphysical cases, such as a 22 m$^2$ tunnel in Fig. 4.9.

![Fig. 4.9 Overset mesh behaviour for non-realistic 22 m$^2$ tunnel.](image1)

In this case the overset mesh moving region intersects the tunnel wall, so some overset mesh cells become inactive. The overlap region is not as clean as in the previous cases as it is much closer to the train wall, so now it is made of three layers. Even if the area between the train and tunnel is extremely limited in this case, the simulation converged. This case would have been hard to set-up using a sliding mesh with an in-place interface. Anyway the result for this case are not realistic as the tunnel really is too small.

A visualisation of the error introduced by the overlap region interpolation of the overset mesh approach applied at the 22 m$^2$ cross section tunnel is in Fig. 4.10.

![Fig. 4.10 Isobars superposition in overlap region for non-realistic 22 m$^2$ tunnel.](image2)

Looking at the isobars in Fig. 4.10, they do not precisely intersect in the overlap region because of the interpolation error there. An important consideration is that the smaller the overlap region is the smaller the interpolation error is in that area. In order to limit the size of the overlap region the two mesh layers should have the same cell shape and size.

Another visualisation of the errors coming from the overset mesh interpolation in the overlap region, is a case in which the train is not at the centre of the tunnel, but it is shifted towards the wall as if in a double track tunnel, as in Fig. 4.11.
In the situation of Fig. 4.11 the train is close to the tunnel wall, and the mesh size of the tunnel wall and ground mesh is 0.5 m, so double the general size of 0.25 m inside the overset region. The white lines show the boundaries of the overset region. While far front from the train nose the low cell size variation across the interface grants a low interpolation error across the overlap region, below the train nose the cell size variation across the interface is huge, so one can expect an accuracy corresponding to the coarsest size of 0.5 m; this interpolation error can be visualised looking at the distortion of the isobars in that area. That area is extremely critical also because of the extreme skewness of the first layer of cell on the tunnel wall near the edge connecting the wall to the ground. If the train were even closer to the wall a refinement would have been needed in that region, as will be explained in Chapter 5 for the train crossing simulations.

Even if this simulation is validated by the AeroTRAIN requirement on the maximum gradient, a mesh convergence study must be carried out to further verify the result. A limited number of mesh convergence simulations have been carried out and are listed in Tab. 4.3, compared with the benchmark simulation.

**Tab. 4.3 Mesh Convergence study simulations.**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mesh Size</th>
<th>Time Step Size</th>
<th>Maximum Gradient comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>benchmark</td>
<td>0.25 m</td>
<td>0.001 s</td>
<td>8989 Pa/s</td>
</tr>
<tr>
<td>1</td>
<td>20% finer</td>
<td>Unchanged</td>
<td>-1.5% (8854 Pa/s)</td>
</tr>
<tr>
<td>2</td>
<td>20% finer</td>
<td>20% smaller</td>
<td>-0.5% (8944 Pa/s)</td>
</tr>
<tr>
<td>3</td>
<td>No tunnel coarsening</td>
<td>Unchanged</td>
<td>Unchanged</td>
</tr>
</tbody>
</table>

The results from the mesh convergence study confirmed the independence of the main result of the simulation from the mesh size, as changing the mesh size by 20% only changed the maximum gradient of 0.5% when keeping the acoustic CFL number close to one. Simulation 1 in table 4.3 also showed that if one reduces the cell-size leaving the time step unchanged and so increasing the CFL number by 20%, then the accuracy
decreases, as the simulation 1 is further from the benchmark one than simulation 2, so it looks like the main factor for accuracy in the maximum gradient computation is the CFL number. Simulation 3 also showed that the single coarsening in the tunnel 70 m after the entrance does not influence the maximum gradient value. A further simulation with two successive coarsenings inside the tunnel showed both an increased error in the waves propagation and instability problems when the moving region reaches the coarsest one.

Clearly more simulations would have been needed to confirm mesh independence without the AeroTRAIN validation, but considering both the AeroTRAIN validation and the fact that all these three mesh convergence simulations fell within the AeroTRAIN tolerance, the baseline mesh choices are considered sufficiently confirmed.

4.2.4. Solver and Motion settings

The first solver setting is whether to use a coupled or a segregated flow approach (described in Sections 3.2.3 and 3.2.4). The Coupled flow approach requires more memory and it is more computationally expensive as it solves the whole NS system at a time for each iteration, but its increased robustness allows for a higher time step size, while the segregated flow formulation is less computationally expensive as it uses a predictor corrector approach to solve continuity and momentum one at a time. Moreover, the coupled flow inner iterations inside each time step march in pseudo-time, with a different pseudo-time step size for each cell, while the predictor corrector approach used for the segregated flow does not need any dual time technique.

So, the settings needed by the coupled flow formulation are the physical-time step size, number of inner iterations and Courant number for the solver to compute the local pseudo-time step size for each cell, while the setting for the segregated flow are time step size, number of inner iterations for each time step and under-relaxation factors. Both approaches have been implemented and compared in this work, as shown in Tab. 4.4.

<table>
<thead>
<tr>
<th>Simulation:</th>
<th>Δt [s]</th>
<th>N</th>
<th>Cour</th>
<th>URF</th>
<th>Max grad [Pa/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Coupled-Acceptable</td>
<td>0.0075</td>
<td>9</td>
<td>100</td>
<td>/</td>
<td>8800</td>
</tr>
<tr>
<td>2) Coupled-Accurate</td>
<td>0.0037</td>
<td>9</td>
<td>75</td>
<td>/</td>
<td>9040</td>
</tr>
<tr>
<td>3) Segregated-Final</td>
<td>0.001</td>
<td>9</td>
<td>/</td>
<td>p: 0.3 Mom: 0.8 Energ: 0.9 TKE: 0.8 SDR: 1</td>
<td>8989</td>
</tr>
</tbody>
</table>

In Tab. 4.4 some interesting simulation setups are reported. Many more tries have been needed to reach these acceptable setups and to find the best combination of parameters for the coupled flow time integration. The first two simulations in table 4.4 have been carried out with the coupled flow approach. Already with a time-step 0.0075 s an acceptable value of gradient was reached: when comparing the overall number of iterations of this first simulation with the segregated-final one, it is evident that they increase by a factor of 7.5, so even when taking into account that each coupled flow iteration is slower than a segregated one, the overall computational effort was much lower for the coupled flow simulation. However to reach an accurate enough maximum pressure gradient the time-step had to be lowered to 0.0037 s and together with the time step size also the courant number for the pseudo time step size has been reduced as less advancement in pseudo time is needed. The pseudo time step size defines the Cour number, which is the same as the CFL number, but the latter is computed with the physical time step size. The Cour number choice cannot really be justified theoretically, it came from trials and errors: the lack of robust ways to determine the Cour together with the
important impact it has on the results is one of the main factors which discarded the coupled flow approach for this simulation despite the important reduction in computational time.

The second factor against Coupled flow approach for this simulation set-up are instabilities, which frequently arise in coupled flow simulations from minor mesh or motion problems and which would not arise in the same simulation using segregated flow. As an example, many divergence problems came from the turbulence equations which had problems in areas with cell size variations, for example at the overset or sliding mesh regions boundaries. Those problems are much more serious for coupled flow approach simulation because of the higher physical time-step size and probably also because the two turbulence equations are anyway solved after the NS system, so they are not coupled.

Concluding the comparison, these two factors in the end make the segregated flow approach much more robust and easy to set-up, and in the end preferable over the coupled flow approach for this simulation.

All the simulations carried out for this work used a first order accurate implicit time integration scheme and a second order accurate space discretisation. The first order time integration scheme has been preferred over the second order one in order to avoid unphysical oscillations which could take place with higher order integration schemes.

The segregated-final simulation has a quite low time-step of 0.001 s which corresponds to an acoustic CFL (for the physical time-step) close to 1 (computed with the mesh general size of 0.25 m and the speed of sound), thus granting optimal accuracy in the time integration, which is the main source of error for this simulation, as shown by the mesh convergence study (Tab. 4.3). The under-relaxation factors are close to the default ones, they are chosen high enough to grant the quickest convergence possible to each inner iteration while avoiding instabilities. In Tab. 4.4 TKE stands for Turbulent Kinetic Energy and SDR stands for Specific Dissipation Rate, they are the two turbulence equations.

The settings in terms of time-step size, number of inner iterations and URWs must grant a sufficient convergence inside each time-step on the mesh used. This is verified by both the mesh convergence study and by the various tries made when deciding the solver settings, but a further check can be made on the residual decrease inside each time-step.

![Residuals](image)

**Fig. 4.12 Residuals for several time steps.**
As introduced in Section 3.2, while for a transient simulation one usually looks for the maximum residual decrease achievable after as many iterations needed, for an unsteady simulation the residual decrease indicates the convergence inside each time step only, as for each time step the unsteady terms of the NS equations are updated bringing also up the residuals. So for each time step one first looks for a monotonic decrease of all the residuals, which shows the absence of divergence problems. Secondly the number of inner iterations must be not too high in order not to waste computational time, as it is better to have more time steps with fewer inner iterations, and not too low in order to grant a decent residual decrease inside the time step. Looking at Fig. 4.12 one can check that the three momentum equations residuals drop of about two orders of magnitude inside each time step, with most of the dropping placed at the first two iteration of the time step. Continuity residual also shows a monotonic decrease inside each time step, but its decrease is less than one order of magnitude. Energy residual is nearly constant as the problem is adiabatic without any source term in the energy equation. Both turbulence equations residuals also show a monotonic residual decrease followed by a constant region inside each time step in this case. For more problematic cases the two turbulence equations were always the first one to diverge, in which case turbulent viscosity and kinetic energy got limited in the domain in order to try to continue the simulation.

The settings and residual decrease described in this section regard the most important part of the simulation, which is while the train is entering the tunnel and the pressure waves are propagating. Particular care must be taken when setting up the train motion initialisation and first phase of the motion, as one has to avoid generating instabilities and pressure disturbances in that phase while also having the chance to increase the time step in the less interesting part of the simulation, while the train is travelling in open air. The flow is initialised with zero velocity and zero differential pressure everywhere in the domain, which presents only outlets, so the only moving force of the simulation is the train motion. There are a few techniques which help getting the train motion initialisation as smooth as possible, which are listed below in order of importance for this case:

1. **Gradual train velocity increase:** The simulation would not have convergence problems even if the train started at its full speed from the first iteration, but by doing so the train starting would originate extremely strong pressure waves, just as the moving piston in the shock tube in Section 2.1.7, which would keep on propagating in the domain making the simulation completely useless. For this reason the train velocity must be increased as smoothly as possible to let the flow field around the train grow smoothly without generating pressure waves before entering the tunnel.

2. **Frozen Rigid Body Motion:** The problem which arises when smoothly increasing the train velocity is that a very long domain before the tunnel entry would be needed to let the train get to its full speed. A solution to this problem is Star-CCM+ Frozen Rigid Body Motion feature, which allows the train to remain fixed in its initial position while imposing fluxes at the train wall corresponding to the train motion. This generates a flow field around the train which is quite close to the one it would generate if it were moving. So one can set-up an initial phase of the simulation in which the velocity gradually grows and the RBM is frozen, as shown in Tab. 4.5.

3. **Distance from tunnel:** An appropriate distance must be left between the initial position of the train and the tunnel entry, in order to both let the physical flow field a few time to take place after the frozen RBM has been removed and to let the pressure disturbances due to the frozen-normal RBM transition damp out before the train enters the tunnel.

4. **Gradual time step decrease:** The phase of motion initialisation can be carried out using a high time step and a low number of inner iterations, as accuracy is not required in this phase and it is also good to have an increased numerical dissipation in the time integration process that can help damp out pressure disturbances. But the transition from a high time step to a low one should not be imposed in a single time step, as that would generate pressure disturbances, so it has been distributed over about 10 time steps.

The initialisation procedure developed for the tunnel entry simulation includes all of these aspects, and it is described in Tab. 4.5.
Tab. 4.5 Motion Settings.

<table>
<thead>
<tr>
<th>Position from entrance [m]</th>
<th>Time [s]</th>
<th>Motion</th>
<th>Velocity [km/h]</th>
<th>Time step [s]</th>
<th>Inner Iterations</th>
<th>Acoustic CFL ((c_s\Delta t/\Delta x_b))</th>
<th>Train CFL ((V_{tr}\Delta t/\Delta x_b))</th>
<th>Highest CFL ((V_{tr}\Delta t/\Delta x_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0-0.5</td>
<td>Frozen RBM</td>
<td>Linear increase</td>
<td>0.01</td>
<td>6</td>
<td>13.6</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>50</td>
<td>0.5-0.75</td>
<td>&quot;</td>
<td>250</td>
<td>&quot;</td>
<td>&quot;</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>50-25</td>
<td>0.75-1.1</td>
<td>Normal RBM</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.8</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
<td>25-end</td>
<td>1.1-9</td>
<td>&quot;</td>
<td>&quot;</td>
<td>0.001</td>
<td>9</td>
<td>1.36</td>
<td>0.28</td>
<td>2.24</td>
</tr>
</tbody>
</table>

The columns of Tab. 4.5 are position of train nose from tunnel entrance, simulation time, kind of rigid Body Motion modelling, train velocity, time step size, number of inner iterations and three different CFL numbers, which will be introduced later on in this section.

The train initial position is at 50 m from the tunnel entry, and it stays there for the initial 0.75 s of the simulation. The first part of this frozen RBM phase lasts 0.5 s and shows a linear velocity increase from 0 to 250 km/h, and the second one lasts 0.25 s and leaves the flow field established with a constant velocity. At 0.75 s of physical time the frozen RBM turns into normal RBM, so the train starts moving in the domain at that moment, generating a weak pressure disturbance which cannot be avoided. This weak pressure disturbance is difficult to estimate as it tends to remain with the train as long as it reaches the tunnel, so a few simulations with an initial train distance of 100 m from the tunnel have also been performed to evaluate this source of error, which turned out to consist of pressure oscillations of about 20 Pa in the pressure signature initial pressure rise without influence on the maximum pressure gradient, so it looks acceptable.

These initial three phases of the simulation are extremely inexpensive thanks to the high time step size and low number of inner iterations, then at 1.1 s of physical time the time step size drops to 0.001 s and the inner iterations number gets to 9 with a linear variation distributed over 10 time steps. By doing so that the train is moving and the settings are the most accurate ones at 25 m from the tunnel entry.

This complicated motion initialisation procedure has been first tuned with a few initial simulation tries and then saved into a macro which could be run automatically without user assistance, allowing for the parameter sweeps simulations to be carried out in a reasonable time.

The setting are then left unchanged for the whole 500m tunnel crossing (which lasts until about 9 s of physical time) in order to ensure to properly capture the wave propagation. If only the pressure signature is needed then the simulation can be stopped when the train nose reaches the pressure probe at 100 m inside the tunnel.

Looking again at Tab. 4.5, the CFL numbers are always computed as a reference velocity times the time step divided by a cell size, and depending on which values one chooses one can look at the accuracy of the implicit time integration procedure with respect to different flow features. The acoustic CFL is computed using speed of sound and the general size of the mesh \((\Delta x_b=0.25m)\), so it represents the time integration accuracy with respect to the propagation of the pressure waves in the refined region of the tunnel, so it is the most important indication of accuracy for this simulation, and the time step has been kept as low as 0.001 s in order to keep the acoustic CFL close to 1. The train CFL should be lower than 1 to fulfil the overset mesh time step requirement (Section 3.2.2), but the overset mesh algorithm has been capable to handle the 2.8 train CFL at the beginning of the train motion. The most stringent CFL number is the one computed with the train velocity.
and the smallest cell size ($\Delta x = 0.25/8 = 0.03$ m), so it represents the situation of the smallest cells around the train nose. It is higher than one, but not too much, and the time integration accuracy there is less important than for the travelling pressure waves, as the flow there does not change much in time.

Concluding, this set-up has been validated with the TransAERO results and, thanks also to the simplified geometry, it is capable of modelling the whole tunnel passage requiring just a few hours run on a 100 cores cluster.

![Fig. 4.13 Computational domain used for whole tunnel passage simulations.](image)

The whole tunnel passage simulation has been carried out with a computational domain including the outer domain at both tunnel ends (Fig. 4.13) and without coarsened region inside the tunnel in order to properly capture wave propagation. The acoustic CFL close to one has allowed not only to capture the whole pressure time history on the train and in the whole tunnel for this case, but also the MPW (Micro pressure Waves) emission at the tunnel ends.

### 4.2.5. Turbulence modelling and roughness

The areas in which turbulence has a stronger influence in this tunnel entry simulation are, in order of importance:

1. **Boundary layers on tunnel walls and ground:** The boundary layers on those walls have an impact on the flow motion caused by the travelling pressure waves, and they are strongly influenced by those walls roughness. In the end the influence of those boundary layers on the head compression wave has been found negligible, as the wave had only propagated 100m before being measured, but in longer tunnel their influence would be of greater importance.

2. **Boundary layer around train front:** As for the previous point, in this simulation the boundary layer around the nose and underbody is very thin and there is no separation at all, but with real train geometries the boundary layers around the nose and especially the underbody separated flow regions would definitely displace more flow. Anyway this would mainly impact the friction rise, so it is not a concern for simulating the head compression wave.

3. **Boundary layer growth around train body and wake:** Turbulence definitely has a major influence both on the boundary layer thickness around the train body and on the wake separated flow region. Anyway both those regions cannot be properly modelled with a simplified train geometry, as in a realistic train the boundary layer growth would be strongly affected by boogies, pantographs and inter-car gaps. Besides, the focus of these simulations is to model the head compression wave, so this is not a concern.

The $K-\omega$ SST turbulence has been employed in this work, together with a rough wall function for tunnel walls and ground which uses the equivalent sand roughness $K_s$ (Eq. (3.8) in Section 3.1.3).

The value chose for $K_s$, after a literature search and a few simulations tries for a flat plate, is $K_s = 5$ mm, which is representative of a smooth slab track tunnel. Higher $K_s$ values could have been chosen to partially take into
account ballast and rails, but that would not be enough to model a ballast-track tunnel, as the main reason why ballast damps the pressure wave is because of the flow of air into the ballast, which clearly is not modelled by turbulence.

Many tunnel entry simulations have been performed to assess the influence of wall roughness on the pressure signature, which turned out to be very low. It does not look relevant to get into the detailed results of this study, as the influence of roughness was about the same order of magnitude of the influence of the mesh choice, well inside the AeroTRAIN tolerance.

The main trend is that increasing the wall roughness slightly increases the maximum gradient of the head compression wave as recorded at 100m (of about 10 Pa/s), but then the compression wave also gets more damped as it travels, so at 300 m inside the tunnel the maximum gradient is the same for the smooth and the rough tunnel. Of course if the wave propagation had been modelled for a longer tunnel the roughness influence on the travelling pressure wave would be stronger. Furthermore, wall roughness has an influence on the friction rise, which is caused by the resistance to flow by the train and tunnel wall.

![Image](image.png)

**Fig. 4.14 Friction rise at successive positions inside the tunnel. Left: Ks=0. Right: Ks=4 cm.**

In Fig. 4.14 the friction rise part of the pressure signature recorded at successive position into the tunnel is reported. One can visualise that increasing roughness to such a level as 4 cm increases the maximum pressure reached in the pressure signature of about 5-10 Pa because of the higher viscous losses in the tunnel wall boundary layer in the train-tunnel annulus area. The peak of the 50 m chart is due to the train passing the probe, while the 300 m chart should not be considered as it already feels the influence of the tunnel far end portal (at 500 m from the train entry portal).

Concluding, the influence of wall roughness is very low on the pressure signature as the tunnel is very short. In real ballast-track tunnels the main damping of the pressure waves is due to ballast, which anyway cannot be modelled using turbulence, while real slab-track tunnel can be represented by this approach.
4.2.6. Results overview for benchmark case

Now that the simulation set-up has been properly exposed the results of the train entry simulation for the benchmark case can be introduced. The main results are the pressure time histories recorded both on the train wall probe and on tunnel wall probe placed 100 m inside the tunnel, as shown in Fig. 2.5 in Section 2.2.1. Fig. 2.5 is extremely useful as it allows to understand the evolution in time of all the phenomena happening during the tunnel crossing. At this point the main phenomena happening during the tunnel passage should be briefly recalled. As soon as the train nose enters the tunnel it generates a compression wave (Fig. 4.17 Nose entry compression wave generation and Fig. 4.18) which travels into the tunnel (black X Fig. 2.5, Fig. 4.21), while when the tail enters it generates an expansion wave (Fig. 4.22), which immediately hits the train probe (green + in Fig. 2.5). The two waves then reflect at the tunnel end changing sign, travel back into the tunnel and hit the train at 4 s, causing the loads computing which is the ultimate goal of this simulation.

Each of these phases can be visualised looking at 3D images taken directly from Star, as in the following of this section. Actually these images come from huge groups of images saved by Star and which have been edited using Windows Movie Maker to create animations of the whole tunnel passage from different perspectives, thus allowing to very effectively visualise the flow.
1. **Open air flow field around train nose:**

![Image of open air flow field around train nose](image)

**Fig. 4.15 Open air flow field around train nose**

The pressure field around the train in open air, before it reaches the tunnel, shows a stagnation region in front of the nose where the flow is pushed forward with respect to the ground, and a lower pressure around the nose corners where the flow accelerates around the nose. The red box on the ground around the train represents the overset mesh region.

2. **Train pressure disturbance arrives at the tunnel:**

![Image of train pressure disturbance at the tunnel](image)

**Fig. 4.16 Train pressure disturbance arrives at the tunnel**

When the stagnation region of the train reaches the tunnel, the flow is pushed into the tunnel and it is forced to proceed parallel to the tunnel direction, thus originating a planar isobar inside the tunnel. That planar isobar is the head of the nose entry compression wave, and it starts travelling inside the tunnel at the speed of sound as soon as it is generated.
Nose entry compression wave generation:

While the stagnation region in front of the train nose is entering the tunnel, the pressure at the tunnel entry increases, generating the initial part of the nose entry compression wave. It is very important to note that the pressure has already increased considerably at the tunnel entrance, much before the nose actually gets there because of the extension of the stagnation region in front of the train nose (Fig. 4.17 and Fig. 4.18). The main reason why the 1D NUMSTA code cannot correctly predict the rise-time of the head compression wave (Section 4.1), is that it cannot simulate that 3D flow field around and in front of the nose and its upstream influence.

The generation phase of the nose entry compression wave is highly 3D. The stagnation region in front of the train nose pushes air inside the tunnel parallel to the tunnel direction and also around the nose towards the train tail, pushing air out of the tunnel through the tunnel portal, and this results in the isobars corresponding to the stagnation region breaking down in two parts. The fore part of the isobar gets planar as it moves inside the tunnel at the speed of sound, while the aft part connects the train nose with the tunnel wall. The flow in the area around the train nose flows parallel to the pressure gradient in each point from higher pressure areas to lower pressure ones, and so it exits the tunnel through the tunnel portal. The time it takes to the head
compression wave to develop is approximately the time the flow field in front and around the nose takes to enter the tunnel.

4. **Train Body entrance, head compression wave already generated:**

   ![](image1)

   **Fig. 4.19 Train Body entrance**

After the train nose has entered the tunnel generating the head compression wave, a high pressure region in front of the train takes place and pushes air inside the tunnel towards the tunnel far end. The flow in the train-tunnel annulus area goes in the direction opposite to the train, exiting the tunnel through the tunnel portal and generating a vortex around the portal corner. This happens because the nose of the train pushes air through the tunnel, so the pressure in front of the nose is higher, so some portion of air will also travel backwards with respect to the train. The pressure in front of the nose keeps on rising while the train is entering the tunnel as the train tunnel annulus becomes increasingly longer, so an increasing pressure drop is needed to keep on pushing air through it. The amount of friction pressure rise heavily depends on the boundary layer developing around the train, and so on the train geometry and roughness. It also depends on the boundary layer on the tunnel wall, which is anyway much weaker than the one around the train, as the flow velocity is much lower with respect to the tunnel wall than to the train wall.

   ![](image2)

   **Fig. 4.20 Higher pressure region in front of the train nose**

Looking from the train side forward (Fig. 4.20) one can see the high pressure region in front of the train nose which ends with the travelling nose entry compression wave travelling towards the tunnel end.
It is important to underline that at this point the train pressure probe still has not recorded any pressure variation due to travelling pressure waves, even if the train nose has already entered the tunnel, like at a physical time of 2 s in Fig. 2.5.

By looking at the pressure inside the tunnel (Fig. 4.21), one can visualise the high pressure region in front of the train nose. The nose entry compression wave is at 160 m inside the tunnel and it is travelling at the speed of sound at this moment, while the train nose is at approximately 30 m inside the tunnel, so its pressure variation is also travelling at the train velocity. It is relevant to note that the nose entry compression wave is about 80 m wide at this moment, which is even more than the train length. This means that its rise time is about 0.24 s (80m/340m/s). Looking at the pressure drop located at the train nose, which has the same magnitude of the head compression wave, it is about 10 meters wide, corresponding to a rise-time of about 0.14 s (10m/250km/h), so it would look more intense than the head compression wave to a stationary observer.

5. Tail wave generation:

While the train tail enters the tunnel it generates the tail expansion wave, which also travels inside the tunnel at the speed of sound. The tail pressure wave is actually the first travelling pressure wave recorded by the probe on the train, so it is also the first one felt by the passengers, at a physical time of 2.25 s in Fig. 2.5. An
important consideration is that the tail entry wave is always consistently weaker than the nose entry wave because of the wake and of the air pushed forward as the tail enters.

6. Situation after tail wave generation and before reflections:

After the tail wave has passed the train, it keeps on travelling into the tunnel at the speed of sound. It can be visualised as the tail of the yellow high pressure region in Fig. 4.23. The yellow high pressure region in Fig. 4.23 can also be visualised in the pressure distribution along the tunnel in Fig. 4.24.

7. Loads on the train resulting from the described pressure time history:

Describing the pressure time history in the tunnel has been useful to introduce the phenomena happening, but the main result from this simulation is the load on the train. As already introduced in Section 2.3.2, several ways to compute the pressure loads on the train walls have been set-up. The loads in Fig. 4.25 have been
computed with the simplest approach, the “Point τ” one, in which the internal pressure time history is directly computed by the external one as recorded by a point probe on the train wall. The more accurate model which also takes into account the carriage free length will be used in Section 4.6.

Fig. 4.25 External and internal pressures and load time histories, whole tunnel passage, τ=0.3 s.

One can see in Fig. 4.25 that the internal pressure follows the external one quite quickly, as the carriage pressure tightness is low and the time constant is 0.3 s; this is the case of a non-tight train. The first pressure variation felt at the train wall is the pressure drop due to the tail expansion wave reaching the train pressure probe, showing a magnitude of about 1200 Pa. The internal pressure decreases following the external one with a delay, and the difference between the external and the internal pressure is the pressure load on the train wall. The maximum load arrives at about half the external pressure drop, at about the same moment when the maximum pressure gradient is reached, and that load is about -650 Pa. Looking at the internal pressure time history, in the 4 seconds interval between 2 s and 6 s it varies of about 5000 Pa (taking the absolute values of variations): looking at Tab. 2.2 in Section 2.3.3 the passenger comfort limit of 3000 Pa variation in a 4 seconds time interval is definitely unsatisfied, so a pressure sealing system would be needed on this train to cross the 63 m² tunnel at 250 km/h.

Looking then at the later pressure oscillations in Fig. 4.25, one can see the reflected nose entry wave as the pressure drop at 4 s of physical time. The maximum load due to that pressure wave is about -800 Pa, so it is definitely stronger than the one from the expansion wave. The strongest load felt by the train walls during the tunnel crossing happens anyway at 6.5 s thanks to the superposition of both head and tail entry waves as expansion waves; this shows that the problem of computing the loads from a generic tunnel passage is complex, as one does not know a priori which wave combination will give the maximum load.

The influence of τ on the load time history is clearly very strong. If a carriage has a lower τ, then its internal pressure will follow the external one much more quickly, so the loads will be much lower, as shown in Fig. 4.26 for a τ value of 0.1 s.
Comparing the $\tau=0.1$ s load time history with the $\tau=0.3$ s one, it can be underlined that not only the loads are much lower everywhere, as expected, but also the location of the maximum load is different. This shows the importance of computing the right internal pressure for the load prediction. The maximum load (excluding the one at the tunnel exit, which feels the influence of the train portal) for the $0.1$ s $\tau$ case is -503 Pa, about half the maximum one for a $\tau$ of 0.3 s.

It is important to note that for both the cases in Fig. 4.25 and Fig. 4.26 the maximum load happens at a reflection of the nose entry compression wave, which is the strongest one.

The oscillatory loads resulting from the tunnel passage are important to dimension the train wall structure both for the maximum load sustainable and for the fatigue load. With regards to the maximum load one can be fairly sure that it will come from a nose entry reflection, but one cannot know a priori how much the wave has damped before reaching the train and whether it will superpose with the other wave. For what concerns fatigue loads, all the tunnels met by the train in its lifetime should be considered to estimate the overall fatigue life of the structure.

For these reasons it is not clever to compute the load for a specific tunnel passage as in Fig. 4.25 and Fig. 4.26, as this way is not general enough to cover all the situations the train could encounter. Being the problem more complex one needs instead to know what happens to the maximum load for different tunnels, velocities, carriage free lengths and so on.

In the following of this work the loads are computed the pressure signature as recorded at 100 m inside the tunnel. This simplifies the problem a lot, as by doing so one can avoid looking at the wave propagation and reflection, and it is conservative, as usually the pressure waves get damped as they propagate inside the tunnel. Clearly this is an approximation of the real problem, first because when the pressure signature meets the train its amplitude varies because of the change in flow cross sectional area between the empty tunnel and the train-tunnel annulus (Eq. (2.24), Section 2.2.3), and then because one should also take into account the relative velocity between the train and the wave, which also depends on the direction in which the wave is travelling. Using the head compression wave recorded at 100 m is also quite accurate in terms of non-linear steepening effect, as in a real tunnel the generated head compression wave would travel along the tunnel getting steeper and then get back to the train getting again about as wide as it was at the generation, neglecting the damping due to ballast and unsteady friction.
For realistic load calculation then, the pressure signature as recorded at 100 m can be given in input to a specific tool (the “load tool”) that manipulates it to take into account the wave propagation and damping as well as the particular case needed in

The main goal of this thesis is to accurately compute the generated head compression wave, which can then be given in input to the load tool. Only in order to assess the impact of the computed head compression waves on the load for non-tight trains the pressure signature as recorded at 100 m has been used to compute the loads without taking into account the wave propagation, train blockage effect, and relative velocity, which will then be taken into account by load tool.

Looking at the loads computed using the pressure signature as recorded at 100 m, the maximum load is the one coming from the nose entry head compression wave, as shown in Fig. 4.27.

![Fig. 4.27 Loads computed using the nose entry compression wave as recorded at 100 m inside the tunnel.](image)

The red chart in Fig. 4.27 is the head compression wave pressure time history as recorded by a stationary probe at 100m inside the tunnel. When that pressure is used to compute the load through a *Point* $\tau$ model with a $\tau$ value of 0.1 s, the resulting maximum load is 541.8 Pa.

With regards to the tail expansion wave, it is always weaker than the head compression one, as shown in Fig. 4.28.

![Fig. 4.28 Nose and tail entry waves comparison.](image)
The tail entry wave recorded at 100 m inside the tunnel is an expansion wave, so its absolute value has been plotted in Fig. 4.28 to allow the comparison with the head compression one. In this case the tail expansion wave shows 20% less amplitude and 18% less maximum gradient, which result in a 19% lower maximum load.

Another key advantage of using the nose entry compression wave as recorded at 100 m inside the tunnel to compute the loads is that, having that wave quite a simple shape in time (Fig. 4.27), it can be fitted. Fitting that wave means developing a quick mathematical procedure which employs the results from CFD parameter sweeps simulations to predict the shape of the nose entry compression wave time history for different combinations of parameters such as train velocity and train and tunnel shape. This fitting procedure will be introduced in the following section.
4.3. Fitting procedure for head compression wave

As introduced at the end of the last section, the goal of the fitting procedure is to find a quick mathematical procedure to predict the pressure time history measured at 100 m inside the tunnel for any physical combination of train velocity \( (V_{tr}) \), train \( (S_{tr}) \) and tunnel \( (S_{tu}) \) cross section, nose length \( (L_N) \) and track spacing \( (2L_{ax}) \); these five quantities are named free variable, as they are the inputs which define the case analysed. The fitting procedure is based on both CFD parameter sweeps results and theoretical equations, and the resulting pressure time history have been used to compute the pressure loads on the train. The resulting load does not take into account the wave propagation and the train blockage effect, but by comparing the CFD loads with the ones coming from the fitting one can assess the fitting procedure accuracy. Another useful output of the fitting procedure is the head compression wave rise-time, which can be used to improve the one predicted by the 1D NUMSTA code.

The fitting procedure inputs are the five free variables, the outputs are the pressure and pressure gradient time histories at 100 m, and the procedure can be divided in two parts, as shown in Fig. 4.29.

\[
\Delta p_N = \frac{\rho V_{tr}^2}{2} \frac{1 - (1 - B)^2}{(1 - M)[1 + (1 - B)^2]}
\]

\[
\frac{\partial p}{\partial t}_{\text{max}} = \frac{\Delta p_N}{\Delta t}; \quad \Delta t = \frac{L}{V_{tr}}; \quad L = f(d_h, d_{\text{train}}, L_N, L_{ax})
\]

The first part of the fitting procedure uses the five free variables input to determine the pressure drop across the head compression wave \( (\Delta p_N) \) and the maximum pressure gradient. The rise-time of the head compression wave is also computed. The second part of the procedure takes the pressure drop across the head compression wave and the maximum gradient and uses them to shape an arctangent profile for the pressure time history. The choice of an arctangent profile comes from the literature and it has been justified by comparing it to the CFD one. At this point the main outputs, namely the pressure time history and the gradient time history, have been computed, so they can be used for example to compute the pressure load on the train wall.

It is important to note that the fitting procedure has been tuned using the CFD parameters sweeps results simulations, which will be introduced in Section 4.4. Both the characteristic length used for the maximum pressure gradient estimate and the shaping procedure have been developed to bring the fitting results as close as possible to the Star ones, so this section will be concluded with a comparison of CFD and fitting results for the benchmark case in order to assess the level of error associated with the fitting procedure.

The following two sections of this section describe respectively the pressure drop and maximum gradient estimation procedure and the arctangent shaping procedure.
4.3.1. Pressure drop and maximum gradient estimates procedure.

This procedure takes as input the five free variables which define the case and has the goal to find the pressure drop \( \Delta p_N \) across the head compression wave and the maximum gradient, which will then be given to the shaping procedure to find the pressure time history. \( \Delta p_N \) and the maximum gradient have been chosen as parameters used to shape the pressure time history as they are the most influent ones on the maximum pressure load. For example, one could have used the rise-time \( \Delta t \) of the head compression wave and the overall pressure drop, but the result would have been worse, as the maximum load for non-tight trains mostly depends on the maximum pressure gradient across the head compression wave.

The first step of this procedure is to determine the overall pressure drop \( \Delta p_N \) across the head compression wave. In order to do so Eq. (2.16), which has been introduced in Section 2.2.2 and is also reported in Fig. 4.29, has been used.

\[
\Delta p_N = \frac{\rho V_{tr}^2}{2} \frac{1 - (1 - B)^2}{(1 - M)[M + (1 - B)^2]};
\]  

(2.16)

In Eq. (2.16) \( B \) is the blockage ratio, which is the ratio between train and tunnel cross section, and \( M \) is the train Mach number. It is interesting to note that this very simple formula coming from inviscid compressible quasi-1D flow analysis already gives a result close enough to the Star one for the pressure drop across the head compression wave. This can be justified as the boundary layer is usually very thin and well behaved around the train nose (Fig. 4.7).

The second part of the estimation procedure is to estimate the maximum pressure gradient of the head compression wave. In order to do so, the overall pressure drop across the head compression wave (from Eq. (2.16)) is divided by a characteristic time, which is computed as a characteristic length divided by the train velocity, as in Eq. (2.20) (from Section 2.2.2).

\[
\frac{\partial p}{\partial t}_{\text{max}} = \frac{\Delta p_N}{\Delta t}; \quad \Delta t = \frac{L}{V_{tr}}
\]  

(2.20)

Looking at Eq. (2.20) one can realise that it corresponds to defining the characteristic time \( \Delta t \) for the head compression wave as the ratio between the nose entry compression wave magnitude and the maximum pressure gradient, so the actual rise time of the head compression wave will be higher than the characteristic time \( \Delta t \). This is also the reason why the proportionality coefficient in Eq. (4.5) is higher than 1 (equal to 1.49).

By employing Eq. (2.20), one includes the influence of train velocity on the maximum pressure gradient. If the train velocity is higher, then the time it takes for the pressure field around the train nose to enter the tunnel must be lower (proportionally to \( V_{tr} \)), while the overall pressure drop across the head compression wave would be higher (proportionally to \( V_{tr}^2 \)); then, being the maximum pressure gradient proportional to the ratio of those two quantities, in the end the maximum pressure gradient is proportional to the third power of the train velocity.

While the influence of velocity on the characteristic time \( \Delta t \) is very well modelled by the simple Eq. (2.20), an analytical expression for the other four free variables influence on \( \Delta t \) could not be found, so those variables influence on \( \Delta t \) is modelled through the characteristic length, as in Eq. (4.1).

\[
L = L_{\text{bench}} + c_{dh} \Delta (d_h - d_{h,\text{train}}) + c_{Ln} \Delta L_n + c_{Lax} \Delta L_{ax};
\]

\[
\begin{align*}
\Delta X &= X - X_{\text{bench}} \\
L_{\text{bench}} &= 10.61 \text{ m} \\
c_{dh} &= 1.2 \\
c_{Ln} &= 0.6 \\
c_{Lax} &= -0.85
\end{align*}
\]  

(4.1)

This formulation for the characteristic length allows to take into account the influence of train and tunnel cross section, nose length and track spacing using the results from the Star parameter sweeps variations simulations.
In Eq. (4.2) \( d_h \) is the tunnel hydraulic diameter while \( d_{h_{\text{train}}} \) is the train hydraulic diameter, \( L_N \) is the train nose length and \( L_{ax} \) is half the track spacing. \( L_{bench} \) is the length which allows to precisely fit the benchmark case maximum gradient of 8989 Pa/s, so for the benchmark case the second, third and fourth terms of \( L \) are equal to zero, as they are formulated through their difference from the benchmark case \( (\Delta X = X - X_{bench}) \). When one of the free variables \( d_h, d_{h_{\text{train}}}, L_N, L_{ax} \) has a value different from the benchmark one then its term is different from zero, allowing to model the influence of that variable on the maximum gradient. This formulation will be further justified looking at the parameters sweeps results, which will also give the coefficients \( c_{dh}, c_{ln}, c_{Lax} \) values and quantify the error coming from the whole fitting procedure. It must be pointed out that, while Eq. (2.20) comes from literature [8] advises to use it with an \( L \) proportional to the tunnel diameter only), the characteristic length formulation (Eq. (4.1)) is an arbitrary extension of Eq. (2.20) in order to take more parameters into account.

At this point the pressure drop and maximum gradient estimates procedure is complete, and the two main outputs can be sent to the pressure time history shaping procedure.

### 4.3.2. Pressure time history shaping procedure.

The goal of the pressure history shaping procedure is to find an arctangent profile for the pressure time history which satisfies the pressure drop across the head compression wave and the maximum gradient. In order to do so, a generic arctangent profile is taken as in Eq. (4.2).

\[
p(t) = c_0 + c_1\arctan(c_2t)
\]  

(4.2)

The choice of an arctangent profile comes from empirical estimates of the Shinkansen train head compression waves found in the literature, and its accuracy can be checked in Fig. 4.30, Fig. 4.31 and Fig. 4.32. In particular, according to [43], the arctan shape for the head compression wave has been suggested by Yamamoto [42].

This generic arctangent profile gives three free coefficients which one can choose to satisfy three constraints. Many constraints combinations can be used to fit the head pressure gradient, but the most accurate combination found is reported in Tab. 4.6.

<table>
<thead>
<tr>
<th>#</th>
<th>Time</th>
<th>Constraint</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( t_1 = 0 )</td>
<td>( \frac{\Delta p}{\Delta t} ) max</td>
<td>( c_1 * c_2 = \frac{\Delta p}{\Delta t} ) max</td>
</tr>
<tr>
<td>2</td>
<td>( t_2 = c_{t_2} * \Delta t )</td>
<td>( \Delta p_N )</td>
<td>( c_0 + c_1 \arctan(c_2t_2) = p_{max} )</td>
</tr>
<tr>
<td>3</td>
<td>( t_3 = c_{t_3} * \Delta t )</td>
<td>0</td>
<td>( c_0 + c_1 \arctan(c_2t_3) = 0 )</td>
</tr>
</tbody>
</table>

The first constraint imposed to the pressure time history is the value of its maximum time derivative, at \( t_1 = 0 \). The second and third constraints represent respectively the points in which the maximum pressure should be reached (the maximum pressure is \( \Delta p_N \)), and the point at which the pressure should be zero. The three constraints together form a non-linear system of three equations in the three variables \( c_0, c_1 \), and \( c_2 \) which can be quickly solved using the “fsolve” MATLAB function, thus obtaining the three coefficients needed for the arctangent profile in Eq. (4.2).

The last two constraints points are reached at the instants \( t_2 \) (which is positive) and \( t_3 \) (which is negative), and by looking at Fig. 4.30 and Fig. 4.31, one can realise that they generate a discontinuity in the pressure derivative and that before \( t_3 \) the pressure is equal to zero, and after \( t_2 \) the pressure remains equal to \( \Delta p_N \), so the instants \( t_2 \) and \( t_3 \) are the ones in which the arctangent profile is truncated. The points in which the arctangent profile gets truncated influence the load time history, so they have been chosen to bring the loads from the fitting procedure as close as possible to the CFD ones, as shown in Fig. 4.32.
The time instants $t_2$ and $t_3$ are specified through the coefficients $c_{t_2}$ and $c_{t_3}$ times the characteristic time $\Delta t$ from Eq. (2.20): by doing so, after having chosen and fixed $c_{t_2}$ and $c_{t_3}$ for the benchmark case, $t_2$ and $t_3$ automatically adapt to the variations of rise-time from all the five free variables. This will be shown in the parameter sweeps results Section 4.4.

The choice of $c_{t_2}$ and $c_{t_3}$ is as in Eq. (4.3).

\[
\begin{align*}
  c_{t_2} &= \left( \frac{t_2}{\Delta t} \right)_{\text{bench}} = \frac{0.1 \text{s}}{0.1528 \text{s}} = 0.6545 \\
  c_{t_3} &= \left( \frac{t_3}{\Delta t} \right)_{\text{bench}} = \frac{0.275 \text{s}}{0.1528 \text{s}} = -1.800
\end{align*}
\]  

(4.3)

$c_{t_2}$ and $c_{t_3}$ have been fixed by simply choosing their values for the benchmark case in order to match the maximum load. One can check in Fig. 4.30 and Fig. 4.31 that $t_2$ and $t_3$ are respectively +0.1 s and -0.275 s for the benchmark case.

At this point the pressure time history is defined by Eq. (4.4), and the pressure gradient can be analytically computed as.

\[
\frac{\partial p}{\partial t}(t) = c_1 \frac{c_2}{1 + (c_2 t)^2}; \quad t_3 < t < t_2
\]  

(4.4)

With the gradient time history the fitting procedure is complete. Now the results from fitting procedure can be compared with the ones from CFD in terms of pressure time history, pressure gradient time history and load time history for the benchmark case.

**4.3.3. Comparison of CFD and fitting results for benchmark case.**

The main result from the fitting procedure is the pressure time history, which can be compared with the one from Star in Fig. 4.30.

![Fig. 4.30 CFD vs Fitting comparison: pressure time histories at 100 m.](image)

In Fig. 4.30 one can first note that the maximum pressure reached is close to the one from Star (it is slightly conservative). If one needed a maximum pressure close to the Star one a formulation such as Eq. (2.18) could easily be used instead of Eq. (2.16) for the maximum pressure.
The second feature one can appreciate is that the central part of the pressure rise is very closely matched thanks to imposing the maximum gradient value as input to the shaping procedure. This is very important, as the maximum load is mainly due to this area of the pressure rise for non-tight trains.

The last feature one can appreciate is that before t3 the pressure is constantly equal to zero, while after t2 the pressure is constantly equal to $\Delta p_N$. Actually this last area is not physical, as one should attach a fitting of the pressure rise after t2 in order to fit the pressure signature, but this is not a goal of this work.

Overall, the pressure predicted using the fitting procedure is quite close to the one simulated by Star for the benchmark case, so one can expect that also the loads will not be much different. Of course some error is introduced by the fitting procedure, especially near the instants t2 and t3. Furthermore, the error introduced by the fitting procedure, which is quite low for the benchmark case in Fig. 4.30, will increase up to about 8% in terms of maximum gradient for the parameters sweeps, because of the error introduced by the fitting of the characteristic length in Eq. (4.1). The fitting error will be quantified in Section 4.4.

![Fig. 4.31 CFD vs Fitting comparison: pressure gradients time histories.](image)

Looking at the comparison of the CFD and fitted pressure gradients time history in Fig. 4.31, one can first note that the maximum gradient is precisely the same, as this is the benchmark case and the $L_{bench}$ term in Eq. (4.1) grants to match the maximum gradient for this case. What changes between the fitted and the CFD gradients time histories is the shape, as, while the arctangent gradient is precisely symmetrical with respect to t=0 (see Eq. (4.2)), the CFD gradient has a steeper decrease and a more gradual increase. This is probably due to the nose shape considered, and can be quantified noting that the value of 1000 Pa/s is reached at -0.15 s and +0.1 s. The asymmetry of CFD gradient generates a noticeable error in the arctangent-fitted pressure gradient time history, so choosing the location of t2 and t3 has played an important role in the accuracy of load computation from the fitting procedure, as shown in Fig. 4.32.
The t3 point could be placed fairly upstream (-0.275 s) of the maximum gradient point, as the CFD and arctangent gradients are quite close in that region, so the CFD and fitted loads in that region are also very close one another.

The maximum load is then reached shortly afterwards the maximum gradient point. With the lowest value of \( \tau \) (0.1 s), the maximum load is 543.8 Pa and it is reached at 0.05 s both for the CFD and fitted loads, so the error from the gradient time history is not felt, as the maximum load is reached much before the truncation point of the maximum gradient at 0.1 s. When \( \tau \) increases up to 0.5 s, instead, the maximum load is reached later, as it takes more to the internal pressure to reach the external one, and so the value of pressure acquires more importance for the load and it is not anymore only the maximum pressure gradient which counts. For this reason the maximum load for a \( \tau \) of 0.5 s is reached at 0.075 s when using the CFD pressure, while it is reached at the t2 point at 0.1 s (where the gradient is truncated) when using the fitted pressure. For this reason the t2 point could have been placed sooner, at about 0.08 s, but in that case the \( \Delta p_N \) would also have needed to be increased to fit the pressure time history, thus requiring a different formulation than Eq. (2.16). So t2 has been chosen at 0.1 s, thus also keep the fitting procedure slightly conservative for the benchmark case. Also the choice of t2 would depend on how the friction rise would be modelled and connected to the head entry compression wave, which is not part of this work.

Another conclusion which can be drawn from Fig. 4.31 and Fig. 4.32 is that the arctangent shape for the pressure time history as recorded 100 m inside the tunnel is consistent with the Star one for the case considered. This can be visualised for example in how close the pressure gradient time histories are in Fig. 4.31, and it is also interesting to note that the NUMSTA area distribution is not able to reach such an accurate result (Fig. 4.51 in Section 4.5.2).

Concluding, the error of the fitting procedure when computing loads increases with increasing pressure tightness of the carriage, but when considering the usual range of \( \tau \) values for non-tight trains, which can be between 0.1 s and 0.5 s, the error in terms of load remains lower than 5% for the benchmark case, and the fitted loads are always conservative for any \( \tau \) value.

Clearly this error has to be summed with the one from the interpolation of the characteristic length in Eq. (4.1) in case of free variables variations, which will be quantified in the following section.
4.4. Star parameters sweeps simulations results

The goal of the Star Parameters sweeps is first to assess the influence of their variation on the main results, which are the pressure increase across the head compression wave, the maximum gradient of the head compression wave, and the load computed using the external pressure as recorded at 100 m inside the tunnel using a Point $\tau$ model with a $\tau$ of 0.2 s, corresponding to a non-tight train. The second goal of the parameter sweep is to assess the performance of the fitting procedure introduced in the last section by comparing the fitted pressure and pressure gradient time histories with the CFD ones.

In order to reach these goals, more than 17 Star runs have been performed to record the pressure signature at 100 m inside the tunnel. This has been possible thanks to the simplified geometry used in the simulations, which allowed reasonable simulation times, and also thanks to the fully automated procedure developed using macros and start files. For each run the user only had to set-up the case before the simulation and to open the finished simulation checking the convergence and saving the pressure signature. Each pressure signature was then processed using Matlab to compute the gradient and load and perform the fitting. The Star runs variables combinations are reported in Tab. 4.7.

Tab. 4.7 Star Variables Sweeps overview. Benchmark values underlined.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ [km/h]</td>
<td>150, 200, 225, 250, 275</td>
</tr>
<tr>
<td>$S_{tu}$ [m$^2$]</td>
<td>37, 50.4, 63, 75.6, 93.1</td>
</tr>
<tr>
<td>$S_{tr}$ [m$^2$]</td>
<td>11, 10, 9</td>
</tr>
<tr>
<td>$L_n$ [m]</td>
<td>2, 4, 5, 8</td>
</tr>
<tr>
<td>$L_{ax}$ [m]</td>
<td>0, 1.5 ($S_{tu} 93.1$), 1.5 ($S_{tu} 63$), 3 ($S_{tu} 93.1$)</td>
</tr>
</tbody>
</table>

The first sweep is the velocity one, which is composed of four simulations plus the benchmark one (underlined values in Tab. 4.7). After that, two separate sweeps have been performed for train and tunnel cross section, which respectively vary between 37 and 93.1 m$^2$ for the tunnel cross section and between 9 and 11 m$^2$ for the train. A nose length sweep has also been performed ranging from a nose length of 2 m to 8 m. The last sweep is the track spacing, in which $L_{ax}$ is the distance between tunnel symmetry plane and track symmetry plane and so it corresponds to half the track spacing.

4.4.1. Velocity sweep

The velocity sweep is made of Star runs from 150 km/h to 275 km/h, leaving the other free variables at the benchmark value.

Tab. 4.8 Velocity sweep-fitting.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
<th>Other variables</th>
<th>Coefficient</th>
<th>Error on $\frac{dp}{dt}$ max $\tau = 0.2$ s</th>
<th>Error on max load $\tau = 0.2$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ [km/h]</td>
<td>150, 200, 225, 250, 275</td>
<td>$S_{tu} = 63$ m$^2$; $S_{tr} = 11$ m$^2$; $L_n = 4$; $L_{ax} = 0$</td>
<td>$L_{bench} = 10.61$ m</td>
<td>1%</td>
<td>2%</td>
</tr>
</tbody>
</table>
With regard to the fitting procedure, the velocity is analytically included in Eq. (2.16) and Eq. (2.20), so no coefficient had to be tuned for this sweep. The sweep allowed anyway to evaluate the accuracy of the fitting procedure for the benchmark case, thus confirming the dependence on train velocity in Eq. (2.16) and Eq. (2.20) as well as the accuracy of the $L_{bench}$ value for different values of velocity. Being the velocity included analytically in Eq. (2.20), the error on the maximum gradient is extremely low (less than 1%) for all the tested values of velocity. The error on the load is slightly higher due to the conservative choice in term of t3 (see Section 4.3.3). The fitted pressure time history have not been reported in the following figures for this sweep as they were very close to the CFD ones.

With regards to the CFD results for the velocity sweep, they are reported in Tab. 4.9.

### Tab. 4.9 Velocity sweep-CFD results.

<table>
<thead>
<tr>
<th>Case</th>
<th>CFD Δ$p$ [Pa]</th>
<th>CFD max. Grad. [Pa/s]</th>
<th>CFD max load $\tau=0.2$ s [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>1311</td>
<td>9000</td>
<td>738</td>
</tr>
<tr>
<td>V=275 km/h</td>
<td>1612</td>
<td>12000</td>
<td>921</td>
</tr>
<tr>
<td>V=150 km/h</td>
<td>469</td>
<td>1960</td>
<td>215</td>
</tr>
</tbody>
</table>

Increasing the train velocity increases the pressure drop across the head compression wave proportionally to the square power of velocity, while it decreases the rise-time proportionally to the velocity, so it increases the maximum pressure gradient across the head compression wave with the third power of train velocity.

For this reason an increase of only 25 km/h in velocity (from 250 to 275 km/h) causes the maximum pressure to increase of 23%, the gradient to increase of 33%, and the load to increase by 25%.

![Pressure Time history at 100m from tunnel entrance.](image)

**Fig. 4.33 Pressure time history - velocity sweep.**

In Fig. 4.33 one can first appreciate the increase in maximum pressure drop across the head compression wave, and then also the influence of the velocity on the rise-time.

Also, looking at the friction rise part of the pressure signature, one can see that it is quicker and more powerful for higher velocity, as the train takes less time to enter the tunnel and the friction losses are higher.
In Fig. 4.34 it is evident how strongly the velocity influences the maximum pressure gradient. Given that this influence goes with the third power of velocity, it is maximum for higher velocity values. In particular, comparing the maximum and minimum gradients of the sweep, they differ by a factor of 6 for velocity values differing a factor less than 2. One can also note that the rise time reduces as the velocity increases.

The loads time histories also follow the overall trend of strong increase for higher velocity. In particular, comparing the maximum and minimum loads of the sweep, they differ by a factor of more than 4 for velocity values differing a factor less than 2.

The main conclusion is that the velocity has an extremely strong influence on each of the three outputs considered, and this underlines that the train structure obviously has to be properly dimensioned for the train velocity.
4.4.2. Tunnel cross section sweep

The tunnel cross section sweep has been executed with four cross sections plus the benchmark one, ranging from 37 m$^2$ to 93.1 m$^2$, as visualised in Fig. 4.36.

Each case has required a dedicated geometry and mesh, but the numerical settings have been kept unchanged. A 22 m$^2$ cross sectional tunnel has also been performed and it did converge despite the challenges posed to the overset mesh as shown in Fig. 4.9 and Fig. 4.10, but it has not been included in the parametric study.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
<th>Other variables</th>
<th>Coefficient</th>
<th>Error on $\frac{dp}{dt}$ max</th>
<th>Error on max load $\tau = 0.2 , s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{sw}$ [m$^2$]</td>
<td>37, 50.4, 63, 75.6, 93.1</td>
<td>$V_{tr} = 250 , km/h; S_{tr} = 11 , m^2; L_n = 4; L_{ax} = 0$</td>
<td>$c_{dh} = 1.2$</td>
<td>2%</td>
<td>4%</td>
</tr>
</tbody>
</table>

The tunnel cross section sweep allowed to determine the $c_{dh}$ coefficient in Eq. (4.1) and also to assess the error on the maximum gradient estimate (Eq. (4.1)). The five cases have been interpolated with a $c_{dh}$ coefficient of 1.2, resulting in an error on the maximum gradient lower than 2%, as also shown in Fig. 4.38. The characteristic length L in Eq. (4.1) is given by Eq. (4.3) for the tunnel cross section sweep.
\[ L = L_{\text{bench}} + c_{dh}\Delta(d_h - d_{h,\text{train}}) \]  

(4.3)

So for increasing tunnel cross section \( L \) increases proportionally to the variation of the hydraulic diameter of the tunnel, as the train hydraulic diameter is fixed. For varying tunnel and train hydraulic diameters, the characteristic length would instead be proportional to the variation of the difference between the two diameters.

**Tab. 4.11 Tunnel cross section sweep- CFD results.**

<table>
<thead>
<tr>
<th>Case</th>
<th>CFD ( \Delta p_N ) [Pa]</th>
<th>CFD max. Grad. [Pa/s]</th>
<th>CFD max load, ( \tau=0.2 ) s [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>1311</td>
<td>9000</td>
<td>738</td>
</tr>
<tr>
<td>Stu=93 m(^2)</td>
<td>829</td>
<td>4684</td>
<td>438</td>
</tr>
<tr>
<td>Stu=37 m(^2)</td>
<td>2674</td>
<td>24000</td>
<td>1653</td>
</tr>
</tbody>
</table>

Increasing the tunnel cross section has two main effects:

1. It reduces the blockage ratio thus reducing the pressure increase across the head compression wave. This can be physically visualised as increasing the tunnel cross section the annular cross sectional area between train and tunnel wall increases, so more flow can pass through that area and less flow needs to be pushed forward into the tunnel.
2. It increases the rise-time of the head compression wave. This can also be visualised in Fig. 4.37. Actually that rise-time turned out to be nicely proportional to the difference between the hydraulic diameters of train and tunnel, and not only to the tunnel hydraulic diameter as in [8].

These two factors contribute to reduce the maximum pressure gradient for increasing tunnel cross sectional area.

Comparing the pressure increase across the head compression wave for the two extreme cases, they differ by a factor of 3.22, while the two cross section areas differ by a factor of 2.5, so the cross section influence is less extreme than the velocity one, but it is still very strong.

**Fig. 4.37 Pressure time history, tunnel cross section sweep**
In Fig. 4.37 one can both visualise the increase in maximum pressure and the decrease in rise-time by looking at the t3 points different tunnel cross sectional areas. Another consideration is that the fitted pressure time history lies always very close to the CFD one, so the fitting consistency looks confirmed.

Fig. 4.38 Pressure gradients. Left: time history. Right: fitting error.

In Fig. 4.38 one can realise that the influence of varying the cross sectional area is much stronger on the maximum gradient than on the maximum pressure. Comparing the maximum gradient for a 50 m$^2$ with the one for 37 m$^2$ one, it nearly doubles. This extremely strong influence comes from both the increased maximum pressure and the decreased rise-time. The decrease in rise-time for increasing tunnel cross section can also be visualized by looking at the t3 position (placed at the gradients discontinuity at about 0.1 s).

Looking at the fitting procedure error in terms of maximum gradient, which is the error of Eq. (4.1), it is about -2% for both the smallest and the biggest tunnel cross sections.

Fig. 4.39 Loads time history, tunnel cross section sweep. $\tau=0.2$ s.
The loads confirm the conclusions made in terms of maximum pressure and maximum pressure gradient, as the maximum load for the smallest tunnel is about four times higher than the bigger tunnel one. Looking at the accuracy of the load computed using the fitted pressure time history, one realises that the accuracy is quite good, even if the error due to the CFD gradient asymmetry with respect to \( t=0 \) and to the higher pressure rise of the fitting when compared to the CFD one remains.

Concluding, the tunnel cross sectional area has an extremely strong influence on both the maximum gradient and the load. This means that the structural design of the train should take into account the cross sections of the tunnel it will travel through. Another consideration is that the tunnel cross section, as well as the velocity, given their strong influence on the maximum pressure gradient, are key factors also in determining the intensity of MPW emissions at the tunnel ends.

### 4.4.3. Train cross section sweep

This sweep is less important than the previous one, it has mainly been set-up to assess the best way to include the train and tunnel hydraulic diameter in the characteristic length estimate of Eq. (4.1)

**Tab. 4.12 Train cross section sweep – fitting.**

| Sweep \( S_r \) \([m^2]\) | Values | \( V_{tr} = 250 \text{ km/h} ; S_{tu} = 63 \text{ m}^2; \)  
L\( _n = 4; L_{ax} = 0 \) | Coefficient \( \frac{dp}{dt}\) max | Error on max load \( \tau = 0.2 \text{ s} \) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr</td>
<td>11, 10, 9</td>
<td>( Showed \ (dh-dh_{\text{train}}) )</td>
<td>0.5%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

The cross sectional area of trains have a range of variation much more limited than the ones of tunnels, so the smallest train used for this sweep has a cross section of 9 \( \text{m}^2 \).

The main reason why this sweep has been carried out was to choose whether to make the characteristic length \( L \) vary proportionally to the tunnel hydraulic diameter and to the train hydraulic diameter through the same coefficient or through two different coefficients.

Basically the coefficient of 1.2 worked also for the variation of train hydraulic diameter, so this shows that the characteristic length is proportional to the variation of the difference of the two hydraulic diameters. So if both train and tunnel hydraulic diameters vary what counts is the difference between the two, and so physically it is the distance between train and tunnel wall which determines the rise-time for varying cross section.

**Tab. 4.13 Train cross section sweep - CFD results.**

<table>
<thead>
<tr>
<th>Case</th>
<th>CFD ( \Delta p_n ) ([\text{Pa}])</th>
<th>CFD max. Grad. ([\text{Pa/s}])</th>
<th>CFD max load, ( \tau=0.2 \text{ s} ) ([\text{Pa}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>1311</td>
<td>9000</td>
<td>738</td>
</tr>
<tr>
<td>( \text{Str}=9 \text{ m}^2 )</td>
<td>1020</td>
<td>6832</td>
<td>570</td>
</tr>
</tbody>
</table>

Decreasing the train cross section has the very same effects as increasing the tunnel one:

1. It reduces the blockage ratio thus reducing the pressure increase across the head compression wave.
2. It increases the rise-time of the head compression wave.
These two factors contribute to reduce the maximum pressure gradient for increasing tunnel cross sectional area.

Comparing Fig. 4.40 with Fig. 4.37, the difference between the pressure time histories for different tunnel cross sections is lower, as the variation imposed to the train cross section is much lower than the one imposed to the tunnel cross section in the previous section. The fitted pressure time histories remain very close to the CFD ones.

The conclusions in terms of pressure gradients are the same one of the last section. The train hydraulic diameter variations also shift the t3 and t2 points, and the error coming from the fitting is very low, at about 0.5 %. It is interesting to note that the error of the gradient estimate Eq. (4.1) in terms of maximum gradient
remains lower than 2% using a single coefficient \( c_{dh} = 1.2 \) to fit six cases (4 tunnel cross sections plus 2 train ones). This confirms that the fitting is very good in terms of cross sectional areas.

Fig. 4.42 Loads time history, train cross section sweep. \( \tau = 0.2 \) s.

The loads time history also confirms both that the load is higher for a bigger train and that the fitted loads are close to the CFD ones.

Concluding, the train cross section sweep mainly showed that the characteristic length \( L \) is proportional to the variation of the difference between train and tunnel hydraulic diameters, as in Eq. (4.1) and Eq. (4.3), and that the fitting accuracy for train and tunnel cross section variations is quite good in terms of maximum gradient of the head compression wave.
4.4.4. Nose length sweep

The nose length sweep was made of three simulations plus the benchmark one, ranging from a nose length of 2 m (defined as in Fig. 4.1) to a nose length of 8 m, as visualised in Fig. 4.43.

Fig. 4.43 Geometry visualisation. Above: 2 m long nose. Below: 8 m long nose.

The maximum and minimum lengths used for this study are considered as extreme cases, so they are expected to give a strong influence on the results, especially in terms of maximum gradient. Intuitively, one would expect an influence comparable to the ones of velocity and cross section.

Tab. 4.14 Nose length sweep – fitting procedure.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
<th>Other variables</th>
<th>Coefficient</th>
<th>Error on $\frac{dp}{dt}$ max</th>
<th>Error on max load $t = 0.2$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_n$[m]</td>
<td>2, 4, 5, 8</td>
<td>$V_{tr} = 250 \frac{km}{h}$; $S_{ru} = 63 m^2$; $S_{tr} = 11 m^2$; $L_{ax} = 0$</td>
<td>$c_{ln} = 0.6$</td>
<td>5%</td>
<td>6%</td>
</tr>
</tbody>
</table>

The nose length sweep allowed to tune the $c_{ln}$ coefficient in Eq. (4.1) to a value of 0.6, which gives a maximum error of 5% on the maximum gradient, as also shown in Fig. 4.44.
Increasing the nose length has no influence on the pressure rise across the head compression wave. This is because it practically does not influence the amount of flow pushed by the train into the tunnel, which mainly depends on the train velocity and on the train and tunnel cross sections. On the other hand, the nose length clearly influences the rise time of the wave, but it does so in a weaker way than expected. This is because the characteristic length $L$, that models the rise-time, is physically close to the length of the pressure field in front of and around the train nose, and not to the train nose length directly. Looking at the figures in Section 4.2.6, one realizes that this length is much longer than the nose length. Quantitatively $L$ is about 11 m for the benchmark case, while for that case the nose length is 4 m only. This means that reducing the nose length does reduce $L$, but even with a nose length equal to zero $L$ would remain close to about 7 m, so the nose length variation has a much lower influence on the maximum gradient than the train velocity or the two cross sectional areas.

Fig. 4.44 Pressure time history, nose length sweep.

Fig. 4.44 confirms that the maximum pressure is the same for all the nose lengths. The pressure time history for the 8 m nose is delayed not only as the rise-time increases for such a long nose, but also because the shape of the pressure gradient time history changes for that case, as shown in Fig. 4.45.
Fig. 4.45 Pressure gradients. Left: time history. Right: fitting error.

Fig. 4.45 confirms that increasing the nose length reduces the maximum pressure gradient, but varying the nose length of four 4 times (2 m to 8 m) reduces the maximum pressure gradient by 38%, so the influence is strong but much weaker than the one from velocity or cross sectional areas. Another interesting feature is that for the longest nose the CFD pressure time history shows a more shallow and symmetrical shape than for the other nose lengths. All the time histories are aligned placing the maximum gradient point at t=0, and one can see that the CFD pressure gradient time history for the longest nose rises later and falls later than the others, always reaching the maximum at t=0. This can be physically visualised as a more gradually varying flow field takes place around the longer nose, so also the pressure gradient would increase and decrease more gradually.

The error in the maximum gradient estimate is about 5% for both the longest and the shortest nose. This error is higher than the one associated with the train and tunnel cross section variations as the nose length influence on the pressure gradient has been chosen arbitrarily, while the cross sections and velocity influence on the maximum gradient came from the literature. In particular Eq. (2.20) coming from [8] advices to use a characteristic length proportional to the tunnel hydraulic diameter only. The idea of taking that length as in Eq. (4.1) comes from trials and errors. So the nose length and track spacing terms in Eq. (4.1) have been arbitrarily introduced, so a 5% error on the maximum gradient looks acceptable. Furthermore, one can note that the nose length is the only one in Eq. (4.1) which is not in the radial tunnel direction but in the axial one.
The loads time histories confirm the conclusion taken in this section, as among the three shortest noses the maximum load varies less than 4% while the longest nose shows a much lower load. This is again because the external pressure for longest nose varies more smoothly, so the internal pressure has more time to increase, so the maximum load is lower.

Concluding, the influence of the nose length on the three outputs is much lower than the one of velocity and cross sections and the fitting procedure for varying nose length shows a higher but still acceptable error of 5%.
4.4.5. Track spacing sweep

The track spacing sweep has been made on three simulations plus the benchmark one. Given the room needed by the train in order to be shifted towards the tunnel wall, also the tunnel cross section had to be increased from the 63 m$^2$ benchmark one to 93.1 m$^2$ for the highest track spacings, as shown in Fig. 4.47.

![Geometry visualisation. Above: Lax=0, Stu=93 m$^2$. Below: 6 m track spacing, Stu=93.1 m$^2$.](image)

The two cases in Fig. 4.47 show the benchmark train entering a 93.1 m$^2$ cross section tunnel. The track spacing in the lower plot is 6 m, which is quite a high value, as this is the most extreme case. The overset mesh approach has allowed to simulate this case without problems, while, looking at the lower plot of Fig. 4.47, one can realise that it would have been quite difficult to set-up this case using a sliding mesh approach. The overset mesh behaviour for this simulation can also be visualised in Fig. 4.11.

The simulations which have been run for the track spacing sweep are shown in Tab. 4.16.

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
<th>Other variables</th>
<th>Error on $\frac{\partial p}{\partial t} \text{max}$</th>
<th>Error on max load $\tau = 0.2 \text{ s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{ax}$[m]</td>
<td>0.15 ($S_{tu}93.1$), 1.5 ($S_{tu}63$), 3 ($S_{tu}93.1$)</td>
<td>$V_{tr} = \frac{250 \text{ km}}{h}; S_{tr} = 11 \text{ m}^2; L_n = 4;$</td>
<td>6%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
The parameter $L_{ax}$ is half the track spacing, and it has been chosen for the characteristic length formulation in Eq. (4.1) as it represents the variation of the distance between train and tunnel wall for varying track spacing. Comparing the train and tunnel cross section term of Eq. (4.1) with the track spacing one, they both model the variation in distance between train and tunnel walls. This choice is expected to keep the model as close as possible to the physical phenomenon.

**Tab. 4.17 Track spacing sweep - CFD results.**

<table>
<thead>
<tr>
<th>Case</th>
<th>CFD $\Delta p_n$ [Pa]</th>
<th>CFD max. Grad. [Pa/s]</th>
<th>CFD max load, $\tau=0.2$ s [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>1311</td>
<td>9000</td>
<td>738</td>
</tr>
<tr>
<td>Lax=1.75 m</td>
<td>1335</td>
<td>10160</td>
<td>771</td>
</tr>
</tbody>
</table>

Increasing the track spacing has two effects:

1. It reduces the rise time of the head compression wave, as the stagnation region in front of the train nose is closer to the tunnel wall on one side of the train.
2. It slightly increases the pressure rise across the head compression wave. This is due to the pressure field in front and around the nose being closer to the tunnel wall, thus slightly increasing the blockage effect. Anyway this last phenomenon is very weak, so it has not been modelled in the fitting procedure.

Overall, varying the track spacing has a lower influence on the maximum gradient than changing velocity, train and tunnel cross sections or nose length. The 1.75 m $L_{ax}$ in Tab. 4.17 corresponds to 73% of the maximum track spacing geometrically possible, and the increase in maximum gradient is only 13%. This magnitude anyway makes the track spacing variation non-negligible, also because it is quite common for tunnels to feature a double track.

![Fig. 4.48 Pressure time history, track spacing sweep](image)

In Fig. 4.48, which had to be magnified in order to make the various pressure time histories distinguishable, one can see that the two higher pressure time histories are for the 63 m$^2$ benchmark tunnel, while the three lower ones are for the 93.1 m$^2$ tunnel. A noticeable feature is that the maximum pressure slightly increases
for increasing track spacing. This slight effect has not been modelled in the fitting procedure, so increasing the track spacing actually brings the CFD pressure time history closer to the fitted one, as the fitted one has been tuned with a slightly conservative maximum pressure.

![Fig. 4.49 Pressure gradients. Left: time history. Right: fitting error.](image)

In Fig. 4.49 one can visualise that increasing the track spacing reduces the rise-time of the wave, thus increasing the maximum pressure gradient. This effect is much weaker than the velocity, train and tunnel cross section variations ones. Furthermore, one can realise that the error of the fitting procedure in terms of maximum gradient becomes consistent for the highest track spacing of 3 m. As represented in the right plot of Fig. 4.49, the maximum error on the gradient estimated by the fitting procedure through Eq. (2.20) and Eq. (4.1) is about 8% for the 6 m track spacing simulation, but the errors from less extreme track spacings are lower than 2%. These errors are listed in Tab. 4.18.

**Tab. 4.18 Track spacing sweep error on the maximum gradient.**

<table>
<thead>
<tr>
<th>L&lt;sub&gt;ax&lt;/sub&gt; [m] ( %L&lt;sub&gt;ax&lt;/sub&gt; max )</th>
<th>S&lt;sub&gt;tu&lt;/sub&gt; [m&lt;sup&gt;2&lt;/sup&gt;]</th>
<th>Error from c&lt;sub&gt;dh&lt;/sub&gt;</th>
<th>Error from c&lt;sub&gt;Lax&lt;/sub&gt;</th>
<th>Combined error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (93.1)</td>
<td>93.1</td>
<td>-2%</td>
<td>/</td>
<td>-2%</td>
</tr>
<tr>
<td>1.50 (43%)</td>
<td>93.1</td>
<td>-2%</td>
<td>+4%</td>
<td>+2%</td>
</tr>
<tr>
<td>1.75 (73%)</td>
<td>63</td>
<td>/</td>
<td>+0.2%</td>
<td>+0.2%</td>
</tr>
<tr>
<td>3.00 (94%)</td>
<td>93.1</td>
<td>-2%</td>
<td>-5.5%</td>
<td>-7.5%</td>
</tr>
</tbody>
</table>

The main concept in Tab. 4.18 is that the errors for the track spacing sweeps runs performed on the 93.1 m<sup>2</sup> tunnel actually are the combination of the fitting error for the tunnel cross section variation from the 63 m<sup>2</sup> tunnel (c<sub>dh</sub> term in Eq. (4.1)) and of the fitting error for the track spacing variations (c<sub>Lax</sub> term in Eq. (4.1)).
When estimating these errors for the most extreme case of $3 \, m \, L_{ax}$, one realises that 2% of the error comes from the tunnel cross section variation fit and 5.5% comes from the track spacing variation fit. On the other hand, for the $1.5 \, m \, L_{ax}$ case these errors were in opposite directions so they compensated one another. Overall, one can also expect an increased discretisation error from the higher track spacings CFD runs, as the overset mesh interpolation can get much more difficult in those cases, as shown in Fig. 4.11. It is also interesting to note that the errors on the maximum pressure gradient in Tab. 4.18 are mostly towards lower gradients, so they sum up to the conservative choice in terms of $t2$ (Section 4.3.3) to give a maximum error on the loads of 2.5 %.

Looking at the loads time histories in Fig. 4.50 one realises that the influence of track spacing variations is very limited, as it is also with regard to the maximum pressure gradient. This also contributes to reduce the maximum gradient estimation error impact on the load.

Concluding, track spacing variation is the one which has the lowest effect on loads, so the higher error of both the fitting procedure and the CFD runs in this case is easier to accept.
4.4.6. Final comparisons

A final comparison of the main results from each parameter sweep is performed in this section.

**Tab. 4.19 Star Variables Sweeps overview in terms of fitting.**

<table>
<thead>
<tr>
<th>Sweep</th>
<th>Values</th>
<th>Coefficient</th>
<th>Error on $\frac{dp}{dt} max$</th>
<th>Error on max load, $\tau = 0.2$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>V [km/h]</td>
<td>150, 200, 225, 250, 275</td>
<td></td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>$S_{tu}$ [m$^2$]</td>
<td>37.50.4, 63, 75.6, 93.1</td>
<td>$c_{dh} = 1.2$</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>$S_{tr}$ [m$^2$]</td>
<td>11, 10, 9</td>
<td>Showed (dh-dh$_{train}$)</td>
<td>0.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$L_{n}$ [m]</td>
<td>2, 4, 5, 8</td>
<td>$c_{Ln} = 0.6$</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>$L_{ax}$ [m]</td>
<td>0.1.5 ($S_{tu}$93.1), 1.5 ($S_{tu}$63), 3 ($S_{tu}$93.1)</td>
<td>$c_{Lax} = -0.85$</td>
<td>6%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Looking at Tab. 4.19 one can visualize all the simulations runs used for the parameters sweeps. Each parameter sweep led to a coefficient definition for the fitting procedure as well as to an estimate of the fitting procedure maximum error on the estimated maximum gradient and on the estimated maximum load when varying the corresponding parameter. The error on the estimated maximum gradient comes from the characteristic length procedure used to compute the gradient, while the error on the estimated maximum load also includes the influence of the conservative choice made in terms of $t_2$ and also of the value of $\tau$.

For what concerns the error on the maximum gradient, the main conclusion is that the variation of velocity and tunnel and train cross sections are very accurately predicted by the fitting procedure, as the corresponding terms in Eq. (4.1) model the physics of the phenomenon and they are justified by the literature [8]. For what concerns the nose length and track spacing sweeps, their relative error in terms of maximum gradient is higher. This higher error can also be justified when recalling that the nose length and track spacing variations terms in Eq. (4.1) have been arbitrarily introduced.

For what concerns the error on the maximum load, one has to add to the error on maximum gradient the influence of the conservative choice made in terms of $t_2$ and of the $\tau$ value chosen. In particular, if the fitted maximum gradient is higher than the CFD one, then the conservative choice in terms of $t_2$ adds up to this error increasing the load, as for example for the nose length sweep. In this case a higher $\tau$ would increase the error. On the other hand, if the fitted maximum gradient is lower than the CFD one, then the conservative choice made in terms of $t_2$ helps reducing the error in terms of load, as in the track spacing sweep. One also has to consider that the choice of $t_2$ should also depend on the choice of friction rise modelling, which is not a part of this work. So the maximum gradient can be taken as the main parameter with which to validate the fitting procedure, and the maximum load can be taken as an estimate of the error introduced by the $t_2$ choice. In order to assess the influence of these parameters on the load one can look at Tab 4.20.
Looking at Tab. 4.20, one can compare the CFD results for the extreme cases of each sweep performed. The first three sweeps are the velocity, tunnel cross section and train cross section ones. They all have a strong influence on both the pressure increase across the head compression wave and on the rise-time of the wave: both of these factors add up to give a very strong influence on the maximum gradient, which in turn is what mainly influences the loads for non-tight trains.

The nose length and track spacing variations have practically no influence on the pressure increase across the head compression wave, while they do have an influence on the head compression wave rise-time and so on the maximum gradient across the head compression wave, but it is a much weak influence than by the velocity and cross sections variations.

Looking at the maximum load variation from the 738 Pa benchmark case load, it ranges between 215 Pa for the slowest speed in the benchmark tunnel to the 1653 Pa for the 250 km/h case in the smallest tunnel, so the range of load variation is huge.

In order to dimension the train structure for the pressure loads due to the head compression wave one has to take into account many different scenarios, so using a 3D CFD code is not feasible, so it is important to assess the validity of 1D codes such as NUMSTA. In the next chapter NUMSTA simulation results will be introduced together with a procedure to increase NUMSTA accuracy using as input a nose length proportional to the characteristic length developed in this chapter to estimate the maximum pressure gradient in Eq. (4.1).
4.5. NUMSTA simulations

The main goal of the NUMSTA simulations performed in this work is to assess its accuracy when compared to the results from Star. As NUMSTA is a 1D code it cannot model the 3D pressure field in front of the train nose, so its prediction will be wrong in terms of nose entry compression wave rise time. For this reason NUMSTA nose length has been increased from the physical length in order to improve the nose entry compression wave rise time prediction.

4.5.1. NUMSTA nose length extension procedure

If NUMSTA is run using a “NUMSTA nose length” \( L_n^N = 4 \text{ m} \) for the benchmark case, which corresponds to the physical nose length of the AeroTRAIN benchmark case, the resulting maximum pressure gradient of the nose entry compression wave is much too high, as one can visualise in Fig. 4.51 and Tab. 4.21. Basically the right value of gradient is 9000 Pa/s and the one predicted by NUMSTA is 41630 Pa/s, so if one needs to predict the load the nose entry compression wave generates on a non-tight train NUMSTA with the physical nose length will be very conservative. In particular, with a \( \tau \) of 0.2 s, the Star load is 738 Pa, while the NUMSTA one is 1054 Pa (45% more), as reported Tab. 4.21. For this reason a procedure was developed to find a virtual extension of the nose length that makes the NUMSTA results best fit the Star simulated nose entry compression wave pressure time history at 100 m.

The train geometrical parameters given in input to NUMSTA are the nose length \( L_n^N \) and the train length \( L_{TR}^N \). In order to bring NUMSTA rise-time closer to the Star one, the most straightforward way is to increase \( L_n^N \). Physically this directly increases the rise time of the head compression wave predicted by NUMSTA, helping to fix the missing 3D pressure field in front of the NUMSTA train nose.

A valid way to increase \( L_n^N \) is to choose a \( L_n^N \) proportional to the characteristic length \( L \) (Eq. (4.5)) used in the fitting procedure to estimate the maximum gradient of the head compression wave.

\[
L_n^N = 1.49 L; \text{with } L = L_{bench} + c_{dh} \Delta (d_h - d_{h_{train}}) + c_{tn} \Delta L_n + c_{Lax} \Delta L_{ax}; \tag{4.5}
\]

The coefficient 1.49 was found by trial and error in order to fit the gradient for the benchmark case. A very useful feature of this procedure to extend the NUMSTA nose length is that it employs the fitting procedure, which includes the results from the Star parameters sweeps. So using Eq. (4.5) NUMSTA directly becomes much more accurate in terms of maximum gradient for any free variable combination. Using Eq. (4.5) to estimate \( L_n^N \) for the benchmark case, one gets a value of 15.8 m instead of the 4 m physical nose length. Looking at this difference one can realise that the smoother area variation needed by NUMSTA directly accounts for the presence of the pressure field in front of and around the train nose, which can be visualised looking at the train entry figures in Section 4.4.6. This approach recalls for example what can be done if one wants to model for example the flow around a car with an inviscid 2D solver, in which case one can add behind the car a fictitious body which represents the wake.

When the nose length used by NUMSTA is extended from Eq. (4.5) the train length also needs to be modified. A way to do so is Eq. (4.6).

\[
L_{TR}^N = L_{TR} + L_n^N \tag{4.6}
\]

In Eq. (4.6) \( L_{TR}^N \) is the NUMSTA train length, while \( L_{TR} \) is the physical train length. The goal of Eq. (4.6) is to align the NUMSTA maximum area variations points with the physical train tip and tail, in order to match as closely as possible the physical train geometry. Anyway the train length has no influence on the nose entry compression wave but on the friction rise.

Using as input for the NUMSTA runs the train and nose lengths from Eq. (4.5) and Eq. (4.6) one corrects the NUMSTA prediction of the nose entry rise-time, getting a much more accurate result in terms of maximum pressure gradient for any combination of the fitting free variables. This extension procedure will be validated in the following sections.
4.5.2. Train entry and tunnel passage for benchmark case

The benchmark case is particularly useful to tune NUMSTA numerical and geometrical parameters, to assess its accuracy against the validated Star results, and to find the best approach to extend the NUMSTA nose length. For brevity, the version of NUMSTA with the nose length from Eq. (4.5) will be called extended NUMSTA, while the one with the physical nose length will be called baseline NUMSTA.

With regards to the numerical parameters, it is not necessary to care about them too much as they have been chosen so as to get extremely accurate results, as NUMSTA is a 1D CFD solver, so its running time is extremely short. The friction coefficient chosen for the tunnel wall is 0.01, while the one for the train wall is 0.001: these values have been chosen quite low in order to give results close to the Star ones which comes for a geometrically smooth rough surface ($k_s = 5\text{mm}$) wall and a very simplified geometry.

![Pressure and Pressure gradient Time history at 100m from tunnel entrance.](image)

**Fig. 4.51 Star vs extended NUMSTA vs baseline NUMSTA - pressure signatures and gradients.**

In Fig. 4.51 one can compare the pressure signatures and gradient time histories as computed by Star, the extended NUMSTA and the baseline NUMSTA.

Looking at the blue chart, which corresponds to the baseline NUMSTA, one realises that the nose entry pressure rise and the tail entry pressure drop are extremely steeper than the Star ones. This is confirmed when looking at the maximum pressure gradient, which is of $41630\ \text{Pa/s}$ instead of the $8989\ \text{Pa/s}$ of the Star simulation. Looking at the gradient time history plot it is evident how smaller the rise-time is for the baseline NUMSTA.

Looking instead at the extended NUMSTA pressure time history, coloured in green in Fig. 4.51, it is clearly much closer to the Star one both for the head entry compression wave and for the tail entry pressure drop, even if a dedicate formulation for the NUMSTA tail length would be needed to grant accuracy for the tail expansion wave prediction. Looking closer at the left plot of Fig. 4.51 one can realise that the head of the nose entry pressure wave is delayed and more sudden for the extended NUMSTA when compared with the Star one, as the NUMSTA area variation remains more abrupt than the Star one. This can also be visualised in the corner the NUMSTA gradient time history presents at the head of the nose entry wave. Furthermore, the two
pressure time histories stay very close in the nose entry pressure rise, reaching practically the same maximum gradient, as also shown in Tab. 4.21. The NUMSTA friction rise then shows a very different shape than the Star one, as, especially for such a short (50 m) train, the friction coefficient model is not enough to predict the boundary layer development on the train and tunnel wall, as well as the 3D effects around nose and tail. The friction coefficients chosen for train and tunnel are respectively 0.001 and 0.01.

After that, the tail entry pressure drop time histories of both Star and extended NUMSTA look superposed, confirming the formulation used for the NUMSTA train length in Eq. (4.6). The reason why the NUMSTA pressure drop reaches about 175 Pa instead of the Star 300 Pa is that clearly NUMSTA cannot model the wake, which instead displaces flow in the Star simulation preventing the Star pressure time history to reach such a low value of pressure.

The impact of the differences between the three pressure signatures in Fig. 4.51 on the loads can be visualised in Fig. 4.52.

![Load comparison Star VS NUMSTA, τ=0.2](image)

**Fig. 4.52 Star vs extended NUMSTA vs NUMSTA - load comparison, \( \tau = 0.2 \text{s} \).**

The main conclusion from Fig. 4.52 is that the load from baseline version of NUMSTA is very conservative, as one can also appreciate in Tab. 4.21 Star vs NUMSTA comparison. Besides, also the extended version of NUMSTA presents a considerable error when computing the loads for the benchmark case. This is because, even though the nose length extension procedure grants the same maximum gradient as Star, the NUMSTA rise-time is still slightly too short, as highlighted by the gradient time history in Fig. 4.51. In turn, this is due to the area distribution in the NUMSTA 1D domain, which is from a spline polynomial fitting and cannot be modified by the user.
Looking at Tab. 4.21 one can first note that the pressure increase across the nose entry compression wave is practically the same for Star, NUMSTA, and the extended NUMSTA. When it comes to the maximum pressure gradient, the maximum baseline NUMSTA gradient is 4.6 times stronger than the NUMSTA one, while the extended NUMSTA gradient is close to the Star one thanks to the nose length extension procedure.

In terms of maximum load, both versions of NUMSTA are conservative. The impact of the difference in maximum gradient between the two versions of NUMSTA can be appreciated when looking at the maximum loads, so for a $\tau$ value of 0.2 s the difference in load is 36%, while for a less non-tight train with a $\tau$ of 0.5 s this difference is 13%. This shows that the impact of the conservativeness the baseline NUMSTA shows when predicting the maximum gradient is considerable mostly for non-tight trains, as the internal pressure variations for non-tight trains are much quicker. Besides, the extended NUMSTA error in terms of maximum load confirms that, even with nearly the same pressure drop and maximum gradient, shows that the shape of the pressure time history is fundamental to compute the load for non-tight train. Also, the absence of such an error when using the fitted pressure time history to compute the loads further confirms the validity of the arctan shape for the pressure time history found in the literature.

One could wonder why the extended NUMSTA nose length in Eq. (4.5) has not been chose to fit the maximum load instead of the maximum gradient. A valid reason to support this choice is that the length needed to fit the maximum load depends both on the $\tau$ value and from the pressure time history, so it would be different for each case, as one can appreciate from the parameters sweeps results in section 4.5.3. It can anyway be appropriate to leave the extended version of NUMSTA slightly conservative.

**Tab. 4.21 Star vs NUMSTA comparison.**

<table>
<thead>
<tr>
<th>Tool</th>
<th>CFD $\Delta p_N$ [Pa]</th>
<th>CFD max. Grad. $\nabla p$ [Pa/s]</th>
<th>CFD max. Load. $\tau = 0.2$ s [Pa]</th>
<th>CFD max. Load. $\tau = 0.5$ s [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>1311</td>
<td>8989</td>
<td>738</td>
<td>945</td>
</tr>
<tr>
<td>Baseline NUMSTA</td>
<td>1335</td>
<td>41630</td>
<td>1054 (+45%)</td>
<td>1138 (+20%)</td>
</tr>
<tr>
<td>Extended NUMSTA</td>
<td>1340</td>
<td>9123</td>
<td>807 (+9%)</td>
<td>1011 (+7%)</td>
</tr>
</tbody>
</table>

Fig. 4.53 Star vs NUMSTA: pressure time histories for whole tunnel passage.
Comparing the Star and the extended NUMSTA pressure time histories in Fig. 4.53 one can first check that the pressure signature is the same of Fig. 4.30, and appreciate the difference due to the lack of wake modelling in NUMSTA. Looking at the NUMSTA pressure oscillations one can note that they are anticipated with respect to the Star ones, especially towards the end of the tunnel passage. Also, one can note that the peaks in NUSMTA pressure distribution are sharper than Star ones. The main factor which can explain these two features is that the Star results come from a simulation with outer domains such as the ones in Fig. 4.13, so when the pressure wave gets to a tunnel end it gets delayed and weakened at the reflection as it emits the MPW, as introduced in Section 2.2.4. The attenuation might also come from the propagation of the wave as it travels into the tunnel. Another factor is that the Star simulation for sure also features a higher numerical dissipation as well as the unsteady friction introduced in Section 2.2.3, which both can act to attenuate and un-steepen the pressure waves.

### 4.5.3 NUMSTA Parameters sweeps

The main goal of the NUMSTA parameters sweeps is to validate the NUMSTA nose length extension procedure for any combination of fitting free variables. The physical results of these sweeps have all already been introduced in Section 4.4.

![Fig. 4.54 Star vs NUMSTA: velocity sweep.](image)

For increasing train velocity one can note not only an increase of pressure rise and maximum gradient across the head compression wave, but also an increase in friction rise, which is present in both NUMSTA and Star results and is due to the increase in boundary layer friction losses in the train-tunnel annulus flow. The tail entry pressure drops are aligned for each train velocity, so this confirms the train length extension used.

Also, the Star and NUMSTA gradients are very close one another, getting practically coincident for the lowest train velocity as also shown in Tab. 4.22, so this confirms the extension procedure used for the NUMSTA nose length.

The results of the velocity sweep confirms that the extension model for NUMSTA allows it to generate an accurate prediction for the maximum pressure gradient, which is fundamental to compute loads on non-tight trains, not only for the benchmark case but also for different train velocities.
For decreasing tunnel cross section one can not only note the increase of maximum pressure rise and gradient across the nose entry wave, but also a very strong increase of friction rise, as the blockage effect of the train and tunnel wall boundary layers increases for decreasing tunnel cross section. The gradients are quite accurately predicted by the corrected NUMSTA, getting to a maximum gradient of 24753 Pa/s, which is 3% higher than the 24000 Pa/s Star one.

Increasing the nose length increases the nose entry compression wave rise-time, thus reducing the maximum pressure gradient of the nose entry compression wave. This effect is correctly predicted both by Star and the extended NUMSTA, as the gradients are quite close also for this sweep. In particular, for the longest 8 m nose the NUMSTA gradient is 7200 Pa/s, 3% higher than the Star 6994 Pa/s one. This is a further confirmation that doubling the train nose length (as an example from the 4 m benchmark one to 8 m) does not half the maximum
gradient, as the baseline NUMSTA would predict, but it reduces the maximum gradient from 9000 Pa/s to 6994 Pa/s, so by 29%.

![Pressure and Pressure gradient Time history at 100m from tunnel entrance; Lax sweep](image)

**Fig. 4.57 Star vs NUMSTA: track spacing sweep.**

Again, for increasing track spacing the Star and NUMSTA predicted gradients remain close enough to validate the NUMSTA correction procedure. In particular, looking at Tab. 4.22 one can realise that the error for the $1.75 \, L_{ax}$ case is 2%, which is very low also thanks to the only 0.2% error of the fitting procedure for the same case (Section 4.4.5).

**Tab. 4.22 NUMSTA parameters sweep overview.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Tool</th>
<th>CFD $\Delta p_n$ [Pa]</th>
<th>CFD max. Grad. [Pa/s]</th>
<th>CFD max. Load. $\tau = 0.2 , s$ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benchmark</strong></td>
<td>Star</td>
<td>1311</td>
<td>9000</td>
<td>738</td>
</tr>
<tr>
<td></td>
<td>NUMSTA</td>
<td>1340</td>
<td>9123</td>
<td>807 (+9%)</td>
</tr>
<tr>
<td><strong>V=150 km/h</strong></td>
<td>Star</td>
<td>469</td>
<td>1960</td>
<td>215</td>
</tr>
<tr>
<td></td>
<td>NUMSTA</td>
<td>476</td>
<td>1966</td>
<td>235 (+9%)</td>
</tr>
<tr>
<td><strong>Stu=37 m²</strong></td>
<td>Star</td>
<td>2674</td>
<td>24000</td>
<td>1653</td>
</tr>
<tr>
<td></td>
<td>NUMSTA</td>
<td>2706</td>
<td>24753</td>
<td>1767 (+7%)</td>
</tr>
<tr>
<td><strong>Ln=8 m</strong></td>
<td>Star</td>
<td>1311</td>
<td>6994</td>
<td>689</td>
</tr>
<tr>
<td></td>
<td>NUMSTA</td>
<td>1340</td>
<td>7200</td>
<td>737 (+7%)</td>
</tr>
<tr>
<td><strong>Lax=1.75 m</strong></td>
<td>Star</td>
<td>1335</td>
<td>10160</td>
<td>771</td>
</tr>
<tr>
<td></td>
<td>NUMSTA</td>
<td>1330</td>
<td>10360</td>
<td>836 (+8%)</td>
</tr>
</tbody>
</table>
Looking at the maximum loads in Tab. 4.22, one can appreciate that the error between the NUMSTA ones and the Star one remains of the same order of magnitude throughout all the sweeps, thus ultimately confirming the choice for the NUMSTA nose length extension.

The main conclusion of this section is that by using the NUMSTA nose length extension one can hugely improve its accuracy in terms of maximum gradient and maximum load prediction for the solo passage of a tunnel, by just employing the results from the fitting procedure. Given that the fitting procedure has been tuned using the results from the CFD parameters sweeps, also the extended NUMSTA can give predictions as accurate as the fitting procedure for any physical combination of train velocity, train and tunnel cross sections, nose length and track spacing. It must be kept in mind anyway that the extended nose length is only valid for the prediction of the nose entry compression wave, and it does not hold for example for train passing loads.

This makes the corrected NUMSTA a valid tool for computing loads on non-tight trains, as it is inexpensive to run when compared to Star.

4.6. Structural loads from wave encounter

The main goal of this section is to assess the influence of the carriage free length on the pressure loads on a non-tight train for the wave encounter scenario. With wave encounter scenario is meant a situation in which the train meets pressure waves, in this case the pressure signature (nose entry compression wave, friction rise, tail entry expansion wave) it generated when entering the tunnel. The results would be similar in terms of magnitude if the sign on the pressure waves were opposite, as for example after the reflection.

In order to assess the carriage free length influence on the loads, the “free-length” model for load has been implemented and its results will be compared with the simpler “Point-Tau” model ones. These two models have been introduced in Section 2.3.2, and their main features are recalled in Fig. 4.58.

Looking at Fig. 4.58, the equation in the blue box in the upper right corner is Eq. (2.27), which is the pressure tightness model ODE equation used to compute the internal pressure time history given the external one. This equation can be applied to the pressure time history coming from the stationary probe at 100 m inside the tunnel, thus obtaining the internal pressure time history one can use to compute the loads; this procedure is the “Point tau” model for loads.

In order to model the carriage free length influence on loads following the “Free Length” model for loads, one needs the average external pressure time history on the car wall. One might directly record it from the Star results, but in order to compare the two models results it is more appropriate to start from the same external pressure time history recorded at 100 m inside the tunnel, and use it to compute the average external pressure on the car wall, as described later on in this section. At this point one can apply the tau model to compute the internal pressure time history from the average external pressure, and compare it with the external one from a probe placed in a precise position $\Delta x_{probe}$ along the carriage to compute the loads at the probe location.

\[
\frac{dp_{int}}{dt}_{Time\ Constant} = \frac{k}{1+k} \frac{dp_{ext}}{dt} + \frac{1}{\tau(1+k)} \Delta P_{ext-int}(t)
\]
The position of the external pressure probe is extremely important, as if for example one wants the load at the carriage front end then looking at the pressure time histories in that location he realises that while the internal pressure varies the internal pressure remains nearly constant, thus generating a strong load. For this reason the loads are computed for front centre and back of each carriage in this section.

Assessing the coupled influence of the carriage free length $L_{\text{free}}$ and of the probe position $\Delta X_{\text{probe}}$ on wave encounter loads is the main goal of this section, and the details of the “free-length” model for loads used are listed in the following numbered list:

1. **External pressure:** The external pressure time history used for load computation comes directly from Star results. It is the one recorded at 100 m inside the tunnel in the train entrance simulation with realistic tunnel inlet and outlet domains; this time history has been preferred over the fitted one as it contains the friction rise and tail passing too. The train length is 50 m, and the case is the benchmark Aerotrain one, with $V_{\text{tr}} = \frac{250 \text{ km}}{\text{h}}, S_{\text{tu}} = 63 \text{ m}^2, S_{\text{tr}} = 11 \text{ m}^2, L_n = 4 \text{ m}, L_{tr} = 50$.

   It has to be said that the actual pressure felt by a probe on the train will not be the same as the one felt by a stationary probe, first because the flow cross sectional area is different in the portion of tunnel containing the train than in the one where the stationary probe has been placed, and then because the relative velocity between the train and the stationary probe makes the external pressure time history felt one the train wall quicker or slower when compared with the stationary probe. In the pressure wave encounter scenario the relative velocity between the train and the wave is used to determine the delay in time between the various external pressure probe time histories, but it does not influence the actual shape of the pressure signature as it would do in reality. However the goal of this comparison is not to find the loads for a specific case, but to assess the influence of the Free Length on those loads, so this simplification is acceptable.

2. **Free-length average:** The Free Length is representative of a carriage, so one needs the time history of the average external pressure along the Free Length, as shown in Fig. 4.58. Given the external pressure time history on the car wall at one position, one can assume that the same pressure variation occurs on all other lengthwise positions with a time shift. After having divided the Free Length into many intervals, by shifting in time the input pressure time history, one can obtain the pressure time history at each interval, and by averaging it in time get the average external pressure along the Free Length, which is named $\text{lengthavg}$ pressure time history. For the train entry pressure wave encounter scenario, one should make sure that the chosen Free Length of the carriage does not exceed the length of the train used to record the whole pressure signature, otherwise the result would not be physical. However, given the short train length used in the simulations, values of Free Length up to 100 m have been tested anyway. Since the length between front and tail waves is longer than 100 m (for a 50 m train travelling at 250 km/h that length is about 245 m) they will still not appear on the train at the same time.

3. **Internal Pressure:** The Free Length is representative of a carriage, so the internal pressure is assumed to be homogeneous along this length at every instant. For this reason one can compute the internal pressure by simply applying the $\tau$ model to the lengthavg average external pressure. Given that the internal pressure is homogeneous along the Free Length, the loads will be computed by subtracting the internal pressure time history from the external one coming from probes at different locations along the carriage.

4. **Loads probes:** Three probes have been chosen to extract the external pressure used for the load computation. The front probe is placed at the edge of the carriage which first encounters the travelling pressure wave. If the train is travelling in the opposite direction than the pressure wave, the front probe will be towards the front of the train, otherwise it will be towards the back of the train. The centre probe is placed at the centre of the Free Length, while the back probe is placed at the edge of the carriage which encounters the travelling pressure wave at a later time.

   The $\text{LinRise}$ probe employs an external pressure coming from a linear rise (and fall) with a rise-time of 0.02 s, i.e. vary close to a step change. Then it computes the internal pressure and resulting load by applying the $\tau$ model directly to that external pressure, so it does not model the Free Length. Finally the $\text{PointTau}$ probe uses the same external pressure as the centre probe and computes the internal pressure.
and load applying the “Point τ” model to that pressure time history. The resulting load is usually very close to the centre probe one, so the PointTau probe has not been plotted in the figures.

Fixed the input external pressure, the variables which determine the load are reduced to the following three ones:

1. \textbf{L free}: \( L_{\text{free}} \) is the length of the carriage open section: along this length the internal pressure is assumed to be homogeneous. This parameter is the most important one as it directly defines the amount of delay of the back probe when compared to the front one.

2. \textbf{V rel}: \( V_{\text{rel}} \) is defined as the relative velocity between the train and the travelling pressure wave. Given that the Train velocity should be the same one of the simulation, then \( V_{\text{rel}} \) can assume two values, a smaller one if the train is travelling in the same direction as the travelling pressure wave and a bigger one if the train is travelling in the opposite direction. If the train velocity is 250 km/h and the speed of sound is 340 m/s, then these two velocities are 974 km/h and 1474 km/h, so the difference among them is not negligible.

3. \textbf{Tau}: \( \tau \) is the time constant which models the pressure tightness of the carriage. It can be compared with \( \Delta t_{\text{char}} \), which is defined as the ratio between \( L_{\text{free}} \) and \( V_{\text{rel}} \), and which represents the delay in time between the front external pressure time history and the back one. When \( \Delta t_{\text{char}} \) gets close to or higher than \( \tau \) then the Free Length influence on wave encounter loads is maximum.

In the following the influence of Free Length on loads for a benchmark case will be assessed. Then the wave encounter loads for parameters sweeps over carriage free length, time constant, train direction and \( \Delta t_{\text{char}} \) will be quantified and commented, and in the end conclusions will be given with regards to the pressure wave encounter loads.

\textbf{4.6.1. Benchmark case results}

The benchmark case is defined as one with a Free Length of 50m, a relative velocity of 974 km/h corresponding to the train travelling in the same direction of the wave (the smaller of the two alternatives has been chosen in order to enhance the Free Length effect on the loads) and a \( \tau \) of 0.2 s. The resulting \( \Delta t_{\text{char}} \) is 0.18 s, quite close to \( \tau \). The carbody rigidity coefficient \( k \) is in all cases 0.1.

In Fig. 4.59 the pressure and loads time histories are plotted together with their time derivatives.
In order to read these plots, one has to first look at the external pressure time histories. The three ones felt by the carriage are the front, centre and back ones. Time=0 corresponds to the beginning of the front time history, and one can check in the gradients figure (lower plot) that the back time history has a delay of 0.18 s ($\Delta t_{\text{char}}$) with respect to the front one. The $\text{lengthavg}$ is the average of the external pressure time histories among many locations along the carriage, so it shows a much lower gradient, corresponding to a higher rise time to the same maximum pressure.

The internal pressure is then computed applying the $\tau$ model to the $\text{lengthavg}$ external pressure, so the overall delay between the external and the internal pressure time histories is made of three parts:

1. **External pressure probe, car centre distance**: depending on whether the external pressure probe is at the front or at the back of the Free Length the external pressure time history has to be translated in time. This directly influences the load, and it is the main effect the Free Length has on the load. One can visualize it as an example looking at the back probe, where the internal pressure rises before the external pressure does, thus generating a weak negative load before the positive load.

2. **Lower external pressure gradient**: the $\text{lengthavg}$ pressure gradient is much less strong than the input one from the stationary probe, so the internal pressure rise gets delayed, thus increasing positive loads. This is a secondary effect when compared to the other two.

3. **Tau delay**: the time constant directly determines how delayed and deformed the internal pressure time history is with respect to the external one. Higher time constant corresponds to higher delay and deformation, thus increasing the load.

The overall delay and deformation of the internal pressure with respect to the external one gives the load. The carriage free length influence on the load is given by the first two points in the previous list, so it has to be assessed in which conditions they get relevant. In order to do so, one can effectively look at the comparison between $\Delta t_{\text{char}}$ and $\tau$: if $\Delta t_{\text{char}}$ is much lower than $\tau$ then the car Free Length influence on the load is smaller.

For the benchmark case, $\Delta t_{\text{char}}$ is similar to $\tau$, so the car Free Length influence on the load is high; this means that the front load is much different from the back load, as shown in Fig. 4.59. In order to quantify this difference one can compare the various probes loads with the Point $\tau$ one (Tab. 4.23), which comes from directly applying the $\tau$ model to the external pressure probe time history.
If one does not take the influence of the Free Length into account and uses the external pressure from the point probe to compute the internal pressure, then the maximum load is 736 Pa. When taking the Free Length into account this figure can increase by 38% for the Front load (1017 Pa) or decrease by 36% for the Back load, so the effect of the Free Length on the wave encounter load in this case is considerable. It is also interesting to note that the Centre load is very close to the Point Tau one. This conclusion is not straightforward as the Centre probe uses the external pressure from the point probe (gradient 9000 Pa/s) and the internal one from applying the τ model to the lengthavg one (gradient 6000 Pa/s), while the Point τ probe uses the same external pressure, but the internal one from the Point τ model.

The LinRise probe always gives the highest load, as its rise time is much shorter; it is also the most approximate model, as the only physical figures it contains are the maximum and minimum values of pressure, so it does not model neither the CFD external pressure time history nor the Free Length. On the other hand it has to be underlined that much of what is earned when using the most accurate external pressure history instead of the LinRise one (-39% load) can then be lost when taking into account the Free Length influence on the load (-16% instead of -39%). Looking at Fig. 4.59, the LinRise probe has been plotted aligned with the front one to show that they can get quite close. Actually for extremely long Free Lengths the Front load can even get slightly higher than the LinRise one. Generally this would suggest that the LinRise conservativeness might be appropriate for maximum load computations.

When the focus comes to fatigue loads, instead, one can consider that the difference between front load and centre load (37%) remains usually quite close to the difference between the centre and the back one (37%), and this conclusion also hold for the peak-to-peak values of those loads which include the effect of the tail wave. This suggest that the Point Tau probe peak-to-peak load can generally be used for fatigue computation.
4.6.2. Carriage free length sweep

Increasing the Free Length linearly increases the delay in time between the front and the back profile, as shown in Fig. 4.60.

![Carriage free length sweep](image1)

![Carriage free length sweep](image2)

**Fig. 4.60 Carriage free length sweep. Above: 25 m. Below: 100 m.**

The higher delay of the back external pressure time history with respect to the front one results into the internal pressure growing much more slowly than the external ones. This increases the front load and decreases the back one, leaving nearly unaltered the centre one, as also shown in Tab. 4.24. The increase of the front load brings it closer to the LinRise one and the decrease of the back load brings it to a change in sign.
of the peak. As an example, the maximum positive load for the back probe (+350 Pa) actually happens at 1.4 s, so for the tail passing wave and not for the head passing one.

For the highest $L_{\text{free}}$ the front maximum load gets closer to $\text{LinRise}$ (-7%), so one would not earn much in modelling both the correct external pressure time history and the Free Length averaging when compared to just using the $\text{LinRise}$ external pressure time history. This is very important as the front maximum load is the overall maximum one.

The peak-to-peak loads which can be used for fatigue evaluation also increase for higher Free Length, and the increase is close to the sum of the increase of the two single peaks for the front probes. The peak-to-peak values listed in the tables are obtained as difference between maximum and minimum, so they do not take into account further oscillations than the main one, and this is why the back load looks decreasing for the highest Free Length. The peak-to-peak PointTau load looks still appropriate for fatigue estimation, thus the fatigue load seems not to feel the influence of Free Length for the wave encounter scenario, given that the front and the back side of the carriage get swapped once in a while.

From the passenger comfort point of view, a higher Free Length leads to a lower lengthavg external pressure gradient, which in turn gives a lower internal pressure gradient which, depending on the train length, can also lead to a lower maximum value of internal pressure. Even if it has not been plotted, the internal pressure from the Point $\tau$ model shows a 20% higher peak and a considerably higher gradient than the internal one from the lengthavg model for the benchmark case (it has to be highlighted that in this case the train is only 50 m long, while if it had been longer the internal pressure would have had time to equalise, so only the lower gradient advantage would hold). This can be visualised by looking at the gradients in Fig. 4.59: the external pressure gradient for a Free Length equal to 0 would be 9000 Pa/s, while it is 6000 Pa/s for a 50m Free Length.

<table>
<thead>
<tr>
<th>Case</th>
<th>Probe</th>
<th>Max Load (usually head entry press rise)</th>
<th>Relative to Point tau</th>
<th>Relative to Lin Rise</th>
<th>Peak to Peak loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>carriage free length sweep</td>
<td>Tau= 0,20</td>
<td>Front</td>
<td>902</td>
<td>23%</td>
<td>-25%</td>
</tr>
<tr>
<td></td>
<td>dt char= 0,09</td>
<td>Centre</td>
<td>739</td>
<td>0%</td>
<td>-39%</td>
</tr>
<tr>
<td></td>
<td>Lfree= 25</td>
<td>Back</td>
<td>585</td>
<td>-20%</td>
<td>-51%</td>
</tr>
<tr>
<td></td>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1207</td>
<td>64%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>PointTau</td>
<td></td>
<td>736</td>
<td>0%</td>
<td>-39%</td>
</tr>
</tbody>
</table>

A more general way to look at this result is to take into account the comparison between $\Delta t_{\text{char}}$ and $\tau$. An increase in Free Length linearly increases $\Delta t_{\text{char}}$, so the results listed above for an increase of Free Length can be extended as results for an increase in $\Delta t_{\text{char}}$. Those results will also hold in the following sections, where as an example a decrease in $\tau$ would lead to the same main results than an increase in $\Delta t_{\text{char}}$.

The highest Free Length used for this sweep is double as long as the train. This means that the results are not strictly physical, but looking at Fig. 4.60 the external lengthavg pressure gets to the same maximum level of the point probes, so it looks sensed to accept that pressure time history, as the head and tail waves do not happen to encounter the free length together. Star-CCM+ runs have been performed with a 100m long train, but the results from the shorter trains have been preferred for this report as they feature a lower delay between the head entrance and tail entrance waves.
4.6.3. Time constant sweep

Increasing $\tau$ has two main effects. First of all it increases all the positive loads as it takes more time for the internal pressure to follow the external one. Second, increasing $\tau$ brings it further from $\Delta t_{char}$, thus reducing the difference in load between the front and back probe.

Fig. 4.61 Tau sweep. Above: $\tau = 0.1$ s. Below: $\tau = 0.5$ s.

The increase in positive loads coming from increasing $\tau$ is considerable for all the probes but the LinRise one: for the latter probe $\tau$ is already too far from the pressure rise-time to have a strong influence (0.02 s against 0.1 to 0.5 s).
For decreasing \( \tau \) from 0.5 s to 0.1 s, the difference between the \textit{front} and the \textit{back} loads increases strongly from 395 Pa to 710 Pa, and even more strongly in relative terms comparing to the \textit{PointTau} probe (from 34\% to 132\%), so the separation in loads between the \textit{front} and \textit{back} probe remains relevant for all the \( \tau \) values corresponding to a non-tight train.

It is interesting to highlight that in this case the \textit{front} maximum load is closer to the \textit{LinRise} one for the highest \( \tau \) value, as a higher \( \tau \) corresponds to getting further from the external pressure time scale.

It is also interesting to note that for increasing \( \tau \) the \textit{front} load changes slightly for these two values of \( \tau \), as the internal pressure is still nearly equal to zero when the \textit{front} load is maximum (looking at the train entrance wave in Fig. 4.61), so \( \tau \) only slightly influences the internal pressure there. Furthermore the minimum load for the \textit{front} probe is actually stronger for the lower \( \tau \) than for the higher one, as in the latter case the internal pressure does not have time to reach the external one (this effect would not hold for a longer train). These two factors bring the \textit{front} peak-to-peak load to be nearly constant for the two values of \( \tau \), thus allowing the peak-to-peak \textit{PointTau} load to still be close to the average of the \textit{front} and the \textit{back} peak-to-peak ones, so in the end the \textit{PointTau} load looks still suitable for fatigue computations for this 50 m long train.

\begin{tabular}{|c|c|c|c|c|c|}
\hline
Case & Probe & Max Load (usually head entry press rise) & Relative \textit{Point tau} & Relative \textit{Lin Rise} & Peak to Peak loads \\
\hline
\textbf{Tau= 0.10} & \textbf{Front} & 921 & 71\% & -20\% & 1675 \\
\textbf{dt char= 0.18} & \textbf{Centre} & 554 & 3\% & -52\% & 1002 \\
\textbf{Lfree= 50} & \textbf{Back} & 211 & -61\% & -82\% & 406 \\
\textbf{Vrel= 974} & \textbf{LinRise} & 1155 & 114\% & 0\% & 2080 \\
\textbf{PointTau} & 540 & 0\% & -53\% & 978 \\
\hline
\textbf{Tau= 0.50} & \textbf{Front} & 1119 & 18\% & -10\% & 1684 \\
\textbf{dt char= 0.18} & \textbf{Centre} & 954 & 1\% & -23\% & 1432 \\
\textbf{Lfree= 50} & \textbf{Back} & 794 & -16\% & -36\% & 1190 \\
\textbf{Vrel= 974} & \textbf{LinRise} & 1239 & 31\% & 0\% & 1882 \\
\textbf{PointTau} & 948 & 0\% & -24\% & 1422 \\
\hline
\end{tabular}

\textbf{4.6.4. Train and pressure wave travelling in opposite directions}

In all the other sweeps the pressure wave travels in the same direction of the train, in order to highlight the effect of the \textit{Free Length} on the wave encounter loads. When instead it travels in the opposite direction, the separation in time between the \textit{front} and the \textit{back} external pressures and loads decreases, so \( \Delta t_{\text{char}} \) gets further from \( \tau \), so the \textit{Free Length} influence on wave encounter loads decreases.
The *front-back* load difference resulting from the train and the wave travelling in the opposite direction is considerably reduced, but it is generally not enough to bring that difference to a negligible level. For example, in these cases the train travels at 250 km/h and that influence is still considerable. On the other hand, for slower train velocities that influence decreases, as the difference in velocity between the two cases of train and wave directions reduces.

The reduction in *front-back* load difference results in a weaker positive *front* load and a stronger positive *back* one, which is what happens for the peak-to-peak loads as well. The *PointTau* probe remains suitable for fatigue computations.

**Tab. 4.26** Train and pressure waves travelling in opposite directions: load comparison between different probes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Probe</th>
<th>Max Load (usually head entry press rise)</th>
<th>Relative to <em>Point tau</em></th>
<th>Relative to <em>Lin Rise</em></th>
<th>Peak to Peak loads</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benchmark</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td><em>Front</em></td>
<td>1017</td>
<td>38%</td>
<td>-16%</td>
<td>1791</td>
</tr>
<tr>
<td>dt char= 0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lfree= 50</td>
<td><em>Centre</em></td>
<td>745</td>
<td>1%</td>
<td>-38%</td>
<td>1311</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td><em>Back</em></td>
<td>470</td>
<td>-36%</td>
<td>-61%</td>
<td>823</td>
</tr>
<tr>
<td><em>LinRise</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>PointTau</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Train and wave opposite direction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td><em>Front</em></td>
<td>946</td>
<td>28%</td>
<td>-22%</td>
<td>1666</td>
</tr>
<tr>
<td>dt char= 0.12</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lfree= 50</td>
<td><em>Centre</em></td>
<td>741</td>
<td>1%</td>
<td>-39%</td>
<td>1304</td>
</tr>
<tr>
<td>Vrel= 1474</td>
<td><em>Back</em></td>
<td>545</td>
<td>-26%</td>
<td>-55%</td>
<td>957</td>
</tr>
<tr>
<td><em>LinRise</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>PointTau</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1295</td>
</tr>
</tbody>
</table>
4.6.5. Characteristic time sweep

\( \Delta t_{\text{char}} \) is the separation in time between the front and the back external pressure time histories, it corresponds to the ratio between the Free Length and \( V_{\text{rel}} \), and the comparison between \( \Delta t_{\text{char}} \) and \( \tau \) is the main factor which determines the influence of the Free Length on the pressure wave encounter load. For a \( \Delta t_{\text{char}} \) lower than \( \tau \), the influence of the Free Length on the wave encounter load is lower.

In order to strongly vary the \( \Delta t_{\text{char}} \) all the variables together have been taken to the extreme values of the previous sweeps.
For the lowest \( \Delta t_{char} \) case the difference between the front and the back loads is the lowest, but still it is not negligible (116 Pa, 12% of the PointTau maximum load).

For higher \( \Delta t_{char} \) (and lower \( \tau \)) the front maximum load gets closer to the LinRise one, as the difference between the front and back maximum load increases.

For the highest \( \Delta t_{char} \) the difference between the front and the back loads becomes huge not only in terms of maximum load but also in terms of shape, as the back load gets much stronger peaks with opposite signs when compared to the front one. This happens because the internal pressure has already risen considerably before the pressure wave crosses the back of the car, causing the maximum positive load to happen for the tail entrance wave for the back probe. For this reason in the highest \( \Delta t_{char} \) case the PointTau peak-to-peak load is not suitable for fatigue calculations anymore, as it does not lay in between the front and back peak-to-peak load anymore. In this case even the Centre probe is not suitable for modelling peak-to-peak load at the ends of the carriage, so each location should have the load computed using its dedicated probe.

When it comes to maximum load computations, then the front probe gets closer to the LinRise one for the higher \( \Delta t_{char} \), as the difference between front and back load increases.

**Tab. 4.27 Dt char sweep: load comparison between different probes.**

<table>
<thead>
<tr>
<th>( \Delta t_{char} ) sweep</th>
<th>Case ( \tau = 0.50 )</th>
<th>Probe</th>
<th>Max Load (usually head entry press rise)</th>
<th>Relative to Point Tau</th>
<th>Relative to Lin Rise</th>
<th>Peak to Peak loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>1009</td>
<td>6%</td>
<td>-19%</td>
<td>1514</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre</td>
<td>949</td>
<td>0%</td>
<td>-23%</td>
<td>1424</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td>893</td>
<td>-6%</td>
<td>-28%</td>
<td>1340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LinRise</td>
<td>1239</td>
<td>31%</td>
<td>0%</td>
<td>1882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PointTau</td>
<td>948</td>
<td>0%</td>
<td>-24%</td>
<td>1422</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta t_{char} = 0.06 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front</td>
<td>1065</td>
<td>97%</td>
<td>-8%</td>
<td>1928</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centre</td>
<td>568</td>
<td>5%</td>
<td>-51%</td>
<td>1029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back</td>
<td>464</td>
<td>-14%</td>
<td>-60%</td>
<td>991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LinRise</td>
<td>1155</td>
<td>114%</td>
<td>0%</td>
<td>2080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PointTau</td>
<td>540</td>
<td>0%</td>
<td>-53%</td>
<td>978</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta t_{char} = 0.10 )</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Front</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Centre</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Back</td>
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<tr>
<td>LinRise</td>
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<td>PointTau</td>
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<tr>
<td>( \Delta t_{char} = 0.37 )</td>
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<tr>
<td>Front</td>
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</tr>
<tr>
<td>Centre</td>
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</tr>
<tr>
<td>Back</td>
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<td></td>
</tr>
<tr>
<td>LinRise</td>
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<td></td>
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</tr>
<tr>
<td>PointTau</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Comparative Table and conclusions for wave encounter scenario

Tab. 4.28 Overall comparative table. External pressure time history from a stationary probe in the Aerotrain bench. Sim. (\(Vtr= 250 \text{ km/h}, Stu=63 \text{ m2}, Str=11 \text{ m2}, Ln=4 \text{ m}, Lax=0, Ltr=50\)).

<table>
<thead>
<tr>
<th>Case</th>
<th>Probe</th>
<th>Max Load (usually head entry press rise)</th>
<th>Relative to Point tau</th>
<th>Relative to Lin Rise</th>
<th>Peak to Peak loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td>Front</td>
<td>1017</td>
<td>38%</td>
<td>-16%</td>
<td>1791</td>
</tr>
<tr>
<td>dt char= 0.18</td>
<td>Centre</td>
<td>745</td>
<td>1%</td>
<td>-38%</td>
<td>1311</td>
</tr>
<tr>
<td>Lfree= 50</td>
<td>Back</td>
<td>470</td>
<td>-36%</td>
<td>-61%</td>
<td>823</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1207</td>
<td>64%</td>
<td>0%</td>
<td>2124</td>
</tr>
<tr>
<td>PointTau</td>
<td>736</td>
<td>0%</td>
<td>-39%</td>
<td>1295</td>
<td></td>
</tr>
<tr>
<td>carriage free length sweep</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td>Front</td>
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<td>23%</td>
<td>-25%</td>
<td>1588</td>
</tr>
<tr>
<td>dt char= 0.09</td>
<td>Centre</td>
<td>739</td>
<td>0%</td>
<td>-39%</td>
<td>1301</td>
</tr>
<tr>
<td>Lfree= 25</td>
<td>Back</td>
<td>585</td>
<td>-20%</td>
<td>-51%</td>
<td>1029</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1207</td>
<td>64%</td>
<td>0%</td>
<td>2124</td>
</tr>
<tr>
<td>PointTau</td>
<td>736</td>
<td>0%</td>
<td>-39%</td>
<td>1295</td>
<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td>Front</td>
<td>1128</td>
<td>53%</td>
<td>-7%</td>
<td>1963</td>
</tr>
<tr>
<td>dt char= 0.37</td>
<td>Centre</td>
<td>745</td>
<td>1%</td>
<td>-38%</td>
<td>1311</td>
</tr>
<tr>
<td>Lfree= 100</td>
<td>Back</td>
<td>350</td>
<td>-53%</td>
<td>-71%</td>
<td>688</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1207</td>
<td>64%</td>
<td>0%</td>
<td>2124</td>
</tr>
<tr>
<td>PointTau</td>
<td>736</td>
<td>0%</td>
<td>-39%</td>
<td>1295</td>
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</tr>
<tr>
<td>Tau sweep</td>
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<td></td>
</tr>
<tr>
<td>Tau= 0.10</td>
<td>Front</td>
<td>921</td>
<td>71%</td>
<td>-20%</td>
<td>1675</td>
</tr>
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<td>dt char= 0.18</td>
<td>Centre</td>
<td>554</td>
<td>3%</td>
<td>-52%</td>
<td>1002</td>
</tr>
<tr>
<td>Lfree= 50</td>
<td>Back</td>
<td>211</td>
<td>-61%</td>
<td>-82%</td>
<td>406</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1155</td>
<td>114%</td>
<td>0%</td>
<td>2080</td>
</tr>
<tr>
<td>PointTau</td>
<td>540</td>
<td>0%</td>
<td>-53%</td>
<td>978</td>
<td></td>
</tr>
<tr>
<td>Tau= 0.50</td>
<td>Front</td>
<td>1119</td>
<td>18%</td>
<td>-10%</td>
<td>1684</td>
</tr>
<tr>
<td>dt char= 0.18</td>
<td>Centre</td>
<td>954</td>
<td>1%</td>
<td>-23%</td>
<td>1432</td>
</tr>
<tr>
<td>Lfree= 50</td>
<td>Back</td>
<td>794</td>
<td>-16%</td>
<td>-36%</td>
<td>1190</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1239</td>
<td>31%</td>
<td>0%</td>
<td>1882</td>
</tr>
<tr>
<td>PointTau</td>
<td>948</td>
<td>0%</td>
<td>-24%</td>
<td>1422</td>
<td></td>
</tr>
<tr>
<td>train and wave opposite direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau= 0.20</td>
<td>Front</td>
<td>946</td>
<td>28%</td>
<td>-22%</td>
<td>1666</td>
</tr>
<tr>
<td>dt char= 0.12</td>
<td>Centre</td>
<td>741</td>
<td>1%</td>
<td>-39%</td>
<td>1304</td>
</tr>
<tr>
<td>Lfree= 50</td>
<td>Back</td>
<td>545</td>
<td>-26%</td>
<td>-55%</td>
<td>957</td>
</tr>
<tr>
<td>Vrel= 1474</td>
<td>LinRise</td>
<td>1207</td>
<td>64%</td>
<td>0%</td>
<td>2124</td>
</tr>
<tr>
<td>PointTau</td>
<td>736</td>
<td>0%</td>
<td>-39%</td>
<td>1295</td>
<td></td>
</tr>
<tr>
<td>Tau= 0.50</td>
<td>Front</td>
<td>1009</td>
<td>6%</td>
<td>-19%</td>
<td>1514</td>
</tr>
<tr>
<td>dt char= 0.08</td>
<td>Centre</td>
<td>949</td>
<td>0%</td>
<td>-23%</td>
<td>1424</td>
</tr>
<tr>
<td>Lfree= 25</td>
<td>Back</td>
<td>893</td>
<td>-6%</td>
<td>-28%</td>
<td>1340</td>
</tr>
<tr>
<td>Vrel= 1474</td>
<td>LinRise</td>
<td>1239</td>
<td>31%</td>
<td>0%</td>
<td>1882</td>
</tr>
<tr>
<td>PointTau</td>
<td>948</td>
<td>0%</td>
<td>-24%</td>
<td>1422</td>
<td></td>
</tr>
<tr>
<td>dt char sweep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau= 0.10</td>
<td>Front</td>
<td>1065</td>
<td>97%</td>
<td>-8%</td>
<td>1928</td>
</tr>
<tr>
<td>dt char= 0.37</td>
<td>Centre</td>
<td>568</td>
<td>5%</td>
<td>-51%</td>
<td>1029</td>
</tr>
<tr>
<td>Lfree= 100</td>
<td>Back</td>
<td>464</td>
<td>-14%</td>
<td>-60%</td>
<td>991</td>
</tr>
<tr>
<td>Vrel= 974</td>
<td>LinRise</td>
<td>1155</td>
<td>114%</td>
<td>0%</td>
<td>2080</td>
</tr>
<tr>
<td>PointTau</td>
<td>540</td>
<td>0%</td>
<td>-53%</td>
<td>978</td>
<td></td>
</tr>
</tbody>
</table>
In Tab. 4.28 the red fields corresponds to the main variable which define the case.

The yellow fields have been highlighted as they show the load difference between the front and back probe, which is the main effect of the Free Length on the wave encounter loads. One should be careful as for high \( \Delta t \text{char} \) this does not hold as the back probe peaks get swapped (the maximum load happens at the tail entrance wave).

The cyan fields highlight the difference between the maximum front load and the LinRise one for the cases in which they are closer. In those cases one would not earn much in modelling both the correct external pressure time history and the Free Length averaging when compared to just using the LinRise external pressure time history.

The most relevant conclusions for the wave encounter scenario are the following:

- The influence of the carriage free length on the loads in the pressure wave encounter scenario has never been found negligible in the cases considered. This influence can be quantified by the difference between the front and back probes maximum loads, which is never less than 12% (114 Pa) for the cases considered. This difference gets higher if \( \Delta t \text{char} \) is close to or higher than \( \tau \).

- The front probe always shows the strongest maximum, minimum and peak-to-peak loads as it is by definition the first one which feels the travelling pressure waves. For the same reason the back probe always feels the weakest maximum, minimum and peak-to-peak loads.

- The centre probe maximum load is always close to the PointTau one. The difference among the two is never higher than 5%, and also this difference gets higher if \( \Delta t \text{char} \) is close to or higher than \( \tau \).

- With regard to maximum load estimates one should distinguish between different locations along the carriage:
  - When looking for the maximum load close to the centre of the carriage, the PointTau maximum load is suitable as it is always close to the Centre one. The PointTau load is about between 25% and 50% lower than the LinRise one, so it is very convenient to model both the right external pressure distribution and Free Length averaging in this case.
  - When looking for the maximum load at both carriage ends, one should always look at the Front load, which is closer to the LinRise one than to the PointTau one. So for the cases analysed it is still slightly (between 7% and 25%) convenient to model both the right external pressure distribution and Free Length averaging, but it must be underlined that it would be absolutely not conservative to only model the right external pressure distribution and not the Free Length averaging. For even higher Free Length values LinRise can even become slightly not conservative.

- With regards to fatigue loads, given that the two ends of the carriage get swapped once in a while, the PointTau peak-to-peak load is suitable, except when the \( \Delta t \text{char} \) is too high. In the latter case nor the PointTau nor the Centre probes would be suitable, so each location should have the load modelled with its dedicated probe.
4.7. Conclusions for single train entry and passage

One of the main achievements of this thesis work has been developing a **Star-CCM+ simulation set-up** capable of modelling both the train entry into the tunnel and the whole tunnel crossing. This set-up has been validated with the AeroTRAIN benchmark case in terms of maximum gradient of the nose entry compression wave, it allows for reasonably quick runs and, also thanks to the overset mesh approach, the user can choose to simulate quite extreme cases in terms of track spacing.

A **fitting procedure** has also been developed which can predict the nose entry compression wave pressure history for any parameters combination chosen. In order to do so, it first employs the results from Star parameter sweeps simulations to predict the pressure drop and maximum pressure gradient of the head compression wave, then it uses those quantities to determine an arctan shape for the pressure time history. The fitting procedure results showed about 6% error both on the predicted maximum gradient and on the predicted maximum load when compared to the Star results; this confirms the choice done in terms of characteristic length formulation and also the consistency of the arctan shape pressure time history.

Another useful result of the fitting procedure is the formulation of a characteristic length for the maximum gradient prediction which can be employed to hugely improve NUMSTA accuracy in terms of the maximum gradient of the head compression wave for any parameters combination chosen.

The automation of the Star simulation set-up using Java macros and start files allowed to execute more than 17 **parameter sweeps simulations** for the single train entry case. The most influent parameters on the load for sure were the train speed and the tunnel cross section, with head entry compression wave loads ranging from 215 Pa to 1653 Pa for a for a τ of 0.2 s from the simulations performed for those sweeps. The train cross section variation has the same kind of influence of the tunnel cross section variation, but it is weaker as the train cross section does not vary much between different trains when compared to the tunnel one. The nose length and track spacing sweeps showed that those two variables influence on loads is lower, especially for the track spacing one, but still not negligible.

A further part of the work was to assess and **improve NUMSTA accuracy** when computing loads on non-tight trains. The main problem NUMSTA has when trying to compute loads for non-tight trains is that, being it a 1D code, it cannot simulate the 3D interaction between the train nose and the tunnel portal, so it cannot properly predict the rise-time of the nose entry compression wave, which gives a significantly steeper pressure wave, thus making NUMSTA conservative when computing loads on non-tight train unless the front length is extended. That adjustment has been developed using a nose length for the NUMSTA train proportional to the fitting procedure gradient estimation characteristic length, which has been tuned using coefficients found through the Star parameters sweeps. This adjustment brings NUMSTA maximum gradient close to the fitting procedure one (about 6% error) which, given also the good accuracy of NUMSTA prediction of the pressure rise across the head compression wave, allows NUMSTA to reach a satisfactory accuracy in predicting the whole pressure signature, and so the loads. This conclusion is very useful, as NUMSTA is extremely cheaper to run than Star, so by employing this front length adjustment NUMSTA becomes a very efficient way to compute head entry compression wave loads. On the other hand, this length adjustment is not valid for the train crossing inside the tunnel, in which case a different adjustment is needed (Chapter 5).

The last part of the work regarding the single train tunnel entrance was to employ the “free-length” model for load prediction to assess the influence of the carriage free length on the loads for a non-tight train in the **wave encounter scenario**. This influence was found to be extremely important and never negligible for non-tight trains, especially when one wants to compute the loads on the train walls near the carriage ends. Furthermore, multiple models for load prediction have been compared in that section: the most approximate “LinRise” model uses as external pressure a 0.02s linear rise to the maximum value of pressure, the more accurate “PointTau” model uses the correct pressure signature but does not model the **Free Length** influence, while the most accurate **Free Length** model also computes the influence of the carriage free length and probe position. The conclusion of this analysis allowed to assess the performance of the different models for load computation: the “LinRise” model is the most conservative, the “PointTau” model is the most optimistic but it can become
not conservative near the carriage ends, and the most accurate “LinRise” model is more optimistic than the “LinRise” one and less optimistic than the “PointTau” one.

In the end, computing the loads on the train walls coming from travelling pressure waves generated the train tunnel entry turned out to be a complex task, as the problem depends on many variables, many of which do not even depend on the train design. The variables assessed in this work have been train velocity, train and tunnel cross sections, train nose length, track spacing, time constant for pressure tightness, Free Length of the carriage, external pressure probe position, and also pressure wave travelling direction relative to the train. Not only multiple variables are needed to compute the loads, but also many tools are available to do so. The most accurate one used is Star-CCM+, but also results from NUMSTA and even from just computing the pressure increase across the nose entry compression wave (“LinRise” method) can be used to compute the loads, so an accurate evaluation of each of those tools errors was needed.

But the structural loads a train withstands when encountering its own pressure signature are neither the only ones nor the strongest ones it feels while crossing the tunnel, as the train crossing phase, developed in the following section, generates stronger structural stresses on the train walls.
5. Train crossing inside tunnel

The main goal of the train crossing simulations is to assess the pressure loads on a train when it meets another one inside a tunnel. In order to visualise the source of this loads, one can visualise a single train travelling into a tunnel, in particular the pressure is lower in the train-tunnel annulus area than in the portions of tunnel upstream and downstream the train. Given that, if two trains travelling in opposite directions meet, then a probe on a train wall feels a very quick pressure decrease when the opposing train nose passes in front of it and a quick pressure increase when the opposing train tail passes the probe. The pressure changes felt by the probe can have an intensity of about 1000 Pa and a time scale of about 0.08 s for trains travelling at 250 km/h, so they can cause at least as much load as the wave encounter does.

In order to compute the train wall load time history, the same approach of the single train tunnel entry simulations has been adopted, so at first a benchmark case simulation has been set-up using Star. After having analysed Star results for the benchmark case, a fitting procedure has been developed to predict the pressure time history for the benchmark case. The Star parameters sweeps simulations have been executed to determine the influence of several parameters on the train crossing phase and to extend the fitting procedure to take into account the influence of those parameters.

Another task for the train crossing analysis was to assess and possibly improve NUMSTA accuracy when predicting train crossing loads. As for the single train tunnel entry, the pressure change rise time computed by the fitting procedure developed to fit Star pressure time history were used to increase NUMSTA accuracy and bring NUMSTA results closer to Star ones.

A key feature of the train crossing pressure loads is that they are not homogeneous on the train cross section, while the travelling wave loads are. If for example the probed train has two point pressure probes, one for each side of the train, while the probe on the train-to-tunnel side (the train side closer to the tunnel wall) only feels a smooth pressure decrease as the opposing train nose passes, the probe on the train-to-train side directly feels the 3D pressure field around the opposing train nose. This causes very quick and strong pressure changes on the train-to-train side wall, denoted “3D effect”, which cause a very strong load on that side of the train structure. These loads can even lead to incidents, as on the 20/07/2015, when one of the two panel of a brand-new regional train carriage door separated inside a tunnel in the Firenze-Arezzo line in Tuscany, most probably due to the encounter of a high speed train [36].

5.1. Star simulations for benchmark case

A “benchmark case” for the results can be defined with two 11 m² cross section 4 m nose length trains travelling at 250 km/h in a 93 m² tunnel, with a 1 m distance between the two trains wall, corresponding to a 4 m track spacing. Another “extreme benchmark case” to test the set-up has been taken as the same case but with a 63 m² tunnel with 3.5 m track spacing corresponding to a 0.5 m distance between the trains. The choice of two different benchmark cases can be confusing, but it was needed to test the solver settings for the worst case.

Having the single train tunnel entry simulation set-up for both these cases, the most straightforward way to set-up the benchmark case train crossing simulation is to mirror the domain and model both trains entrance and passage of the tunnel. This train entry and crossing simulation has been set-up and it was capable to simulate both the travelling train entry pressure waves and the train crossing phase, but the two phenomena could not be separated from each other. Given that the goal of the train crossing simulations is to compute the train crossing loads only, the train entry and crossing set-up was not appropriate, so a new set-up was chosen with both train starting from inside the tunnel.

In the following part of this section both these setups will be introduced. After that, the mesh and solver settings for the train starting from inside the tunnel case will be described and in the end that case results will be visualised and commented.
5.1.1. Train entry and crossing case

This case can be very easily set-up for the for the 63 m² tunnel “extreme benchmark case” starting from the single train entry one for the same combination of parameters. One just has to add an outer domain at the far end of the tunnel, as well as another train symmetrical to the first one. Also one has to refine the tunnel centre area where the two trains will meet as well as the two portals, where the travelling train entry pressure waves are generated.

The computational domain made of one tunnel and two outer domains for this simulation is shown in Fig. 4.61.

The chosen tunnel length is 500 m, and the chosen train length is 94 m. These values have been tuned in order to have the train crossing happening when the train entry pressure waves are further from the tunnel centre.

Another task in order to simulate the train crossing case is to define several pressure probes on the train. Quite many probes are needed in order to correctly assess the 3D effect, which causes pressure peaks on the train wall as the 3D pressure field around the opposing train nose passes it. In order to record the external pressure on the train wall needed for load computation, 40 point pressure probes have been placed on the train wall. Those probes were placed in five locations 15 m after each other, so using eight point probes for each train cross section, as shown in Fig. 5.9.
Fig. 5.2 Train point probes pressure time histories - whole tunnel passage for the 63 m² tunnel.

In Fig. 5.2 the results from most of the 40 point probes on the train wall are shown. The large scale pressure variations are due to the train entry travelling waves, the first of which is the compression wave due to the opposing train entry into the far tunnel portal, and the second of which is the expansion wave due to the probed train tail entry. The magnitude of the nose entry compression waves is about 1300 Pa, in accordance with the results from the single train entry simulations. Due to the superposition of the four travelling pressure waves generated by the two trains entering the two portals, the pressure felt at the train wall smoothly varies between about +1500 Pa and -4000 Pa during the whole tunnel passage.

Looking at the train crossing phase, the probes on the train wall show very strong oscillations, highlighted in Fig. 5.3, which magnifies the train crossing phase in Fig. 5.2. Due to problems in the probes geometrical definition, which have been solved in the following simulations, only the probes at 15, 30, 45 and 75 m from the train nose are shown in Fig. 5.2 and Fig. 5.3.

The main feature one can visualise in Fig. 5.3 is that the train crossing disturbance in the pressure time history is superposed with pressure variations coming from train entry travelling pressure waves. In particular, when the opposing train nose passes the point probe, it records a pressure reduction, while when the opposing train tail passes it records a pressure increase. In Fig. 5.3 one realises that between these two events the background level of pressure changes because of the travelling train entry pressure waves.

Even if the train crossing has been placed in the instant where the travelling pressure waves are further from the train meeting zone, the problem is that the travelling train entry pressure waves have already crossed the tunnel several times, so even if their centre is far from the train crossing location a non-negligible background oscillation still remains.

This simulation is capable of modelling the superposition of the two phenomena and its results are perfectly physical, but one cannot evaluate the loads due to the train crossing separately from the one due to the travelling waves, so this set-up has been discarded.
5.1.2. Trains starting from inside the tunnel case

In order to avoid the trains meeting the travelling pressure waves during the train crossing phase, one can make the two trains start already from inside the tunnel. By doing so the two trains can be started quite close one another and the outer domains are not needed, so the simulation can be much quicker.

The domain for this simulation is a 2000 m long tunnel for the 93 m² tunnel “benchmark case”. Creating that geometry using the Star CAD editor revealed a problem, as the Star CAD editor domain is a 1000 m long box, so in order to create a 2000 m tunnel one has to create multiple subsections of the tunnel superposed one with each other, and then translate and attach them later on, in the Star solver. Given the simple shape of the computational domain, there is no need to show it in a picture.

In order to introduce this simulation one can again look at the train wall point probes pressure time histories.

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**Fig. 5.3** Train point probes pressure time histories - train crossing only for the 63 m² tunnel.

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**Fig. 5.4** Train point probes pressure time histories - whole simulation for the 93 m² tunnel.
Fig. 5.4 visualises the simulation time evolution. At the instant t=0 both trains have been started using a step increase of velocity from 0 to 250 km/h, from initial positions at 100 m from the tunnel centre (so 200 m distance between the two trains noses). The solver could handle such an abrupt initialisation, so a complicated starting procedure such as the one used for the train entrance simulations was not needed. Such sudden train starting generates travelling pressure waves, mainly one compression wave for each train nose and one expansion wave for each tail, close to what happened for the shocktube in Section 2.1.7. These waves are visible in the first 1 s physical time of simulation. The first pressure rise near t=0 s is the backward travelling compression wave generated by the probed train nose starting, it is interesting to note that the probes closer to the train nose first feel the probed train nose starting backward travelling compression wave, while the ones closer to the train tail first feel the probed train tail starting forward travelling expansion wave. The ones at the middle of the train feel the two disturbances at about the same time. At about t=0.4 s the flow field around the probed train is established, and the probed train starting waves have passed, while the other train starting waves are about to reach the probed train. The first one to do so is the opposing train nose starting compression wave, recorded at the probed train at about 0.6 s, while the opposing train tail starting expansion wave gets to the probed train at about 0.85 s. At this point all of the trains starting pressure waves have reached the probed train, so the train probes are about to be ready to properly record the train crossing, and the train has travelled 59 m. But a further margin of about 40 m has been taken before the trains meeting, in order to allow the secondary pressure variations that take place between 1 and 1.4 s of physical time to damp out. These secondary pressure oscillations can be due to several factor, one of which is the secondary wave generation when a pressure wave meets a flow cross sectional area change, as described by Eq. (2.24) in Section 2.2.3. The extent of the secondary pressure waves oscillations on the train crossing phase looks limited enough; this can be visualised in Fig. 5.5, noting that the head passing pressure drops are quite well aligned one with each other, so the background pressure variation level is acceptable.

Fig. 5.5 Train point probes pressure time histories - train crossing only for the 93 m² tunnel.

The train wall point probes pressure time histories in Fig. 5.5 are the most important result of the train crossing simulation. As described earlier, each of the five groups of eight probes each is placed at a distance from the train nose (Fig. 5.9). Each probe group is made of three probes for each train side, plus one for the train floor and one for the train roof. They all begin recording the opposing train nose passing at a value of pressure of -800 Pa, then the probes on the train-to-tunnel side show a smooth monotone pressure decrease to about -1600 Pa, which is about double the initial value, as the two trains low pressure regions approximately sum up for the train crossing. On the
contrary, the probes on the train-to-train side show both a positive and a negative peak in the pressure decrease due to the so-called 3D effect. One can attribute the positive peak to the stagnation region in front of the opposing train nose, and the negative one as the lower pressure region due to the flow accelerating around the opposing train nose corners. The pressure remains at -1600 Pa after the opposing train nose passing, then, 0.7 s after the nose passing one can visualise the tail passing.

The opposing train tail passing is recorded on the probed train as a pressure increase, from about -1600 Pa to about -900 Pa, as the pressure cannot come back to the -800 Pa initial value because of the flow losses in the train wake. An interesting feature of the train-to-train wall point probes tail passing is that they only show the 3D effect negative peak and not the positive one. This is because of the wake which prevents a neat stagnation region to take place at the train tail, as would happen in a potential flow. It is interesting to note that it was the stagnation region in front of the train nose which generated the positive pressure peak in the nose passing pressure time histories. This feature will be visualised later on in this chapter.

When comparing the point probe pressure time histories for the train entry and crossing case with the trains starting from inside the tunnel case ones (Fig. 5.3 and Fig. 5.5), it is evident that the latter are much better in order to compute the train passing loads, as the background pressure is constant in that case thanks to the travelling pressure wave being very far from the train in the crossing phase.

At this point the best case among the two is the trains starting from inside the tunnel one, so it will be the focus for the remainder.

5.1.3. Mesh and solver settings

The mesh main features have been kept the same as for the single train entry simulations, featuring a 0.25 m general size overset mesh with refined regions around both trains’ noses and tails and using three mesh layers, a stationary one for the tunnel plus one for each train. As for the single train entry simulations, the mesh general size and the time step size must be chosen together to respect the CFL requirement.

An overview of the mesh around one train nose is in Fig. 5.6. The general size of 0.25 m is the one in the light yellow planes, in which one can also appreciate the overset region boundary (the overlap region). The moving region, fixed with respect to the train, is highlighted by the horizontal blue plane. One can see that it extends far in front of the train in order not to influence the flow field there. Looking at the green mesh on that plane, one can also visualise the refined region around the train nose, in which the cell-size is half the base one, as well as the prismatic layers. The empty spaces near the tunnel wall are due to the overlap region between the moving train region and the stationary tunnel one.
In order to visualise the moving regions’ intersection procedure one can look at Fig. 5.7, in which the train on the left side travels towards the figure point of view, while the train on the right side (travelling in the opposite direction) has been hidden in order to show the mesh there.

The light yellow horizontal plane is a section plane of both the moving regions. On this plane one can visualise the white lines overset mesh boundaries where the two moving region intersect each other. Besides, the region between the two parallel white lines is the overlap region, where the two mesh layers are superposed and the solution is interpolated from one layer to the other. A numerical error is always introduced by this interpolation, and this can be visualised in Fig. 5.8.

Still looking at the overlap region in Fig. 5.7 one can appreciate its being composed by one single layer of cells, thanks to the choice of a trimmed mesh with the same size for both regions. In the area where the two refined
regions near the trains’ noses intersect, one can see that the overset mesh boundary is a single white line, as the overset mesh algorithm chooses to place a clean interface there instead of an overlap region.

A very important feature of the overset mesh for this case is that the interpolation between the two trains moving regions is performed in a single step between those two regions, as they do overlap each other. If those two regions did not overlap each other with a big enough overlap region then the overset mesh algorithm would have chosen to perform the interpolation in two step, first from a moving region to the stationary tunnel one, and then from the stationary to the other moving one, effectively doubling the interpolation error. This consideration is also important when it comes to computing the CFL condition for this case: given that the two moving regions directly interact, then one region might see a flow velocity up to about the opposing train velocity with respect to the moving region itself, thus corresponding to a value of double the train velocity.

Another feature one can appreciate in Fig. 5.7 is the boundary between the right hand side moving region and the stationary tunnel region, near the right hand side tunnel wall. In that area the stationary region is only made of the prismatic layers plus a single layer of cells, so the overlap region interpolation is likely to generate an error there as well (which also can be visualised in Fig. 5.8). When setting up the overset mesh approach it is of paramount importance to follow the User Guide advices, especially when deciding the overset region size and shape. In particular, it is advised to choose the moving region as big as possible, so that the algorithm itself can choose where to cut it and how much to extend the interpolation region. In this case the train moving region lower boundary was taken coincident with the ground, while the two lateral boundaries were placed completely outside the tunnel wall (for the train-to-tunnel side) and about 1 m beyond the tunnel symmetry plane for the train-to-train side.

A visualisation of the overset mesh interpolation error in the overlap region is Fig. 5.8, taken from the train entry case.

![Visualisation of the overset mesh interpolation errors in the overlap region.](image)

The visual indication of the interpolation error can be seen when looking closer at isobars at the moving region boundary. One can see that in the overlap region the isobars coming from the moving region are superposed to the one coming from the background region. If the interpolation were perfect, the two isobars would be perfectly superposed, while because of the interpolation error they cross without being perfectly superposed, as indicated by the arrows in Fig. 5.8. It must be said that Fig. 5.8 comes from the train entry case, and at the transversal cutting plane location the background mesh in the tunnel was coarsened, with a size of 0.5 m as opposed to the 0.25 m of the moving region, thus making the interpolation error in the overlap region more evident. The most important conclusion with regard to the overset mesh interpolation error is that the level
of accuracy is given by the coarsest cell size among the two overlapping layers. Furthermore, a mismatch in
the isobars can be found also in sliding mesh in-place interfaces, even if the interpolation error in that case is
generally lower than the one in the overset mesh overlap region.

When it comes to the solver settings for the trains starting from inside the tunnel case, the most relevant CFL
condition for time integration accuracy does not need to be computed with the speed of sound but with the
two trains’ relative speed. This is because the interesting output of this simulation is not the travelling pressure
wave propagation at the speed of sound, but the train crossing phase, and, given the overset mesh
interpolation behaviour in that phase, the characteristic velocity of that phenomenon is double the train
velocity.

A brief mesh convergence study has been performed for the more extreme 63 m² tunnel with 3.5 m track
spacing case in order to test the settings for the most challenging case, and it is described in Table 5.1.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mesh Size</th>
<th>Time Step Size</th>
<th>CFL (2V_{tr})</th>
<th>(\Delta p_{P_{TP}}) [Pa]</th>
<th>(\Delta p_{end}) [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final set-up</td>
<td>0.25 m</td>
<td>0.002 s</td>
<td>1.1</td>
<td>2026</td>
<td>-1278</td>
</tr>
<tr>
<td>Small time step</td>
<td>0.25 m</td>
<td>0.001 s</td>
<td>0.55</td>
<td>2027</td>
<td>-1282</td>
</tr>
<tr>
<td>Finest settings</td>
<td>0.125 m</td>
<td>0.001 s</td>
<td>1.1</td>
<td>2032</td>
<td>-1294</td>
</tr>
</tbody>
</table>

In Tab. 5.1 one can read the mesh general size in the moving region (so in the refined area around the trains
noses and tails the size is always half of it), the time step size (which was constant throughout the simulation),
the CFL number computed using Eq. (3.17) computed with double the train velocity and the general mesh size
of 0.25 m, and two results considered the most representative for the solution accuracy. The \(\Delta p_{P_{TP}}\) is the
pressure difference between the positive and the negative peaks of the pressure time history as recorded
during the head passing by the train probe place at the train-to-train side 60 m behind the train nose and 2 m
above the ground. \(\Delta p_{end}\) is the change in pressure between before and after the nose passing.

The results of the mesh convergence study, together with the confidence coming from using very similar mesh
and solver settings as for the train entry case, confirm the final set-up chosen, as the variations of the two
outputs among one simulation and the other was negligible. A feature of the two more expensive simulations
was the appearance of small amplitude and very high frequency oscillations especially in the pressure gradient
time histories, which was already a reason good enough to prefer the final settings to the more expensive
ones. More simulations have also been performed to define the initial distance between the train noses, which
has been fixed at 200 m as explained earlier.

The final mesh used has about 5 million cells, two millions of which are in the moving domains and 3 million
of which are for the background tunnel mesh. This causes quite an increases in time-step CPU elapsed times
compared to the two million cells meshes used for the single train entrance cases. The increase in CPU times
is also due to the much more complicated task the overset mesh algorithm must face, as the interfaces
between three different regions must be computed, and the moving regions are now double as long as they
were for the single train entry runs. This causes about 30% the overall time-step elapsed CPU time to be
dedicated to the overset mesh update. One can realise that this simulation set-up would be extremely
expensive to implement for a real train geometry.

The turbulence settings have been left unaltered, using the SST k-\(\omega\) model together with an all-\(y^+\) wall function
with a roughness set at \(k_s = 5\) mm at the tunnel walls. Also the prism layers have been left unaltered.

A further visualisation of the train mesh together with the point and surface pressure probes is shown in Fig.
5.9.
In Fig. 5.9 one can appreciate the extent of the refined regions around the train nose and tail for the final setting benchmark case. Also represented in Fig. 5.9 are the point probes used to record the external pressure time histories needed to compute the loads, as well as the surface regions used to record the average pressure on each carriage surface in order to then compute the internal pressure for the load with the “free-length” model. A total of 40 point probes have been placed at 15, 30, 45, 60 and 75 m from the train nose, so each cross section includes eight point probes, three for each train side plus one for the roof and one for the floor of the train.

5.1.4. Results overview for benchmark case

In order to give a comprehensive overview of the results for the 93 m² tunnel case, the train crossing simulation can be divided into four main parts, and flow visualisations can be given for each of those parts. As for the train entry simulations, these pictures comes from animations.
1. Flow field before train meeting:

Looking at the pressure field before the two trains meet (Fig. 5.10), it is evident that the pressure in the train-tunnel annulus area is lower than upstream and downstream of the train, and this can be justified when looking at the flow velocities in this phase. Already before the trains meet one can appreciate the 3D flow field in front of the train nose, which have been kept transparent in order not to hide the pressure field beyond it. Particularly important are the stagnation region (higher pressure region) in front of the train nose, as well as the lower pressure region where the flow accelerates around the train nose sides. One can already note that on the tunnel wall on the right hand side of the picture the variation of pressure is monotone, while on the left hand side one it shows the 3D effect peaks.

Looking at the flow velocities before the trains meet (Fig. 5.11), one can first see that in the tunnel region between the two trains’ noses the velocity is very close to zero, as the case is symmetrical with respect to the centre-tunnel transversal plane. The trains are moving one towards the other, and the flow in the train-tunnel annulus area is directed in the opposite direction with respect to the train speed, in order to move the air the train nose is displacing towards the train tail to fill the “empty room” left by the tail moving forward. Given that the pressure in the tunnel area between the two trains noses is close to zero, the pressure in the train-tunnel annulus will be lower than zero (about -800 Pa) as the flow velocity there is higher. One can also appreciate the 3D flow field where the flow accelerates around the train nose. In this picture the black arrows represent the component of velocity parallel to the train direction, while the white ones represent the horizontal velocity component perpendicular to the train wall.
2. Trains Noses meeting:

![Fig. 5.12 Trains heads meeting](image)

When the two train noses meet (Fig. 5.12), one can see the interaction of the two stagnation regions in front of the trains. In this picture the body of the train on the right hand side of the picture has been hidden, while its nose has been kept transparent to show the tunnel in front of it.

![Fig. 5.13 Pressure and velocity fields at heads meeting](image)

Looking at the velocity field at the trains noses meeting (Fig. 5.13), one can see that the region with zero velocity between the train noses has vanished as the train have approached one each other. The flow in the train-tunnel annulus area still goes in the opposite direction of the train for both trains, so in the region around the two train noses the flow is complex, showing strong horizontal velocity components perpendicular to the train walls.
3. Head passing and 3D effect:

The most important part of this simulation is capturing the head passing pressure disturbance on the probed train, as shown in Fig. 5.14 where the train in the left hand side of the picture is travelling towards the point of view.

Visualising a pressure point probe fixed on the left hand side wall of the right hand side train (the train-to-train side), it will first record a higher value of pressure (about -800 Pa, Fig. 5.15) before the opposing train nose passing, then it will record a lower pressure (about -1600 Pa) after the opposing train nose has passed. While the opposing train nose is passing the probe, the peaks due to the 3D effect take place, as the pressure first increases to a maximum (about -400 Pa) due to the influence of the stagnation region in front of the opposing train nose, and then it decreases to a minimum (about -1900 Pa) due to the influence of the lower pressure region where the flow accelerates around the opposing train nose.

The 3D pressure field in front of and around the crossing train nose is what generates the 3D peaks in the pressure time histories recorded by the point probes on the train-to-train side, showed in detail in Fig. 5.15.

![Fig. 5.14 Head passing and 3D effect](image)

![Fig. 5.15 Pressure time histories for the probes at 60 m from train nose for the 93 m² tunnel.](image)
In Fig. 5.15, the “tl” probes are on the “left hand side”, by which the train-to-train side is meant, the “_1” probes are placed at 1 m height from the ground, and the “tt” probe is on the train top while the “tb” probe is at the train bottom.

Looking at the 3D effect for the probe at 1m height from the ground (the red one), one can see that the positive peak is much stronger than the negative one (about 400 Pa against 200 Pa magnitude of the peaks); this can also be visualised in the Fig. 5.15 when looking at the left hand side wall of the right hand side train. It is clear that the stagnation region ahead of the crossing train nose causes a pressure increase on the lower part of that wall (represented by the circular isobar in the yellow higher pressure region), which really is the 3D effect positive pressure peak. On the other hand, in the higher part of that wall the influence from the lower pressure region where the flow accelerates around the crossing train nose is much stronger, so the negative pressure peak is much stronger there, as one can visualise in the blue pressure time history from the wall probes in Fig. 5.15. The difference among pressures recorded at different heights on the train wall would also give different loads, but given that it would be prohibitive to take that influence into account, a representative probe has been chosen as the one at 2 m height from the ground, and it has been used to tune the fitting procedure in order to then compute the loads.

Looking instead at the train-to-tunnel side probes of the right hand side train, they show a monotone pressure decrease, and this can be visualised both in Fig. 5.15 and in the previous one, as the isobars on the tunnel wall at the right hand side of the picture are parallel, so the pressure decreases monotonically there.

![Fig. 5.16 Pressure and velocity fields - head passing and 3D effect](image)

Looking at the velocity field in Fig. 5.16, one can realise that in the region were both trains are crossing the flow velocity is zero, as the case is perfectly symmetrical with respect to the tunnel centre. In the portion of tunnel where one single train is passing the flow instead goes in the opposite direction with respect to that train, as previously explained. So the 3D flow field around the crossing train nose is mainly due to the air in front of the crossing train accelerating around its sides but then swiftly turning towards the same direction of the crossing train, as highlighted by Fig. 5.17 (made for a smaller 54 m² cross section tunnel case).
Fig. 5.17 Pressure and velocity field on tunnel symmetry plane

The arrows in Fig. 5.17 show the velocity with respect to the ground reference frame, and the figure highlights that the 3D effect around the crossing train nose is due to the flow accelerating and swiftly turning around the nose and then reaching finally a flow velocity in the same direction of the crossing train one.

4. Tail passing:

While the train tail on the right hand side of Fig. 5.18 is passing the probed train placed on the left hand side, the pressure felt at the probed train train-to-train wall increases showing a 3D effect only for the negative pressure peak, as shown in Fig. 5.15. This feature can be justified when looking at Fig. 5.18, as around the tail corners the flow does accelerate, thus generating a lower pressure region which directly generates the lower pressure peak in Fig. 5.15, but behind the tail the wake of course prevents the pressure recovery, thus also preventing the formation of a stagnation region; this is what causes the absence of positive pressure peaks in the tail passing pressure time histories, as shown in Fig. 5.15. If the flow behaved as a potential flow then a stagnation region would take place behind the tail, thus generating the positive pressure peak.
5.2. Data processing and fitting procedure

A thorough data processing procedure is needed in order to extract the most important information from the 40 point probes and 6 surface probes time histories saved as output by Star for each single train crossing simulation, especially considering that several parameters sweeps simulations will be executed.

First the translation and cutting procedure will be introduced, which basically cuts the pressure time histories and aligns them one with each other, thus allowing both to compare more effectively the loads generated by different probes time histories and to develop a fitting procedure. After that, the fitting procedure will be introduced and justified for the point probes pressure time histories.

Finally the loads computed using the fitted pressure time histories for the 93 m² tunnel benchmark case will be exposed in order to show the results of the data processing and fitting procedure.

5.2.1. Pressure time histories translation and cutting

The goal of the pressure translation and cutting procedure is to take the input pressure time histories from Star and cut them in order to extract only the interesting parts. One such procedure had to be developed both for the point pressure probes and for the surface pressure probes.

The cutting procedure only cuts and translates the pressure time histories, it takes each probe pressure time history saved by Star and cuts out the head passing portion of pressure time history as well as the tail passing for both point and surface probes. The cutting procedure was needed to align the pressure time histories in order to better compare them, and it was also necessary in order to develop the fitting procedure.

Point probes

Looking at Fig. 5.19 one can visualise the cutting process for the point pressure probes time histories. The inputs are the pressure histories from the point probes placed 60 m behind the train nose, which have been chosen as they looked the most regular among the similar-looking 45 m and 75 m ones (shown in Fig. 5.5).

The chosen input pressure histories are plotted in the top picture of Fig. 5.19, and the first step of the cutting process is to cut out the head passing pressure histories and the tail passing ones, manually choosing a length in time (a 0.09 s semi-interval in this case); that length in time is named $\Delta t_{end}$.

After being cut, the head and tail pressure time histories are translated both in time, in such a way to place the maximum pressure gradient point at the instant $t=0$ s, and in pressure, in such a way that the first point of the pressure time history (the point at the time $t = -\Delta t_{end}$) gets to a pressure of 0 Pa. This procedure allows for an easier comparison of the different pressure profiles as well as for an easier computation of pressure loads.

Looking closer at the various cut pressure time histories in Fig. 5.19, one finds the “tl1, tl2, tl3” probes which are placed on the train left side (train-to-train side) and which have been averaged into the “left avg”. Other probes are the “tr2” on the train right side, as well as the “tt” and “tb” on the top and bottom of the train. The “tr1” and “tr3” probes are very close to the “tr2”. All of the eight pressure time histories from the point probes placed at 60 m from the train nose have then been averaged together into the “car avg” pressure time histories.

A fundamental feature of those pressure time histories is that the train right side ones smoothly vary from the first to the final instant, while the left hand side ones present the 3D effects, with peaks and quick pressure variation. An interesting finding is that the “car avg” probe has no peaks but its variation is as quick as the left train side probes. This can be visualised comparing the red cut pressure time histories in Fig. 5.19 with the green (train-to-train side) and blue one (train-to-wall side).

Looking at the head passing gradients, one can appreciate that their intensity on the train-to-tunnel side is about 9 000 Pa/s, almost double the 5000 Pa/s maximum gradient of the nose entry compression wave for this case, while on the train-to-train side the maximum gradient is about 80 000 Pa/s, so taking into account the 3D effect when computing the load on a non-tight train really is of paramount importance.
Fig. 5.19 Point probes pressure time histories data processing - cutting procedure

The cut head and tail pressure time histories can be either used to directly compute the loads, or to shape the fitted head and tail pressure time histories through four parameters. The first two of them are the $\Delta t_{\text{end}}$ and $\Delta p_{\text{end}}$, which represent the time and pressure of the last position of the cut head and tail pressure vectors. The third and fourth parameters used to shape the fitted pressure time histories are $\Delta t_{3D}$ and $\Delta p_{3D}$, which respectively represent the distance in time between the two 3D effect pressure peaks, and the pressure difference among them.
Surface probes

Looking at Fig. 5.20 one can visualise the cutting process for the surface pressure probes time histories.

The input to the cutting procedure are the pressure time histories recorded by the surface probes (Fig. 5.9) placed on the carriages in the Star simulations, which are represented in the upper picture of Fig. 5.20. The carriage numbers are from 2 to 7 as the average pressure on the two train ends is not useful. Looking at those pressure time histories one realises that both the head and tail passing generate linear variations in average pressure on each car of the probed train. This can be justified as while for example the opposing train nose passes the probed carriage, the probed surface can be divided in two parts, one at a higher pressure (before the nose passes) and one at a lower pressure (after the nose has passed). The constant velocity of the passing trains means that the rate of change of the two car surface portions dimensions is also constant, so the reduction in average surface pressure is linear in time.

After having manually cut and translated each carriage probe head passing pressure decrease one gets the lower-left picture of Fig. 5.20, in which one can appreciate that all the probes recorded a very similar linear pressure decrease; this suggest to simply fit that pressure decrease with a line.

Fig. 5.20 Surface probes pressure time histories data processing - cutting procedure
When looking at the gradients, oscillations appear in all the CFD gradients. The source of this oscillation has not been precisely identified, but it looks connected with the cell lengthwise size on the train wall. Anyway they are quite small amplitude oscillations of the time derivative of a fundamental quantity, with a period of about 0.02 s (ten time steps), so they can be accepted. Refining the mesh and reducing the time step even turned out to increase those oscillations. These oscillations might have an influence when computing the loads, and their magnitude changes for different cases, so the best solution was to only use the fitted linear pressure time history to compute the loads. This also simplifies the load calculation process, as the linear pressure time history has a simple analytical formulation.

For each parameter sweep simulation run, the fitted linear pressure time histories for head and tail passing have been manually computed (as the oscillations in gradients prevented an automated formulation). Those fitted surface-averaged pressure time histories have finally been used to compute the internal pressure in the car. Given that the length of the probed surface was 12.5 m, one can use the linear fitted surface-averaged pressure time histories for that length to compute the ones for higher car lengths. For example if the car length is 50 m the linear fitted pressure is a line with a four times smaller gradient.

Concluding, the data from the surface pressure probes have been used to shape a linear fitting of the external pressure variations on the carriage external surface, which in turn can then be used to compute the internal pressure inside the carriage for any given carriage length (given the linearity of the pressure variation).

5.2.2. Fitting procedure for point probes

Before showing the loads on the cars computed using these pressure time histories, the fitting procedure for the point probes pressure time histories needs to be introduced.

The goal of this procedure is to fit the most useful point probes pressure time histories in a similar way as for the train entry head compression wave. The first part of the fitting procedure employs analytical and fitting formulae to predict the value of the four parameters then used to shape the pressure profile, namely $\Delta t_{end}$ and $\Delta p_{end}$ as well $\Delta t_{3D}$ and $\Delta p_{3D}$, which have been introduced in Section 5.2.1 and can be visualised in Fig. 5.21. The second part of the procedure takes as input those four parameters and with a simplified shape it draws pressure profiles matching them, and it does so for the three most interesting probes: the train-to-train side “tl2”, the train-to-tunnel side “tr2” and the “caravg” one.

The results of the fitting procedure for the benchmark 93 m$^2$ tunnel case are shown in Fig. 5.21.

![Fig. 5.21 Fitted pressure time histories - 93 m$^2$ tunnel benchmark case](image)

Looking at Fig. 5.21 one can visualise that the fitting procedure is capable of fitting three different pressure probes using a different combination of the four parameters for each probes. Each probe time history starts
at the point at \( t = 0 \) s and \( p = 0 \) Pa, and arrives at the point \( t = \Delta t_{\text{end}} \) and \( p = \Delta p_{\text{end}} \). The \( tr2 \) probe gets there smoothly, while the \( tl2 \) probe features the 3D peaks of magnitude \( \Delta P_{3D} \) and time interval \( \Delta t_{3D} \), and the \( caravg \) probe has no peaks but its pressure drop time is \( \Delta t_{3D} \), so its pressure variation is quicker.

A fourth probe, \( LinRise \), has been included for comparison. It simply features a linear pressure variation with time interval 0.02 s, representing a most simple model.

The fitting procedure is able to draw those four probes time histories given the four input parameters \( \Delta t_{\text{end}}, \Delta p_{\text{end}}, \Delta t_{3D} \) and \( \Delta P_{3D} \). In order to do so one has to choose how to satisfy the constraints given by the four parameters, and that has been done employing linear pressure gradients variations, corresponding to quadratic pressure time histories, as shown in Fig. 5.22. The continuous time histories in Fig. 5.22 are the fitted ones, while the crosses represent the Star results for the 93 m\(^2\) tunnel benchmark case.

Looking first at the \( tr2 \) probe (green), one can see that it arrives to the final point through a linear (triangular) gradient time history, and the pressure varies throughout the whole time interval. The \( caravg \) probe also arrives to the final point using a triangular pressure variation, but the pressure only varies throughout \( \Delta t_{3D} \), so the gradient is stronger. The \( tl2 \) probe instead has the two peaks of given in intensity \( \Delta P_{3D} \) implemented using three triangles in the pressure gradient time history profile.

Comparing the fitted pressure time histories with the CFD ones, the main error is close to the end point, as the CFD pressure time histories do not precisely converge to the same value. Except for that error both the maximum gradient and the time histories are fitted well enough. The reason why the CFD time histories do not converge to the same point is the time interval chosen for the cutting procedure which is not big enough to let them converge, as by looking at Fig. 5.19 one can appreciate that the CFD “un-cut” pressure time histories do converge at the same point. So it is good that the fitting procedure has the pressure time histories converging at the same end point.

Now that the process of drawing the pressure time histories given the four input parameters \( \Delta t_{\text{end}}, \Delta p_{\text{end}}, \Delta t_{3D} \) and \( \Delta P_{3D} \) has been introduced, one has to look at how those four parameter can be estimated from the inputs to the procedure, which are the same five free variables used for the head compression wave fitting procedure: train velocity (\( V_{tr} \)), train (\( S_{tr} \)) and tunnel (\( S_{tu} \)) cross sections, nose length (\( L_N \)) and track spacing (\( 2L_{ax} \)).

The first step is to determine an expression for \( \Delta p_{\text{end}} \) from Eq. (5.1) and Eq. (5.2).
\[
\Delta p_{\text{end}} = \Delta p_{\text{end}}^b \left( \frac{V}{V_b} \right)^2 \left( \frac{f}{f_b} \right)^{0.85}
\]
with \( f = \frac{1-(1-B)^2}{(1-M)[M+(1-B)^2]} \) and \( B = \frac{S_{TR}}{S_{TU}} \). \tag{5.1}

Looking at Eq. (5.1), \( \Delta p_{\text{end}} \) is found correcting \( \Delta p_{\text{end}}^b \) (which is the \( \Delta p_{\text{end}} \) value from CFD for the benchmark case) for varying velocity and blockage ratio, aspiring to Eq. (2.16). The velocity counts with the second power of velocity, while the blockage ratio term is expressed as the ratio of the blockage ratio functions “f” computed for the actual case over the benchmark one, at a power of 0.85. The choice of using that power comes from the necessity of fitting the pressure time histories for smaller tunnel, as explained in Section 5.3. The blockage ratio function “f” is Eq. (5.2), in which \( M \) is the Mach number computed with the train velocity and \( B \) is the blockage ratio. The values of \( \Delta p_{\text{end}}^b \) are -829 Pa for the head passing and +642 for the tail passing.

The second step is to find an expression for \( \Delta t_{\text{end}} \).
\[
\Delta t_{\text{end}} = \Delta t_{\text{end}}^b \frac{V}{V_b}; \Delta t_{\text{end}}^b = 0.08 \text{ s}
\]
Looking at Eq. (5.3), the \( \Delta t_{\text{end}} \) is found correcting \( \Delta t_{\text{end}}^b \) (which is a manually chosen value to fit the benchmark case time scales) for varying velocity. This process assumes that both trains travel at the same speed.

At this point \( \Delta t_{3D} \) and \( \Delta p_{3D} \) can be found through two adimensional coefficients \( c_{dt3D} \) and \( c_{dp3D} \), defined respectively as \( \Delta t_{3D}/\Delta t_{\text{end}} \) and \( \Delta p_{3D}/\Delta p_{\text{end}} \), and expressed as a function of the free variables using a fitting of the Star results as follows:
\[
c_{dt3D} = 0.2245 + 0.0938\Delta w_d + 0.04444\Delta L_n
\]
Eq. (5.4) is the fitting expression for \( c_{dt3D} \), found using the results from the parameters sweeps which will be introduced in Section 5.3. The \( \Delta \) quantities are meant as the difference between the considered case and the benchmark one, \( w_d \) is the distance between the walls of the two crossing trains and \( L_n \) is the nose length, as introduced for the train entry simulations and the benchmark case values are 2 m for \( w_d \) and 4 m for the nose length.

\[
c_{dp3D} = c_{dp3D}' + \left( c_{dp3D}' - 1 \right) * \left[ \left( \frac{V - V_{fbc} \frac{V}{V_b} \frac{S_{TU}}{S_{TR}}}{V - V_{fbc}} \right)^2 \left( \frac{f}{f_b} \right) - 1 \right]; V_{fbc} = 11.74 \text{ m/s}
\]
\[
c_{dp3D}' = \begin{cases} 
\text{Head pass:} & 1.8227 - 0.66\Delta w_d - 0.2392\Delta L_n + 0.0117\Delta L_n^2 \\
\text{Tail pass:} & 1.72 - 0.41\Delta w_d - 0.2175\Delta L_n + 0.0112\Delta L_n^2
\end{cases}
\]
Looking at Eq. (5.5), \( c_{dp3D} \) is found correcting \( c_{dp3D}' \) for the tunnel cross section variation influence, as \( c_{dp3D}' \) is expressed as a fitting function of track spacing and nose length only. One would expect the tunnel cross section variation to affect only the \( \Delta p_{\text{end}} \) and not \( c_{dp3D} \), but it turned out that for increasing tunnel cross sections \( c_{dp3D} \) strongly increases. This effect will be introduced and justified in Section 5.3, so this expression will also be justified there. \( V_{fbc} \) (far field benchmark flow velocity) is the flow velocity in the train tunnel annulus around the probed train far front of the other one in the benchmark case.

Concluding, given a combination of the five input free variables this fitting procedure can draw the external point probe pressure time histories for the \( tl2, tr2 \) and \( caravg \) probes for both head and tail passing employing the results from the Star parameter sweeps simulations, in a very similar way as for the train entry fitting procedure. Also a fourth \( LinRise \) probe pressure time history is generated in order to compare the more accurate results from CFD with the least accurate one of the linear rise model with a fixed rise time (approximate step change).
5.2.3. Load calculation

The train crossing loads have been computed using the “free-length” model for loads introduced in Section 4.6, Fig. 4.58.

The internal pressure time history is computed from the fitted surface-averaged pressure probe for the chosen carriage length, so it is the same for each probe, as the internal pressure is assumed to be homogeneous inside the carriage.

The external pressure time history used to compute the load is chosen as one of the fitted point probes pressure time histories, depending on the location in which one wants to compute the load. A very important parameter needed to compute the load with the free-length model is the distance between the chosen point probe location and the centre of the carriage (namely Δx, positive if the probe is towards the front of the carriage). Another parameter needed to compute the loads is the carriage pressure tightness time constant τ (the carbody rigidity coefficient k remains 0.1).

The results of this procedure to compute the loads are shown in Fig. 5.23. The most important probes in that figure are the t2,tr2 and caravg probes, which have been fitted using the Star parameters sweeps results for the point and surface probes, and for which the internal pressure has been computed from the surface average one. Less important probes are the LinRise one, which uses a simplified external pressure time history consisting of a linear pressure decrease and the “point-tau” model for load computation. The last probe used for this comparison is the component one, which feels the external pressure from the t2 probe but then uses a “point-tau” model to compute the loads, so the component load is different from the LinRise one.

The main feature of the loads in Fig. 5.23 is that even if the τ value is low the internal pressure variation time scale is much longer than the external pressure variation one. This causes the internal pressure to vary quite slowly in time, so the load mainly follows the external pressure variation, close to what it would do for a tight train. The situation would change drastically for different values of Δx, as explained later on. These loads time histories will be analysed much more in detail in Section 5.3, where the main focus will be on the influence of parameters variations one the loads.

![Graph showing pressure and loads for 93 m² tunnel benchmark case.](image)

Fig. 5.23 Pressure and loads for 93 m² tunnel benchmark case.
5.3. Pressure and loads for parameters variations

In this section the influence of several parameters variations on the pressure and loads time histories will be described. For each variable sweep at first a comment will be given on that variable influence on the pressure time history, in order also to assess the fitting procedure accuracy for that variable variation. The loads will then be computed always using the fitted pressure time histories which does introduce an error.

The error introduced by the fitting is as follows for the interval of variations of the CFD sweeps:

- Velocity sweep: from 150 km/h to 300 km/h the error between CFD and fit is always less than 1% in terms of $\Delta p_{end}$.
- Tunnel cross section sweep: the error is less than 5% in terms of both $\Delta p_{end}$ and $\Delta p_{3D}$ except for the smallest tunnel cross section (54 m$^2$), in which case pressure waves due to head-head crossing appear which change the shape of pressure time histories. The fitting remains always conservative.
- Nose length sweep: less than 1% error (in terms of $\Delta p_{3D}$, as the influence on $\Delta p_{end}$ is very low) except for smallest $L_n$ of 2 m (7% error).
- Track spacing sweep: less than 5% error (in terms of $\Delta p_{3D}$, as the influence on $\Delta p_{end}$ is very low).

So the fitting does introduce an error, but first of all it allows to get a smooth time history for computing the load (without spurious oscillations and gradients of pressure far from the crossing instant, which could spoil the load computation). Furthermore it allows to quickly obtain new pressure time histories for any combination of variable inside the CFD sweep intervals, and also to exceed that interval slightly. It has to be added that the parameters $\tau$, $L_{free}$ and $\Delta x$ only influence the post-processing, so the fitting procedure does not introduce errors with regard to those parameters variations, which in the end are the most influent.

A very important part of this section is the comparison between the results of the three CFD probes ($tl2$, $tr2$ and $caravg$) with the approximated LinRise one, as the much lower computational expense of the LinRise probe makes it very attractive. Each load pressure time history will also be quantified using three quantities: the Peak-to-peak load, which is the difference between the peaks in the load time history, the maximum load, which is meant as the maximum positive load (compression), and the minimum load, which usually is the maximum negative load (expansion). Each of these quantities can be used for different loads requirements such as maximum expansion loads, maximum compression loads and fatigue loads, each of which requires a different structural design, and so its own dedicated load.

**Which output is to be used for load prediction?**

1. **Peak-to-Peak load and maximum/minimum load**: For fatigue loads, it is better to use the peak-to-peak variation of load for the case considered. The peak-to-peak value of a pressure time history is computed as maximum value minus minimum one, so it is always positive. For maximum strength analyses, it is both the maximum (maximum compression, positive) and minimum (maximum expansion, negative) value of load which counts. Load is computed as $p_{ext} - p_{int}$, so positive loads are compression ones.

2. **Which probe to use**: The most representative load for the car structure is the one coming from the $caravg$ probe. This is an average level of load on a car cross section. If the load on a window or door is needed, then the most representative ones are $tl2$ and $tr2$ (depending on the required side). For maximum load computation one should always use the $tl2$ load, while for fatigue computations one should use a combination of both (given that the train sides get swapped once in a while). If the load on an external component is needed, one should look at the component load. In case of a component lying inside the underfloor plate, it would feel the $caravg$ external pressure, and the internal pressure should be computed with a Point $\tau$ model. This situation is usually very close to the LinRise load, so it is not plotted. Each of these loads can then be compared with the LinRise load, in order to assess in which case LinRise is accurate enough and in which cases it needs to be improved.
In which cases does LinRise need to be improved?

It is better to first analyse the case of the head passing for a non-tight train with \( \tau = 0.2 \) s (Fig. 5.16 and Tab. 5.3).

1. **caravg probe**: Also by looking at Fig. 5.16, one can realise that the LinRise load is close to the fitted caravg one. This is especially true for the minimum load (721 Pa for LinRise against 688 Pa for the fitted, which means caravg load is 5% weaker than LinRise load). This is because the time scales of the LinRise load (0.02 s) and of the caravg one (0.034s) are both quite close to one another, as caravg has no 3D effect peaks, and very far from the time scale of variation of internal pressure for the benchmark case (about 0.2 s).

2. **other probes**: For the other cases, especially for the tl2 and component probes, it is of paramount importance to take into account the peaks in external pressure due to the 3d effect. In order to realise their impact on the load, one can visualise the case of a perfectly tight train with an internal pressure constantly equal to zero. In that case the load would be equal to the external pressure distribution, and it would be fundamental to take into account the peaks in the external pressure time history not only for the peak-to-peak load but also for the minimum load (which would be reached at the lower peak). The difference between the tl2 peak-to-peak load and the LinRise one is 99% for the benchmark case and can get up to 142% (so \( \text{tl2 load} = 2.42 \times \text{LinRise load} \)). The component load has a very similar behaviour to the tl2 load. The tr2 probe instead gives a load about 20% weaker than the LinRise one for the benchmark case.

Generally, the most representative case is the caravg one (unless the probe is placed far upstream or downstream the car centre), so it is very convenient that the LinRise pressure variation time scale of 0.02 s is already close to the 0.034 s for the caravg benchmark case. Furthermore, when varying velocity, tunnel cross section, nose length and track spacing, the only varying parameter between the LinRise external pressure time history and the caravg one is the time scale of the latter, which has a very low influence on the load because it is already very far from the internal pressure time scale. For this reason the LinRise load remains quite close to the caravg one in all those sweeps. Anyway for lower values of tau and lower velocities, the external pressure time scale gets closer to the caravg one, so the error of the LinRise load increases.

On the other hand there are a few situations in which the LinRise predictions are consistently far from the caravg load.

As an example if the car is very non-tight (\( \tau = 0.05 \) s) the LinRise minimum load is 16% stronger than the caravg one, as the difference between the two internal pressures used gets more relevant. For the same reason, if the Velocity is 150 km/h and \( \tau = 0.1 \) s (the case of a not high-speed non-tight train), the LinRise minimum load is 19% stronger than the caravg one (so LinRise is conservative). Furthermore, for \( \tau = 0.2 \) s, \( L_{\text{free}}=25 \) m and \( \Delta x=-12 \) m, the LinRise minimum load is 13% weaker than the fitted one, so LinRise is not conservative. If \( L_{\text{free}}=200 \) m and \( \Delta x=+99 \) m, the LinRise maximum load is 88% stronger than the caravg one. \( L_{\text{free}} \) and \( \Delta x \) have a strong influence on caravg maximum load because they basically translate the caravg internal pressure profile, thus increasing the difference with the LinRise one.

For this reason, the most important conclusion of this section is that the most influent parameters on the loads is \( \Delta x \).

### 5.3.1. Benchmark case

The 93 m² benchmark case is an intermediate one, as it uses an intermediate value for each variable. In Tab. 5.2 the value of each variable for the minimum case of the sweep, benchmark and maximum case is exposed for each variable.
Tab. 5.2 Parameters for minimum, benchmark and maximum cases.

<table>
<thead>
<tr>
<th>V [Km/h]</th>
<th>Tunnel cross section [m²]</th>
<th>Nose Length [m]</th>
<th>Train Wall to Train Wall distance [m]</th>
<th>Tau [s]</th>
<th>Number of cars in Lfree (12.5 m each)</th>
<th>Δx probe [m] (2 cars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>bench</td>
<td>max</td>
<td>min</td>
<td>bench</td>
<td>max</td>
<td>min</td>
</tr>
<tr>
<td>150</td>
<td>250</td>
<td>350</td>
<td>44</td>
<td>93</td>
<td>110</td>
<td>2</td>
</tr>
</tbody>
</table>

Each of these seven variables has been subject to a sweep in order to assess its influence on the load. The train wall to train wall distance is 3m less than the track spacing. The interval of τ value is representative of a non-tight train. It is important to note that each variable sweep has been executed keeping the benchmark value of the other variables (unless otherwise specified).

The first task is to assess the fitting accuracy for the benchmark case, which is quite good as the benchmark case is the starting point of all the variables interpolations used for the fitting. The fitting accuracy can be visualised in Fig. 5.22 in the previous section.

After that, one can look at the fitting procedure results for the benchmark case in Tab. 5.3 and Fig. 5.24.

<table>
<thead>
<tr>
<th>Head Passing</th>
<th>BEN</th>
<th>CHM</th>
<th>ARK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press</td>
<td>dp  end</td>
<td>-829</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dp  3D</td>
<td>1511</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cdp 3D</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>Load (from fitting)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TL2 comp</td>
<td>PtP 1438</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max  -1029</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min  1312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TR2 comp</td>
<td>PtP  573</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max   8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min  -655</td>
<td></td>
<td></td>
</tr>
<tr>
<td>caravg</td>
<td>PtP  756</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max   68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min  -688</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LinRise</td>
<td>Min  -721</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% abs difference to LinRise (if negative load tool is conservative)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TL2 comp</td>
<td>PtP  99%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min   43%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TR2 comp</td>
<td>PtP  82%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min   43%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>caravg</td>
<td>PtP  5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min   -5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 5.3 and Fig. 5.24 Quantitative results for benchmark case.

Tab. 5.3 exposes the values of pressure and loads for the head passing in the benchmark case (also plotted in Fig. 5.16). The first three lines of the table express the values of Δpend, Δp3d, and cdp3d.

Lines 4 to 17 of the table express the each probe load intensity. For each probe load the Peak-to-Peak (always positive), Maximum (maximum compression) and Minimum (maximum expansion) loads are exposed.
The last 8 lines compare each probe load with the LinRise one. As an example the -5% in the last line states that the minimum of the caravg load is 5% lower (in absolute value) than the LinRise one. The +99% in the first line states that the Peak-to-Peak TL2 load is 99% higher than the LinRise one (so 1.99 times higher).

The LinRise load (-721 Pa) is close to the minimum caravg one (-688 Pa, 5% lower in absolute value than -721 Pa). The maximum caravg load is extremely weak because it is only caused by the decreasing internal pressure and not from a 3D-effect peak in the external one.

The comment for the “Load (from fitting)” section of Tab. 5.3 is in this paragraph. The TL2 and component loads are much higher than the LinRise one with respect to peak-to-peak, maximum and minimum load because of the presence of peaks in the external pressure time history. The maximum load for TL2 and component is however much weaker than the minimum one, because the first is caused by one peak only, while the latter is caused by the other peak plus the depend. When comparing TL2 loads against component loads, the second one are always lower because the Point τ model can follow much more quickly the external pressure variation. The TR2 load is the lowest, as its external pressure variation is the slowest one, so the internal pressure has more time to follow it.

The comment for the “% abs difference” section of Tab. 5.3 is in this paragraph. The most important conclusion is that the minimum load from caravg is the only one close to the LinRise one. It is also important to note that the minimum LinRise load is conservative as the internal pressure from the surface average is already lower than zero when the opposing train is passing, thus shifting some of the caravg minimum load to the maximum one. Of course if the probe were much closer to the head of the car (Δx<0) the situation would change.

The TL2 and component loads are of course much higher than the LinRise one, while the TR2 ones are lower (in absolute terms) than the LinRise one. Quantifying these variations, the TL2 Peak-to-Peak load is 99% more than the LinRise one, and the TR2 Peak-to-Peak load is 21% less than the LinRise one. This means that LinRise is not conservative for fatigue calculations, as it does not take the 3D effect into account. As an example, for a window which sometimes bears the TL2 Peak-to-Peak load and sometimes the TR2 one the most appropriate Peak-to-Peak load for fatigue would be around 39% (average between +99% and -21%) higher than the LinRise one. This 39% addiction to LinRise would fit the 3D-effects and the different time scales for the benchmark head passing case.

Concluding, it has to be stressed that a very important parameter for this model is τ. If τ were higher (for example 0.5 s), then the internal pressure would be much closer to zero. This would bring the minimum caravg load closer to the LinRise one, and it would actually hide the effects of the parameter sweeps which follow.

After having shown and justified the loads for the benchmark case, one can now look at how those loads change when varying each of the parameters sweep variable. The best way to do so is to list each of those sweeps in order of importance, starting from the most influent one, which is the probe position sweep.

**5.3.2. Probe position sweep**

This sweep is based on these probe positions (Δx): -12 m, -6 m, 0 m, 6 m, 12 m (for a 25 m carriage free length). Δx is zero if the probe is at half the Free Length of the carriage, and it is positive if the probe is towards the tail of the probed train, so Δx cannot be higher than half the Free Length. In order to be able to place the probe further away from the centre of the carriage, beyond the sweep done with the benchmark Free Length of 25 m, another sweep has been carried out using a Free Length of 200 m.

Changing the probe position does not require further Star simulations, as the external point probe time history just needs to be translated while the internal one can be analytically modified, as it is just a line. The external pressure profiles horizontal translation causes the three CFD probes (TL2, caravg, TR2) nose passing point in Fig. 5.17 to be at -0.09 s for Δx=-12, and at +0.09 s for Δx=+12.

Increasing the Δx, which corresponds to shifting the probe towards the tail of the carriage, brings the internal pressure at head passing instant further from zero (so closer to the minimum pressure) and increases the gradient of internal pressure (in absolute terms) at that instant. The first effect heavily reduces the minimum
loads (in absolute terms) and increases the maximum ones. The second effect slightly decreases the peak-to-peak loads. Changing the probe position does not change the internal pressure time history, which comes from a dedicated surface-average probe. These conclusions only hold for those probes which use the free-length model for internal pressure (\(TL2, caravg, TR2\)). The \textit{component} and \textit{LinRise} probes instead, which use a \textit{Point} \(r\) model for internal pressure, are not influenced by \(\Delta x\) variations.

In Fig. 5.25 one can visualise and quantify the loads for varying probe position. A new section appears in Tab 5.4, which represents the percentage difference between the considered case load and the maximum one in that variable sweep. So, for example, the \(TL2\) probe peak-to-peak load is maximum for \(\Delta x = -12\) m and it is 5\% weaker for \(\Delta x = +12\) m.

Fig. 5.25 and Tab. 5.4 Quantitative results for probe position variation. Upper plot: -12 m. Lower plot: +12 m (25 m Free Length).

Looking at the two plots in Fig. 5.25, for increasing \(\Delta x\) the main effect is that the loads get translated higher (more compression load), as a direct effect of the lower internal pressure at the head passing instant. The internal pressure at the head passing instant in turn is lower because if the probe is further from the front of the carriage then the internal pressure has been decreasing for a longer time before the crossing train passes the probe.
Looking at the $\Delta x=+12$ m case pressure histories, one can visualise how higher the maximum loads get when the probe is placed at the rear end of the carriage, as the combined effect of both the lower internal pressure at the head passing instant and the positive pressure peak due to the stagnation region in front of the opposing train nose generates a maximum TL2 load of 601 Pa for a 25 m long carriage. That load gets to 1070 Pa for a 200 m Free Length, as shown in Fig. 5.28, so for long carriages the compression loads at the carriage tail can be very strong.

For this reason it is extremely important to use a Free Length model for load computation and to take $\Delta x$ into account when computing the train passing loads.

Fig. 5.26 PtP, max and min loads as function of probe position for each probe. LEFT: absolute loads; RIGHT: relative to each max.

Fig. 5.26 shows mainly that for increasing $\Delta x$ the maximum loads increase while the minimum one decrease in absolute terms, because of the lower internal pressure at the head passing instant. These two variations have about the same magnitude, so the variation of maximum loads is much stronger in relative terms, as maximum loads remain lower than minimum ones in absolute terms. A less important trend is the slight decrease of peak-to-peak load when increasing $\Delta x$. Comparing the probes loads with the LinRise one (Fig. 5.27), it should first of all be underlined that, being the LinRise load constant for varying $\Delta x$, the left plot of Fig. 5.27 is the same as the left plot of Fig. 5.26 apart for the scale.
Fig. 5.27 Comparison of all the probes loads with the min LinRise load.

In Fig. 5.27 one can visualise the ratio between each probe load and the Linrise one, thus allowing to assess in which case LinRise can be accurate enough and in which case it is not.

Fig. 5.27 shows that for higher $\Delta x$ the minimum caravg load gets consistently weaker than the Linrise one. This is a direct consequence of the lower internal pressure at the head passing instant, and LinRise does not take this effect into account. For the same reason when the probe is close to the carriage head the caravg minimum load is 13% higher than the LinRise one. In this situation LinRise is not conservative anymore. It has to be remembered that the caravg minimum load is the strongest load, so LinRise is not conservative of about 13% for the case of maximum absolute load on the front of a 25m non-tight carriage. It is also 33% conservative for the back of the carriage.

The influence of $\Delta x$ is even more important if the car is longer. With a Free Length of 200 m the range of $\Delta x$ goes from about -99 m to 99m. Looking at the last line of Tab. 5.4, the resulting minimum caravg load for $\Delta x=-99$ m is close to the one for $\Delta x=-12$m. This is because already with a $\Delta x$ of 12 m the internal pressure is nearly zero throughout the whole head passing. On the other hand, the situation for the probe at $\Delta x=+99$m is different, as one can visualise in Fig. 5.28.
Looking at Fig. 5.28, with a Free Length of 200m, when the crossing train is close to the tail of the Free Length still before meeting the point probe, then the surface average probe on the probed train wall already records a pressure close to the minimum one. For this reason the internal pressure is very close to the minimum one too, so at this instant the caravg load is positive (compression load) and nearly equal to the minimum pressure in absolute terms. After the nose of the crossing train has passed the probe, the loads get to zero.

Fig. 5.28 misses the LinRise and component probes, as they are plotted at t=0. In this situation, the maximum load gets even higher than the minimum one (in absolute terms). This can happen for head passing only if the probe is much downstream of the centre of the Free Length.

Concluding, in case of a non-tight train, especially for longer Free Lengths, in order to compute the load at a location it is necessary to take into account its position with respect to the centre of the Free Length. The minimum load (which is usually the strongest one) is stronger if the probe is closer to the front of the carriage. The maximum load (which is usually much weaker than the minimum one) can get considerably high if the probe is much downstream of the centre of the Free Length.

So in the end for probe locations far from the carriage centre the LinRise probe is inaccurate as the free-length model for load computation is needed to compute the probe position influence on the loads.

5.3.3. Tau sweep

The τ (pressure tightness time constant) sweep is based on these values, in [s]: 0.05; 0.1; 0.2; 0.3; 0.5. The τ sweep is another one which does not require Star runs, as τ is only needed to compute the internal pressure.

Increasing τ keeps the internal pressure further from the external one and so closer to zero, at any time. This is particularly evident on the component and LinRise probes, as they both use a Point τ model, and in that case τ directly defines the internal pressure time scale. On the other hand for TL2, TR2 and caravg probes the internal pressure time scale depends on both τ and the time it takes for the crossing train to pass the probed Free Length.
Looking at the two plots in Fig. 5.29, for increasing $\tau$ the internal pressure gets much closer to zero. This both increases the minimum loads and brings the internal pressure time histories much closer one another. The latter effect brings the $\text{caravg}$ and $\text{LinRise}$ load closer to each other and the same holds for the TL2 and component ones.

The reason for the increase of peak-to-peak loads for increasing $\tau$ is instead the decrease in internal pressure gradient.

Decreasing the $\tau$ brings the time scales of the external pressure variation closer to the internal one, thus highlighting the differences between different probes external pressures time scales. This is the reason why

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**Tab. 5.5 and Fig. 5.29 Quantitative results table for Tau sweep.**

Upper plot: 0.05 s. Lower plot: 0.5 s.

Looking at the two plots in Fig. 5.29, for increasing $\tau$ the internal pressure gets much closer to zero. This both increases the minimum loads and brings the internal pressure time histories much closer one another. The latter effect brings the $\text{caravg}$ and $\text{LinRise}$ load closer to each other and the same holds for the TL2 and component ones.

The reason for the increase of peak-to-peak loads for increasing $\tau$ is instead the decrease in internal pressure gradient.

Decreasing the $\tau$ brings the time scales of the external pressure variation closer to the internal one, thus highlighting the differences between different probes external pressures time scales. This is the reason why
the TR2 and caravg minimum loads get much further from the LinRise one for lower \( \tau \) in the right plot of Fig. 5.30, so when \( \tau \) is lower than about 0.3 s it becomes extremely important to have the correct time scale for the external pressure variations. This is also confirmed in Fig. 5.31. On the other hand, for \( \tau \) values higher than about 0.5 s (so for pressure tight trains) the importance of the internal pressure time history when computing the train passing loads gets much lower as the internal pressure remains very close to zero throughout the opposing train passing: in this situation the loads get practically coincident with the external pressure time history.

![Fig. 5.30 PtP, max and min loads as function of tau for each probe. LEFT: absolute loads; RIGHT: relative to each max.](image)

Looking again at Fig. 5.30, all the minimum and peak-to-peak loads increase for increasing \( \tau \). The maximum load for the component probe does the same, as it uses a Point \( \tau \) model for the internal pressure. The maximum loads do the opposite for the TL2, caravg and TR2 probes, as they are caused by the premature decrease of internal pressure due to the free-length model used for those probes internal pressure computation.

Looking at Fig. 5.31, the component loads stay mostly parallel to the LinRise one, while the others do not. This is because the LinRise probe uses the Point \( \tau \) model for internal pressure computation, so it is more influenced by \( \tau \) variation than the others, which all use the free-length model for internal pressure computation.
The most important conclusion is that for $\tau$ higher than about 0.3 s the time scale of internal pressure variation becomes so much higher than the one for external pressure variation that it is not necessary to have the right time scale for the external pressure variation anymore, so the LinRise probe can in this situation be used to predict a load correspondent to the minimum caravg one, as long as $\Delta x$ is small.

For high $\tau$ the internal pressure from the Point $\tau$ model (LinRise probe) is very close to the one from the Free Length $\tau$ model (LinRise probe); this causes the minimum caravg load to get coincident to the minimum LinRise load for $\tau=0.5$ s (Fig. 5.31). For lower $\tau$ LinRise gets up to 16% ($\tau=0.05$ s) more conservative as its 0.02 s time scale gets closer to the caravg one.

### 5.3.4. Free Length sweep

This sweep is based on these numbers of 12.5 m long carriages and Free Lengths: 1 (12.5m); 2 (25m); 4 (50m); 8 (100m); 16 (200m).

Increasing the Free Length brings the internal pressure at the head passing instant further from zero (so closer to the minimum pressure) and reduces the gradient of internal pressure (in absolute terms). Both these effects are due to the fact that with a higher Free Length the internal pressure has more time to equalise the external one. The first effect heavily reduces the minimum loads (in absolute terms) and increases the maximum ones. The second effect slightly increases the peak-to-peak loads. These conclusions only hold for those probes which use the free-length model for internal pressure (TL2, caravg, TR2). The component and LinRise probes instead, which use a Point $\tau$ model for internal pressure, are not influenced by variation of Free Length. The probe always lays at the centre of the Free Length for this sweep.

The results from this section highlight the paramount importance of taking into account the effect not only of the probe position but also of the carriage free length on the loads. Clearly the Free Length model for load computation is needed to assess that influence. If one used the Point $\tau$ model instead of the Free Length one then the train passing compression loads (the positive ones) close to the carriage tail would be heavily underestimated.
Tab. 5.6 and Fig. 5.32 Quantitative results table for Free Length sweep.
Upper plot: 12.5 m. Lower plot: 200 m.

Looking at the two plots in Fig. 5.32, for increasing Free Length the main effect is that the loads get translated upwards (more compression load), as a direct effect of the lower internal pressure. The internal pressure in turn is lower because with a longer Free Length the nose of the passing train reaches the head of the probed carriage sooner (for the same probe position), so the pressure inside the probed carriage has more time to decrease before the crossing train arrives at the probe. For an infinitely long carriage, the internal pressure would be half the external one when the crossing train arrives at the probe (which is placed at half length of the probed carriage). On the contrary, for a shorter carriage the expansion loads are much stronger than the compression ones.
Fig. 5.33 PtP, max and min loads as function of *Free Length* for each probe. LEFT: absolute loads; RIGHT: relative to each max.

Fig. 5.33 PtP, max and min loads as function of *Free Length* for each probe. LEFT: absolute loads; RIGHT: relative to each max. Fig. 5.33 shows mainly that for increasing *Free Length* the maximum load increases, while the minimum one gets weaker, because of the lower internal pressure. These two variations have about the same magnitude, so the variation of maximum loads is much stronger in relative terms, as maximum loads remain weaker than minimum ones. The less important trend is the slight increase of peak-to-peak load when increasing *Free Length*.

Fig. 5.34 Comparison of all the probes loads with the min LinRise load.
Comparing the probes loads with the LinRise one (Fig. 5.34), it should first of all be underlined that, being the LinRise load constant for varying Free Length, the left plot of Fig. 5.34 is the same as the left plot of Fig. 5.33 apart for the scale. Fig. 5.34 shows that for higher Free Length the minimum caravg load gets consistently lower than the LinRise one. This is a direct consequence of the lower internal pressure at the head passing instant, and LinRise does not take that into account. The difference among the two can become up to 27%, but the LinRise probe remains anyway conservative.

The Free Length sweep was the last one not requiring Star runs to be executed, as both the probe position, time constant and Free Length ones only influenced the way the loads were computed from the benchmark pressure distributions.

5.3.5. Velocity sweep

The train velocity sweep is made using the following velocities, in km/h: 150, 200, 250, 300 and 350.

Increasing the train velocity strongly increases the $dpend$ (proportionally to second power of velocity), while linearly decreasing the $dtend$. The $cdt3d$ remains constant, while the $cdp3d$ decreases slightly. Overall $dt3d$ decreases and $dp3d$ increases. This increases each kind of load.

Furthermore, the LinRise load will only feel the $dpend$ increase and not the $dtend$ decrease. At lower velocities, the higher $dtend$ and $dt3d$ will bring the external pressure time scales closer to the internal ones, thus making the minimum caravg load weaker than the LinRise one, which does not feel this effect. This last phenomenon is strongly influenced by the value of $\tau$, so, while most of the results will be exposed both for $\tau = 0.2$ s, some results will also be exposed for $\tau = 0.05$ s, $\tau = 0.1$ s and $\tau = 0.5$ s. These values cover the range of $\tau$ for non-tight trains (but 0.05 s is very low).
Tab. 5.7 Quantitative results and comparison for velocity sweep.

<table>
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<tr>
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<th>BEN</th>
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<th>ARK</th>
<th>TL2 (from fitting)</th>
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<th>V [Km/h] tau=0.1</th>
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</tr>
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<td>565</td>
<td>83</td>
<td>529</td>
<td></td>
</tr>
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<td>-160</td>
<td>-2070</td>
<td>-338</td>
<td>-2018</td>
<td></td>
</tr>
</tbody>
</table>

| Load         |     |     |     | caravg              |                  |                  |
| PtP          | 756 | 261 | 1542| 247                | 1486             |                  |
| Max          | 68  | 33  | 114 | 49                 | 167              |                  |
| Min          | -688| -229| -1428| -199               | -1319            |                  |
| LinRise      |     |     |     | LinRise             |                  |                  |
| Min          | -721| -257| -1448| -246               | -1385            |                  |

<table>
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<th>comp</th>
<th>TR2</th>
<th>caravg</th>
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<table>
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<th>comp</th>
<th>TR2</th>
<th>caravg</th>
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</thead>
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<td>82%</td>
<td>21%</td>
<td>5%</td>
</tr>
<tr>
<td>Min</td>
<td>43%</td>
<td>43%</td>
<td>43%</td>
<td>5%</td>
</tr>
</tbody>
</table>

A visualisation of what happens when velocity increases is in Fig. 5.35.

The two plots in Fig. 5.35 look very similar as they have been plotted on different scales (otherwise the left plot would not have been visible). For increasing velocity the loads increase and the pressure variations are quicker. It is interesting to note that for the lowest velocity the internal pressures are closer to the external ones as the corresponding time scales are closer one another. Fig. 5.36 quantifies the variation of loads with velocity.
The right plot in Fig. 5.36 shows the ratio between the considered load at the considered velocity and the maximum value of the considered load for any velocity (always at 350 km/h). The main conclusion is that for increasing velocity all the kinds of load grow nearly of the same relative amount, following very well the proportionality to velocity squared.

This results in the highest absolute growth for the PtP Load which gets as high as 2874 Pa for the TL2 probe at 350 km/h. Furthermore TL2 minimum load is -2094 Pa at 350 km/h. Considering that the LinRise load for 350 km/h is 1448 Pa, the amount of correction to apply to LinRise to take 3D effects into account is consistent, as confirmed by Fig. 5.37.
Fig. 5.37 Comparison of all the probes load with the min *LinRise* load. The right plot is a magnification of the left one.

The fact that all the probes time histories in Fig. 5.37 are not parallel to the min load *LinRise* one shows that for varying velocity *LinRise* varies in a different way from all the other probes. This is because *LinRise* only sees the variation of $d_{\text{end}}$, and not the one of $dt_{\text{end}}$. When looking at all the other probes minimum loads, they are parallel one another, as they feel both the variations in the same way.

The right plot in Fig. 5.38 shows very clearly that for high train velocity the external pressure time scales are very far from the internal pressure ones, so the *LinRise* load is closer to the minimum $caravg$ one. For lower train velocity the minimum and peak-to-peak loads get translated downward.

But velocity is not the only parameter which defines how far the external and internal pressure variations time scales are from each other: $\tau$ plays a very important role too. Fig. 5.39 displays the influence of both velocity and $\tau$. 
The impact of the value of $\tau$ on the variation in velocity is displayed in Fig. 5.38. First of all, a lower tau allows the internal pressure to equalise the external one much more quickly, thus increasing the positive loads and weakening the negative ones. A lower $\tau$ brings the external pressure time scales closer to the internal pressure one. So for a lower $\tau$ not only the $\text{LinRise}$ load is closer to the minimum $\text{caravg}$ one, but also the variations of velocity have a higher impact on the loads, as comparing the two upper plots of Fig. 5.38, the shape of the pressure histories varies considerably between them. On the other hand, comparing the two lower plots of Fig. 5.38, the shape of the pressure histories is much more similar. This is because the internal pressure gradient is much lower and the internal pressure is much closer to zero for higher $\tau$, so the internal pressure influence on the loads is less strong.

Also, looking at Tab. 5.7, the $\text{LinRise}$ load is 19% lower than the minimum $\text{caravg}$ one at 150 km/h for $\tau = 0.1$ s, instead of 11% for $\tau = 0.2$ s, and of just 2% for $\tau = 0.5$ s. As already stated, this is because a lower value of $\tau$ amplifies the influence of the internal pressure on the loads, which in turn amplifies the influence of other variations (such as velocity variation) on the loads.
5.3.6. Tunnel cross section sweep

The tunnel cross section sweep is made using the following values, in m$^2$: 44, 60, 76, 93.1 and 110. This range of values is slightly longer than the one used for the CFD sweep which ranges from 54 m$^2$ to 93.1 m$^2$.

Increasing the tunnel cross section strongly decreases the $d_{pend}$ (in absolute terms) and increases the $cdp3d$, while leaving the $cdt3d$ and $dtend$ unaltered. The increase of $cdp3d$ was unexpected, and the reason for that increase is the decrease of velocity in front of the crossing train for bigger tunnels (in the tunnel reference frame, around the probed train). This decrease actually increases the velocity magnitude in the crossing train reference frame, so, if one assumes the $c_p$ distribution around the train nose to remain constant for varying tunnel cross section, the train nose stagnation region maximum pressure increases and the minimum pressure in the area where the flow accelerates around the train nose decreases. This seems the reason why the intensity of the 3D pressure peaks increases for a bigger tunnel. Looking at the CFD results, $cdp3d$ is found to be 1.82 for a 93.1 m$^2$ tunnel and 1.31 for a 54 m$^2$, which is a consistent difference.

A further problem is that, even when constraining a constant $c_p$ distribution around the train nose, $cdp3d$ does not decrease enough for decreasing cross section, so the error of the fitting procedure gets considerable for the smallest tunnel cross sections, as shown in Fig. 5.39.

![Fig. 5.39 CFD VS fitting results for the smallest 54 m$^2$ cross section tunnel.](image)

This simulation for the 54 m$^2$ very small tunnel cross section was performed twice, once with default mesh and time step size, and once with half the mesh size and half the time step, getting very similar results. The results in Fig. 5.39 are from the more expensive simulation (mesh size 0.125 m and time step 0.001 s). One can see that the CFD pressure time histories are very different in shape when compared to the one for bigger tunnels. It is not clear why such a smaller tunnel generates that difference in the pressure time history, it might be the higher importance of the flow displaced by the train and tunnel wall boundary layers as well as the higher magnitude of the secondary pressure waves generated as the two train noses cross.

For more normal tunnel cross sections, the accuracy of the fitting procedure is anyway much better, as shown in Fig. 5.40, which represents a comparison between the fitted and CFD pressure time histories for the 63 m$^2$ tunnel case.
The procedure to impose a constant $c_p$ is analytical and it is expressed in Eq. (5.5) in Section 5.2.2, which is also reported in Eq. (5.5).

$$c_{dp3D} = c_{dp3D} + (c_{dp3D} - 1) \times \left[ \frac{(v-V_{fbc} \beta S_{tu})^2}{(v-V_f)^2 \beta^2} \right] ; V_{fbc} = 11.74 \text{ m/s}$$

$$c'_{dp3D} = \begin{cases} \text{Head pass:} & 1.8227 - 0.66 \Delta w_d - 0.2392 \Delta L_n + 0.0117 \Delta L_n^2 \\ \text{Tail pass:} & 1.72 - 0.41 \Delta w_d - 0.2175 \Delta L_n + 0.0112 \Delta L_n^2 \end{cases}$$

In Eq. (5.6), $\Delta p_{p+}, \Delta p_{p-}$ are the pressure magnitude respectively of the positive 3D effect pressure peak and for the negative one, as shown in Fig. 5.40. They can be adimensionalised as $a c_p$ using as velocity $(V - V_f)$, which is the difference between the train velocity and the flow velocity $V_f$ in the train-tunnel cross sectional area around the probed train far in front of the other one. This velocity is $V_{fbc} = 11.74 \text{ m/s}$ for the benchmark case, and it varies for varying tunnel cross section approximately following Eq. (5.7).

$$V_f = V_{fbc} \frac{v S_{tu}}{v_s S_{tu}}$$

So, one can impose a constant $c_p$ around the train nose by fixing $(c_{p+} + c_{p-})$ in Eq. (5.6). At this point, for increasing tunnel cross section $V_f$ decreases, so $(V - V_f) \Delta p_{p+} \Delta p_{p-}$ increases and $\Delta p_{p+} \Delta p_{p-}$ decreases: both these factors cause $c_{dp3d}$ to increase when the $(c_{p+} + c_{p-})$ quantity is constrained to remain constant. The details of how to derive the first line of Eq. (5.5) from Eq. (5.6) are omitted.

The result of this correction of $c_{dp3D}$ for varying tunnel cross sections is evident in Fig. 5.41.
Looking at Fig. 5.41 (noticing that both plots have the same axis) it is evident that the $d_{\text{pend}}$ variation with tunnel cross section is higher than the $c_{\text{dp3d}}$ one, so the Peak-to-Peak and minimum TL2 and component loads decrease for increasing cross section (even if the $c_{\text{dp3d}}$ increases). The maximum TL2 and component loads instead increase for increasing cross section, as they mainly feel the influence of the $c_{\text{dp3d}}$ variation (Fig. 5.42 right plot). Comparing the external pressure 3D effect peaks intensity for the two cases, one realises that they are much stronger for the bigger tunnel case both relative to $d_{\text{pend}}$ and in absolute terms. This finding was completely unexpected.

The fact that varying tunnel cross section does not influence the time scales implies that the $\text{caravg}$ and the $\text{LinRise}$ probes will always vary of the same amount, as they both only feel the $d_{\text{pend}}$ variation and not the $c_{\text{dp3d}}$ one (see last two lines of Tab. 5.8).

Tab. 5.8 and Fig. 5.41 Quantitative results table for Tunnel cross section sweep. Upper plot: 44 $m^2$. Lower plot: 110 $m^2$. 
Looking at the left plot of Fig. 5.42, all the minimum and Peak-to-Peak loads decrease in magnitude for increasing cross section because of the $d_{pend}$ variation. Looking at the right plot in Fig. 5.42, the $caravg$ and $LinRise$ loads are the ones which decrease most (because they only feel the $d_{pend}$ variation). The $TL2$ and $component$ ones decrease less because they also feel the $cdp3d$ variation.

![Quantitative result of sweep:Stu](image1)

![Relative to each max; sweep:Stu](image2)

**Fig. 5.42** PtP, max and min loads as function of tunnel cross section for each probe. LEFT: absolute loads; RIGHT: relative to each max.

When comparing all the probes with the $LinRise$ one, in Fig. 5.43, it is at first evident that the $LinRise$, $caravg$ and $TR2$ probes charts are parallel, so they vary in the same way for varying cross section, as all of them only feel the $d_{pend}$ variation. On the other hand the $TL2$ and $component$ loads vary in a different way for increasing cross section, as they also feel the $cdp3d$ variation.

![Relative to LinRise; sweep:Stu](image3)

**Fig. 5.43** Comparison of all the probes load with the min $LinRise$ load.
5.3.7. Nose length sweep

The nose length sweep is based on the following nose lengths, in m: 2, 4, 5, 6, 8.

Increasing the nose length decreases the \( cd p_{3D} \) and increases the \( cd t_{3D} \), while leaving the \( d pend \) and \( dt end \) unaltered. This implies that the LinRise and TR2 probe are not affected by the nose length variations. The caravg probe only feels the \( cd t_{3D} \) variation, while the TL2 and component probes feel both the variations. It has been unexpected to find out that \( dt end \) is constant for varying nose length, but this is evident when looking at CFD results, as will also be discussed in the following.

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Tab. 5.9 and Fig. 5.44 Quantitative results table for Nose length sweep. Upper plot: 2m. Lower plot: 8m.
Looking at the two plots in Fig 5.44, for increasing nose length, the coupled influence of the decreasing \( cdp3d \) and increasing \( cdt3d \) smoothen the peaks considerably.

Looking at Fig. 5.45, it is confirmed that the \textit{LinRise} and \textit{TR2} probes are not influenced by the nose length. The \textit{caravg} probe is the one which is less influenced by the nose length variation, as it only feels the \( cdt3d \) influence and not the \( cdp3d \) one. The \textit{TL2} and \textit{component} probes vary following the same trend, and their minimum loads get close to the \textit{caravg} and \textit{LinRise} ones for high nose lengths due to the lower peaks; their maximum loads vary a lot in relative terms because their absolute value is very low.

**Fig. 5.45** PtP, max and min loads as function of nose length for each probe. LEFT: absolute loads; RIGHT: relative to each max.

**Fig. 5.46** Comparison of all the probes loads with the LinRise load.
Comparing the probes loads with the *LinRise* one (Fig. 5.45), it should first of all be underlined that, being the *LinRise* load constant for varying nose length, the left plot of Fig. 5.45 is the same as the left plot of Fig. 5.46 apart for the scale.

Looking at Fig. 5.46, increasing the nose length lowers the *TL2* and *component* peak-to-peak and minimum loads, bringing them closer to the *caravg* one, because the peaks are both reduced in magnitude and extended over a longer time. Furthermore, increasing the nose length increases the time scale of the *caravg* external pressure variation, thus weakening the corresponding load and bringing it further from the *LinRise* one. This is represented in the right plot of Fig. 5.46: for the longest nose the *LinRise* load is 9% higher than the *caravg* one (*LinRise* is again conservative). The *LinRise* error increases because the external pressure time scale gets longer and so further from the 0.02 s *LinRise* time scale. As already mentioned, this kind of error gets either negligible for higher \( \tau \) or amplified for lower \( \tau \).

The most interesting feature of the nose length sweep is probably that the time scale of the variation of the right hand side probe \( dt_{end} \) is not influenced by the nose length. On the other hand the nose length variation does have an impact on \( dt_{3d} \), as the shape of the external pressure peaks really change for a different shape of the nose, as shown in Fig. 5.47. This confirms that the 3D effect peaks are due to the direct influence on the probed train of the pressure field around the opposing train nose.

![Fig. 5.47 CFD VS fitting results comparison. Left Ln=2 m; Right: Ln= 8 m;](image)

As represented in Fig. 5.47, the different shape of the 3D peak effect also has an impact on the fitting procedure accuracy for varying nose length.

The main effect of a shorter nose is an increased intensity of both the 3D effect pressure peaks, as the flow needs to turn more swiftly around the shorter nose, so both the stagnation region and the lower pressure region where the flow accelerates around the train nose are more intense. It is also interesting to note that for a shorter nose the negative 3D effect peak recorded at a 2m height from the ground is stronger than the positive one, while the opposite happens for a longer nose. Anyway in the fitting procedure the two 3D effect peaks always have the same intensity.

### 5.3.8. Track spacing sweep

The Track spacing sweep is based on the values in **Tab. 5.10 Track spacing sweep cases**. Tab. 5.10, in which Lax is half the track spacing:
### Tab. 5.10 Track spacing sweep cases.

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Increasing the track spacing decreases the $cdp3d$ and increases the $cdt3d$, while leaving the $dp\text{end}$ and $dt\text{end}$ unaltered. The $LinRise$ and $TR2$ probe are not affected by the varying track spacing, the $caravg$ probe only feels the $cdt3d$ variation, while the $TL2$ and $component$ probes feel both the variations. This trend is exactly the same as for the nose length variation.

### Tab. 5.11 Quantitative results table for Track spacing sweep.

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#### Load (from fitting)

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<td>/</td>
<td>0%</td>
<td>-58%</td>
</tr>
<tr>
<td>Max</td>
<td>/</td>
<td>0%</td>
<td>-100%</td>
</tr>
<tr>
<td>Min</td>
<td>/</td>
<td>0%</td>
<td>-43%</td>
</tr>
<tr>
<td>TR2</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>PtP</td>
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<td>0%</td>
</tr>
<tr>
<td>Max</td>
<td>/</td>
<td>0%</td>
<td>-33%</td>
</tr>
<tr>
<td>Min</td>
<td>/</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>caravg</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>PtP</td>
<td>/</td>
<td>0%</td>
<td>-7%</td>
</tr>
<tr>
<td>Max</td>
<td>/</td>
<td>0%</td>
<td>-25%</td>
</tr>
<tr>
<td>Min</td>
<td>/</td>
<td>0%</td>
<td>-5%</td>
</tr>
<tr>
<td>LinRise</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>Min</td>
<td>/</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

#### % abs difference to LinRise (if negative load tool is conservative)

<table>
<thead>
<tr>
<th>TL2</th>
<th>BEN</th>
<th>CHM</th>
<th>ARK</th>
</tr>
</thead>
<tbody>
<tr>
<td>PtP</td>
<td>99%</td>
<td>139%</td>
<td>0%</td>
</tr>
<tr>
<td>Min</td>
<td>43%</td>
<td>63%</td>
<td>-8%</td>
</tr>
<tr>
<td>comp</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>PtP</td>
<td>82%</td>
<td>118%</td>
<td>-8%</td>
</tr>
<tr>
<td>Min</td>
<td>43%</td>
<td>63%</td>
<td>-8%</td>
</tr>
<tr>
<td>TR2</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>PtP</td>
<td>-21%</td>
<td>-21%</td>
<td>-20%</td>
</tr>
<tr>
<td>Min</td>
<td>22%</td>
<td>22%</td>
<td>-22%</td>
</tr>
<tr>
<td>caravg</td>
<td>BEN</td>
<td>CHM</td>
<td>ARK</td>
</tr>
<tr>
<td>PtP</td>
<td>5%</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td>Min</td>
<td>5%</td>
<td>3%</td>
<td>-8%</td>
</tr>
</tbody>
</table>
Looking at the two plots in Fig. 5.48, for increasing track spacing, the coupled influence of the increasing \textit{cdp3d} and \textit{cdt3d} smoothen the peaks considerably. Actually for the maximum track spacing the \textit{cdp3d} is equal to 1, so the peaks disappear and the \textit{TL2} probe becomes coincident with the \textit{caravg} one. Looking at Fig. 5.49, it is confirmed that the \textit{LinRise} and \textit{TR2} probes are not influenced by the track spacing. The \textit{caravg} probe is the one which varies less for varying track spacing, as it only feels the \textit{cdt3d} influence. The \textit{TL2} and \textit{component} probes vary following the very same trend, and their minimum loads get coincident to the \textit{caravg} and \textit{LinRise} ones for high track spacing due to the absence of peaks; their maximum loads vary a lot in relative terms because their absolute values are very low.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig5.48}
\caption{Fig. 5.48 PtP, max and min loads as function of half the track spacing for each probe. LEFT: absolute loads; RIGHT: relative to each max.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig5.49}
\caption{Fig. 5.49 Comparison of all the probes loads with the min \textit{LinRise} load.}
\end{figure}

Comparing the probes loads with the \textit{LinRise} one (Fig. 5.49), increasing the track spacing lowers the \textit{TL2} and \textit{component} peak-to-peak and minimum loads, bringing them closer (and even coincident) to the \textit{caravg} one,
because the peaks are both reduced in magnitude and extended over a longer time. Furthermore, increasing the track spacing increases the time scale of the $caravg$ external pressure variation, thus lowering the corresponding load and bringing it further from the $LinRise$ one. This is represented in the right plot of Fig. 5.50. For the highest track spacing the $LinRise$ load is 8% higher than the $caravg$ one ($LinRise$ is again conservative).

It is physically consistent that increasing the nose length has the same effect as increasing the track spacing. In both cases the variation in $cp$, which causes the 3D effect gets reduced. Around a longer nose the flow has to accelerate less to flow around it, so the variation in $cp$ reduces. Further from the body the variation in $cp$ is less than closer to it. With regard to the variation in $cdt3d$, a longer nose brings the two peaks of pressure on the probed train wall further one another. CFD results show that the same happens when the probed train is further from the passing one.

5.3.9 Tail Passing

The tail passing situation is characterised by different external pressure time histories when compared to the head passing one. The main differences are:

1. The external pressure goes from a lower value (corresponding to the pressure around the crossing trains) to a higher one (corresponding to the pressure in the tunnel around the probed train after the opposing train has passed).
2. $dpend$ is lower for the tail than for the head because of the wake, which prevents the pressure from going back to the freestream one. This effect is amplified for small tunnels, and it is generally difficult to be quantified. For the benchmark case $dpend$ is 22% lower for the tail than for the head.
3. $dtend$ is considerably higher for the tail than for the head. This is again because of the wake, and the difference is 40% for the benchmark case, so the time scale for the $TR2$ probe external pressure is 40% longer for the tail passing than for the head passing.
4. The pressure peaks due to the 3D-effect should be treated in a different way. In particular the second peak is consistently smeared when compared to the first one. This is a direct effect of the wake, which prevents the flow from remaining attached to the tail wall (which it did for the nose wall). The detachment of the flow prevents it to regain pressure forming a stagnation region behind the tail, thus reducing the second peak magnitude. Given the difficulties in modelling the amount of smearing (which totally depends on the wake behaviour), the same fitting developed for the head passing has been applied to the tail passing as well. In this fitting the two peaks are symmetrical, so for the tail case the CFD peak-to-peak variation has been fitted with symmetrical peaks. For this reason the lower (first) peak from the fitting will be less strong than the lower peak from CFD, and the higher (second) peak from the fitting will be stronger than the CFD one (see Fig. 5.51). The $cdp3d$ required for the tail passing is 5% lower than the one required for the head passing for the benchmark case, so the $dp3d$ is 26% lower for the tail passing than for the head passing.
5. $cdt3d$ has to be lowered of 25% for tail passing when compared to head passing for the benchmark case. Considering that $dtend$ had been raised by 40%, the $dt3d$ is 5% ($0.75 \times 1.4 - 1$) higher for the tail passing than for the head passing.

The comparison between the coefficients for the benchmark case head and tail passing is shown in Tab. 5.12:

<table>
<thead>
<tr>
<th>Tab. 5.12 Comparison between head and tail external pressures for the benchmark case.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tail vs Head</td>
</tr>
<tr>
<td>Tail minus Head</td>
</tr>
</tbody>
</table>

These values given for the benchmark case are relative differences between the head and tail passing, so in general they hold for each variable combination of the sweep, so if the head $d pend$ doubles, also the tail one does so. More in particular, this precisely holds for the $d pend$, $dt end$ and $cdt3d$ values from the fitting, so for example $d pend$ is always 22% lower for the tail passing than for the head passing for any variable combination. This is because the expressions of $d pend$, $dt end$ and $cdt3d$ as a function of the sweep variables (Section 5.2.2)
are the same for the head and tail passing. In other word the sweep variables variation influence the head and tail passing $d\text{pend}$, $d\text{tend}$ and $c\text{dt3d}$ values in the same way. On the other hand, the situation is different for $c\text{dp3d}$, as the positive peak of the tail passing pressure time history is weaker than the first one. This required a different formulation for $c\text{ap3d}$ for the head and tail passing, as shown in Section 5.2.2.

The comparison between CFD and fitted external pressure time histories for tail passing is shown in Fig. 5.51, which shows that the negative CFD peak is stronger than the fitted one, and the opposite holds for the positive peak. The asymmetry between the two CFD peaks also impacts on the $c\text{aravg}$ probe external pressure time history. The agreement between fit and CFD is acceptable for the benchmark case, even if it does introduce a consistent error, which also increases considerably when trying to execute the variable sweeps for the tail passing, mainly for the lack of ways to model the wake.

On the other hand it is less important to accurately model the tail passing, as the corresponding loads are always lower than the head passing ones. For these reasons for the tail passing the focus is on the benchmark case only, and the variables sweeps will not be exposed.

The comparison between head and tail passing can be made through Tab. 5.13 and Fig 5.52.
Tab. 5.13 and Fig. 5.52 Quantitative results table, head and tail passing, benchmark case.


The most influential difference between head and tail load is the different $d_{\text{pend}}$, which goes from -829 Pa for the head passing to +642 Pa for the tail passing, showing a 22% difference. All the probes for the tail passing cases have the same $d_{\text{pend}}$. This can be appreciated in Tab. 5.14.

Looking again at Tab. 5.13, the most relevant loads to be compared are the minimum (expansion) loads for the head passing and the maximum (compression) loads for the tail passing. This comparison confirms that the tail passing generates lower loads. With respect to the $\text{caravg}$ probe, the minimum load for head passing (-688 Pa) is 31% stronger than the maximum load from the tail passing (+524 Pa).

When compared with the others, the $\text{LinRise}$ tail passing probe is also more conservative for the tail passing than for the head passing. This is mainly because of the longer time scale of the tail passing, especially for the $\text{TR2}$ probe.

In the end, a conservative way to handle the tail passing would be to consider it symmetrical to the head one, compute the loads, and then reduce their magnitude by a factor of 30%. This factor is still conservative for any load.
### 5.3.10. Comparative table and conclusions for the parameters variations

The result of all these sweeps are collected in Tab. 5.14, which is made of all the columns exposed separately in each of the previous sections.

<table>
<thead>
<tr>
<th>Head Passing</th>
<th>BEN ChM ARK</th>
<th>V [Km/h]</th>
<th>Tau=0.2</th>
<th>V [Km/h]</th>
<th>Tau=0.1</th>
<th>Tunnel cross section [m²]</th>
<th>Nose Length [m]</th>
<th>Train Wall distance [m]</th>
<th>Tau [s]</th>
<th>Number of cars (12.5 m each)</th>
<th>Delta x probe [m] (2 cars)</th>
<th>Delta x probe [m] (8 cars)</th>
<th>Head Tail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press</td>
<td>dp end</td>
<td>-829</td>
<td>-296</td>
<td>-1665</td>
<td>-296</td>
<td>-1665</td>
<td>1819</td>
<td>1109</td>
<td>-0.05</td>
<td>0.5</td>
<td>-12</td>
<td>-12 -99 -99</td>
<td>Head Tail</td>
</tr>
<tr>
<td></td>
<td>dp 3D</td>
<td>1511</td>
<td>542</td>
<td>2996</td>
<td>541,6</td>
<td>2996</td>
<td>2173</td>
<td>1452</td>
<td>1.8</td>
<td>2</td>
<td>1823</td>
<td>1823 1823 1823 1823</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>cd3D</td>
<td>1.82</td>
<td>1.8</td>
<td>1.82</td>
<td>1.8</td>
<td>1.82</td>
<td>1.195</td>
<td>2058</td>
<td>1.20</td>
<td>0.5</td>
<td>1.20</td>
<td>1.20 1.20 1.20 1.20</td>
<td>1.20</td>
</tr>
</tbody>
</table>

### Load (from fitting)

#### % difference to each max

<table>
<thead>
<tr>
<th>Load (from fitting)</th>
<th>TL2</th>
<th>TR2</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### % difference to each min

<table>
<thead>
<tr>
<th>Load (from fitting)</th>
<th>TL2</th>
<th>TR2</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### % difference to each Lin Rise

<table>
<thead>
<tr>
<th>Load (from fitting)</th>
<th>TL2</th>
<th>TR2</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

It must be underlined that the probe position is the most influential variable on these loads, as it can easily swap the sign of the load, especially if the Free Length is very high. This consideration is enough to require the load to be always computed with the free-length model to take the probe position into account.

Furthermore, if one wants the load at the carriage centre, with the probe fixed at the half the Free Length (Δx=0), the most relevant comparison which can be done is the one between the minimum (expansion) LinRise load and the minimum (expansion) caravg load, which is highlighted in the last line of Tab. 5.14. The first load represents the approximated one computed with a linear decrease in a fixed 0.02 s time interval, while the second one represents the actual load on a car cross section taking into account the right time scale for pressure variation and the 3D-effect peaks (from fitted CFD results). Both of them are meant to be used for maximum strength structural analyses for a whole car cross section, so they can effectively be compared.

The result of this comparison is first that LinRise is always conservative except if the probe is far upstream the centre of the Free Length. Then that LinRise is accurate for this kind of load if all of the following conditions are fulfilled:
• $\tau$ is higher than 0.3 s.
• The Free Length is low.
• The distance between the probe and the centre of the Free Length is low.

For what concerns the other kinds of load (compression loads, fatigue loads or component loads) in other locations than the average around the car cross section at $\Delta x=0$ then LinRise is not useful, as it is not capable of taking those cases into account.

The conclusions on the accuracy of LinRise for head passing situations are summarised with regard to the kind of structural calculation required:

1. Location: **average of loads along the car cross section.** This location is meant for load on the whole car cross section. It is the most important one.
   a. **Fatigue Load:** In order to compute the fatigue load for the car cross section one should compute the fatigue load for the sides instead of looking at the $\text{caravg}$ peak-to-peak probe, otherwise the peaks due to the 3D effect would not be included in the fatigue calculation.
   b. **Expansion Load:** Comparing the LinRise load with the minimum $\text{caravg}$ one (highlighted line in Tab. 5.14), LinRise is accurate enough as long as $\tau$ is higher than 0.3 s and the Free Length and $\Delta x$ are low. If any of these conditions is not fulfilled then LinRise is anyway always conservative unless $\Delta x$ is very high.
   c. **Compression Load:** LinRise predicts zero compression load for the head passing, but the compression load is usually quite low for the head passing (as long as there are no peaks), especially when compared to the compression load caused by the tail passing. The only case in which the compression load become consistent for head passing is when the $\Delta x$ is very high, especially if $\tau$ is low.

2. Location: **carriage sides.** This location is meant for load on windows, doors or other structural components lying on a carriage side. Given that the two sides of the carriage get swapped once in a while, each component will withstand loads on both sides during its lifetime.
   a. **Fatigue Load:** The overall fatigue load is proportional to an average between peak-to-peak loads on the left and right side of the carriage. For the benchmark case this corresponds to a load which is 78% stronger than the LinRise one. The difference between the two loads increases for higher $\tau$ values, higher velocities, higher tunnel cross section and lower nose lengths and track spacings.
   b. **Expansion Load:** Comparing the LinRise load with the minimum TL2 one, the difference is again considerable as the strongest expansion load happens at the lower peak. For the benchmark case LinRise is not conservative, and the difference is 43%. This difference can get beyond 60% for shorter noses and smaller track spacings.
   c. **Compression Load:** The compression load for the TL2 probe can become considerable due to the peaks. It is 409 Pa for the benchmark case (not negligible compared to the 721 Pa of predicted expansion load from LinRise) and it can get up to 559 Pa for a short nose or even higher if the probe is moved towards to the tail of the car.

3. Location: **component.** This probe is meant for a component lying on the bottom of the train. Its external pressure is from the left side probe, and the internal one comes from a point-$\tau$ model. The component load is very close to $\text{TL2}$ in terms of minimum load, and about 10% different from it in terms of peak-to-peak loads. This difference gets higher for lower $\tau$, because then the internal pressure becomes more important.

Concluding, what LinRise misses to compute the train passing loads accurately enough for non-tight train is:

1. **Internal pressure:** using the internal pressure from a Point $\tau$ model instead of the one from a free-length $\tau$ model is the main source of error for the LinRise load. This error increases, in order of importance, if the probe is far from the centre of the carriage, if the car is longer and if the $\tau$ value is low.
2. **3D effect**: taking into account the peaks in the pressure time history due to the 3D effect gets fundamental only for the carriage sides (and component) locations. It is not necessary for computing average compression or expansion loads on the whole car cross section.

3. **Correct time scales**: taking into account the correct time scales for external pressure variation and 3D effect is important, as each probe has its own time scale. On the other hand this is less important than the previous points, as the external pressure variation time scale is usually much bigger than the internal one.
5.4. NUMSTA simulations

As introduced in the previous chapter about NUMSTA, the main goal of the NUMSTA simulations performed in this work is to assess its accuracy when compared to the results from Star. NUMSTA is a 1D code, so it cannot model the 3D pressure field in front of and around the train nose and tail, so its prediction will be wrong in terms of head and tail passing rise-times. With regard to the tail passing, its magnitude will be overestimated by NUMSTA as it cannot model the wake behind the passing train. These limitations can be acceptable in exchange of a much lower computational expense when compared to Star.

For these reasons NUMSTA nose and tail lengths have been extended in order to increase the head and tail passing time scales predictions, thus bringing them closer to the Star ones.

The first part of this section introduces the extension procedure for the NUMSTA nose and tail lengths. After that, NUMSTA results for the benchmark case will be introduced, both for the unextended and for the extended versions of NUMSTA. In the third part of this section NUMSTA extended version will be validated against Star results for all the parameters sweeps already introduced in the previous section.

5.4.1. NUMSTA nose length Extension procedure

If NUMSTA is run using a “NUMSTA nose length” $L^N_n = 4 \text{ m}$ for the benchmark case, which corresponds to the physical nose length of the AeroTRAIN benchmark case, the resulting pressure drop across the head compression wave would be about -750 Pa and the maximum pressure gradient would be -39 000 Pa/s for the 93 m$^2$ tunnel benchmark case.

Given that the Star head passing pressure drop is -829 Pa and the maximum gradient is -7400 Pa/s for the TR2 probe and about -32000 Pa/s for the caravg probe, one realises that NUMSTA accuracy with regard to the head passing pressure drop time scale must be improved: for this reason an extension procedure has been developed for the NUMSTA nose length. What cannot be corrected in NUMSTA is that it cannot simulate either the 3D effect peaks or the wake, as it is a quasi 1D solver, so it cannot simulate the 3D flow field around the train nose and tail and it cannot include turbulence and unsteady friction. On the other hand the magnitude of the pressure drop is predicted well enough (about 10% error), so the goal of this extension procedure is to make NUMSTA predicted time scale more accurate, thus reaching an overall degree of accuracy slightly better than the LinRise probe described in the previous section.

The extension procedure developed for the NUMSTA nose and tail lengths has been developed in a similar way as the one for the nose entry compression wave introduced in Section 4.5.1. The NUMSTA nose length to be used to fit the head passing as recorded by the TR2 probe (train-to-tunnel side) is Eq. (5.8).

$$ (L^N_n)_{TR2} = 22 \text{ m} = (2\Delta t_{end})^b \cdot (2V_{TR})^b $$.  \hspace{1cm} (5.8)

The NUMSTA length can be expressed as a time scale times a velocity. The time scale is the one associated with the whole pressure drop as felt by TR2 probe in the benchmark case, using $\Delta t_{end} = 0.08 \text{ s}$, and the velocity is the relative velocity between the two trains, so $2V_{TR} = 500 \text{ km/h}$ for the benchmark case. Eq. (5.8) is analytical, and it does not include a coefficient to fit the NUMSTA gradient to the Star one, while Eq. (4.5) for the head entry compression wave did include an empirical coefficient of 1.49 to fit them. For brevity the tail length can be chosen identical the nose length one, as NUMSTA cannot in any case be accurate for the tail passing.

If on the other end one wanted to use NUMSTA to model the caravg probe, which is the only other probe without peaks, he could use the Eq. (5.9) for the NUMSTA nose length.

$$ (L^N_n)_{caravg} = c_{d3D} \cdot 22 \text{ m} = (0.2245 + 0.0938\Delta w_d + 0.04444\Delta L_n) \cdot 22\text{ m} $$. \hspace{1cm} (5.9)

Eq. (5.9) uses the $c_{d3D}$ coefficient introduced in Section 5.2.2 as the ratio between the time scale of the caravg (and TL2) probe and the TR2 one to tune the NUMSTA nose length in order to fit the maximum gradient
of the \( \text{caravg} \) probe. \( c_{d,3D} \) is expressed using the results from the Star parameters sweeps simulations, so it is valid for any combination of those parameters.

After having chosen the probe one wants to compute the load for, and after having computed the corresponding NUMSTA nose length through Eq. (5.8) or Eq. (5.9), one also has to adapt the train length using Eq. (5.10):

\[
L_{TR}^N = L_{TR} + L_n^N
\]  

The goal of Eq. (5.10) is to align the NUMSTA maximum area variations points with the physical train tip and tail, in order to match as closely as possible the instants at which the head and tail passing happen.

It must be underlined that the NUMSTA nose lengths from Eq. (5.8) and Eq. (5.9) are different from the one in Eq. (4.5) developed to fit the maximum gradient of the nose entry compression wave. This is because those three equations are aimed to fit different quantities, so the resulting NUMSTA nose length is different. In the end this means that one has to run a different simulation with a different nose length for each case.

Another important aspect is that both Eq. (5.8) and Eq. (5.9) are valid for any combination of train velocity, tunnel cross section, nose length and track spacing tested, as will be shown in the following sections.

### 5.4.2. NUMSTA benchmark train crossing case results

Taking as reference the train crossing benchmark case for the 93 m\(^2\) tunnel, with a train velocity of 250 km/h, a nose length of 4 m, a track spacing of 4 m (\( w_d = 1 \) m), and a train length of 100 m, the nose lengths in Eq. (5.11), which have been computed from Eq. (5.8) and Eq. (5.9), have been used in NUMSTA to match the Star results for the benchmark case.

\[
\begin{align*}
(L_n^{N})_{TR2}^b &= 22 \text{ m} \\
(L_n^{N})_{\text{caravg}}^b &= 4.94 \text{ m}
\end{align*}
\]  

The fact that \( (L_n^{N})_{\text{caravg}}^b \) is quite close to the physical nose length means that physically the head passing length scale is very close to the nose length, which confirms that the 3D effect peaks are due to the stagnation pressure area just in front of the nose and to the lower pressure area where the flow accelerates around the nose sides.

When using the NUMSTA nose lengths in Eq. (5.11) one gets the results in Tab. 5.15.

<table>
<thead>
<tr>
<th></th>
<th>( \Delta p_{\text{end}} )</th>
<th>( TR2 ) max. grad.</th>
<th>( \text{caravg} ) max. grad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star (cut)</td>
<td>-829 Pa</td>
<td>-7400 Pa/s</td>
<td>-40000 Pa/s</td>
</tr>
<tr>
<td>Star (not cut)</td>
<td>-829 Pa</td>
<td>“</td>
<td>-32000 Pa/s</td>
</tr>
<tr>
<td>NUMSTA (ext.)</td>
<td>-760 Pa</td>
<td>(( Ln=22 ) m) ( \Rightarrow ) -7300 Pa/s</td>
<td>(( Ln=4.94 ) m) ( \Rightarrow ) -31740 Pa/s</td>
</tr>
</tbody>
</table>

First of all one should specify how to treat the averaging of the probes used to get the \( \text{caravg} \) one. If the eight probes time histories are cut and translated in order to be aligned presenting the maximum gradient at \( t=0 \), then one gets a maximum gradient of -40 000 Pa/s for the \( \text{caravg} \) probe, as in Fig. 5.22. This averaging procedure grants the maximum possible gradient to the resulting \( \text{caravg} \) probe. If instead one just averages all the pressure time histories without cutting and translating them, one gets a maximum gradient of -32000 Pa/s, very close to the one from Eq. (5.9).

Looking at the extended version of NUMSTA, the extended nose length grants a very good agreement with regards to the time scale of the head passing for both the \( TR2 \) and \( \text{caravg} \) probes, as also shown in Fig. 5.53.
Fig. 5.53 NUMSTA vs Star comparison - 93 m² tunnel benchamrk train crossing case.

With regard to the head passing TR2 probe, one can appreciate that the maximum gradient of -7400 Pa/s is reached by both Star and NUMSTA, thus confirming the validity of Eq. (5.8), and that both gradient time histories are well aligned, thus confirming the validity of equation of Eq. (5.10). Also the head passing recorded by the caravg probe show the same features, thus also confirming the validity of Eq. (5.9). Looking at the pressure time histories for the head passing, one can see that NUMSTA is very close to Star, except at the end of the head passing. In that region the Star probes get at a lower minimum pressure then stabilising and remaining constant, while the NUSTA ones decrease linearly; this difference is due to the different boundary layer approximations, and clearly Star is more accurate than the NUMSTA fixed c_f approach (the friction coefficients chosen for train and tunnel are respectively 0.001 and 0.01). Star reaches a lower pressure because it models the boundary layer flow displacement, thus increasing the blockage ratio in the train-tunnel annulus. This effect is stronger for smaller tunnel and higher velocity, as also shown in the following section.

At about 0.4 s after the head passing, a bump appears in all the probes pressure time histories. This is probably due to secondary waves which originate when the head of the passing train meets the tail of the probed one.

Looking at the tail passing, one can see that the NUMSTA head passing shows a very high magnitude when compared to the Star one, as NUMSTA cannot model the turbulent wake behind the tail, so in NUMSTA the pressure recovery behind the tail is nearly complete, the only pressure losses being due to the boundary layers in the train-tunnel annulus.

Concluding, the accuracy of the extended version of NUMSTA is very good for the head passing for the caravg and TR2 probes, but it still cannot model neither the tail passing nor the 3D effect peaks.
5.4.3. Parameters sweeps results

A useful feature of the formulation chosen for the NUMSTA fitted nose length is that it includes the results of the Star parameters sweeps, so it is valid for any combination of velocity, tunnel cross section nose length and track spacing tested.

In order to assess the accuracy of the NUMSTA nose length fitting procedure, one can compare the Star results with the NUMSTA ones for different sweeps. For brevity, only the TR2 probe accuracy will be assessed in this section.

Fig. 5.54 NUMSTA vs Star - TR2 probe - Velocity sweep: V=150 km/h

In Fig. 5.54 one can check that the 22 m nose length works fine for the TR2 probe also at 150 km/h. Furthermore the NUMSTA depend is identical to the Star one for this case thanks to the lower train speed which reduces the blockage ratio increase due to the boundary layer flow displacement in the train-tunnel annulus.
In this case both the tunnel cross section and the track spacing have been reduced. One can appreciate both in Fig. 5.55 and in table Tab. 5.16 NUMSTA parameters sweep overview, that the choice of a nose length of 22 m still works fine for the TR2 probe both in terms of $d_{pend}$ and in terms of maximum gradient of the head passing. An error close to about 10% is introduced in the $d_{pend}$ most probably because of the stronger influence of the boundary layers in the train-tunnel annulus which make the Star pressure decrease more after the head passing.

**Fig. 5.55 NUMSTA vs Star - TR2 probe - Stu sweep: Stu=63 m$^2$ and Lax=1.75 m**

**Fig. 5.56 NUMSTA vs Star - Nose length sweep**
The NUMSTA 22 m nose length used to fit the Star TR2 probe does not vary with varying nose length. This is confirmed also by the Star results, in which the head passing time scale does not depend on the nose length, as shown in the right plot of Fig. 5.56 NUMSTA vs Star - Nose length sweep. What happens is that for decreasing nose length the maximum gradient increases slightly and the $d_{pen}$ decreases considerably after the head passing. This last factor might be explained by the increase in boundary layer displacement thickness around the passing train nose, which might increase the blockage ratio reducing the pressure felt on the probed train on the train-to-tunnel side.

The results of the NUMSTA sweep are reported in Tab. 5.16.

**Tab. 5.16 NUMSTA parameters sweep overview.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Tool</th>
<th>$\Delta p_{end}$ [Pa]</th>
<th>TR2 max. Grad. [Pa/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>Star</td>
<td>-829</td>
<td>-7400</td>
</tr>
<tr>
<td>NUMSTA</td>
<td>-760</td>
<td>-7300</td>
<td></td>
</tr>
<tr>
<td>$V=150$ km/h</td>
<td>Star</td>
<td>-272</td>
<td>-1510</td>
</tr>
<tr>
<td>NUMSTA</td>
<td>-272</td>
<td>-1530</td>
<td></td>
</tr>
<tr>
<td>$Stu=63$ m$^2$</td>
<td>Star</td>
<td>-1250</td>
<td>-12180</td>
</tr>
<tr>
<td>$Lax=1.75$ m</td>
<td>NUMSTA</td>
<td>-1150</td>
<td>-11420</td>
</tr>
<tr>
<td>$Ln=8$ m</td>
<td>Star</td>
<td>-789</td>
<td>-6700</td>
</tr>
<tr>
<td>NUMSTA</td>
<td>-760</td>
<td>-7300</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.16 shows that NUMSTA accuracy is acceptable but its overall error can be about 10%, both in terms of $d_{pen}$ and of maximum gradient. This is also because Eq. (5.8) and Eq. (5.9) are a direct application of the fitting lengths without the introduction of a further fitting coefficient.

An interesting feature of this parameters sweep is that the NUMSTA nose length has always been kept to 22 m for any value of velocity, tunnel cross section, nose length and track spacing, against one would expect. On the other hand the NUMSTA nose length for the $caravg$ probe does depend on those parameters value.

Overall NUMSTA can be used to approximately compute the TR2 loads, reaching a better result than the $LinRise$ probe, but the 3D effect is really needed to compute loads for the TL2 probe.
5.5. Conclusions for train crossing

Regarding the train crossing scenario, **two Star simulation setups** have been developed, the first one capable of modelling the two trains tunnel entry and passage with crossing inside the tunnel, and the second one with both trains starting from inside the tunnel. Both set-up are valid, but for the first one it is impossible to separate the travelling train entry pressure waves from the train passing, so if one wants to model the train passing pressure changes he needs to use the second set-up developed. Both setups employed the overset mesh technique, which allowed to simulate very small tunnels also with the trains very close one another. Several point and surface probes recorded the pressure felt on any part of the train wall, thus allowing both to have the average surface pressure input for the internal pressure computation and to highlight the differences between the pressure train histories on both train sides, as well as on the train roof and floor walls. One of the main goal of the Star simulations for the train passage was to quantify and justify the **3D effect pressure peaks** which appear only in the train-to-train side wall. Thanks also to visual animations of the train crossing phase, it was possible to identify the source of the 3D effect as the direct influence of the pressure field around the passing train nose and tail with the probed train wall. In particular, for the head passing the positive 3D effect peak comes from the high pressure stagnation region in front of the passing train nose, while the negative one comes from the lower pressure region where the flow accelerates around the passing train nose.

The high number of probes needed required two complicated **data processing** procedures, one for the point probe pressure time histories, which have been cut out, shifted and averaged, and another one for the surface probe, which have been fitted linearly. The point probe cutting and shifting allows to develop a **fitting procedure** for those probes employing the results from several parameters sweeps simulations to predict the pressure time histories of the most interesting probes, thus granting homogeneous pressure time histories, with smooth gradients and symmetrical peaks, from which one can compute and compare effectively the loads for different cases.

More than 11 Star simulations have been run for the **parameters sweeps**, ranging over different velocities, tunnel cross sections, nose lengths, and track spacings, and allowing both to tune the fitting procedure and to assess its fitting error. The error was always lower than about 7% in terms of pressure time histories except for the smallest 54 m² tunnel case, in which the pressure time histories show quite different shapes because of the boundary layer influence. For each parameter sweep, the loads were computed applying the free-length model to the fitted pressure time histories, thus highlighting the very strong influence both of the carriage free length and of the probe position on the loads. As an example, the head passing loads on the tail region of a carriage will be strongly shifted towards compression ones, as the internal pressure will already be low before the opposing train head passes that location, so the compression load coming from the positive 3D effect pressure peak due to the stagnation region in front of the passing strength will be boosted. This effect can lead to a change in sign of the train passing loads, so it is of paramount importance to take it into account when predicting the loads on a non-tight carriage. The sweep allowed to confirm that for a tight carriage this effect strongly reduces, as the internal pressure remains closer to zero throughout the whole train passing.

Beyond the three pressure tightness parameters (τ, Free Length and probe position), also the case parameters (train speed, tunnel cross section, nose length and track spacing) do influence the loads. A higher **train velocity** increases the pressure drops and decreases the rise-times for all the probes, so it strongly increases the loads. For a 0.2 s τ train travelling in a big 93 m² tunnel, a representative load at 150 km/h is 261 Pa, while it gets to 756 Pa for 250 km/h and to 1542 Pa for 350 km/h; this is why tunnels for high speed trains must be separated by the ones for regional trains which are not certified to withstand such loads. Again, when this rule is broken incidents can happen, as on the 20/07/2015, when one of the two panel of a brand-new regional train carriage door separated inside a tunnel in the Firenze-Arezzo line in Tuscany, in a much smaller tunnel than 93 m², most probably due to the encounter of a high speed train [36].

The **tunnel cross section** variation has two effects on the train passing loads, the main one being on the blockage ratio, thus strongly increasing the $d_{pend}$ magnitude for smaller tunnel. On the other hand this
parameter sweep has also shown that an increase in tunnel cross section leads to a strong increase in 3D effect peaks magnitude, due to the increase in velocity magnitude for the flow around the crossing train nose which increases the stagnation region pressure and decreases the one of the lower pressure where the flow accelerates around the passing train nose. This very unexpected and important finding would not have been easily predictable without looking at the Star result for the tunnel cross section parameter sweep.

The last parameters sweeps executed regarded the nose length and track spacing, increasing both of which the 3D effect peaks decrease in magnitude and increase in time scale, without influencing the depend.

A further part of the work for the train crossing scenario was to evaluate and improve NUMSTA accuracy when computing the train passing pressure time history. NUMSTA is a 1D code, so it cannot predict the 3D effect pressure peaks and the influence of the wake, but its prediction of the train passing pressure time history can be improved by tuning the NUMSTA nose length using results from the fitting procedure, in order to at least give the right time scale to the NUMSTA pressure variations. The extension of the NUMSTA nose length depends on the side of the train for which one wants to compute the pressure time history, and it is different from the one developed to fit the train entry compression wave. By adapting the NUMSTA nose length one gets a very good accuracy in terms of head passing for probes without 3D effects peaks, while the tail passing pressure drop is always overestimated by about 20% as NUMSTA does not model the reduction in pressure recovery behind the tail due to the wake.
6. Conclusion

Loads on non-tight trains passing tunnels heavily depend on the internal pressure inside the carriage, as for a non-tight carriage the internal pressure quickly follows the external one. For this reason the internal pressure must be accurately predicted taking into account the Free Length of the carriage, the position along the carriage on which the loads are required and the pressure tightness time constant of the carriage. Also the time scales of the external pressure variations are more influent on non-tight trains, but they cannot be predicted by 1D CFD codes, so 3D CFD codes are needed to simulate them, but it is not affordable to execute a 3D CFD study for the tunnel passage of each new train model through all possible tunnels, so simplified models are needed.

A key result of this work is the Star-CCM+ simulation setup for the tunnel entry and passing scenario as well as for the train crossing one using the recently available overset mesh approach, which allows quicker and more versatile runs with close proximity of the train and tunnel walls when compared to the traditional sliding mesh approach based on an in-place interface. The tunnel entry set-up has been validated against the AeroTRAIN benchmark case in terms of maximum gradient of the nose entry compression wave, thus confirming that the overset mesh interpolation error is acceptable when compared with sliding mesh results.

The simplified geometries of train and tunnel made the full scale 3D unsteady turbulent overset mesh simulations quick enough to allow to execute both full tunnel passage train-crossing simulations and thorough parameters sweeps for both the tunnel entry and train crossing scenarios, totalising more than 30 simulations for the parameters sweeps. The results of the parameters sweeps for both scenarios were used to develop parameter fitting formulas capable to predict the train pressure signature and train passage pressure time histories for any given combination of train velocity, tunnel cross section, nose length and track spacing.

With regard to the single train tunnel entry results, the main output is the pressure signature. This work has confirmed that the arctan shape is a good approximation for the head compression wave, as it gave loads very close to the Star ones. For a given pressure signature shape, the most important parameter to compute the loads on a non-tight train is the maximum pressure gradient across the head compression wave. The parameters sweep for the train entry simulations allowed to confirm that the maximum gradient varies proportionally to the third power of the train velocity. Another very important quantity which determines the nose entry wave magnitude and maximum gradient is the tunnel cross section. In particular, the amplitude of the nose entry wave is known to depend on the ratio between the train and tunnel cross section (blockage ratio), while the rise time of that wave has been found in this work to be proportional to the difference between the train and tunnel hydraulic diameters. Furthermore, an increasing nose length was confirmed to reduce the maximum gradient, but its influence is lower than expected, as the rise time of the wave depends more on the difference between the train and tunnel hydraulic diameters than on the nose length, against one would expect. Also an increase in track spacing was found to have an adverse influence on the maximum gradient.

The nose entry compression wave fitting procedure proved to be capable of predicting the maximum pressure gradient with an error of 6% in the range of variables analysed. It must be underlined that the fitting procedure error increases as the case gets further from the benchmark one. In spite of that, the fitting procedure prediction of the nose entry compression wave rise time have been used to adapt the NUMSTA (1D CFD code) nose length, thus hugely improving NUMSTA accuracy in terms of maximum gradient of the nose entry compression wave. Comparing also the extended NUMSTA results for the whole tunnel passage with the same results from Star-CCM+, the agreement among the two is definitely satisfactory. Given the very low computational expense required by NUMSTA and its satisfactory level of accuracy with regards to the nose entry compression wave it becomes more convenient than Star for single train entry and passage simulations, but its main drawback comes for the train crossing simulations, as it cannot model the 3D effect pressure peaks and the wake behind the train.
The last topic addressed for the single train entry scenario has been the pressure wave encounter, in which
the train meets the same pressure waves it generated when entering the tunnel. This analysis confirmed the
paramount importance of taking into account the Free Length of the carriage and the position along the
carriage when computing the loads for non-tight carriages, especially of course if the carriage free length is
long, which is the case for modern trains. In particular, this analysis showed that the LinRise approximation of
the nose entry compression wave with a fixed rise time of 0.02 s is conservative, as it predicts higher loads
than the more accurate Free Length model along the whole carriage. On the contrary, applying the point-tau
model for load prediction to the Star simulated nose entry compression wave, thus neglecting the Free Length
and probe position influence, turned out to be too optimistic for the maximum load occurring along the free
length of the carriage.

With regard to the train crossing scenario, one of the main results has been quantifying and justifying the 3D
effect pressure peaks in the pressure time history recorded by a probe on the train-to-train side wall. In
particular, with regard to the head passing, the positive peak of the 3D effect comes from the high pressure
stagnation region in front of the passing train nose, while the negative pressure peak comes from the lower
pressure region where the flow accelerates around the train nose. Furthermore, a second fitting procedure
has been developed which can predict the head and tail passing pressure time histories and so the 3D effect
peaks intensity. A very important feature of the train passing pressure time history is that it strongly depends
on the side of the train considered: for the wall on the side of the train closest to the opposing train the
pressure variations will be very quick and with peaks, while at the train side closest to the tunnel wall the
variation will be much slower and without peaks.

The train crossing scenario parameters sweeps simulations showed that the velocity remains the most
influent parameter which influences both the amplitude and the time scale of each load, justifying the need
for strict regulations in tunnels where low speed non-tight trains meet high speed ones. With regard to the
tunnel cross section sweep, a bigger tunnel leads to a smaller blockage ratio, thus reducing magnitude of the
train passing pressure disturbance (dpend), as expected. A secondary unexpected effect of increasing the
tunnel cross section is a strong increase in the magnitude of the 3D pressure peaks; this effect has been
quantified and partially justified theoretically, but it would have been hard to predict without the Star tunnel
cross section parameter sweep. Furthermore, increasing the nose length and the track spacing both lead to a
decrease in 3D pressure peaks magnitude and an increase in separation in time between the two peaks,
without influencing the magnitude of the train passing pressure disturbance (dpend).

A second extension procedure of the NUMSTA nose length has been developed starting from the fitting
procedure results, so with the extended front length NUMSTA can predict the right time scale for the pressure
variation on the train-to-tunnel side or for the car cross-sectional average pressure, thus becoming capable of
predicting the head passing loads for those locations. On the other hand NUMSTA cannot predict the 3D
pressure peaks, so it cannot be applied to the train-to-train side probes, and it also cannot model the wake
behind the tail, so it cannot model the tail passing loads. For these reasons the unextended NUMSTA
computed train passing loads will not be fully representative.

Concluding, this thesis work has allowed to develop from scratch several Star simulations setups for the tunnel
entry, tunnel passage and train crossing scenarios. Furthermore, the parameters sweeps executed allowed to
assess the influence of many factors on the loads for non-tight trains, as well as to develop a fitting procedure
which can quickly predict a first approximation of the pressure time histories and of the loads for both
scenarios and for any combination of train speed, tunnel cross section, nose length and track spacing. A further
result is the assessment of NUMSTA accuracy, as well as the development of a NUMSTA nose length extension
procedure to better predict either scenario for any parameter combination. The work also highlights the strong
influence of the carriage free length and of the position along the carriage when computing the loads for a
non-tight train.
7. Notation

7.1. Variables

7.1.1. Chapter 2 – Theoretical background

\( p \): Static pressure.

\( p_0 \): Ambient pressure.

\( \rho \): Static density.

\( h \): Static enthalpy per unit mass.

\( s \): Static entropy per unit mass.

\( R \): Ideal gas constant.

\( c_p \): Specific heat capacity at constant pressure.

\( \gamma, k \): Heat capacity ratio (\( k \) is later used as elastic car body deformation coefficient).

\( \tau, \tau_s \): Isothermal and isentropic compressibility (\( \tau \) is later used for pressure tightness time constant).

\( u \): 1D: only velocity component. 3D: velocity component along \( x \).

\( \mathbf{V} \): Velocity vector.

\( V_{tr} \): Train velocity.

\( M, Ma \): Mach number.

\( a \): Speed of sound.

\( M^* \): Characteristic Mach number.

\( W \): Velocity of shock wave with respect to the ground.

\( u_p \): Flow velocity downstream the shock wave with respect to the ground.

\( c_f \): Friction coefficient.

\( \tau_w \): Wall shear stress.

\( \mu \): Dynamic viscosity.

\( D/Dt \): Material derivative (Lagrangian derivative).

\( \nabla \cdot () \): Divergence operator.

\( J_- , J_+ \): Riemann invariants.
\( \lambda_1, \lambda_2, \lambda_3 \): Eigenvalues of the inviscid compressible 1D flow equations.

\( \Delta p_N \): Nose entry head compression wave magnitude.

\( \Delta p_{fr} \): Friction rise magnitude.

\( \Delta p_T \): Tail entry pressure drop.

\( \Delta p_{HP} \): Head passing the probe location pressure drop.

\( \frac{\partial p}{\partial t}_{max} \): Maximum pressure gradient across the head compression wave.

\( B \): Blockage ratio (train cross sectional area over tunnel cross sectional area).

\( \zeta_h \): Head pressure loss coefficient (for Sockel Eq. (2.17)).

\( X_h \): Unknown Mach number (for Sockel Eq. (2.17)).

\( e \): Porosity of ballast.

\( \zeta \): Mass ratio of ballast.

\( h_b \): Thickness of ballast.

\( A_{tu} \): Tunnel cross sectional area.

\( \Delta A \): Tunnel cross sectional area change.

\( \tau \): Pressure tightness time constant.

\( k \): Coefficient of elastic car body deformation.

\( S_{eq} \): Equivalent leakage area.

7.1.2. Chapter 3 – CFD background

\( \vec{v}, \vec{v}_i \): velocity vector.

\( E \): specific internal energy.

\( H \): specific enthalpy.

\( \bar{\tau}, \tau_{ij} \): Shear stresses tensor.

\( \tau_{ij}^V \): Viscous shear stresses tensor.

\( \tau_{ij}^R \): Turbulent shear stresses tensor (Reynolds stresses).

\( k \): thermal conductivity.

\( \vec{f}_e \): external forces vector (for the momentum equation).
\( w_f \): work of external forces (for the energy equation).

\( q_H \): heat fluxes term (for the energy equation).

\( k \): Turbulent kinetic energy.

\( e \): Dissipation rate.

\( \omega \): for turbulence: specific dissipation rate. For Star formulation: Under Relaxation Factor.

\( U, V, W \): mean velocity components (for turbulence).

\( u', v', w' \): oscillation in time of velocity components.

\( \theta \): turbulence velocity scale.

\( l \): turbulence length scale.

\( \mu_T \): turbulent viscosity.

\( V_f \): friction velocity.

\( K_s \): equivalent sand-grain roughness.

\( K_s^+ \): adimensional equivalent sand-grain roughness.

\( y^+ \): adimensional wall distance.

\( \Delta x \): mesh size.

\( \Delta t \): time step.

\( \alpha \): generic advection velocity.

\( \phi \): generic scalar (Star formulation).

\( \Delta \): Laplace operator (Star formulation).

\( \chi \): void fraction for multi-phase flows (Star formulation).

\( V_0, V \): cell volume (Star formulation).

\( \mathbf{v} \): flow velocity vector (Star formulation).

\( \mathbf{v}_g \): grid velocity vector (Star formulation).

\( \Gamma \): diffusion coefficient (Star formulation).

\( S \): source term (Star formulation).

\( \mathbf{a} \): cell boundary area vector, magnitude is cell area, direction is normal to the face (Star formulation).
$F, T$: convective inviscid fluxes tensor (Star formulation).

$G$: grid fluxes tensor (Star formulation).

$G$: viscous and turbulent fluxes vector (Star formulation).

$H$: source terms (Star formulation).

$Q$: primitive variables column vector (Star formulation).

$\Gamma_0$: preconditioning matrix (Star formulation).

$\tau$: pseudo-time (Star formulation).

$\lambda_{max}$: maximum eigenvalue of the inviscid Navier Stokes system (Star formulation).

$\sigma$: Von Neumann number (Star formulation).

$\omega$: under relaxation factors (Star formulation).

$\dot{m}_f$: mass flow through the cell face (Star formulation).

$e_t$: specific total internal energy (NUMSTA formulation).

$h_t$: specific total enthalpy (NUMSTA formulation).

$c_{f,TR}$: train wall friction coefficient (NUMSTA formulation).

$c_{f,TU}$: tunnel wall friction coefficient (NUMSTA formulation).

**7.1.3. Chapter 4 – Single train tunnel entry and passage**

$\delta$: Prism layer thickness.

$L_{bench}$: characteristic length to fit the benchmark case maximum gradient.

$c_{dh}$: adimensional fitting coefficient for tunnel and train hydraulic diameters variation.

$c_{Ln}$: adimensional fitting coefficient for nose length variation.

$c_{Lax}$: adimensional fitting coefficient for track spacing variation.

$d_h$: tunnel hydraulic diameter.

$d_{h_{train}}$: train hydraulic diameter.

$L_n$: train nose length.

$L_{ax}$: half the track spacing.

$c_{t2}$: adimensional fitting coefficient for the maximum pressure time instant of the head compression wave.
$c_{t3}$: adimensional fitting coefficient for the minimum pressure time instant of the head compression wave.

$L_{n}^{N}$: train nose length given in input to NUMSTA.

$L_{TR}^{N}$: train length given in input to NUMSTA.

$L_{free}$: carriage free length.

$V_{rel}$: relative velocity between the train and the travelling pressure wave.

dtc, $\Delta t_{char}$: ratio between $L_{free}$ and $V_{rel}$.

### 7.1.4. Chapter 5 – Train crossing inside tunnel

$w_d$: distance between the two trains walls

$\Delta p_{end}$: pressure on the probed train wall immediately after the head (or tail) passing.

$\Delta t_{end}$: time at the end of the head (or tail) passing.

$\Delta p_{3D}$: pressure drop between the two 3D effects peaks recorded on the probed train wall.

$c_{dp3D}$: adimensional coefficient (ratio between $\Delta p_{3D}$ and $\Delta p_{end}$).

$\Delta t_{3D}$: time of the second 3D effects peak recorded on the probed train wall.

$c_{dt3D}$: adimensional coefficient (ratio between $\Delta t_{3D}$ and $\Delta t_{end}$).

$\Delta p_{p+}$: for head passing: positive 3D effect peak pressure.

$\Delta p_{p-}$: for head passing: pressure drop between negative 3D effect peak and $\Delta p_{end}$.

$V_{fbc}$: flow velocity in the portion of tunnel upstream of the opposing train nose, for the benchmark case.

$V_{f}$: flow velocity in the portion of tunnel upstream of the opposing train nose.

$\Delta X$: probe position with respect to the carriage centre; also mesh cell size.

### 7.2. Abbreviations

#### 7.2.1. Chapter 2 – Theoretical background

**CFD**: Computational Fluid Dynamics.

**Star**: Star-CCM+, 3D commercial CFD code.

**NUMSTA**: (Numerical Simulation of Tunnel Aerodynamics) 1D commercial CFD code.

**RANS**: Reynolds averaged Navier Stokes equations.

**PDE**: Partial Differential Equation.
ODE: Ordinary Differential Equation.

1D, 3D: One dimensional and three dimensional.

TSI: Technical Specifications for Interoperability.

SpL: Sound pressure Level (dB).

MPW: Micro Pressure Waves, pressure waves emitted at the tunnel portal.

Point τ model: computes the car internal pressure and loads approximating the car as a point.

Free Length model: computes the internal pressure and loads taking into account the length of the car.

7.2.2. Chapter 3 – CFD background

NS: Navier-Stokes equations.

RANS: Reynolds Averaged Navier-Stokes equations.

FEM: Finite Elements Method.

FV: Finite Volume space discretisation.

FD: Finite differences space discretisation.

BC: Boundary Conditions.

CFL: Courant-Friederichs-Lewy number.

7.2.3. Chapter 4 – Single train tunnel entry and passage

AeroTRAIN: (Aerodynamics: Total Regulatory Acceptance for the Interoperable Network) benchmark case from a collaborative EU project within railway aerodynamics.

TKE: Turbulent Kinetic Energy.

SDR: Specific Dissipation Rate.

URF: Under Relaxation Factors.

RBM: Rigid Body Motion.

baseline NUSMTA: NUMSTA run using the physical nose and train length.

extended NUSMTA: NUMSTA run using the extended nose and train length.

front probe: probe placed at the end of the carriage where the travelling pressure wave arrives first.

centre probe: probe placed at the centre of the carriage length.
"back probe": probe placed at the end of the carriage where the travelling pressure wave arrives later.

7.2.4. Chapter 5 – Train crossing inside tunnel

\( P_tP \): Peak-to-Peak.

\( end \): immediately after the head (or tail) passing.

\( tl2 \) probe: probe on the left (train-to-train) side of the probed train, at 2 m height from the ground.

\( tr2 \) probe: probe on the right (train-to-tunnel) side of the probed train, at 2 m height from the ground.

\( caravg \) probe: time history of the average pressure on the carriage cross section.

\( LinRise \) probe: linear pressure variation with a fixed duration of 0.02 s.

\( tl2 \) probe: probe on the left side of the probed train. The left side is the train-to-train side.

\( b \): benchmark case.
8. References


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