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Straathof, J.B.

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Jochem Straathof
Personal information

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Date: July 19th, 2013
Student name: Jochem Straathof
E-mail address: j.b.straathof@student.tue.nl
Student number: 0749185

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Supervisory committee

Chairman: prof. dr. ir. B.J.E. Blocken
E-mail address: b.j.e.blocken@tue.nl

1st daily supervisor: ir. W.D. Janssen
E-mail address: w.d.janssen@tue.nl

2nd daily supervisor: ir. A.A.Khayrullina
E-mail address: a.Khayrullina@tue.nl

External supervisor: ir. M.E. Valk
E-mail address: mart.Engel@Deerns.nl

External supervisor: dr. ir. P.J.W. van den Engel
E-mail address: peter.van.den.Engel@Deerns.nl
Preface

This thesis is prepared for the completion of the Master of Science program in Building Physics and Services at Eindhoven University of Technology. In this preface, I would like to express my appreciation to the people who helped me with the establishment of this research:

- Prof. dr. ir. Bert Blocken. Thank you for the professional supervision and knowledge transfer regarding CFD and wind flow in the urban environment and for giving me the freedom to give my own interpretation to this subject.

- ir. Wendy Janssen. Thank you for the extensive and professional help during the entire project and the knowledge you have brought me on CFD simulations.

- ir. Adelya Khayrullina. Thank you for your enthusiasm and for the quick and elaborate answers to the many questions I had during this project.

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- All the Postdocs, PhD’s and students who were so kind to listen to my monthly chat and provide me with feedback during the Urban Physics Progress meetings.

Without their knowledge, help and interest this research would have been less advanced and results would have been less interesting.

Jochem Straathof
Eindhoven, June 2013
The Netherlands has one of the world’s most crowded railway networks, where trains are allowed to travel with high speed. The movement of a train causes deformation of the surrounding air, creating aerodynamic effects. This could result in wind nuisance at a platform, especially if this platform is located in a tunnel, where the air ahead of and behind the train is forced to flow into a certain direction. This is an underestimated subject. Therefore, this research focuses on the possibility of wind discomfort or even danger at an underground railroad platform.

The factors that characterize the flow around a train as well as wind discomfort and danger criteria are discussed by means of a literature study. A possibly critical situation with a train travelling at a maximum allowed speed through a relatively narrow tunnel is simulated using Computational Fluid Dynamics (CFD). Through an extensive validation study the most reliable simulation method for studying this situation has been investigated. Next, two situations that are likely to occur at a Dutch platform have been examined in the case study; 1) including a Dutch intercity train and 2) including a freight train. Both trains are travelling through a tunnel including a platform with their maximum allowed speed on the Dutch railroads.

It is difficult to determine in advance what velocity magnitude is to be expected at an underground railroad platform, since little research has been done regarding this subject. After performing the two simulations it can be concluded that it is unlikely for a train to cause wind danger when the design guidelines for platforms in the Netherlands are maintained and the trains travel with their currently allowed speed. Wind danger at an underground railroad platform might only occur due to specific design aspects. Though, without any background knowledge it is not possible to predetermine the position of wind danger to occur. Therefore, each station should be investigated separately. Remarkably, it is found that the chance of wind danger is larger by the passage of a more aerodynamic intercity train, moving with a speed of 38.9 m/s, than for a freight train, moving with a speed of 27.8 m/s.
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1 Introduction

The problem statement of this research is covered in this chapter, followed by the objectives and the methodology. This research emerged from collaboration between two parties; the research group of Urban Physics at the University of Technology in Eindhoven led by prof. dr. ir. B. Blocken and the research department in building physics of engineering consulting firm Deerns Nederland.

1.1 Problem Statement

The Netherlands has one of the world’s most crowded railway networks where many small platforms are located at the routes between the large stations. The intercity passenger trains only stop at the larger stations and are allowed to travel along the smaller stations with a maximum velocity of 140 km/h. Prorail, the company responsible for the maintenance of the railroads in the Netherlands, has the ambition for the near future to create a connection with six passenger trains instead of four passenger trains per hour between the larger cities, in order to cope with the increasing number of passengers. Beside these trains, different freight trains are forced to travel along the tracks in the period between two passenger trains. This makes the railway network even more crowded. A suggestion by Prorail to lead all trains into the right direction is to increase the maximum allowed running speed for freight trains from 80 to 100 km/h.

The movement of a train causes deformation of the surrounding air, creating aerodynamic effects. Therefore, there is a chance of wind nuisance at the train station platform when a train passes with high speed. Soper et al. (2013) reveals the wind flow aside from a fully loaded moving freight train. At a distance of 1.75 m away from the center of the track a short peak gust with a velocity magnitude higher than the speed of the train can be felt as the nose of the train passes.

Designing underground railroad stations becomes more and more popular from both logistic and aesthetic point of view. It provides new land on a central location, noise is being reduced and the separation of the city due to the railroad disappears. However, Gilbert et al. (2012) shows that the wind velocities inside a tunnel, caused by the passage of a train, last for a longer period due to the so called “piston effect” (elaborated in section 2.2). The most critical wind velocities caused by the passage of a train are therefore likely to be felt at a platform inside a tunnel.

The guidelines by Prorail (Prorail OVS00067, 2012) are currently used when a new railroad platform is designed. The guidelines are intended for platforms next to tracks where trains are allowed to travel with a maximum speed of 140 km/h. The width of the platform is determined by the width of each of its four zones (figure 1.1); a safety zone, a walking zone, a waiting zone and a circulation zone. The width of each zone is determined according to the expected number of people making use of this platform. The risk of wind danger caused by a passing train is not taken into
account. As an example; according to the guidelines by Prorail (Prorail OVS00067, 2012), people are allowed to walk at 0.8 m away from the platform edge during the period a train passes with a speed of 140 km/h. Currently only general signs are applied on some Dutch platforms where passengers are alerted to keep distance from the track when a train passes (see figure 1.2).

By the author’s knowledge, previously no research has been conducted where the wind situation on a platform caused by the passage of a train is studied. Therefore, the focus in this study will be on charting the possible wind discomfort and danger at an underground railroad platform when a train passes. More appropriate measures could be taken when the wind situation at a platform is known and the risk of accidents by train-induced wind can be dealt with more specifically.
1.2 Research Objectives

The main research objective is to study the effect of a passing train on the wind comfort at an underground railroad platform. Four sub-questions have to be answered before this objective can be achieved:

1. What are the main factors affecting the train induced wind flow inside a tunnel?

2. What criteria can be used to assess the wind comfort at a platform?

3. What design guidelines have to be taken into account when designing a new platform?

4. Which of the trains, running on the Dutch tracks, are expected to cause the most wind nuisance?

After an answer to the questions has been found, the most critical situation that is likely to occur can be investigated with a CFD model of a fictive underground railroad station. CFD stands for Computational Fluid Dynamics. When using CFD it is possible to generate numerical solutions for flow problems. An advantage of CFD simulations is that it generates whole flow-field data of for instance wind velocities. Therefore, with use of this CFD model an attempt can be made to answer the main research question:

- Is it possible for a Dutch train, running with its maximum allowed speed, to cause wind danger at an underground railroad platform that meets the design requirements?
1.3 Methodology

Figure 1.3 illustrates the structure in this research, including three main sections: Theory, Validation study, and Case study.

In the theory section an answer is given to the sub-questions described in section 1.2. The previous studies concerning this topic are described and the theory behind wind flow by the movement of a train through a tunnel is explained. It starts with the properties of typical wind flow around a moving train and continues with the aspects causing the aerodynamic effects when a train passes through a tunnel. Afterwards appropriate discomfort and danger criteria for this study are evaluated.

Validation is required in order to obtain reliable results in the case study. The validation section describes the settings that are most suitable for numerical simulations of a train running through a tunnel. Experimental data of a scaled German ICE-2 train running through a tunnel are used to validate the CFD model. Besides an appropriate input for the numerical model, the domain extensions are determined and a grid sensitivity analysis has been performed in order to assess the grid-dependency of the results.

Both theory section and validation study section provide the input to be used for the case study. A fictive underground railroad platform is designed according to the guidelines described in the theory section, and simulations have been performed with two trains. The two trains that are used in the case study are frequently used on the Dutch railroads and are ought to cause the highest wind flow inside a tunnel according to the theory. The occurring wind velocities are assessed against the comfort criteria that are set up in the theory chapter.
2 Theory

This chapter explains the theory behind wind that is induced by the movement of a train through a tunnel. It starts with the properties of typical wind flow around a moving train and continues with the aspects causing the aerodynamic effects when a train passes a tunnel. Discomfort and danger criteria are evaluated to be used in this study. The chapter concludes with the guidelines for CFD modeling and simulation that are important for this study.

2.1 Pressure and Wind Flow Transients in Open Air

According to Baker et al. (2001) and Weise et al. (2006) the wind that is caused by the passage of a rail vehicle can be divided into four regions, as illustrated in figure 2.1:

1. Nose region.
2. Boundary layer region.
3. Near wake region.
4. Far wake region.

Air is pushed into all directions by the nose of the train, resulting in a compression wave. At the tail the exact opposite occurs. Due to the movement of the train, air is expanded behind the train and causes an under pressure zone. This results in an expansion wave that can be felt just after the train has passed. (Figure 2.2)
Figure 2.4 shows the results of wind velocity measurements from a moving-model of a high-speed passenger train (106 m length) by Gilbert et al. (2012). The measurement starts as soon as the nose of the train passes the measurement spot and the vertical dashed line in the figure illustrates the moment the rear of the train passes the measurement spot. The compression wave cannot be seen in the figure. Though, the other three regions that are mentioned by Baker et al. (2001) can clearly be subdivided. Wind velocities are measured at three positions, according to figure 2.3. As can be seen, the velocity magnitude decreases significantly as the distance from the side of the train increases.

The first region is associated with the strong pressure fluctuations caused by the train nose. The three more downstream regions are dominated by the slipstream in the rear of the train. The exact position at which the highest wind velocities occur is strongly dependent on the type of train and the distance away from the platform edge. Passenger trains are relatively smooth. Therefore, they show the highest peak velocity in region 3, when the rear of the train passes. Most freight trains show much higher wind velocities in region 2, since their cargo makes them less aerodynamic (Weise et al., 2006; Soper et al., 2013).

Figure 2.3: Measurement positions, dimensions in mm (Gilbert et al., 2012)

Figure 2.4: Measurement results for a passenger train in the open air (Gilbert et al., 2012)
2.2 Pressure and Wind Flow Transients inside a Tunnel

Inside a tunnel air is confined by the tunnel walls; hence the movement of air is restricted. In open air, when a vehicle travels along, air is being pushed and can move to any direction except into the ground. But inside a tunnel, air cannot move through the tunnel walls and has to be pushed along the tunnel. Behind the moving vehicle, as air has been pushed away, suction is created and air is pulled to flow into the tunnel. This phenomenon is schematized in figure 2.5 and is called the “piston effect”. (Wikipedia, September 2012)

Figure 2.5: Wave generation by a train moving through a tunnel

Due to the piston effect, high pressure waves and wind gusts can be noticed inside a tunnel. Both effects are described in the section below.

2.2.1 Pressure Wave Propagation inside a Tunnel

The piston effect causes a characteristic propagation process of pressure waves, which is clearly described in different papers (Novak, 2006; William-Louis and Tournier, 2005). Figure 2.6 schematizes the principle that can be summarized as follows: as soon as a train enters the tunnel a compression wave with a steep pressure increase is created ①, moving with the speed of sound into the direction of the tunnel exit. This compression wave is followed by a small pressure increase due to the friction of the train body. The entrance of the train tail generates an expansion wave, resulting in a pressure drop ②. Once the nose of the train has passed the measurement spot a sharp pressure drop is noticeable ③, moving with the speed of the train. The friction of the train body ensures a gradual pressure decrease, until the train tail reaches the measurement spot ④. After the tail has passed, the pressure will return to the prevailing atmospheric pressure again. As soon as the compression and expansion waves reach the tunnel exit, part of the pressure is reflected and moves back into the tunnel in opposite direction of the train causing pressure fluctuations again ⑤. The same type of expansion and compression waves are generated when the train leaves the tunnel. Eventually, when the reflected compression and expansion waves are faded, the pressure will return to the atmospheric pressure.
Some waves move at the speed of sound and others move at the speed of the train. For this reason, the pressure wave propagation is highly dependent on the position of the measurement spot inside the tunnel.

The main factors that influence the strength of the pressure waves are the blockage ratio (defined in section 2.2.4), the shape of the front and tail of the train, the shape of the entrance and exit of the tunnel and the roughness of the tunnel walls. Whereas, the position in time of the pressure waves that are moving with the speed of sound are mainly influenced by two factors: the speed of the train and the length of both tunnel and train. Superposition of the compression and expansion waves may occur in particular situations, resulting in exceedingly high pressure fluctuations. Three critical lengths, shown in table 2.1, are mentioned by Bopp & Hagenah (2009). For example, if a train with a length of 200 m runs with a speed of 55.5 m/s through a tunnel of 2178 m, the compression waves will coincide and strengthen each other.

\[
\text{Table 2.1: Critical tunnel lengths (Bopp & Hagenah, 2009)}
\]

<table>
<thead>
<tr>
<th>Critical Tunnel Lengths</th>
<th>Length of the train (m)</th>
<th>Speed of the train (km/h)</th>
<th>Critical tunnel length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>200</td>
<td>2178</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>250</td>
<td>2886</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>350</td>
<td>1572</td>
</tr>
</tbody>
</table>
### 2.2.2 The Tunnel Boom

When a train travels with high speed through a tunnel, it is possible that an impulsive noise can be heard. This typical sound is also called the “tunnel boom” and the theory behind this phenomenon is described in Bopp & Hagenah (2009). Figure 2.7 schematizes this principle. It can be summarized as follows: The compression wave that is generated by the train entry, denoted by ① in figure 2.6, travels through the tunnel with the speed of sound. At first this pressure wave has a low gradient, but several factors such as tunnel surface roughness and temperature differences inside the tunnel make the wave steepen. Depending on the length of the tunnel, the gradient of the pressure wave can get so steep that it produces an impulsive noise at the exit of the tunnel.

![Figure 2.7: The pressure wave propagation process](image)

The appearance of this effect has been proven numerically (Yoon, 2001) and experimentally (Heine and Klaus, 2013; Hieke et al., 2013). Countermeasures are given and have been proven to be effective, for instance air-shafts inside the tunnel or a slanted entry. Mok & Yoo (2001) show that the pressure gradient in the range of 500-800 Pa can be reduced by 29.8% when using a tunnel entrance with a roof slope of 31° instead of a regular straight entrance. Hieke et al. (2013) state that hoods at the tunnel entrance (figure 2.8) are the most qualified arrangements and have the best cost-benefit ratio. However, practice shows that improving the tunnel entrance with a slope does not guaranty the prevention of a tunnel boom, as can be heard by the 7700 m long tunnel between Nurnberg and Ingolstadt, Germany (source: YouTube, Jan 2013).

![Figure 2.8: Example of a tunnel hood (Hieke et al., 2013)](image)
2.2.3 Wind Flow inside a Tunnel

The earlier mentioned pressure waves moving at the speed of the train go together with gusty wind flows inside a tunnel. Figure 2.9 shows the general propagation of the wind flows inside a tunnel. Air starts to move at a certain position inside the tunnel directly after the train enters the tunnel. The wind velocities gradually increase until the nose of the train reaches the measurement spot ①. Acceleration of the wind is dependent on the length of the tunnel. In the period between the passage of the train nose and the train tail, the wind velocities are depending on the roughness of the train surface. Overall the wind velocities are low in this period. The highest wind velocities are caused by the expansion wave, just after the train tail passes the measurement spot ②.

![Image](image.png)

*Figure 2.9: The wind flow inside a tunnel*

Experiments by Gilbert et al. (2012) confirm the appearance of high wind velocities in the nose region and especially the wake region of a moving train inside a tunnel. As can be seen in figure 2.4, the wind velocity reaches a maximum of 0.25 times the train speed in the open air when measuring very close to the side of the train. If the measurement results in figure 2.4 are compared with the measurement results of a passenger train through a tunnel with a blockage ratio of approximately 0.3 (figure 2.11), there is a large increase in wind velocities in the nose region and especially the wake region, rising to 0.35 times the train speed. Again the measurement starts as the nose reaches the measurement spot and the vertical dashed line at 106 m illustrates the moment the tail of the train passes the measurement spot. Therefore, the gradual increase in wind speed generated by the nose of the train cannot be seen. The fact that there is hardly any difference in the measured wind velocities at the wake of the train for the different distances away from the side of the train confirms that the high wind velocities are caused by the piston effect.
2.2.4 Factors Affecting the Wind Velocity Peak in the Tunnel

Baron et al. (2001) state that the occurring piston effect is mainly dependent on three factors: 1) the shape of the nose and end of the train, 2) the blockage ratio, 3) the speed of the train. Novak (2006) and Bopp & Hagenah (2009) add two other factors: 4) the length of the train and tunnel, 5) the roughness of the train and tunnel walls. In all mentioned papers it is stated that the highest wind velocities occur just after the tail of a train has passed a certain spot inside the tunnel and factors 1 to 3 are most important.

The earlier mentioned experiments by Gilbert et al. (2012) have been performed with a model of a German ICE-2 train (see figure 2.12) moving with a speed of 32 m/s (115.2 km/h) through a tunnel with a blockage ratio of approximately 0.3. The shape of the nose and rear of this train are much more aerodynamic in comparison to those of the trains travelling on the Dutch railway tracks (see figure 2.13 and 2.14). Ricco et al. (2007) shows the effect of the shape of the rear and front of the train on the pressure zones inside train tunnels. A pressure increment of 50% is seen when comparing the peaks of the pressure zones of a train with a nose and rear angle of 30° and 60° (figure 2.15).
The blockage ratio ($B$) is calculated by dividing the cross-sectional area of the train ($S_{tr}$) by the cross-sectional area of the tunnel ($S_{tu}$):

$$B = \frac{S_{tr}}{S_{tu}}$$

The topics that are raised in currently available studies concerning moving trains include the following:

- Analyzing train induced slipstreams (Gilbert et al., 2012; Soper et al., 2013; Weise et al., 2006). In order to capture the physics of the flow field induced by a train and to identify the relevant parameters which determine the slipstream behavior of a vehicle.
- Pressure distribution inside tunnels (Baron et al., 2001; Ricco et al., 2007; Hieke et al., 2013). As an example, in order to come to a targeted solution for the nuisance caused by the sonic boom.
- The effect of crosswinds on trains (Sima, 2013; Eichinger et al., 2013). To study the risk of a train falling over when running through an open field.
- Ballast projection. (Weise and Sima, 2013; Saussine et al., 2013). Ballast stones are lifted from the track during the passage of a high speed trains, resulting in damage to the underframe.

In this study a new topic is raised: The focus will lay on the possible wind discomfort and danger in an underground railroad platform at passenger level when a train passes.
2.3 Comfort and Danger Criteria for Gust Winds

This section gives a short summary of currently available criteria for a comfortable wind climate. Guidelines are available for maximum wind velocities to ensure a comfortable indoor as well as outdoor climate. However, so far no guidelines are available for peak wind gusts caused by trains. Research regarding the currently available wind comfort and danger is described and criteria for discomfort are drawn based on this research.

The Beaufort wind force scale is an empirical measure that relates wind speed to observed conditions. This scale was devised in 1805 by Francis Beaufort and is still widely used over the world. It divides all possible wind velocities into twelve categories. The first 9 categories are described in table 2.2. To give an indication of the wind velocity numbers, the effects that occur are mentioned in the right column.

<table>
<thead>
<tr>
<th>Beaufort number</th>
<th>Wind velocities at 1.75 m height (m/s)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0 – 0.1</td>
<td>Calm, smoke rises vertically</td>
</tr>
<tr>
<td>1</td>
<td>0.2 – 1.0</td>
<td>No wind noticeable</td>
</tr>
<tr>
<td>2</td>
<td>1.1 – 2.3</td>
<td>Wind Felt on face</td>
</tr>
<tr>
<td>3</td>
<td>2.4 – 3.8</td>
<td>Hair disturbed, clothing flaps, newspaper difficult to read</td>
</tr>
<tr>
<td>4</td>
<td>3.9 – 5.5</td>
<td>Raises dust and loose paper, hair disarranged</td>
</tr>
<tr>
<td>5</td>
<td>5.6 – 7.5</td>
<td>Force of wind felt on body</td>
</tr>
<tr>
<td>6</td>
<td>7.6 – 9.7</td>
<td>Hair blown straight, difficult to walk steadily, wind on ears unpleasant</td>
</tr>
<tr>
<td>7</td>
<td>9.8 – 12.0</td>
<td>Inconvenience felt when walking</td>
</tr>
<tr>
<td>8</td>
<td>12.1 – 14.5</td>
<td>Great difficulty with balance in gusts</td>
</tr>
<tr>
<td>9</td>
<td>14.6 – 17.1</td>
<td>People blown over</td>
</tr>
</tbody>
</table>

2.3.1 Wind Comfort Criteria

It is generally agreed that the most appropriate approach to assess or predict human environmental wind comfort is the use of wind speed threshold values, defined for specific types or categories of pedestrian activities, in combination with allowable frequencies of occurrence or exceedence within certain duration of time. Holger Koss (2006) listed the available wind comfort criteria in Europe defined by different institutions, as can be seen in table 2.3. A categorization is made in three different activities: ‘brisk walking’, ‘strolling’ and ‘sitting (for a short time; less than 15 minutes)’ and each has a threshold value and a maximum percentage of exceedence hours $P_{exc}$. Figures 2.16, 2.17 and 2.18 have been added to give a clear picture of the values per institution.
Table 2.3: List of institutions with wind discomfort guidelines (Holger Koss, 2006)

<table>
<thead>
<tr>
<th>Institutions with guidelines for wind discomfort</th>
<th>Full name of institution</th>
<th>abbreviation</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Research Establishment</td>
<td>BRE</td>
<td>England</td>
<td></td>
</tr>
<tr>
<td>University of Bristol and Western Ontario</td>
<td>Bristol</td>
<td>England and Canada</td>
<td></td>
</tr>
<tr>
<td>Centre Scientifique et Technique du Batiment</td>
<td>CSTB</td>
<td>France</td>
<td></td>
</tr>
<tr>
<td>DMI Force Technology</td>
<td>DMI</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Nederlandse Norm</td>
<td>NEN</td>
<td>the Netherlands</td>
<td></td>
</tr>
<tr>
<td>Nederlandse Centrale Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek</td>
<td>TNO</td>
<td>the Netherlands</td>
<td></td>
</tr>
</tbody>
</table>

![International wind comfort criteria for brisk walking](image1)

**Figure 2.16:** Criteria for brisk walking

![International wind comfort criteria for strolling](image2)

**Figure 2.17:** Criteria for strolling

![International wind comfort criteria for sitting](image3)

**Figure 2.18:** Criteria for sitting

As can be seen in the figures, when looking at the strictest values of the threshold effective wind speed and their corresponding maximum probability of exceedence for strolling, the most stringent values are drawn by the Dutch central organization for applied scientific research (TNO east). This institution provides the strictest value for the threshold wind velocity as well as the percentage of exceedence hours. However, for brisk walking and sitting there are several institutions with the strictest values for both parameters.

The comfort criteria in figure 2.16 - 2.18 are all established for outdoor climates, where the P_{exc} is calculated with use of hourly averaged wind velocities at pedestrian level. The practicability of this manner is doubtful for the determination of the wind climate in underground railroad stations, since wind velocities are critically high only when a train passes and wind velocities are sufficiently low for the rest of the time. Hence, the hourly averaged wind velocity in the tunnel will be low. This
results in small differences in the average hourly wind speeds, which makes it easy to satisfy the wind comfort criteria for an outdoor climate.

2.3.2 Wind Danger Criteria

NEN 8100 (2006a) indicates a threshold wind velocity of 15 m/s. This criterion for outdoor environments is based on hourly averaged wind velocities. Since the passage of a train causes short wind gusts it is unadvisable to use this value as threshold for wind danger in underground railroad platforms. For gusts, which are assumed to be present in underground railroad stations, NEN 8100 (2006a) describes the following: “the hourly averaged wind velocities are not determinative for wind danger, as well are the velocities of gust wind. The average hourly wind speed is tested instead of gusts since gusts are highly laborious. Different requirements should be handled for regions where a good wind climate with respect to gusts is desired”. However, the suggested different requirements are not described in the NEN 8100 (2006a).

A definition of a wind gust is: “the maxima that exceed the lowest wind speed measured during a ten-minute time interval by 5.3 m/s (10 knots)” (Wikipedia, May 2013). For the purpose of simplicity it is assumed that a dangerous wind gust is considered to be one which causes a person to lose his/her balance. Apart from the physical state of the person, it is shown that there are three critical factors in a gust wind regarding the stability of a person:

- Acceleration of the wind gust;
- Peak magnitude of the wind gust;
- Length of the wind gust.

Acceleration is important for humans since they have the ability to react on a wind speed over a longer period of time and are able to adjust their balance to compensate for the change. A person has a different tolerance to an acceleration depending on which direction the force is applied. This has been investigated by de Graaf (1997). He shows the minimum accelerations per direction causing a person to lose his/her balance. He examined the balance of 22 people with use of a treadmill with a conveyor belt. The values are reported in table 2.4.

<table>
<thead>
<tr>
<th>Limiting accelerations (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
</tr>
<tr>
<td>Backward</td>
</tr>
<tr>
<td>Sideways</td>
</tr>
</tbody>
</table>

Table 2.4: Limiting accelerations for people to lose their balance (de Graaf, 1997)
The values in table 2.4 have been estimated by using a ground moving in the opposite direction. “Forward” in this table refers to the effective force being in their forward direction. This situation can be assumed as equal to a person being exposed to a sudden acceleration in wind speed. If the acceleration of the gust wind is lower than the stated limiting values, the wind cannot be seen as a dangerous gust and the threshold value for wind danger according to the NEN 8100 (2006a) can be maintained. However, a person is not able to balance himself without taking a step if the acceleration of wind exceeds the limiting acceleration. This would result in a person being displaced at lower peak velocities.

Currently, the Technical Specification for Interoperability relating to the ‘rolling stock’ of sub-system of the trans-European conventional rail system (CRS RST TSI, 2011) imposes a limit on the slipstream induced velocities on passengers on a platform, at 3 m from the track center and 1.2 m above the platform. The wind speed caused by a full length passenger train (operating speed > 160 km/h) should not exceed a value of 15.5 m/s. This criterion could be used as a threshold value for wind danger in this study. However, the position on a Dutch platform at which this criterion has to be fulfilled is situated approximately on the edge of the walking zone and the waiting zone. This implies that even higher values are permitted at positions where people are still allowed to walk. In addition, characteristic for a gust is the sudden acceleration of wind speed, which could cause a dangerous situation. Thus, a threshold value for wind gusts should be stricter than a threshold value for hourly averaged wind velocities. However, the value suggested by CRS RST TSI (2011) is higher than the one used in NEN 8100 (2006a). Therefore, it is decided not to use this criterion for this study.

Research by Jordan et al. (2008), gives an overview of the responses of an individual to a sudden change in wind speed. A group of 31 people were subjected to wind speeds up to 20 m/s in a large wind tunnel. The group was comprised of 12 female volunteers weighing 53.4 kg on average and 19 male volunteers weighing 72.2 kg on average. The age of the people ranged from 18 to 50 where 69 % of the group was aged in the range of 18 to 24. In all cases the wind speed increased from a mean value of zero to the target value in approximately 0.2 seconds, which substantially exceeds the earlier mentioned limiting accelerations. The following figures reveal at what wind speeds people start to lose their balance.

![Figure 2.19: Percentage of people displaced while facing the oncoming wind (Jordan et al., 2008)](image1)

![Figure 2.20: Percentage of people displaced while standing back to the oncoming wind (Jordan et al., 2008)](image2)
As can be seen in figure 2.19, approximately 15% of the female volunteers were displaced at a wind velocity of 7 m/s while facing the oncoming wind and all volunteers (both male and female) were displaced at a wind velocity of 15 m/s while facing the oncoming wind. People lose their balance less quickly when standing sideward to the oncoming wind (figure 2.21) because their projected area is smaller.

The third factor is the length of the gust wind. If the peak in a gust wind is too short, people will feel it, though balance will not be lost. According to Bottema (1993) the critical length of a gust \( t_g \) can be determined with use of a formula where the following factors are taken into account: The magnitude of the gust \( U_g \) [m/s], the critical displacement length of a human body \( x \) [m], the drag coefficient \( C_D \), the mass of a person \( m \) [kg], the air density \( \rho \) [kg/m\(^3\)] and the projected area of the body \( A_p \) [m\(^2\)]. All factors are included in the following formula:

\[
U_g \cdot t_g = \left( \frac{4 + x + m}{\rho \cdot A_p \cdot C_D} \right)^{0.5}
\]

Assumptions can be made by filling in different values in this formula. As an example, for an average female weighing 60 kg and standing frontal to a gust wind of 12 m/s, the minimum length of a gust should be 0.47 s before balance is lost. And for an average male weighing 75 kg and standing side on an oncoming gust wind of 12 m/s, the minimum length of a gust should be 0.66 seconds before balance is lost.

According to Fukuchi (1961) it takes approximately 0.375 s before muscular response of an average human body is able to react on sudden changes. During the first 0.375 s a person can be seen as a fixed object which is not able to compensate for a sudden change in wind velocity. Combining the previously described formula of Bottema (1993) with the results by Fukuchi (1961) it can be concluded that if the magnitude of a sudden gust has a velocity where it takes less than 0.375 seconds for the gust to destabilize a person, it will lead to critical situations where people are falling over.
2.3.3 Research Criteria

According to Prorail (2012) a platform has to be subdivided into four zones, as can be seen in figure 2.22. Each zone has its minimum width and the entire width of a newly constructed platform in the Netherlands should have a minimum width of 3.4 m. Benches and information stands have to be positioned in the circulation zone and the safety border of the zone is marked by a white dashed safety line. Each platform must be provided with a stroke of blind tiles, which should be positioned at least 1.2 m away from the platform edge inside the walking zone. Blind tiles have a ridged surface and serve as a provision for visual impaired people.

![Platform requirements (Prorail, 2012)](image)

Figure 2.22: Platform requirements (Prorail, 2012)

Nuisance due to wind can be subdivided in wind discomfort and wind danger. A research criterion for wind discomfort has been set up with use of the research findings described in section 2.3.1. Most institutions maintain a threshold wind velocity of 5 m/s for brisk walking, strolling or sitting. Though they are hourly averaged values instead of gust speeds, the Beaufort wind force scale mentions the effects that are occurring at 5 m/s, e.g. “hair is disarranged” or “newspapers are difficult to read”. Therefore, a peak value of 5.0 m/s is taken as a threshold value for discomfort.

A person waiting at a station platform mostly stands with his face towards the track, which implies that the gust wind is coming from aside. A research criterion for wind danger has been set up with use of the information in section 2.3.2. Jordan et al (2008) has shown that people start to lose their balance at gusts from 12 m/s when the gust wind is coming from the side. Assuming that losing your balance can lead to dangerous situations at a station platform a peak value ≥ 12.0 m/s is taken as threshold value for danger. It has to be kept in mind that the gust wind which exceeds 12.0 m/s should last for at least 0.5 seconds (Bottema, 1993) and have an acceleration of at least 0.43 m/s² (de Graaf, 1997) before it has the ability to destabilize a person.
As mentioned before, Prorail (2012) subdivides a platform into four zones and each zone is linked to a different task; the safety zone should always be avoided and is therefore marked by a dashed line, the walking zone is intended for people to walk over the platform, the waiting zone is meant for people to wait for their train and the circulation zone is used for benches and information stands. Since all zones are intended for different tasks, a different criterion can be linked to each zone illustrated in figure 2.23. Note that there are certain limitations depending on the values that have been chosen for each design criterion.

Dangerous gusts are allowed at the safety zone, since people should never stand within the safety zone. However, the dangerous gusts become critical when they occur at the walking zone or the waiting zone. Therefore, the wind danger criterion should never be exceeded at these two areas. The circulation zone is used for people to sit and wait for their train, where it is uncomfortable if, for example, a newspaper cannot be read. Therefore, the limit that is assigned as wind discomfort should not be exceeded at this zone, especially where the benches are placed.

![Diagram](image)

**Figure 2.23:** Research criteria per platform zone
2.4 CFD Simulation Guidelines

Several best practice guidelines are available (Franke et al., 2007; Tominaga et al., 2008; Blocken & Gualtieri, 2012), which can be used to reduce the errors and uncertainties during a CFD simulation. The guidelines are based on cross-comparison between CFD predictions, wind tunnel test results and field measurements and are mainly focused on a stationary wind climate in an urban area. The current study focuses on a transient situation where the urban environment is of less importance, though many steps in the guidelines should be considered.

The recommended sequences for performing a CFD study differ slightly per guideline. In this study the sequence of the guidelines provided by Franke et al. (2007) is used. Where necessary, the guidelines in this paper are supplemented with guidelines from Blocken & Gualtieri (2012) and Tominaga et al. (2008). Since this study is transient and does not focus on an urban area, some sections are skipped. Derived from Franke et al. (2007) the following steps for performing a CFD simulation are applied in this study:

1. Choice of target variables
2. Choice of approximate equations describing the physics of the flow
3. Choice of geometrical representation of the obstacles
4. Choice of computational domain dimensions
5. Choice of boundary conditions
6. Choice of initial conditions
7. Choice of method for modeling transient situations
8. Choice of computational grid
9. Choice of numerical approximations
10. Choice of time-step size

Each step is described regarding the CFD simulations which are performed in this study. Beside the steps that are undertaken in the best practice guidelines an explanation is given for which method to be used when modeling transient situations.

2.4.1 Target Variables

According to Franke et al. (2007) the first step in running a successful CFD simulation is to define target variables. Target variables are the variables that are representative of the goals of the simulation and those that can be compared with the corresponding experiments. The target variables should be indicative of the numerical errors and uncertainties. Therefore, the sensitivity of numerical treatment and resolution are of importance.

Experimental data of the velocity magnitude inside a tunnel are the aim of investigation for the validation study. Therefore, omnidirectional wind velocities are the main target variable in this study.
2.4.2 Approximate Equations

Turbulent flow within an urban environment is generally modeled by the Navier-Stokes equations. However, the direct solution of these equations for a wind study in an urban environment would require an amount of computational resources that is not available up to now. Fortunately, the Navier-Stokes equations that are needed to be solved within this study can be replaced by simplifications. If the area of investigation lies within the lowest 200m of the atmosphere, the assumption of non-divergent flow fields and constant density might be used without losing accuracy in the model results (Franke et al., 2007). Another simplification is averaging the basic equations so that many scales of turbulent flow are filtered out. To model these filtered out scales a turbulent closure has to be chosen. Different turbulent closure models are available.

Reynolds averaged Navier-Stokes (RANS) equations are a simplification of the Navier-Stokes equations. RANS equations can be solved as steady or transient. In this study the equations are solved transient, since a train is moving through a fixed domain which makes the model time dependent. The linear k–ε turbulence model can be used for turbulent closure of the RANS equations. Its advantages are that it is easy to implement in the model, the low computational demand and the fact that it can provide reasonably good results (Blocken, 2011). Two different k–ε turbulence models are available in Ansys Fluent 12.1: the realizable k–ε turbulence model and the standard k–ε turbulence model. Blocken & Gualtieri (2012) state that the realizable k–ε turbulence model has a good performance for wind flow around buildings and k–ε turbulence models overall show good performance for indoor air flow. According to Franke et al. (2004) the standard k–ε turbulence model should be avoided in the simulation of wind engineering, since it overestimates the turbulent kinetic energy in regions of stagnant flow.

2.4.3 Geometrical Representation of the Obstacles

Nearby obstacles such as trees and buildings are of less importance because only the wind inside the tunnel will be analyzed. Therefore, surrounding buildings and trees will not be taken into account. Though, Franke et al. (2007) states that the central area of interest should be reproduced with as much detail as possible. This increases the number of cells inside the tunnel and near the train. The number of cells in the areas which are of less importance can be decreased accordingly.

2.4.4 Computational Domain Dimensions

Recommendations for the dimensions of the domain for both the validation study and the case study are extracted from Franke et al. (2007), Novak (2006) and Suzuki et al. (2008). The proportions have to take into account both volumetric needs of the problem and computational power available. The wind field around a train has
to be fully developed before it enters a tunnel, in order to generate accurate results inside the tunnel. Therefore, the computational domain consists of three parts as can be seen in figure 2.24: a field zone before the tunnel, the actual tunnel (and underground platform), and again a field zone behind the tunnel. This computational domain is divided into two subdomains; a stationary domain including the tunnel and a moving domain including the train. More information about the two subdomains is found in paragraph 2.4.10.

![Figure 2.24: Computational domain](image)

Regarding domain dimensions recommendations are generally given for RANS models without moving objects. However, a moving train in an open field without inflow boundary conditions is more or less similar to a non-moving train in an open field with an inflowing wind equal to the train speed. Therefore, these guidelines are considered in this study.

Franke et al. (2007) and Tominaga et al. (2008) recommend a maximum blockage ratio of 3% for the flow over a wall mounted cube for the lateral and vertical extensions of the domain. This means that the obstructed region of the vertical cross-sectional area of the domain should be less than 3%. The extensions used by Novak (2006) are 20 m and 50 m in vertical and lateral directions respectively, which equals to a blockage ratio of approximately 1.1%. Suzuki et al. (2008) uses an even smaller blockage ratio of 0.4%.

For the extension of the domain in the direction of the train, Franke et al. (2007) recommends a distance of 5H between the inflow boundary and the object (e.g. train), where H is the height of the object. The longitudinal extension of the domain in the wake region; between the outflow and the object, should be at least 15H for accurate flow re-development. Tominaga et al. (2008) states that a longitudinal extension of 10H in the wake region is sufficient. Suzuki et al. (2008) uses an extension of 20H in the wake region and an extension of 10H between the inflow boundary and the train.
2.4.5 Boundary and Initial Conditions

Boundary conditions are a representation of the surroundings that have been cut off by the computational domain. The inflow, lateral, wall and outflow boundary conditions are all of importance for steady RANS calculations of wind flow in the urban environment. In wind flow studies of an urban environment with a constant wind velocity, it is common to attach a vertical mean wind velocity profile and turbulence quantities at the inlet of the domain. However, this study is performed with a windless environment and the compressibility of air has been taken into account. Using compressible air makes it impossible to add inflow boundary conditions to the domain.

Two different approaches are available to model the shear stress for RANS simulations near walls; the low-Reynolds number approach resolves the viscous sublayer and computes the wall shear stress from the local velocity gradient normal to the wall. This approach requires a very fine mesh resolution in the perpendicular direction. To reduce the number of grid points in the perpendicular direction, wall functions can be applied as an alternative approach. This modeling method is invalid in regions of flow separation, of reattachment and of strong pressure gradients. The effect of wall functions on the solution away from the wall is negligible. Therefore, this approach is possibly useful for the simulations in this study. Important to note is that due to near wall functions, the results near the wall are only reliable when placing at least two nodes between a wall and the position of interest.

Transported turbulence quantities have to be specified in Ansys Fluent 12.1 by filling in values for the turbulence intensity and hydraulic diameter. The turbulence intensity is defined as the root-mean-square of the velocity fluctuations. A turbulence intensity of 1% or less is generally considered as low and turbulence intensities greater than 10% are considered as high. If the flow is fully developed the turbulence intensity may be as high as a few percent. In modern low-turbulence wind tunnels, the free-stream turbulence intensity may be as low as 0.05%. (Ansys Fluent 12.0 user guide, 2009)

The corresponding hydraulic diameter can be calculated with the following formula:

\[ D_H = \frac{4 \times W \times H}{2 \times (W + H)} \]

Where W is the width of the outlet boundary and H is the height of the outlet boundary.
2.4.6 Computational Grid

In order to reduce the truncation error the grid has to be accurately designed. According to Franke et al. (2007) and Tominaga et al. (2008), for RANS simulations the expansion ratio between two adjacent cells should be below 1.3, especially in regions with a steep velocity gradient. Hexahedral cells are preferable to tetrahedral cells. However, complex shapes can make it impossible to use hexahedral cells. Near walls, the grid lines should be perpendicular to the wall. Therefore, prismatic cells are preferred over tetrahedral cells near the wall.

A methodology to avoid the use of tetrahedral cells is introduced by van Hooff & Blocken (2010) to create an urban environment. In this methodology use is made of a series of extrusion operations. The ground planes should be meshed first. By extruding these planes with a pre-meshed line perpendicular to the ground plane, both computational grid and buildings are meshed at once. The volumes of the buildings should be deleted afterwards. This is a useful methodology for the larger part of the domain. However, this method is not applicable near the complex shaped nose and rear of the train.

A systematic grid convergence analysis should be conducted according to Franke et al. (2007) in order to achieve grid independency. At least solutions on three refined or coarsened grids are necessary. Grid-independency is achieved as soon as two solutions are within acceptable agreement to each other. According to Tominaga et al. (2008) the increment or decrement in the number of grid cells per sensitivity step should be approximately a factor 3.4, which equals to 1.5 times the number of cells in each direction.

2.4.7 Sliding Mesh

Two methods are available in Ansys Fluent 12.1 if unsteady interactions of two objects that are moving relative to each other cannot be neglected; the dynamic mesh method and the sliding mesh method. Both methods are extensively discussed in chapter 11 of the Ansys Fluent 12.0 user guide (2009) and chapter 3 of the Ansys Fluent 12.0 theory guide (2009). For a train moving through a tunnel it is advised to use the sliding mesh method. This is the most accurate method for simulating flows in multiple moving reference frames. A disadvantage of this method is the large required computational demand.

The sliding mesh method is used and briefly described in different papers. Shin & Park (2003) used this method for the prediction of wind flow at the tunnel hood when a train enters a tunnel. Novak (2006) used it to predict the train motion aerodynamic effects on the tunnel wall surface and Uystepruyst (2011) validated this method with experimental data regarding the pressure waves generated by high-speed trains entering a tunnel.

In the sliding mesh method for a moving train the domain is subdivided in two domains: one stationary domain including the tunnel and the underground platform,
and a moving domain including the train, as can be seen in figure 2.25. The boundary conditions of each face can be found in the figures of appendix A1 and A2. Most important are the bounded faces where both zones are connected to each other. These faces must have an interface as boundary condition. The air zone in front of the train in the moving domain should be at least as large as the tunnel length, since the train generates air movement through the entire tunnel as soon as the nose of the train enters the tunnel. The same accounts for the air zone in the moving domain behind the train.

![Figure 2.25: Cross section of two zones using the sliding mesh principle](image)

The two zones move relative to each other along the interfaces and the fluxes of the adjacent cells are calculated since the interfaces are connected. With this, an interior face is created. An advantage in this method is that the nodes of the two zones do not have to match one-for-one. Ansys Fluent 12.1 automatically assigns extra nodes to the coarser face.

![Figure 2.26: Working principle behind the sliding mesh method](image)

One of the interface zones extends beyond the other since one of the domains is moving while both domains remain in their original shape. Ansys Fluent 12.1 automatically creates wall faces for the parts of the boundary where the two interfaces do not overlap. This is seen in the right part of figure 2.26.

### 2.4.8 Numerical Approximations

The Non-Iterative Time Advancement (NITA) method is explicitly described in section 18.4.5 in the Ansys Fluent 12.0 Theory guide. In short, the idea underlying NITA is that in order to preserve overall time accuracy, you do not need to reduce the splitting error to zero, but only have to make it the same order as the truncation error. NITA performs one single outer-iteration per time-step, which significantly speeds up transient simulations as in this study.
The pressure-based solver allows it to solve the flow problem in different manners when using Ansys Fluent 12.1. When choosing the NITA option, two pressure-velocity coupling schemes can be chosen: Pressure-Implicit with Splitting of Operators (PISO) or the Fractional Step Method (FSM). Both coupling algorithms are pressure-based segregated. In the Ansys Fluent user guide 12.0 (2009), it is mentioned that the choice for PISO or FSM is dependent on the application. No application examples are mentioned though. FSM is slightly less computationally demanding, but FSM could be less stable than PISO.

The basic equations have to be discretized and transformed into algebraic equations in order to render the basic equations solvable on the computer. According to Franke et al. (2007) and Tominaga et al. (2008) for time-dependent problems, first-order methods should be avoided for the approximation of the time derivatives, because the spatial gradients of the quantities tend to become diffusive due to a large numerical viscosity. Therefore, only second-order upwind discretization schemes should be applied for the momentum, pressure, turbulent kinetic energy and turbulent dissipation rate. The gradient of the spatial discretization scheme should be set on “Least Squares Cell Based”. According to the Ansys Fluent 12.0 user guide (2009) this gradient reconstruction scheme is less computationally expensive as the others, though equal in accuracy.

### 2.4.9 Time-Step Size

The time-step size is an important factor for the accuracy of the results and the length of the calculation time for transient RANS simulations. According to Franke et al. (2007) a method to estimate the time-step in advection dominated places is to use the following formula:

\[ \Delta t = \frac{CFL \cdot \Delta x_{\text{min}}}{V_{\text{max}}} \]

Where \( \Delta x_{\text{min}} \) is the smallest length of a cell in the domain resulting in a grid dependent time-step size, \( V_{\text{max}} \) is the velocity of the moving domain and CFL is the Courant-Friedrichs-Lewy number. This number is typically 1 for a time-marching solver. (Ansys Fluent user manual, 2009)

### 2.4.10 Iterative Convergence Criteria

Ansys Fluent 12.1 uses iterative methods to solve the algebraic system of equations. It starts with an initial guess and it recalculates in each of the iterations until the equations are solved up to a user-specified error. The termination criterion is based on the residuals of the corresponding equations, which should tend towards zero. After the initial guess, Franke et al. (2007) recommends a reduction of the residuals of at least four orders of magnitude for each time-step in order to have sufficient
convergence. Celik et al. (2008) indicates that at least three orders of magnitude decrease in the residuals for each equation should be sufficient. When the calculation diverges or convergence is slow, Tominaga et al. (2008) suggests the following points to be examined:

- The aspect ratio and the stretching ratio of the grids may be too large.
- The relaxation coefficient of the matrix solver may be too small.
- Periodic fluctuations such as a vortex shedding may be occurring.
3 Validation Study

This chapter describes the validation of numerical settings to be used for numerical simulations of a train running through a tunnel. The validation is required in order to obtain reliable results in the case study, described in chapter 4. Results from wind tunnel experiments with a scaled train tunnel performed by Gilbert et al. (2012) are extracted for validation.

The validation study considers the input for the numerical model, the determination of domain extensions, the boundary conditions and the time-step size. A grid sensitivity analysis has been performed in order to assess the grid-dependency of the results. Aside from the comparison of results, notable observations in the results of the numerical model have been described. These observations are provided in section 3.3.2.

3.1 Experimental Data

The experimental data obtained by the Birmingham Centre for Railway Research and Education is used. They bring together a multidisciplinary team from across the University of Birmingham to tackle fundamental railway engineering problems. The faculty has access to The TRAIN (Transient Railway Aerodynamics INvestigation) Rig. This is a moving model rig that can be used for a wide variety of aerodynamic investigations (see figure 3.1). It consists of a 150 m long track along which model vehicles can be propelled in both directions, at speeds of up to 75 m/s. (www.windresearch.org, 2013)

![Figure 3.1: TRAIN Rig, University of Birmingham (wind research, 2013)](image-url)
3.1.1 Measurement Setup

The results from experiments performed at the TRA\textsc{in} Rig by Gilbert et al. (2012) have been used in this validation study. Gilbert et al. (2012) describes and analyses train-induced air movements in a confined space. A 1/25\textsuperscript{th} scale model of a German ICE-2 train (see figure 3.2) is travelling with a speed of 32 m/s through an 8.0 m long tunnel (see figure 3.3), where wind velocities are measured at different positions inside the tunnel.

For this validation study, the measured wind velocities at the first PRB (Cobra Probe head) have been used for comparison. This probe head is positioned 4.88 m inside the tunnel, 0.076 m left from the center of the track, at a height of 0.1015 m as shown in figure 3.4.
TFI Cobra Probes have been used for measuring the wind velocities. The probes have a 45 degree cone of acceptance which indicates that wind flow perpendicular to the cone is measured correctly to an angle of 45°. Wind that flows along the probe outside the 45° cone of acceptance is not measured by the probe. However, an advantage of this probe is that the head diameter is only 2.54 mm, which is considerably smaller than other available measurement devices. Therefore, the various devices do not affect each other’s results.

Gilbert et al. (2012) measured the wind velocities at three positions inside the tunnel; PRB1, PRB2 and PRB4. PRB1 and PRB2 lie close to each other and show practically equal results. PRB4 lies very close to the wall (at 13.6 mm). It is unlikely for a person to be standing this close to the wall. Therefore, only PRB 1 has been used for comparison of the results.

3.1.2 Measurement Results

The experiment has been repeated 25 times. The black line in figure 3.5 shows the 25 runs averaged wind velocities measured at PRB 1. Since there were high fluctuations in the results of all 25 runs, the standard deviation has been added to the graph, which is indicated by the blue line. The results have been normalized by dividing the measured wind velocities with the speed of the train (32 m/s). The time on the X-axis has been translated to full-scale model by multiplying it by 25. The nose of the train reaches PRB 1 at t is 0 s. The full-scale length of the train is 106 m. Consequently the tail of the train reaches the measurement position after approximately 3.3 s.

![Figure 3.5: Measured wind velocities at PRB 1 (Birmingham Center of Railway Research and Education)](image-url)
As illustrated in the graph, the wind velocities start to increase gradually as soon as the train enters the tunnel, rising to a peak value of 0.28 as soon as the nose of the train reaches the measurement position. Wind velocities are relatively low during the period when the side of the train passes PRB 1. Just after the rear of the train has passed PRB 1, a peak value of approximately 0.35 is measured.

The results are in line with the theory as mentioned in section 2.2. Both the compression wave in front of the train and the expansion wave behind the train, which are a result of the piston effect, can be observed in the graph. With this tunnel geometry and at this position the highest wind velocities are caused by the expansion wave behind the train.

### 3.2 Numerical Model

The mesh of the numerical model has been created with use of the pre-processor Gambit 2.4.6. This mesh has been imported in the commercial CFD code Ansys Fluent 12.1. Next, boundary conditions are imposed and a solution method is chosen.

#### 3.2.1 Geometry and Computational Grid of the Two Domains

The domain dimensions are defined according to the recommendations in sections 2.4.4, 2.4.6, and 2.4.10. The blockage ratio in the open field area is 0.0225, which meets the recommendations of Franke et al. (2007) and Tominaga et al. (2008). Simulations with the numerical model have been performed at the same scale as the experimental setup in order to provide equal Re-numbers for the model and experiments. Since the Re-number gives a measure of the ratio of inertial forces to viscous forces. The sliding mesh method has been applied in order to create relative motion between the tunnel and the train. For this method the domain has to be divided into two subdomains: one stationary domain, including the tunnel, and a moving domain, including the train.

#### 3.2.1.1 Stationary Domain

The computational grid of the stationary domain has been generated with use of the surface extrusion technique, which is elaborately described by van Hooff & Blocken (2010). The geometry and grid of a vertical cross section have been created. This surface is swept along a meshed line perpendicular to it (see figure 3.6). This has been done repeatedly and the volumes containing no air have been deleted. The volume where the train domain will be moving through has been deleted as well. The dimensions in figure 3.6 and 3.7 are in full-scale.
The computational grid is fine near the interfaces and becomes coarser as it gets further away from the area of interest. The stationary domain is made up of five zones as illustrated in figure 3.7. The middle part indicates the tunnel and the two parts adjacent to it are the field areas where the blockage ratio of 0.03 should not be exceeded. The outer two zones are also open field area. However, the air is not set into motion in this region, and therefore, cells can be reduced. The volumes are necessary though, since the interfaces change into walls as soon as they are not connected anymore. This results in a moving wall in the outer parts of the domain, as explained in section 2.4.10. This moving wall creates an undesired wind flow. Thus, the most important parts are the three middle parts. The exact dimensions of the stationary domain can be found in appendix A1.

3.2.1.2 Moving Domain

The more complex round faces of the train make it impossible to apply the extrusion technique for the moving domain. Firstly, faces have been created for the computational grid of the moving domain, covering the volume of the train as precisely as possible. Afterwards, a meshed volume is created around the faces (Figure 3.8a-c). Due to the complex geometry of the train it was not possible to use only hexahedral cells. Tetrahedral and prismatic cells have been used for the volumes with deviating geometries. A velocity of 32 m/s is given to this subdomain.
in the “Cell Zone Conditions” tab by selecting “Moving Mesh”. This sets the train domain into motion as soon as the simulation starts. The exact dimensions of the train domain can be found in appendix A2.

3.2.1.3 Grid Sensitivity Analysis

A grid sensitivity analysis has been performed in order to check the grid independency for wind velocities in the computational domain. Figure 3.9 shows the grids that have been used and the number of cells for each domain. The intention was to increase the number of cells for all directions with a factor 1.5 for each
sensitivity step. However, due to the complexity of the mesh, this objective could not always be precisely fulfilled.

<table>
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<th></th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
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<td>App. number of cells per m</td>
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<td>4.0</td>
<td>6.2</td>
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<td>Stationary domain</td>
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<tr>
<td>Nr. of cells: 259,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nr. of cells tunnel height: 14</td>
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<tr>
<td>Stationary domain</td>
<td></td>
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<tr>
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<td>Nr. of cells tunnel width: 40</td>
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<tr>
<td>Number of cells: 2,204,426</td>
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<td></td>
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</tr>
</tbody>
</table>

*Figure 3.9: Number of grid cells for each domain*

Simulations have been performed with the coarse, medium and fine grids. Measured wind velocities have been compared for the same measurement position as described in section 3.1.1 (PRB 1). The results of the grid sensitivity analysis can be seen in figure 3.10.
As can be seen, there is a noticeable difference between the results of the coarse and medium grid. The results of the medium and the fine grid are more similar. Therefore, the medium mesh size is applied for the validation study and the case study.

### 3.2.2 Viscous Model

The URANS equations are closed by the realizable $k$-$\varepsilon$ turbulence model. The realizable $k$-$\varepsilon$ turbulence model (Shih et al., 1995) has been used instead of the standard $k$-$\varepsilon$ turbulence model, since the standard $k$-$\varepsilon$ turbulence model overestimates the turbulent kinetic energy in regions of stagnant flow according to Franke et al. (2004).

### 3.2.3 Boundary and Initial Conditions

Due to the blockage ratio lower than 3 % in the open field area, no air movement is expected near the lateral faces. Therefore, all lateral faces of the field domain are defined as symmetry boundaries. When using the density of ideal-gas which is compressible, it is not possible to define a velocity inlet to a face. Therefore, both inflow and outflow faces are defined as pressure outlets. All floor surfaces and the tunnel faces of the field domain are defined as a wall. The wall roughness for both the tunnel and the train has been kept on default values (roughness height of 0 m and a dimensionless roughness constant of 0.5). As described in section 2.4.7, the connecting faces of both domains are defined as interfaces.

---

**Figure 3.10: Results of the grid sensitivity analysis**
3.2.4 Compressibility of Air

The train in this validation study runs with a speed of 32 m/s, which equals to a Mach number (the ratio of the flow velocity to the speed of sound) of just below 0.1. Generally, compressibility effects only occur if the Mach number of the flow exceeds 0.3. However, when a train enters a tunnel, a compression wave is induced propagating along the tunnel with sonic speed. Therefore, compressibility of air has an influence on the occurring gusts inside a tunnel. Two simulations have been performed to find out if the compressibility of air influences the peak gusts in this particular study. The green and yellow lines in figure 3.11 show the results obtained from simulations with compressible air and incompressible air, respectively.

![Graph showing influence of air compressibility](image)

Figure 3.11: Results of the grid sensitivity analysis

As can be seen, the results of the simulation with compressible air are different from the ones with incompressible air. The peak wind velocities of both the compression and the expansion wave are higher for the simulation with compressible air. Note that the simulation with compressible air shows a more fluctuating pattern in the occurring wind velocities. This is likely to be caused by the overestimation of the pressure waves moving through the tunnel with the speed of sound. Compressibility of air will be enabled though, since the peaks show better agreement.

3.2.5 Time-Step Size

The sliding mesh method has been introduced in the model according to the guidelines in chapter 11 of the Ansys Fluent 12.0 user guide. The time-step size can be calculated with use of the speed of the train and the minimum cell length, according to the following formula:
\[ \Delta t = \frac{CFL \cdot \Delta x_{\text{min}}}{U_{\text{max}}} \]

This formula is explained in section 2.4.9. After filling in the correct values in this formula, the time-step size is $3.44 \times 10^{-5}$ sec. The train has to travel for 0.4456 s before it has completely travelled through the tunnel. This results in a total number of 12,960 time-steps.

### 3.2.6 Other Computational Settings

After performing simulations with different solution methods, the “Fractional step” pressure-velocity coupling scheme showed best agreement with the experimental data. The standard wall functions by Launder and Spalding (1974) are used for the ground, tunnel and train surfaces. Gradient is set on “Least squares cell based” and the spatial discretization for pressure, density, momentum, turbulent kinetic energy, turbulent dissipation rate and energy have all been set on “second order”. The transient formulation is kept on “First order implicit”, combined with “Non-iterative time advancement”.

### 3.2.7 Summary of the Characteristics and Settings

Table 3.1 gives a summary of the calculation settings that have been used to give the best representation of the measured peak gusts in the experimental study.
Table 3.1: Summary of numerical input in the CFD models

<table>
<thead>
<tr>
<th>Compressible air</th>
<th>Calculation demands</th>
</tr>
</thead>
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<tr>
<td>Density</td>
<td>Time-step size</td>
</tr>
<tr>
<td>C_p</td>
<td>3.44*10^{-5} s</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Number of time-steps</td>
</tr>
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<td>Viscosity</td>
<td>12,960</td>
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<tr>
<td>Molecular weight</td>
<td>Boundary conditions</td>
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<td></td>
<td>Inlet and outlet</td>
</tr>
<tr>
<td></td>
<td>Type: Pressure outlet</td>
</tr>
<tr>
<td></td>
<td>Turb. intensity: 0.02 %</td>
</tr>
<tr>
<td></td>
<td>Hydr. diameter: 0.7232 m / 0.156 m</td>
</tr>
<tr>
<td>Computational domain</td>
<td>Ground surface, tunnel, train</td>
</tr>
<tr>
<td>Length stationary domain</td>
<td>Type: Wall</td>
</tr>
<tr>
<td>Length moving domain</td>
<td>Roughness height: 0 m</td>
</tr>
<tr>
<td>Max. blockage ratio field</td>
<td>Roughness constant: 0.5</td>
</tr>
<tr>
<td>Max. blockage ratio tunnel</td>
<td></td>
</tr>
<tr>
<td>Nr. of cells stationary domain</td>
<td></td>
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<tr>
<td>Nr. of cells moving domain</td>
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<tr>
<td>Velocity moving domain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solution methods</td>
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<td>Turbulence model</td>
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<td>Gradient: Least squares cell based</td>
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<td>Pressure: Second order</td>
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<tr>
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<td>Turb. dissip. rate: Second order upwind</td>
</tr>
<tr>
<td></td>
<td>Trans. Formulation: First order implicit</td>
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<tr>
<td>Y+ values at train surface</td>
<td>Non-iterative time advancement</td>
</tr>
<tr>
<td>ICE-2 train: 60 - 500</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Results

In this section the comparison has been made between the results of the experimental study and the final simulations. In addition to the comparison of results the CFD simulations reveal the occurring wind velocities through the entire tunnel. Three other notable observations have been highlighted in section 3.3.2.

3.3.1 Comparison of Wind Velocities

Figure 3.12 shows the comparison of the measured wind velocities by the experiment and the simulated wind velocities at measurement position PRB 1. The line of the measurements has been smoothened an average of the original line. Again the measured wind velocities have been divided by the speed of the train (32 m/s), providing dimensionless values. The time on the X-axis has been translated to the full-scale model by multiplying it with 25 as explained in section 3.1.2. The time is 0 s when the nose of the train reaches PRB 1, and approximately 3.3 s when the tail of the train reaches the measurement position.
As illustrated in the figure, the peaks of both the compression wave and the expansion wave show good agreement. The wind velocities are underestimated during the period when the train passes the measurement position (between 0 and 3.3 s). A possible explanation is that the simulation has been performed with the default values for the roughness height and roughness constant. The roughness of the tunnel and train with which the experiments have been performed are unknown. The default values for roughness height and roughness constant might overestimate or underestimate the actual roughness of the surfaces used in the experiment. Another suggestion is that the side of the train in the simulated model has a completely smooth surface, whereas the experimental model of the train consists of four cabins which give some roughness to this surface.

The peaks of both the compression wave and the expansion wave show good agreement. Note that these waves cause the highest train-induced wind velocities and are therefore decisive in the determination of wind comfort at an underground railroad platform. It can be concluded that the final numerical input in this validation study can be imported to the case study.

### 3.3.2 Notable Observations

An advantage of CFD simulations is that it generates whole flow-field data of for instance wind velocities. So far, data at one discrete point has been provided in this chapter. Some observations regarding the whole flow-field will be described here, that strengthen the choice of CFD for this study.
3.3.2.1 Visualization of the Occurring Piston Effect

Theory states that the compression and expansion wave increase in velocity as a train moves through a tunnel. The results of the CFD simulation are in line with the theory, as shown in figure 3.13 and figure 3.14, where horizontal cross sections at 2.53 m height, including contour-plots of the velocity magnitude are displayed. In both figures the train is colored in white and the moving direction is from left to right. Figure 3.13 shows the comparison of the compression wave in front of the train in the open air and inside a tunnel, whereas figure 3.14 shows the comparison of the expansion wave behind the train in the open air and inside the tunnel.

Figure 3.13: Comparison of the compression wave

Figure 3.14: Comparison of the expansion wave
The effect of the tunnel on the expansion and compression zone can clearly be seen in the figures. At the end of the tunnel the wind velocities start to increase long before the train passes, whereas the compression zone in an open field is very small. From figure 3.14 it can be seen that the expansion zone inside a tunnel cannot be cleared by the surrounding air, resulting in an enlargement of the expansion zone with very high wind velocities near the entrance of the tunnel long after the train has passed.

3.3.2.2 Tunnel Entrance

The study of Gilbert et al (2012) focused on the occurring wind velocities aside from the train, approximately halfway inside the tunnel. However, when looking at the wind velocities aside from the train, the CFD simulations show that the highest wind velocities occur at the tunnel entrance. Simulated wind velocities at 3 measurement positions indicated in figure 3.15 are illustrated in figure 3.16, where the simulated wind velocities at position A, the entrance of the tunnel, are given by the black line. The measurement positions are located at a height and distance from the center of the track according to figure 3.4, which is equal to the position of PRB 1, and at a distance inside the tunnel according to figure 3.16. In figure 3.16, t = 0 s as the train starts moving, t = 0.4 s as soon as the nose of the train enters the tunnel, t = 3.7 s as the rear of the train enters the tunnel, t = 6.7 s as the nose of the train leaves the tunnel, and the rear of the train leaves the tunnel at t = 9.9 s.

Figure 3.15: Top view of measurement positions A - C in full-scale
As can be seen, the highest wind velocities occur at the entrance of the tunnel just after the nose of the train has passed. The high wind velocities at the entrance of the tunnel are indirectly caused by the piston effect. The compressed air ahead of the train gets partially cleared by the open air in front of the tunnel. This results in a wind flow through the tunnel in the direction of the open field with peak velocities higher than 35% of the speed of the train. Figure 3.17a shows a horizontal cross section at the entrance of the tunnel at the moment the train is entering, including contour-plots of the velocity magnitude. The red arrows show the direction of the wind flow. Figure 3.17b shows the vector-field to illustrate the wind direction throughout the figure.

This situation can lead to wind nuisance at the end of an underground railroad platform as soon as the nose of the train enters the tunnel with a platform nearby. The case study will assess the appearance of wind nuisance due to the occurrence of this situation.
3.3.2.3 Tunnel Exit

The expansion wave behind the train increases in intensity during the passage of the train through the tunnel. Despite the increment in intensity, this wave stays at a fixed position behind the train. However, at the moment when the train leaves the tunnel a sudden oscillation is observed. This situation can be seen in figure 3.18, where a vertical cross section of the train leaving the tunnel including contour-plots of the velocity magnitude can be seen.

![Figure 3.18: Vertical cross section including contours of wind velocities at tunnel exit](image)

This oscillation is caused by the shape of the train and tunnel exit. As the train leaves the tunnel, the expansion wave can first be cleared by the air from above due to the aerodynamic shape of the train. This results in a sudden undulation in the expansion zone, which does not directly lead to wind nuisance. However, almost the same situation could occur in the case study when the rear of the train reaches the platform, where the expansion wave can first be cleared by the air at the platform.
Chapter 4: Case Study: Wind Effects at an Underground Railroad Platform.

This chapter describes the case study with use of computational settings derived from the validation study. Simulations have been performed for two cases; 1) a Dutch intercity train and 2) a freight train. Both trains are running with the maximum speed which is allowed on the Dutch railroads.

This chapter is divided into two sections. The first section describes the preconditions of the numerical model and the computational grid of the tunnel and two trains. Results of the simulated wind velocities at the underground railroad platform are described in the second section, where extra attention is given to the positions where wind danger occurs and the phenomena that cause high wind velocities.

4.1 Numerical Model

The guidelines used for the validation study are also applied in the numerical model in the case study. The pre-processor Gambit 2.4.6 is used for the mesh generation and the simulations have been performed in Ansys Fluent 12.1.

The computational grid of the two domains in the case study is generated in a similar manner as the computational grid made for the validation study. A maximum value of 0.03 for the blockage ratio in the open field area has been taken into account, and the sliding mesh method has been applied in order to create relative motion between the tunnel and the train (see also section 2.4). The computational domain is divided into two subdomains: 1) a stationary domain including the tunnel and platform, and 2) a moving domain including one of the trains. Simulations have been performed for two cases: 1) a Dutch intercity train and 2) a freight train. The generation of the two subdomains and the reason for choosing the two cases is subsequently described in the following sections.

4.1.1 Geometry and Grid of the Stationary Domain

Multiple preconditions have been assigned to the model; partly in order to reduce the large computational demand of the type of simulation that is applied in this study, and partly to analyze a critical and realistic situation. The choice of modeling one of the underground railroad platforms that are currently in use in the Netherlands would result in a computational demand that is higher than necessary. Therefore, a model of a fictive underground railroad platform is chosen, which is shorter in length but, still meets the requirements by Prorail (2012), described in section 2.3.3. All assigned preconditions are described subsequently in this section.
4.1.1.1 Length of the tunnel and platform

Both Gilbert et al. (2012) and Novak (2006) indirectly prove that short tunnels give higher peak velocities in the expansion wave. For longer tunnels the length of the expansion wave increases, though, the peak velocity that can be perceived decreases. Since it is the intention to study the most critical realistic situation that can occur, it has been decided to use a rather short tunnel with a total length of 250 m, where the platform is positioned in the middle of the tunnel.

Prorail (2013) summarizes the lengths of all Dutch platforms that are currently in use. The lengths vary in between 120 and 400 m. The modeled intercity has a length of 107.5 m. Keeping this length in mind, the length of the underground railroad platform for this case study has been chosen to be 150 m. With this platform length, the vortices in the wake of the train are fully developed before the nose train leaves the platform again. Figure 4.1 gives an overview of the total tunnel length including platform. Note that the width in this figure is adjusted, resulting in a length and width that are not in proportion.

Figure 4.1: Length of the tunnel including platform

4.1.1.2 Blockage ratios

The width of the platform has been designed with use of the guidelines by Prorail (2012), described in section 2.3.3. According to these guidelines a platform is subdivided into four zones. Each zone has its minimum width and the total width of a newly constructed Dutch platform should be at least 3.4 m. For the ease of people stepping in or out of a train, the center of track is positioned exactly 1.7 m aside from the edge and 0.76 m below the floor level of the platform. Figure 4.2 shows a cross section at the platform including the measures recommended by Prorail.
The modeled intercity train has a cross-sectional area of 11.29 m$^2$, whereas the freight train has a cross-sectional area of 10.53 m$^2$. The total vertical cross section area at the platform is 40.88 m$^2$, resulting in a blockage ratio of 0.28 for the intercity train and 0.26 for the freight train at the platform area.

The cross-sectional area of the tunnel has been chosen equal to the ones that are currently under construction in Delft (Definitive Design drawings, Grontmij Maunsell ICS, 2007). The tunnels are provided with a walkway on the side (1.0 m width) which is connected to the platform. Figure 4.3 shows a cross section at the tunnel including the measures, which are equal to the tunnels at Delft station.

The total cross-sectional area of the tunnel is 29.17 m$^2$. This results in a blockage ratio of 0.39 for the intercity train and 0.36 for the freight train.
4.1.1.3 Computational grid of the stationary domain

The computational grid of the stationary domain has been generated with use of the surface extrusion technique (van Hooff & Blocken, 2010) and shows great resemblance with the field domain in the validation study. Though, the dimensions differ slightly and some details have been added including the platform halfway the tunnel.

![Figure 4.4: Platform domain zoomed in on entrance tunnel](image)

The computational grid is fine near the tunnel and platform and becomes coarser as it gets further away from the area of interest, as illustrated in figure 4.4. The approximate cell size has been determined according to the grid sensitivity analysis described in section 3.2.1. The highest cell density can be found inside the tunnel, where the number of cells is approximately 5 per m. The number of cells over the height of the tunnel is 36 and in total the platform domain consists of 2,991,920 hexahedral cells.

4.1.2 Geometry and Grid of the Moving Domains

Many different types of trains are currently running along the Dutch tracks. It has been decided to perform two simulations with the trains which are expected to cause the most wind nuisance at a platform. The arguments for choosing both geometries are described in the following sections, including their geometry.

4.1.2.1 Moving domain - VIRM intercity train

It has been decided to perform a simulation with a Dutch Verlengd InterRegionaal Verkeer (VIRM) intercity train (see figure 4.5) since this train has the highest vertical cross-sectional area of all trains traveling along the railroads in the Netherlands. This results in a high blockage ratio and therefore higher velocity peak values of wind
gusts. In the Netherlands, passenger trains are allowed to travel with a maximum speed of 140 km/h (38.9 m/s) through urban areas (Prorail Netverklaring, 2013).

The same method as the one used for generating the mesh of the ICE-2 train in the validation study has been applied for the mesh generation of the VIRM intercity train (figure 4.5a). First the train is covered with faces and afterwards a volume is created around each face. Figure 4.5b shows how the train has been covered with faces and the distribution of the cells over the faces can be seen in figure 4.5c and 4.7. Due to the complex geometry of the nose and rear of the train it was not possible to use just hexahedral cells. Therefore, tetrahedral and prismatic cells have been used for the volumes with deviating geometries. The number of cells that is used for this moving domain is 1,611,966. The dimensions of the train are derived from drawings by Nedtrain (VIRM 4 wagen treinstel algemeen plan, 2009) and the exact dimensions of the mesh can be found in appendix A4.
4.1.2.2 Moving domain - Freight train

Freight trains are designed to transport as much cargo as possible and the aerodynamic shape of this type of train is of less importance. In the theory section it is mentioned that the piston effect is mainly affected by three factors including the shape of the train. Consequently, it may be possible that a freight train causes more wind nuisance when crossing a tunnel. Secondly, Prorail has the ambition to increase the moving velocity for freight trains from 80 km/h to 100 km/h (27.8 m/s). Therefore, it is decided to perform a second simulation with a locomotive train (see figure 4.7) including six 45 ft. (13.7 m) container carriages (see figure 4.8) stacked on top of a Gianti flat wagon.

A simplified model of a TRAXX 2803 locomotive including six freight wagons has been generated. An advantage of this rectangular shape is that it is easier to model and it was possible to use just hexahedral cells. Figure 4.9 shows the mesh of this TRAXX 2803 locomotive including one of the six freight wagons and the general measures. The cross-sectional area of this freight train is smaller in comparison to the VIRM intercity train (10.53 m²). Though, despite the lower maximum moving velocity and the lower cross-sectional area in comparison to the VIRM intercity train, wind nuisance is to be expected.

The number of cells that is used for this moving domain is 1,180,074. The dimensions of the containers and flat wagons are derived from drawings of Gianti (www.giantilogistics.ge) and the exact dimensions of this freight train can be found in appendix A5.
4.1.3  Summary of Characteristics and Settings

Table 4.1 gives a summary of the calculation settings that have been used for the simulations in the case study. The used turbulence model, wall functions, and solution methods are derived from the validation study.

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<thead>
<tr>
<th>Compressible air</th>
<th>Calculation demands</th>
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<tbody>
<tr>
<td>Density</td>
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<td>$C_p$</td>
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<td>Viscosity</td>
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<td>Molecular weight</td>
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<tr>
<td></td>
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<td>Compressible air</td>
<td>Time-step size freight : $1.6546 \times 10^{-3}$ s</td>
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<td></td>
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<td>Max. blockage ratio VIRM train : 0.39</td>
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<tr>
<td>Max. blockage ratio freight train : 0.36</td>
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<tr>
<td>Nr. of cells VIRM train domain : 1,611,966</td>
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<tr>
<td>Nr. of cells freight train domain : 1,180,074</td>
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<td>Nr. of cells platform domain : 2,991,920</td>
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<tr>
<td>Moving speed VIRM train : 38.9 m/s</td>
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<td>Moving speed freight train : 27.8 m/s</td>
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</table>

<table>
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<tr>
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</tr>
<tr>
<td>Hydraulic diameter</td>
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</table>

| Ground surface, tunnel, train |
| Type               | Wall               |
| Roughness height   | 0 m                |
| Roughness constant | 0.5                |

<table>
<thead>
<tr>
<th>Solution methods, URANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme</td>
</tr>
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<td>Gradient</td>
</tr>
<tr>
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<th>Y+ values at train surfaces</th>
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</thead>
<tbody>
<tr>
<td>VIRM train</td>
</tr>
<tr>
<td>Freight train</td>
</tr>
</tbody>
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---

Figure 4.9: Mesh of simplified model of a freight train including general measures
4.2 Results

This section gives the results obtained from the performed simulations. Based on the simulated wind velocities at different spots on the platform it is assessed whether the wind climate on these locations is comfortable, uncomfortable (poor) or even dangerous. The research criteria can be summarized as follows:

- 0 - 5 m/s = wind comfort
- 5 - 12 m/s = wind discomfort
- > 12 m/s = wind danger

When a gust wind exceeds 12.0 m/s, it has to last at least 0.5 seconds (Bottema, 1993) and have an acceleration of at least 0.43 m/s² (de Graaf, 1997) before it can destabilize a person. The results are discussed by train type (intercity or freight train) and different platform positions, namely the entrance, middle and exit of the platform.

The expansion wave behind the train significantly increases as a train runs through a tunnel. The vortices behind the trains develop simultaneously, and due to asymmetry of the tunnel, the vortex behind the train starts to oscillate. To clarify this phenomenon, this chapter concludes with observations of the vortex development behind both the intercity and the freight train.

4.2.1 Assessment of Wind Discomfort and Danger

The following sections provide the simulated wind velocities at different positions in the center of each zone. Categorization of the research criteria has been done by highlighting with three different colors. The wind comfort area in both the graphs and the contour-plots is indicated in green, the wind discomfort area is indicated in yellow, and the area where wind velocity exceeds 12 m/s is indicated in red.

The assessment of wind discomfort and danger is subdivided in three parts, as illustrated in figure 4.10. Note that the width in this figure is adjusted, resulting in a length and width that are not in proportion. The simulated wind velocities at the platform entrance, center, and exit are shown chronologically. First the results concerning the VIRM intercity train are covered and afterwards the results concerning the freight train.

*Figure 4.10: Horizontal cross section of the underground platform incl. positions of snapshots*
The most critical areas considering wind nuisance are highlighted in a contour-plot. Though, the wind flow development can best be seen in the movies placed on the attached CD (names of movies: CS-F-1 and CS-I-1).

4.2.1.1  **VIRM Intercity Train**

**Platform entrance**

Figure 4.11 shows a snapshot of the most critical wind situation that occurs at the entrance of the platform due to the passage of a VIRM intercity train. A horizontal cross section at 1.2 m above the platform including a contour-plot of the velocity magnitude is shown. The most critical wind situation is caused by the expansion wave behind the train. Wind velocities have been simulated at four positions (figure 4.12) to analyze the development of the wind. The results are provided in figure 4.13. The location names indicate the type of zone and the distance in meters to the entrance of the platform. For instance, C4 is a point in the circulation zone at 4 m from the platform entrance. All data points are located in the middle of the zone at 1.2 m above the platform.
The results prove the appearance of the oscillation in the expansion wave. The expansion wave starts oscillating as the rear of the train enters the platform, resulting in wind velocities higher than 12 m/s at the platform just after the train has passed. The peak that is simulated at the safety zone can be indicated as dangerous, since it lasts for more than 0.5 s (Bottema, 1993) and has an acceleration more than 0.43 m/s² (de Graaf, 1997). These dangerous wind velocities will presumably not lead to dangerous situations, since people are not allowed to walk at the safety zone. As illustrated in figure 4.13, a peak with a wind velocity in the danger zone is also seen at the walking zone, however, only for a very short time period. No wind danger is noticed at the waiting zone and the circulation zone. Note that very high wind velocities occur at the tunnel before the platform, indicated by the red area in figure 4.11.

The compression wave does not cause any wind discomfort, as illustrated in figure 4.13 (t = 0 to 1.6 s). Though, due to the oscillations in the expansion wave, wind discomfort is noticed at each zone just after the train has passed (t = 4.5 to 10 s in figure 4.13). The oscillation in the wind flow behind the train can be seen best in the movies on the attached CD (name of movie: CS-I-3).

**Center of platform**

Analysis of the wind nuisance at the center of the platform has been done in an equal manner as for the platform entrance. The most critical wind situation that occurs at the middle of the platform is shown by a snapshot in figure 4.14. This situation is caused by the compression wave ahead of the train. Wind velocities have been simulated at four positions (figure 4.15) to analyze the development of the wind. The results are provided in figure 4.16.
At the center of the platform, the highest wind velocities due to the passage of a VIRM intercity train are caused by the compression wave (t = 0 to 3.5 s in figure 4.16). The high wind velocities do not result in wind danger. Though, wind discomfort is felt at all four zones (yellow in figure 4.14). Note that the wind velocities caused by the compression wave are equal for all positions. The grey line (waiting zone) and black line (circulation zone) are mostly following the same path as the green line (walking zone). The wind velocities that are causing discomfort (above 5 m/s) occur for more than 4 s in this simulation (t = 1.5 to 6.2 s in figure 4.16). This is an undesired occurring effect at the circulation zone, since benches are positioned in this area.
Platform exit

Analysis of the wind nuisance at the platform exit has been done in an equal manner as for the platform entrance and center of the platform. The most critical occurring wind situation is shown by a snapshot in figure 4.17. Wind velocities have been simulated at four positions (figure 4.18) to analyze the development of the wind. The results are seen in figure 4.19.

Figure 4.17: Horizontal cross section including contour-plot of most critical wind situation

Figure 4.18: Horizontal cross section including positions

Figure 4.19: Graph including the simulated wind velocities at the positions from figure 4.19

The results of the simulated wind velocities at the exit of the platform prove that the compression wave ahead of the train gets partially cleared by the open area of the platform, resulting in a wind flow with velocities higher than 12 m/s towards the platform (see also section 3.3.2.2). The peak of the velocity magnitude at the walking zone (green line in figure 4.19, t = 5.6 to 6.3 s) can be indicated as
dangerous, since it lasts for more than 0.5 s (Bottema, 1993) and has an acceleration more than 0.43 m/s² (de Graaf, 1997). Although the peak is of short duration, this might lead to a dangerous situation, since it is allowed for people to walk at this zone. Note that the highest wind velocities occur at the walking zone instead of the safety zone.

Wind discomfort at the exit of the platform is caused by both the compression wave (t = 0 to 8 s in figure 4.19). This can be seen best in the movies on the attached CD (name of movie: CS-I-4).

4.2.1.2 Freight Train

In this section the results regarding the simulation with the freight train are illustrated. Results are shown in an equal manner as for the previously elaborated simulation with the VIRM intercity train. The simulated wind velocities at the platform entrance, center, and exit are shown chronologically.

Platform entrance

Figure 4.20 shows a snapshot of the most critical wind situation that occurs at the entrance of the platform due to the passage of a freight train. A horizontal cross section at 1.2 m above the platform including a contour-plot of the velocity magnitude is shown. The most critical wind situation is caused by the expansion wave behind the train. Wind velocities have been simulated at four positions (figure 4.21) to reveal the development of the wind. The results are seen in figure 4.22.
The oscillation in the expansion wave at the entrance of the platform that was seen in the results of the simulation with the VIRM intercity train does not occur as the freight train passes through. This can be found remarkable, since the shape of the freight train should result in a larger expansion wave behind the train. However, the shape of the vortices behind the freight train differs from the vortices behind the VIRM intercity train. The vortices behind the freight train are less sensitive to pressure differences caused by the air at the platform. This is discussed in more detail in section 4.2.2.

The highest occurring wind velocities are illustrated in the contour-plots of figure 4.20. As can be seen, no dangerous wind velocities are seen at the platform entrance in this simulation. Wind velocities in the discomfort range occur at the safety zone and for a short period at the walking zone (t = 7 to t = 13.5 s in figure 4.22). Though, as stated in section 2.3.3, wind discomfort is allowed at these zones.

**Center of platform**

The most critical wind situation that occurs at the center of the platform is shown by a snapshot in figure 4.23. This situation is caused by the compression wave ahead of the train. Wind velocities have been simulated at four positions (figure 4.24) to reveal the development of the wind. The results are shown in figure 4.25.
Figure 4.23: Horizontal cross section including contour-plot of most critical wind situation

Figure 4.24: Horizontal cross section including positions

Figure 4.25: Graph including the simulated wind velocities at the positions from figure 4.25

At the center of the platform, the highest wind velocities due to the passage of a freight train are caused by the compression wave \((t = 0 \text{ to } 5.0 \text{ s in figure 4.25})\). Despite the very short peak in the wind velocities at the safety zone (blue line in figure 4.25), caused by the nose of the train, the high wind velocities do not result in wind danger. Though, wind discomfort is felt at all four zones (yellow in figure 4.23). Note that the wind velocities caused by the compression wave are equal for all positions. The wind velocities that are causing discomfort (above 5 m/s) occur for approximately 2 s in this simulation \((t = 3.0 \text{ to } 5.0 \text{ s in figure 4.25})\). This is an undesired effect to occur at the circulation zone, since benches are positioned in this area.
Platform exit

Analysis of the wind nuisance at the platform exit has been done in an equal manner as for the platform entrance and middle of the platform. The most critical occurring wind situation is shown by a snapshot in figure 4.26. Wind velocities have been simulated at four positions (figure 4.27) to reveal the development of the wind. The results are illustrated in figure 4.28.

![Figure 4.26: Horizontal cross section including contour-plot of most critical wind situation](image)

![Figure 4.27: Horizontal cross section including positions](image)

![Figure 4.28: Graph including the simulated wind velocities at the positions from figure 4.28](image)

The clearance of the compression wave causing a wind flow with peaks higher than 12 m/s into the direction of the platform by the passage of the VIRM intercity train is not seen in this simulation. This can be explained by the lower cross-sectional area of the freight train. The wind flow into the direction of the platform does occur in...
this simulation, though to a limited extend. This can best be seen in the movies appended on the CD (name of movie: CS-F-4).

Wind discomfort at the platform exit is caused by the compression wave (t = 3.0 to 7.5 s in figure 4.28) at all zones except for the circulation zone. Therefore, it can be concluded that this freight train, moving with a speed of 100 km/h, does not cause wind discomfort or wind danger at the relevant zones at the platform exit. Though, wind discomfort will occur at the circulation zone when moving towards the center of the platform (yellow area in figure 4.26). Note that the highest wind velocities occur inside the tunnel ahead of the platform, indicated by the red area in figure 4.26.

4.2.2 Vortex Development in the Near Wake Region

In this section attention is given to the vortex development behind both the freight train and the VIRM intercity train as they move through the tunnel and along the platform. The development of the vortices behind each train is shown by pathlines colored by the velocity magnitude at three different positions: "open field’, “tunnel’ and “platform’. Figure 4.29 illustrates the positions where the vortices are analyzed.

![Figure 4.29: Horizontal cross section incl. positions pathline figures](image)

First the vortices behind the trains are shown as they move through the open air, afterwards the vortices are shown behind the trains when moving through the tunnel and finally the vortices are shown as the rear of both trains enter the platform.

4.2.2.1 Vortex development in the open field

The vortices behind the VIRM intercity train can be seen in the upper part of figure 4.30, whereas the vortices behind the freight train are seen below in this figure. A horizontal cross section with pathlines colored by velocity magnitude is shown at a moment before the trains run through the tunnel (‘open field’ in figure 4.29).
The two trains show completely different vortices, as drawn by the black lines in figure 4.30. Two standing vortices are generated behind the freight train with air flowing towards the rear of the train at the inner side of the vortices. The velocity magnitude of the vortices behind the freight train is higher in comparison to the vortices behind the VIRM intercity train, despite the lower moving velocity.

Two helical shaped vortices are generated behind the VIRM intercity train and there is no recirculation zone behind this train, resulting in a lower speed of the wind inside the vortices. This can be explained by the fact that the VIRM intercity train is more aerodynamically shaped in comparison to the containers of the freight train.

The range in the legend for both velocity magnitudes behind the trains is set on 0 to 45 m/s in order to draw good comparison. Note that the running speed of the freight train is much lower in comparison to the running speed of the VIRM intercity train (27.8 m/s and 38.9 m/s, respectively). Therefore, the difference in velocity magnitude would be even higher if both trains were running with the same speed.

4.2.2.2 Vortex development inside the tunnel

The vortices behind the VIRM intercity train can be seen in the upper part of figure 4.31, whereas the vortices behind the freight train are seen below in this figure. A horizontal cross section including pathlines is shown at a moment the train runs through the tunnel before reaching the platform (“tunnel” in figure 4.29).
When comparing the vortices illustrated in figure 4.31 with the ones in figure 4.30, it can clearly be seen that the velocity magnitude increases, especially for the VIRM intercity train, where the expansion wave stretches out. This can be explained by the high blockage ratio in the case with the VIRM intercity train (0.39 inside the tunnel). The piston effect occurs to a smaller extend in the case with the freight train due to its lower blockage ratio inside the tunnel (0.36). The expansion wave behind the freight train can be cleared more easily by the air aside and ahead of the train. Therefore, the increment in velocity magnitude of the vortices behind the freight train occurs to a smaller extent.

The tunnel where the trains are running through is asymmetrical. The air region left from the trains is slightly larger than the air region right from the trains, due to the walking path which has been added to the tunnel. Despite this asymmetric shape of the tunnel, the vortices behind both trains are still nearly mirror-symmetrically in shape (figure 4.31).

4.2.2.3 Vortex development at platform entrance

The vortices behind the VIRM intercity train can be seen in the upper part of figure 4.32, whereas the vortices behind the freight train can be seen below in this figure. A horizontal cross section including pathlines is shown at a moment when the rear of the train reaches the platform (“platform entrance” in figure 4.29).
Comparing figure 4.32 to figure 4.31, it is seen that the velocity magnitude of the vortices is slightly reduced, though it is higher than in the open air. This can be explained by the increase in the cross-sectional area of the tunnel. The blockage ratio for both trains is lower at the platform in comparison to the blockage ratio inside the tunnel.

In figure 4.32 it can be seen that the mirror-symmetry of the vortices behind the VIRM intercity train has completely disappeared at the moment the rear of the train enters the platform. An oscillation is seen in the expansion wave (dashed black arrows in figure 4.32) and, since this wave was stretched out due to the narrow tunnel, it causes high wind velocities at the platform as described in section 4.2.1. This oscillation is caused by the air zone at the platform, where the static pressure is higher than behind the train. The expansion wave gets more or less sucked towards the platform. This phenomenon can be seen more clearly in the movies on the appended CD (names of movies: CS-F-3 and CS-I-3).

The vortices behind the freight train are much more attached to the rear of the train. Therefore, these vortices are less sensitive to the pressure differences aside from the train caused by the air zone at the platform. Consequently, no wave towards the platform is generated.
4.2.3 Wind Flow inside the Tunnels

Higher wind velocities occur inside the tunnels instead of at the platform, as indicated by the red areas in figure 4.11 and 4.26. No passengers are allowed to walk inside the tunnels. However, the tunnel is provided with a walking path on the side in case of emergency and for trackside workers. The occurring wind velocities at the tunnel before and after the platform are described in this section.

For the safety of track workers, TSI (2011) specifies a maximum permissible air speed of 20 m/s at the moment a train passes. This requirement is originally set up for trains with a maximum operating speed of 249 km/h running in the open field and has to be fulfilled at a distance 3.0 m away from the center of track. The center of the walking path inside the tunnel is only 2.2 m away from the center of track. Nevertheless, this value can be taken as directive when analyzing the wind velocities inside the tunnels.

The simulated wind velocities have been studied at various positions inside the tunnels, though the highest wind velocities were observed at the two points highlighted in figure 4.34 and 4.35. Point T1 is located at 1 m inside the entrance of the tunnel, and point T2 is located 1 m before the exit of the tunnel (figure 4.34). Both points are located at the center of the walking path, 1.2 m above the floor level (figure 4.33).

![Figure 4.33: Vertical cross section including the positions of the points](image)

![Figure 4.34: Horizontal cross section including the positions of the points](image)
4.2.3.1 Tunnel before the platform

Figure 4.35 and 4.36 show the simulated wind velocities at point T1 for the VIRM intercity train and the freight train, respectively. The freight train was moving with a lower velocity in comparison to the VIRM intercity train (38.9 m/s to 27.8 m/s). However, a good comparison between the results can be made since the values have been normalized by dividing the simulated wind velocities by the speed of the train.

Figure 4.35: Wind velocities at point T1 caused by the passage of the VIRM intercity train

Figure 4.36: Wind velocities at point T1 caused by the passage of the freight train
The first parts of the graphs show good similarity. Though, the peak wind velocity in the first two seconds is slightly higher for the freight train. High wind velocities are noticed due to clearance of the compression wave. The compressed air ahead of the train gets partially cleared by the open air before the tunnel. This results in a wind flow through the tunnel in the direction of the open field with a peak velocity around 65% of the freight train's speed. (See also section 3.3.2.2).

The line showing the wind velocities for the VIRM intercity train is smoother during the period the train passes in comparison to the line of the freight train. This is caused by the fact that the freight train is built up out of seven parts. A recirculation zone is seen in between each part, causing a short peak in the wind flow.

Note that the highest wind velocities in the case with the VIRM intercity train are caused by the expansion wave (time > 3 s in figure 4.35). This is a direct result of the piston effect. Remarkably, this effect does not occur in the case with the freight train. An explanation for this can be found in the lower cross-sectional area of the freight train.

It can be expected that the wind velocities move along proportionally with the speed of the train. If so, the TSI (2011) requirement is only met at this part of the tunnel if the freight train moves with a velocity no higher than 30.8 m/s (111 km/h) and the VIRM intercity train moves with a velocity no higher than 33.3 m/s (120 km/h).

4.2.3.2 Tunnel after the platform

Figure 4.37 and 4.38 show the simulated wind velocities at point T2 for the VIRM intercity train and the freight train, respectively. Again, the values have been normalized by dividing the simulated wind velocities by the speed of the train so that a good comparison between the results can be made.
The compression waves ahead of both trains show somewhat similarity (t = 1 to 6.8 s in figure 4.37 and t = 1 to 9.4 s in figure 4.38). The average wind velocities of both compression waves fluctuate around 30 % of the speed of the train, though the VIRM intercity train has outliers to 45 %. The highest wind velocities are noticed just before the rear of the VIRM intercity train reaches point T2. The expanded air behind the train gets partially cleared by the open air ahead of the tunnel. This results in a wind flow through the tunnel in the direction of the expansion wave with a peak velocity of 70 % of the speed of the VIRM intercity train. Remarkably, this effect does not occur in the case with the freight train. Hardly any wind is felt by the passage of the freight train.

If the wind velocities proportionally move along with the speed of the train, the TSI (2011) requirement is only met at this part of the tunnel if the VIRM intercity train moves with a velocity no higher than 28.6 m/s (103 km/h).
5 Discussion

The effect of a passing train on the wind comfort at an underground railroad platform has been investigated in this study by performing different CFD simulations. Simulations including the sliding mesh method have been validated by comparing the results with experimental data obtained by the Birmingham Centre for Railway Research and Education. Afterwards, simulations with two trains, differing in design and speed, running along a fictive platform have been performed. The resulting wind velocities at the platform are assessed against the following criteria:

- 0 - 5 m/s = comfortable
- 5 - 12 m/s = uncomfortable
- > 12 m/s = dangerous

If wind velocities exceed the value of 12 m/s, it should last for at least 0.5 s (Bottema, 1993) and have acceleration higher than 0.43 m/s² (de Graaf, 1997) before it has the ability to destabilize a person. This criterion is formulated by using the results of studies by Jordan et al (2008), Bottema (1993) and Fukuchi (1961), which are elaborately described in section 2.3. The pros and cons of this method and the most noteworthy results are discussed in this chapter.

5.1 Validation Study Results

Theory states that when a train runs through a tunnel two waves are generated: a compression wave ahead of the train and an expansion wave behind the train. This theory is confirmed in the results of experiments by Gilbert et al. (2012), where a 1/25th scale model of a German ICE-2 train is running through an 8.0 m long tunnel with a speed of 32 m/s and wind velocities are measured approximately halfway inside the tunnel. Both waves are clearly distinguishable in the results, despite the aerodynamic shape of the train (section 3.1).

The goal of the validation study was to find out what input is best to be used for simulating a compression wave and an expansion wave, since these waves could be the cause of wind nuisance at a platform. Therefore, the emphasis in this validation study was on correct simulating both waves. Hardly any CFD research was taken with similar situations, except for Novak (2006) and Shin & Park (2003). Finding the most appropriate input thus was a major challenge.

With the computational settings described in section 3.2.7 the expansion and compression wave were best simulated. The peaks at the measured position correspond closely. Nevertheless, the CFD results are in less agreement with the experimental data at the following three positions:
After switching to compressible air (section 3.2.4) the wind velocities start fluctuating. A suggestion is that this is a result of the pressure wave propagation (section 2.2.1). The experiments by Gilbert et al. (2012) show that the pressure waves hardly affect the wind velocity. The effect of the pressure waves on the wind velocity inside the tunnel is overestimated by the CFD simulation.

The peak of the expansion wave shows good agreement at measurement position PRB 1. The experiment shows that the expansion wave causes equal peaks closer to the wall. These peaks are not seen in the results of the CFD simulation. The wind flow behind the train is highly turbulent. Therefore, a suggestion is that this is caused by the fact that simulations are performed in URANS, which averages the turbulence. In LES only the smaller eddies are filtered out, which could result in a better agreement of the highly turbulent wake. However, no simulations in LES have been performed.

The simulated wind velocities in the period between the compression wave and the expansion wave are underestimated by the CFD simulation. A suggestion is that this is caused by the roughness of the train body. Only the wall functions at the surfaces of the train are causing movement of air as the train is moving in the CFD simulations. Roughness at the surfaces of the train used in the experiments is not taken into account.

Aside from the validation, the CFD model provides extra information that has not been obtained in the experimental study by Gilbert et al (2012). In the experimental study it was not possible to analyze the oscillation of the expansion wave during the moment the rear of the train leaves the tunnel and the highest peaks that are noticed at the tunnel entrance. Consequently, the CFD model is a useful addition to the experiments.

### 5.2 Case Study Results - VIRM Intercity Train

From several considerations described in section 4.1 it is decided to set up a model including a tunnel with the dimensions as have been used for the tunnels at Delft station, combined with a platform in the middle with dimensions that meet the minimum requirements according to Prorail (2012).

The goal of this simulation was to find out at what positions at the platform wind nuisance occurs during the period a VIRM intercity train passes. Theory states that wind velocities that are the result of the piston effect are influenced by three factors: the shape of the nose and rear of the train, the speed of the train, and the blockage ratio. The wind flow due to the piston effect, measured in the experimental study, reaches a peak value of approximately 11.5 m/s in the middle of the tunnel. When comparing the model of the validation study with the model of the case study including the VIRM intercity train it is seen that the blockage ratio at the platform is slightly lower in the case study. However, the running speed if the train in the case study is higher and the shape of the rear and front of the train are less
aerodynamic. Therefore, it was not possible to determine in advance if this situation causes wind danger at a platform.

The results show that the piston effect does not directly lead to wind danger at an underground railroad platform during the period a VIRM intercity train passes. Nevertheless, dangerous wind velocities are occurring at specific places at the entrance and exit of the platform and are caused by a sudden change in tunnel width. This suggests that the chance is very small for wind danger to occur in a real situation. However, the critical areas that cause wind danger at specific positions at the simulated platform are also designed in practice at Delft station. This is illustrated in figure 5.1.

![Tunnel at construction site of Delft station](image)

*Figure 5.1: Tunnel at construction site of Delft station (self-taken picture, June 2013)*

The red lines in figure 5.1 indicate the approximate measures that have been applied for the tunnel in the CFD model. The station is currently under construction, though the area in the foreground at the left side is where the platform will be located in the future. Part of the floor plan of Delft station is shown in figure 5.2. The approximate area at the platform where dangerous wind velocities could occur during the passage of a VIRM intercity train is indicated in green. The red arrow points out the position at which the picture in figure 5.1 is taken.
5.3 Case Study Results - Freight Train

The shape of the nose and rear of the train, the speed of the train and the blockage ratio are the three main factors of influence on the wind flow inside a tunnel. A VIRM intercity train and a freight train are the two trains that are scoring worst on these three factors when comparing all trains that are currently running on the Dutch tracks. Therefore, it is decided to perform a second simulation with a freight train. The running speed of this train has been set slightly lower in comparison to the VIRM intercity train (27.8 m/s and 38.9 m/s, respectively), though the shape of the freight train is much more robust. Exact dimensions of this train are found in section 4.1.2 and appendix A5.

The results including the freight train show that again the piston effect does not lead to wind danger. The compression wave ahead of the freight train does create a wind flow with peaks higher than 12 m/s at certain positions at the platform. However, the duration is too short for being able to destabilize a person.

The phenomenon that is causing wind danger by the passage of a VIRM intercity train does not occur by the passage of a freight train. The expansion wave behind the freight train shows higher wind velocities than the expansion wave behind the VIRM intercity train. However, the vortices behind the freight train differ in shape and are less sensitive to pressure differences caused by the surrounding air. This is illustrated in figure 5.3. The black lines in the figure show the approximate track and direction of the vortices and the red arrows indicate the direction and magnitude of the oscillation due to pressure differences aside of the vortices.
5.3 Horizontal cross section including the expansion wave in path-lines as the trains run through the open air

Helical shaped vortices without recirculation zone emerge behind the VIRM intercity train, whereas standing vortices emerge behind the freight train. Wind flow with higher velocities is seen in the standing vortices. However, these vortices do not oscillate as easy as the helical vortices. Note that the running speed of the freight train is much lower in comparison to the running speed of the VIRM intercity train (27.8 m/s and 38.9 m/s, respectively). Despite the difference in running speed, the wind velocity inside the vortices of the freight train is much higher. It is expected that the difference in wind velocity inside the vortices will be even higher if both trains are running with the same speed.

5.4 Strengths and Limitations of this Study

The strengths and limitations of this study can be summarized as follows, starting with the limitations:

- Due to the large computational demand of the CFD simulations only two cases have been studied.

- Due to limited computing capacity, the simulations have been performed using an unsteady RANS calculation method with which turbulence is averaged. LES could provide different and even better results.
- The platform geometry in the case study was highly simplified. Objects that could affect the wind flow, such as information boards or kiosks, have not been taken into account.

- The research criteria should be considered with caution, since different assumptions have been made for the determination of the values that mark the boundaries of the comfort and danger criteria.

Despite the limitations, the following beneficial aspects are considered in this study:

- By the author’s knowledge, no study involving CFD as a tool to analyze the wind flow at a platform generated by the passage of a train has been done before which makes this study the first in its kind. Hopefully more will follow.

- An elaborate validation study shows that it is possible to generate a realistic wind flow when using the sliding-mesh method in combination with RANS.

- The derived results from the case study reveal new insights, such as the change in vortex development behind differently shaped trains.

5.5 Recommendations for Further Research

Not everything has been investigated into detail and some assumptions have been made due to time constraints. Therefore, the following recommendations can be made for further research:

- Perform similar simulations for a more relevant country. This study focused on Dutch train and platform guidelines. However, in Germany as an example, trains are allowed to travel with speeds up to 300 km/h.

- Study the exact influence of the cross-sectional area, the aerodynamic shape, and the running speed of the train on the piston effect by performing different simulations taking into account different geometries and moving speeds.

- Perform simulations using the LES calculation method for more accurate results.
6 Conclusions

The main research objective in this study is to analyze the effect of a passing train on the wind comfort at an underground railroad platform. CFD is used for simulating a moving train along an underground platform. The most critical situations that are likely to occur in the Netherlands have been studied in two cases. Based on the results derived from the two cases, the following conclusions can be made:

- The piston effect, which characterizes the wind flow inside tunnels, does not directly cause dangerous wind gusts (wind flow > 12 m/s) at this platform, due to the low blockage ratio at the site of the platform.

- A VIRM Intercity train, as is modeled in this study, generates two helical vortices in the expansion zone behind the train, which start oscillating as soon as the train reaches the platform. This oscillation is caused by the pressure difference at the platform and results in wind a short dangerous wind gust at the entrance of the platform.

- A freight train, as is modeled in this study, generates two standing vortices in the expansion zone behind the last container. The wind flow inside the vortices increases during the period the train runs through the tunnel. However, this wave stays straight behind the train and does not oscillate towards the platform. Therefore, no dangerous wind velocities are noticed during the period a freight train passes an underground railroad platform.

- The flow that is generated in both cases results in wind discomfort (wind flow 5 -12 m/s) at the investigated platform. This makes it difficult to read a newspaper during the period a train passes without foreclosure of the wind flow.

- In both cases, the expansion wave is larger than the compression wave. However, in general the compression wave causes higher wind velocities at the platform aside from the train.
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Appendix A

A1 - Validation study, stationary domain
A2 - Validation study, moving domain
A3 - Case study, stationary domain
A4 - Case study, moving domain - VIRM intercity train
A5 - Case study, moving domain - freight train
A1 - Validation study, Stationary domain
Dimensions GABIT model, 11-2012
Train RIG moving model facility Derby, tunnel dimensions
University of Birmingham
scale 1/100

Section A - Field

Section B - Tunnel
A2 - Validation study, Moving domain

Dimensions GAMBIT Model, 11-2012
Train RIG moving model facility Derby, German ICE-2 train
University of Birmingham
scale 1/100

Section A - Train

Cross Section - Train
A3 - Case study, Field domain

Dimensions GAMBIT model, 03-2013
scale 1/100

Section A

Section B

Section C
A4 - Case study, Moving domain - intercity

Dimensions GAMBIT model, 03-2013
Dutch intercity train type "VIRM"
scale 1/100

scale 1/50
A5 - Case study, Moving domain - Freight train

Dimensions GAMBIT model, 03-2013
Freight train: TRAXX 2803 locomotive + 6 * 45 ft freight container incl. carriage
scale 1/100

side view locomotive

side view freight carriage incl. container

scale 1/300