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CFD simulation of train aerodynamics: Train-induced wind conditions at an underground railroad passenger platform

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ABSTRACT

The Dutch railways plan to increase the amount of trains and their running velocities to avoid overcrowded trains during rush hours. This can cause pedestrian wind discomfort or danger at the platforms as trains will be allowed to pass small railway stations at high speeds up to 140 km/h. A number of these railway stations lie underground, where wind gusts caused by trains are amplified by space confinement. The purpose of this study is to evaluate the effect of passing passenger trains and freight trains on the wind conditions induced on a passenger platform inside an underground tunnel by means of Large-Eddy simulations (LES). First, the computational model, which includes stationary (tunnel and platform) and moving (train) subdomains, is validated by available experimental data for a train running through a tunnel. Next, case studies are performed for a passenger train and a freight train, where the dimensions of the tunnel and the platform are chosen from the Dutch design requirements for railroad tunnels and platforms. The results of the study show that passengers standing on a platform can experience strong wind effects when passenger trains or freight trains are passing at speeds of 140 and 100 km/h, respectively. These effects might give rise to wind discomfort or even wind danger, and should be taken into account in the design of railway tunnels and platforms and in safety regulations.

1. Introduction

The Dutch railways transport more than 1.2×10^6 passengers a day and 0.6×10^6 passengers during rush hours, resulting daily in more than 5200 train rides. To avoid overcrowded trains, the amount of passenger trains and freight trains will be augmented and their running velocities will be increased up to 140 km/h (ProRail, 2014). Trains passing small railway stations at these high speeds might cause pedestrian wind discomfort or wind danger on the platforms.

A number of railway stations lie underground and due to the space confinement this results in increased air movements and augmented velocities in front of and behind the running train (Baker et al., 2014; Gilbert et al., 2013a, 2013b). Air inside a tunnel is confined by the tunnel walls and, therefore, a compression wave is created in front of the moving train, while an expansion wave is created behind the train (Fig. 1). This phenomenon is called the "piston effect".

The piston effect and the resulting pressure waves propagation are described in (William-Louis and Tournier, 2005; Novak, 2006). The main factors that influence the strength of the pressure waves are the blockage ratio of the train in the tunnel (which is defined as the ratio of the train cross-section to the tunnel cross-section), the shape of the nose and tail of the train, the train velocity, the shape of the tunnel entrance and exit, the tunnel length and the roughness of the train body and the tunnel walls (Baron et al., 2001; Raghunathan et al., 2002; Novak, 2006; Ricco et al., 2007; Bopp and Hagenah, 2009).

Topics that have been addressed in previous studies on train aerodynamics include:

- train-induced slipstreams in open field (Baker et al., 2006; Sterling et al., 2008) and in confined spaces (Gilbert et al., 2013a, 2013b);
- effect of crosswinds on trains and the risk of a train to fall over while running in open field (Hemida and Baker, 2010; Eighinger et al., 2013; Sima and Venkatasalam, 2013);
- pressure distribution and variation inside tunnels (Baron et al., 2001; Raghunathan et al., 2002; Ricco et al., 2007; Hieke et al., 2013);
- ballast flying and projection, displacement of ballast stones induced by high speed of a train and damaging train details (Sima et al., 2008; Saussine et al., 2013; Weise and Sima, 2013).

Baker et al. (2006) and Baker (2010) discussed a number of experimental and numerical studies on the assessment of the

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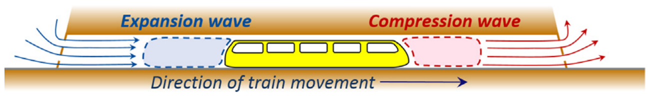

Fig. 1. Wave generation by a train moving through a tunnel.

slipstream gusts caused by passing trains in open field, with and without cross winds. They also described the potential effects of wind gusts on exposed people. They mentioned that there is a large variability in experimental data due to different boundary conditions, train types and complex flow structures induced by a moving train. Three regions around a train moving in open field were distinguished: the nose region, the boundary-layer region, and the wake region. Also, these authors highlighted the development of turbulent gust flows in the near wake for high-speed trains and in the growing boundary layer of freight trains. These unsteady flows can cause discomfort or even destabilize people standing alongside the moving train, by gusts with speed above 15–20 m/s (Baker et al., 2006). Sterling et al. (2008) analyzed experimental data for high-speed passenger trains and freight trains in open field. They examined the different flow regimes within the three regions around a train and, in line with the previously discussed studies, highlighted the intermittent behavior of the near wake flows. The velocities were found to be higher in the near wake and the boundary layer regions than in the nose region of the train. They also mentioned that the boundary layer development was slightly different between full-scale and reduced-scale measurements and that this could influence the near wake flow.

Gil et al. (2008) mentioned considerable run-to-run variability in the measured data for a 1/25th scale train with 3 carriages moving on a circular track with speeds of about 5–15 m/s. They experimentally showed that higher train speeds cause higher ratios of slipstream velocity to train speed. However, Hemida et al. (2010) studied a 1/25 scale model of an ICE train running on a circular track in an open space using validated LES simulations and showed that the Reynolds number effect on normalized slipstream velocities is negligible for trains moving with speeds varying within 20%.

Finally, Hemida et al. (2014) in their LES study investigated the effect of the platform height on the slipstream velocity. The slipstream velocities that occurred with a higher platform were increased due to the blocking of the developing slipstream flow. They also monitored the instantaneous flow in the wake of the train and confirmed the presence of highly turbulent vorticity. The maximum velocities and the largest turbulence intensities were observed in the near wake of the passenger train.

In Wind Engineering, many studies on pedestrian wind conditions were performed in the past decades. By far most of these studies focused on wind around buildings, as outlined in several review papers (Stathopoulos, 1997, 2002, 2006; Baker, 2007; Mochida and Lun, 2008; Blocken et al., 2011, 2012; Moonen et al., 2012; Blocken and Stathopoulos, 2013; Blocken, 2014). While early studies on pedestrian wind conditions around buildings were performed in atmospheric boundary layer wind tunnels, the past decade has seen a rapid increase in the use of CFD for this purpose (Blocken, 2014). This increase has been supported by the development of extensive sets of best-practice guidelines (Casey and Wintergerste, 2000; Franke et al., 2004, 2007, 2011; Britter and Schatzmann, 2007; Tominaga et al., 2008; Blocken and Gualtieri, 2012). Note however that most CFD studies on pedestrian-level wind comfort and wind danger were performed based on the steady Reynolds-Averaged Navier–Stokes equations, rather than on Large Eddy Simulation (LES) (e.g. Yoshie et al., 2007; Blocken, 2014). To the best knowledge of the authors, no studies have yet focused on CFD simulations of train-induced pedestrian wind conditions on platforms inside tunnels.

The purpose of this study is to evaluate the effect of a passing train on the wind flow induced inside a tunnel by means of LES, and assess the wind conditions at an underground railroad passenger platform. First, a validation study is performed, using experimental data of Gilbert et al. (2012) who analyzed train-induced air flow in a confined space and, in line with previous findings, observed occurrence of compression and expansion waves in front of and behind the train, respectively. Next, based on the validation study, simulations are performed for two case studies with two different train types that occur on the Dutch railways. A fictive underground railroad platform is designed according to current national guidelines. The occurring wind velocities on this platform are assessed and compared with threshold values for wind comfort and wind danger for pedestrians.

2. Guidelines for railway platforms and wind speed threshold values

According to ProRail (2012), a platform (underground or aboveground) has to be subdivided into four zones (Fig. 2): (1) a safety zone that should be avoided by people while trains are passing by, (2) a walking zone, (3) a waiting zone, and (4) a circulation zone used for benches and information stands. ProRail does not provide guidelines concerning wind comfort and wind danger. However, we can assume that dangerous gusts are only allowed in the safety zone, where people should not stand. Certainly, dangerous gusts should not occur in the walking zone, the standing/waiting zone and the circulation zone. Discomfortable wind conditions should not occur in the standing/waiting zone and in the circulation zone, where people are sitting and waiting for the train.

A threshold value for wind discomfort is chosen based on the findings that wind speeds of 5 m/s and higher can cause wind discomfort for brisk walking, strolling or sitting (Lawson and Penwarden, 1975). Also, wind velocities of 2.4–5.5 m/s cause hair dissarangement and difficulties with reading the paper and can raise dust and loose paper (Lawson and Penwarden, 1975). Therefore, a wind speed of 5 m/s is taken as the threshold value for wind discomfort in the present study.

Concerning wind danger, Jordan et al. (2008) showed that people can lose their balance at gusts from 12 m/s when the gust wind is coming from the side, as is the case with people standing on the platform and facing the track. In addition, the duration and acceleration of the wind gust should be considered. According to Bottema (1993), the average critical duration of a gust for a female weighing 60 kg and male weighing 75 kg standing sideways to the oncoming gust wind of 12 m/s is around 0.5 s before their balance is lost. Finally, De Graaf and Van Weperen (1997) investigated people's tolerance to acceleration by wind depending on the

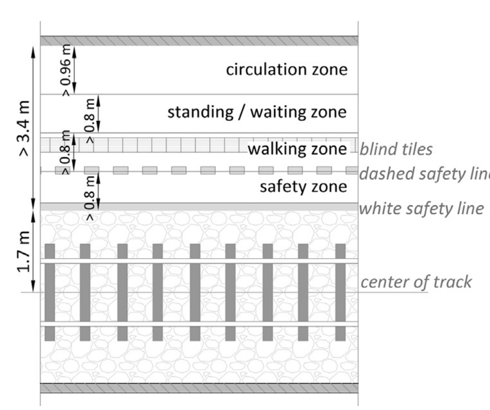

Fig. 2. A train platform in The Netherlands divided into four zones (ProRail, 2012).