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# SENSITIVITY OF THE WAVE-STEEPENING IN RAILWAY TUNNELS WITH RESPECT TO THE FRICTION MODEL

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## 1 INTRODUCTION

With the new line Nuremberg-Ingolstadt going in operation in the mid of 2006 the propagation of compression waves created during the tunnel entry of high-speed trains has received renewed interest within Deutsche Bahn since two tunnels on the slab-track equipped line reach a length in the order of 8 km where micro-pressure wave emission at the exit portal becomes an issue [1, 4]. The need for accurate prediction methods for the wave steepening process has increased since new lines currently under planning or construction will have single track tunnels with smaller cross sections. Among the numerous countermeasures for reducing the emission the optimization of the wave shape during tunnel entry has recently received some attention [3]. The goal of this paper is to proof the capability of a numerical simulation tool to yield accurate predictions by comparison with field measurements and to demonstrate the sensitivity of the results with respect to the choice of the friction model parameters.

## 2 METHOD

The one-dimensional Euler equations augmented by two source terms modeling "quasi-steady" and "unsteady" friction according to

$$\frac{\partial\left(\rho u\right)}{\partial t}+\frac{\partial\left(\rho u^2+p\right)}{\partial x}=-\frac{\lambda}{d_h}\frac{1}{2}\,\rho\,u^2-\epsilon_{us}\frac{16\,\rho\,\nu}{d_h^2}\int_0^T W\left(T-t\right)\frac{\partial u}{\partial t}\,dt \tag{1}$$

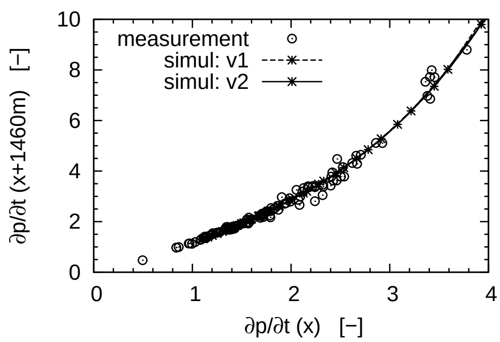
are solved using the Godunov approach. Here, $d_h = 4A/U$ denotes the hydraulic diameter of the tunnel and $W(T-t)$ is a weighting function which depends on the Reynolds number and the roughness [5, 7]. At each cell interface a Riemann problem is solved using library routines from the CLAWPACK package [2]. The weighting function in the history term is approximated efficiently in terms of a series expansion of decaying exponentials as in [6]. The computation proceeds on a mesh which moves with the wave. Simple zero-order extrapolation boundary conditions are specified. The implementation was thorougly tested and validated by comparison with the analytical solution for the inviscid case. The grid independence of the solution was always checked by doubling the resolution.

## 3 RESULTS

It is demonstrated that the choice of the specific form (laminar or turbulent) of the unsteady friction model is irrelevant in this problem due to the short duration of the wave passage. Furthermore, since the effect of roughness [7] is approximately equivalent to a change in the global weight of the entire history term, it is appropriate - and common practice in railway tunnel engineering - to adjust both the parameters $\lambda$ and $\epsilon_{us}$ until satisfactory agreement with field data is achieved.

### 3.1 MODEL VALIDATION

In Fig. 1, 2, 3 and 4 the model predictions are compared with field data from the 8 km long Euerwang tunnel prior and after installation of acoustical absorbers. Model parameters were adjusted to give the best fit for the six consecutive measurement locations. These plots demonstrate the very good agreement of the model with respect to the slowly decreasing amplitude and the steepness of the wave which is crucial for the accurate prediction of the emitted infrasound wave at the tunnel exit. In order to arrive at a good agreement both parameters $\lambda$ and $\epsilon_{us}$ had to be assigned non-zero values simultaneously. Nevertheless, it was found that different combinations of $\lambda$ and $\epsilon_{us}$ gave comparable good predictions. This non-uniqueness of the proposed model approach emphasizes the need for a better theoretical foundation. Ideally, a relation between the model friction parameters and some characteristic parameters of the tunnel walls, the trackbed, and other installations such as catenary and signals should be developpped. The installation of sound absorbers in the trackbed has a significant impact on the wave steepening which demonstrates the strong sensitivity of this process with respect to small modifications in the surface conditions of tunnel walls and the addition of porous material.



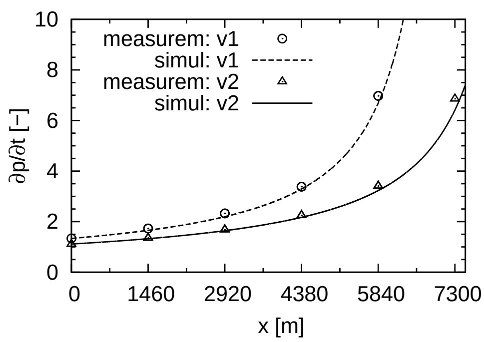




Figure 1: Wave-steepening prior to installation of absorbers: Left: Maximum pressure gradient (in arbitrary units) after propagation through a segment of length 1460 m. Right: evolution of the maximum pressure gradient along the tunnel for two train speeds v1 and v2.

### 3.2 WAVE SHAPE OPTIMIZATION

One way to mitigate the steepness of the compression wave consists in the installation of hoods or flared portals. By careful design of the cross-sections and installation of small side openings in the walls near the portal the shape of the compression wave can be modified. Ideally, the pressure wave has an almost constant gradient.

Here, the propagation of three different waves with identical maximum values of the initial pressure gradient, $\partial p/\partial t = 5000\, Pa/s$,is compared for two sets of the friction model parameters. The chosen settings correspond approximately to the situation in the Euerwang tunnel prior and after installation of sound absorbers.

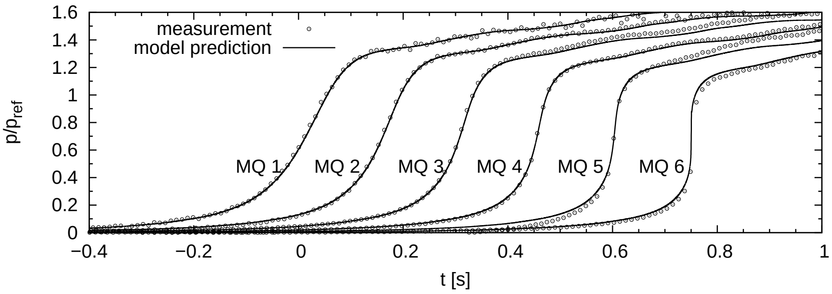



Figure 2: Comparison of measured and simulated wave shape at six locations in the tunnel prior to installation of acoustical absorbers. Only a subset of the measurements is shown.

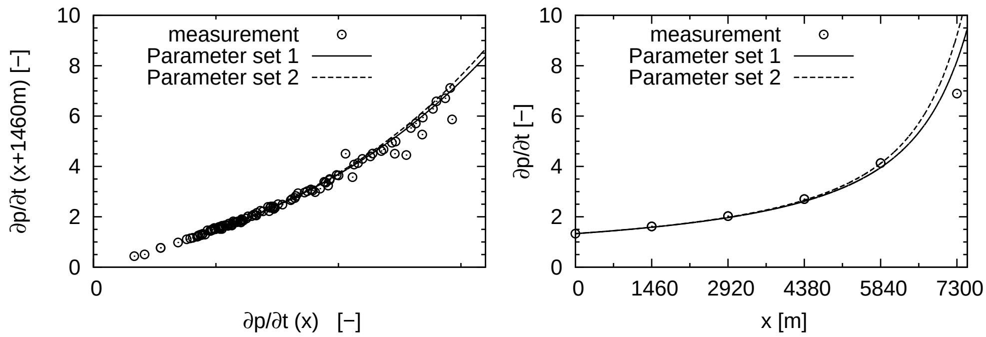



Figure 3: Comparison of wave-steepening after installation of absorbers for two sets of friction parameters. Left: Maximum pressure gradient (in arbitrary units) after propagation through a segment of length 1460 m. Right: evolution of the maximum pressure gradient along the tunnel.

Fig. 5 shows the initial waves and the resulting waves after 6000 m of propagation. Clearly, the choice of the friction model has a strong impact with respect to the optimal wave shape. In case of low friction the wave with the longest rise time, i.e. where the initial maximum pressure gradient is near the tail of the wave, steepens less than the others. The effect is reversed in case of a higher friction coefficient $\epsilon_{us}$. This behaviour can clearly be contributed to a change in the relative importance of the two friction terms.

## 4 CONCLUSIONS

The compression wave steepening in the long tunnels on the new German high-speed line can be well predicted using state-of-the-art models for the friction effects. For the selection of appropriate model parameters field measurements are needed. The development of the wave shape depends crucially on the friction parameters and the relative weight of quasi-stationary

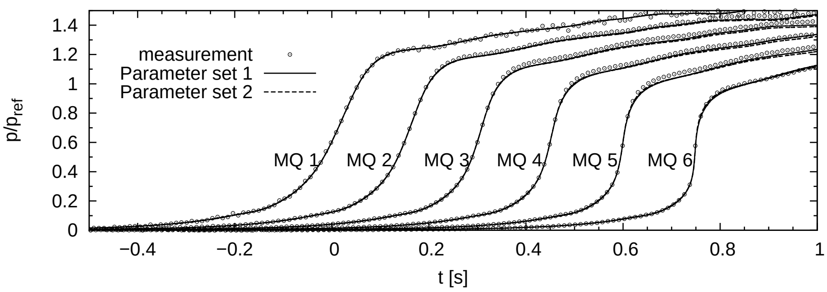



Figure 4: Comparison of measured and simulated compression wave (in arbitrary units) at six locations in the tunnel after installation of acoustical absorbers. Only a subset of the measurements is shown.

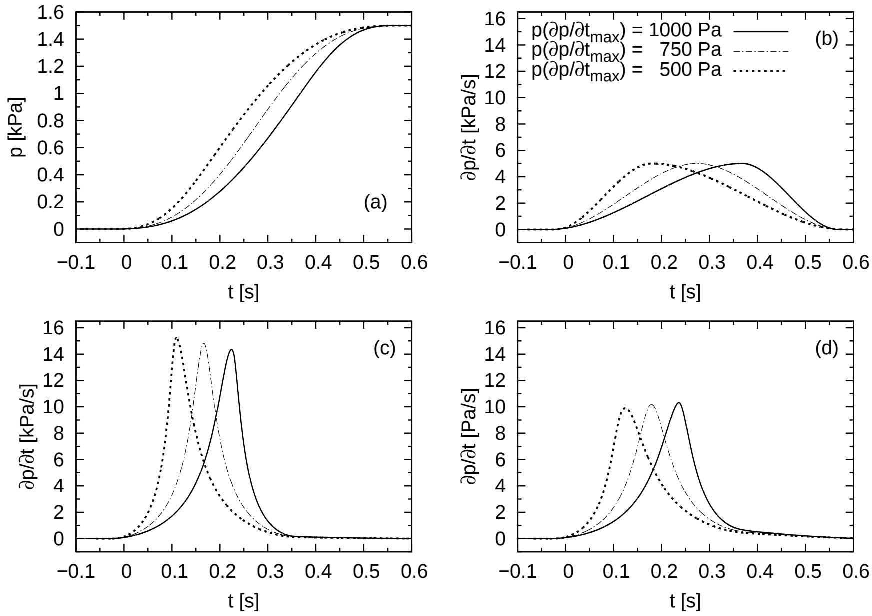



Figure 5: Shape of the initial wave (a),(b) and evolution of the pressure gradient after 6000 m for low $\epsilon_{us}$ (c) and for high $\epsilon_{us}$ (d).

and "unsteady" friction. Wave shape optimization would benefit from a more thorough justification of the friction model.

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