Investigating the effect of train speed and ground clearance on Aerodynamics of a Simplified High-Speed Train

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Abstract

The present paper investigated the effect of train speed and ground clearance on aerodynamic forces on a simplified high-speed train. For this purpose, 20 different cases, including trains with five different speeds and four varied ground clearances were numerically simulated. The results showed that increasing the train speed has a dual effect on increasing the vertical upward lift forces. Non-dimensional ground clearances above than 0.22 at speeds above 250 km/h, results in the upward lift forces dramatically and leaded to instability of the train. At ground clearances below than 0.092, increasing the speed increased the downward force, enhancing the stability of the train. Moreover, further analyzing the ground clearance effect demonstrated that in ground clearance value of about 0.048 lift force has an approximately constant value at different train speeds. The air velocity profiles under the train revealed a dimensionless rise with increasing ground clearance except at the front of the train. This increase was precisely apparent at speeds of 350 km/h and resulted in a 29% increase in some sections below the train. This rise in speed can disrupt the balance of passengers and pedestrians, and workers around the train.

Keywords: Aerodynamic forces; Ground clearance; High-speed train; Stability; fluid flow.

1. Introduction
One of the imperative design items is the aerodynamic force exerted on the train body due to the change of flow lines. The flow around a train would generally undergo a large-scale separation, resulting in large aerodynamic forces and a large amount of instability [1-4]. In the prevailing era, several designers and developers in this industry are focused on simulating and creating an optimal design to deal with aerodynamic flows. Due to the complicated geometry and the existence of turbulent flow structures in different dimensions, the flow around the train has numerous complexities, including high curvature of the flow near the wall, non-isotropic turbulent flow, and velocity and pressure fluctuations in air collision with the car wall [5-8]. This makes numerical simulation challenging with most turbulence models. Numerous numerical studies have been performed in this field.

In [9], utilizing the Large Eddy Simulation (LES) method, simulated reverse wind flow in front of a simple high-speed train model, considering different profiles of train heads at a Reynolds number of $3 \times 10^5$. In this 3D analysis, the effects of changes in train head shapes on some aerodynamic parameters such as drag and lift forces and the field of pressure and speed were investigated. In [10] applied experimental and numerical methods to simulate and analyze the vortex flow and the boundary layer around the head and end of a high-speed train.

In [11] utilized the LES method to simulate the air flow passing through a stationary cargo train. In this study, in order to analyze aerodynamic performance, a 1:20 ratio model of a high-speed train with two wagons and a Reynolds number of $2 \times 10^5$ is simulated. Transverse loads on wagons, drag and lift forces are the most important findings of this research. In [9] used the LES method to simulate the air pressure around a high-speed train. In this investigation, a simplified model with a ratio of 1:20 of a high-speed train with five wagons was considered, and the vortex flow, boundary layer, and air velocity around the train were analyzed as the most substantial parameters.

Johnson et al. [12] deployed the PIV laboratory method in a water towing tank to evaluate the flow velocity profile under the train in three modes with cavities and bogies on the train floor and without them for a 1:50 scale high-speed general train
model. In their study, the Reynolds number of the train is considered \(0.24 \times 10^6\). In [13] compared the numerical method (RANS) and laboratory results from a wind tunnel on the pressure exerted on a high-speed train. In [14] examined the flying ballast phenomenon for a high-speed train at 350 km / h with real dimensions. Their study aimed to analyze the effects of the height of the ballast level, the stone shape in the upper layer of the ballast, and the ballast bed’s compaction on the problem. In [15] utilized the numerical method FFD to assess the performance of aerodynamic characteristics and their optimization, including drag and lift forces on a high-speed train. Air flow in this study was considered three-dimensional, incompressible, stable, and viscous. In [16] simulated and analyzed the aerodynamic performance of a high-speed train using Detached Eddy Simulation (DES) of the computational fluid dynamics and fluent software. They investigated the effects of both stationary and moving ground in their numerical setup. They concluded that under the moving ground conditions, the total drag of the train is higher than under the stationary ground situation.

In [17] evaluated the Unsteady Reynolds-Averaged Navier-Stokes (URANS), the Scale-Adaptive Simulation (SAS) and the DES turbulence models to simulate the flow around the Inter-City-Express 3 (ICE3) high-speed train and investigated the performance of each of these methods and their differences. They concluded that the computational cost of SAS and DES models is 10 to 20 times greater than the URANS method. Nonetheless, they demonstrated that the unsteady k-\(\omega\) SST model has a remarkable ability to estimate the aerodynamic coefficients of lift and drag. Hence, they suggested that this method be utilized instead of costly methods in researches that focus on lift and drag coefficients. In [18] conducted a comparison between a stationary train and a moving train with and without a windbreak wall under the cross-wind effect using numerical simulations. In that survey, they examined the pressure distribution, speed and forces applied on the high-speed train. In another study, [19] numerically analyzed the aerodynamic characteristics of high-speed trains with different nose length. They assessed about the effect of the train nose length on the drag and lift forces applied on the tail vehicle. They
revealed that lift force of the head car is stronger than the effect on other cars, and when the length of the train nose increases, the $C_d$ value of the tail car decreases by 30.53% and the $C_l$ value of the head car increases by 87.98%.

In [20] analyzed cross-wind flows on high-speed trains in two-track rails with porous protection. The simulation method utilized was the Lattice-Boltzmann method. In [21] performed a numerical and experimental methods to evaluate the coefficients of aerodynamic forces of rail vehicles on a hill with a specific geometry. Despite a somewhat considerable number of experimental and numerical studies performed on aerodynamic forces on high-speed trains, few studies have been conducted to determine and assess the distance from the train’s floor to the ground (ground clearance). The mere study to determine the effect of ground clearance on aerodynamic forces is the work of [22, 23]. In the mentioned study, due to the use of the IDDES method (and consequently high computational cost), the speed of a high-speed train was considered 50 km / h. However, the effect of different train speeds on aerodynamic forces has not been completely investigated in their study.

The present survey will investigate the effect of the train’s ground clearance and speed in the simplified ICE3 high-speed train model on aerodynamic coefficients. Meanwhile, it is notable that this type of train is currently used in various parts of Europe and China. Given the fact that the speed of ICE 3 high-speed trains is in the range of 200 to 350 km / h, in this study, five speeds of 50, 150, 200, 250, and 350 km / h and four ground clearances of 0.048, 0.092, 0.136 and 0.22 are taken into consideration.

2. Method

2.1 Turbulence Modelling

Reynolds-Averaged Navier-Stokes (RANS) are typical models of turbulent problems. In this model, variables are discretized in two sections of fluctuating and
mean components. Putting variables in Navier-Stokes equations and averaging it, will lead to averaged Navier-Stokes equations.

By keeping a time derivative terms of the velocity, we will have the equation of ensemble of turbulent flow states of unsteady RANS model. Mean velocity and pressure represent as mentioned below [24, 25]:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} (\nu \frac{\partial \bar{u}_i}{\partial x_j}) + \frac{1}{\rho} \frac{\partial \tau_{i,j}}{\partial x_i}$$

In the above equations, $\tau_{ij} = \bar{u}_i \bar{u}_j$ is the Reynolds stress tensor, which is not able to be figured out in terms of mean flow variables. However, some turbulent flow models have been developed to better predict it. Most of them use some more equations of estimating Reynolds stress in terms of mean flow gradient by varying turbulent viscosity, according to local turbulent time, velocity and length scales. Some auxiliary equations of kinetic energy per unit mass ($k$) and equation of turbulent dissipation ($\varepsilon$) must be solved coupled with this equations. However, to the best of the authors' knowledge, it is possible to use the $k-\omega$ SST shear stress transfer model to match the turbulent model with the desired geometry and conditions. This model has shown its fidelity and performance in similar problems of surface pressure analysis on high-speed trains [26, 27]. Classical $k - \varepsilon$ model is better for predicting free flow out of the boundary layer and classical $k - \omega$ is known as the best model for predicting flow behavior near the wall and boundary layer. To benefit the accuracy and reliability of both, we have to synthesize $k - \varepsilon$ and classical $k - \omega$ models. The answer comes in the form of $k - \omega SST$. This model is one of the best models of URANS predicting large-scale separation phenomena and recommended model of wake flow capture in high-speed trains [28].

2.2 Train Geometry
The model of train and its geometry have been in previous works [3, 29-32] (see figure 1). In this study, a simplified 1:10 model of the Bahn ICE3 high-speed train, is used, which includes four cabins whose length (L), width (W), and height (H) are equal to 10.14, 29 and 0.36 meter respectively. Recent studies in high-speed trains have shown that the effect of wheels on aerodynamic forces can be ignored [33, 34]. In this research, four dimensionless distances of train floor to the ground, \( h/H \) of 0.22, 0.136, 0.092, 0.048, have been considered to evaluate the impact of ground clearance on aerodynamic forces.

Figure 1: Trimetric views, front and side of the ICE3 express train.

2.3 Computational Domain and Boundary Conditions

The computational domain considered is a rectangular space with dimensions of 97 W as length, 20 W as height, and 40 W as width. It is taken wide enough to ensure that boundary conditions would not affect the flow structures around the train. Figure 2 shows the geometry and boundary conditions of the solution domain.

The upper boundary and the lateral boundaries are considered symmetric [35]. To simulate the relative velocity between the train and the ground, the ground boundary condition is considered as a wall with a velocity of free flow (moving ground and fixed train condition). The front nose position of the train is located at a distance of 10W from the entrance boundary of the domain, as illustrated in figure 2. The boundary condition at the output is set as constant zero static pressure. The distance from the end of the train to the output border is 52 W, which is intended to investigate the vortex structures behind the train and ignore the effect of the pressure boundary condition at the output.

The input boundary condition is uniform velocity throughout the entrance surface. The characteristic length (train height) 0.294 m, air density (\( \rho \)) 1.184 kg / m\(^3\) and viscosity 1.855 \( \times 10^{-5} \) kg/m.s are considered in all cases. A turbulence intensity of 1% was assumed at the inlet to simulate free stream condition with low turbulence.
inside the experimental wind tunnel set up. These specifications are mainly intended to confirm in accordance with previous experimental data.

![Figure 2: Solution domain and boundary conditions.](image)

### 2.4 Meshing Strategy

The domain mesh is generated using a predominately Cartesian cut-cell approach. This approach generates more mesh concentration near the body and wake region for more detailed predictions and lowers smoothly as it goes away from the body and ground level. The computational mesh has been generated using GridPro software and imported into OpenFOAM open-source code. Due to the large gradients in the two areas next to the train and the ground clearance, these areas have been subdivided using two separate blocks.

The use of a micro mesh requires the application of an advanced computing system, and it will certainly will be costly. To study the independence of the solution from the network, at first should choose a variable such as (speed, pressure or drag coefficient) and study it in the various numbers of networks in order to achieve the optimal result with the minimum number of networks. In other words, in the first step, the simulation is done with a relatively light network and the desired variables are extracted. Considering that the goal is to choose the most optimal size for gridding, the number of grids should be selected to provide the simulation results so that the computational cost does not increase.

The cells have grown in proportions less than 0.1 from the train’s surface to the outermost regions. Due to the use of unsteady URANS turbulence models as well as the use of the wall function near solid boundaries in this section, the cells near the buckets are arranged so that $y^+$ value should be considered around 30 to 100 in different areas, especially in the area of the train tip, which is a stagnation point. Figure 3 shows the grid on the surface and near the ground.
In this simulation, three different refined grids, coarse, medium, and fine, are assessed, focusing on keeping similar compression factors between meshes. These three grids are considered to achieve better and higher accuracy and represent the above-mentioned critical regions of grid independency.

To consider all main flow features, the refinement regions dimensions were evaluated according to preliminary simulations.

Figure 3: Surface meshing system.

3. Results

The numerical solver utilized in the current paper is the open source code OpenFOAM 7.0. In order to study velocity and pressure and determine the vortices and turbulences around and behind the train, more precisely, the unsteady URANS \( k - \omega \) SST model is employed. Time step is considered so that the CFL number to be less than 0.9. In this way, the time step in each step is calculated, which is estimated to be approximately equal to \( \Delta t = 10^{-4} \) s for most time steps. So, wall-functions based on the \( k - \omega \) SST implemented in OpenFOAM were utilized to model the near-wall behavior of turbulence. Simulations has been carried out for all cases using the incompressible, transient PimpleFOAM solver.

3.1 Validation

The approximate time for convergence in each time-step for the second computing mesh is about 50 to 90 seconds for each processor with a processing power of 3.7 MHz. As unsteady URANS models are used in this simulation, we need to ensure sufficient solution time to accurately estimate average flow variables such as average velocity field and pressure. Otherwise, the average flow fields may not be estimated correctly. For this purpose, Figure 4 shows the value of the total drag coefficient on the whole train from zero to 8 seconds. As it can be seen, 5 seconds is sufficient for the convergence of the average flow quantities. All average committees in this paper are reported from 5 to 15 seconds to ensure the accuracy
of the averaging operation. It was observed that averaging at times longer than 15 seconds did not make a considerable difference in the results of the velocity and pressure fields.

Figure 4: Total drag coefficient on the train from the beginning of the solution up to 7 seconds.

In order to investigate the solution independence from the computational grid, 3 different computational grid sizes have been used for the unsteady $k - \omega$ SST model. The meshing strategy described is the same for all three grids, but the number of computational cells is 4 million, 6.2 million, and 9 million cells for Grid 1, Grid 2 and Grid 3, respectively.

Figure 5-a shows the horizontal velocity profile at a distance below the train to the ground at $x = 0.08$ m, and Figure 5-b shows the vertical velocity of the air flow in the area behind the train at $x = 10$ m. These speed profiles are drawn for the train speed of 250 km / h as well as the ground distance from the train floor equal to $h_1$. For the rest of the cases, the solution grid independence, has been examined.

As can be seen in Figure 5, the results of the average horizontal and vertical velocities for the medium and fine grids are significantly close to each other at different sections, so it can be concluded that further thinning of the grid will not affect the solution.

a) Horizontal velocity below train at $x=0.08$ m b) Vertical velocity behind the train at $x=10$ m

Figure 5: Effect of mesh grid cell number on velocity profile in various sections.

As illustrated in Figure 6, the friction component of the drag coefficient calculated by the coarse mesh is 45% less than the drag coefficient in the fine mesh, whereas the difference between the medium and fine mesh is less than 4%. Furthermore, for the pressure component of the lift coefficient, the difference between coarse and fine mesh is about 30%, and for medium and fine meshes is roughly 5%. Considering all the comparisons mentioned above and other comparisons made for
all speeds (It is not presented here for brevity), most of the simulations in this paper utilize a 6.2 M cell mesh.

Figure 6: Comparison of friction and pressure components of lift coefficient determined by different networks.

Figure 7 shows a comparison of the simulation pressure coefficient of the present work with the experimental data obtained by [33] as well as the numerical simulation of [3].

In [3] studied the geometry of ICE3. They used the LES and RANS hybrid turbulence methods using the IDDES (combined DDES model and the LES wall model). Using nearly 29 million computational cells and a huge computational cost, [3] were able to study the flow around the train as well as the forces on the train. In [36] used the wind tunnel to study the underbody velocity profile of the ICE3 train without the effect of lateral winds, but in their study, the Reynolds number is considered to be $1.65 \times 10^6$, which is somewhat different to the Reynolds number used in this study. Therefore, experimental data are slightly different from the simulations of the present study and [3]. However, the pressure coefficient along the train is qualitatively in line with the laboratory results.

Figure 7: Comparison of pressure coefficient of present work with laboratory data [33] and numerical simulation by IDDES method [3]

3.2 Aerodynamics Coefficients

Figure 8 illustrates the friction and pressure components of the drag (Figure 8a) and lift (Figure 8b) aerodynamic coefficients for various train speeds and for four different ground clearances. In all diagrams related to drag coefficients, it can be easily observed that the contribution of the friction component to the pressure component is multiplied because of the aerodynamic shapes of the train head and
the high train length. As observed in the lift coefficient diagrams at all ground clearances, the drag coefficients decrease as the train speed rises. This reduction functions so that the deceleration is more significant at lower speeds (50 and 150 km / h), and as we move towards higher speeds, this deceleration reduces as the drag coefficient decreases. In a way, particularly in the short ground clearances (h2 and h3), the values of drag coefficients remain constant. Thus, the speed of 250 km / h can be considered a critical speed to retain the drag coefficient constant, given the curvature of the graph and also since the difference between the total drag coefficient at the last two speeds is less than 5%.

Another striking point is that at the speed of 50 km / h and a distance of h0, the maximum amount of drag occurs among all cases, and its value equals 0.421. As the ground clearance decreases at this speed, the $C_d$ gradually decreases to 0.385 at h3, which is equivalent to a reduction of 8.6%. While, at high speeds, the effect of ground clearance on the drag coefficient is highly inconsequential. For instance, at a speed of 350 km / h and in case h0, the value of $C_d$ is 0.267, and for case h3, its value is equal to 0.262, implying a slight variation of 1.8 percent. The reason for this can be sought in Figure 9a, where the effect of pressure and frictional forces on the drag coefficient at different ground clearance remains nearly constant.

The ratio of different components of the lift coefficient is opposite to the drag coefficient (Figure 8b). As demonstrated in Figure 8, the frictional forces produce a force in the positive direction of the vertical axis (positive lift coefficient), deteriorating the train stability. In contrast, the pressure components of the lift forces, which are several times greater than the frictional component, exert a downward force that enhances the stability of the train.

A quite significant point was observed in the study of the effect of the train’s ground clearance on train stability. As shown in Figures 8 at short distances (h2 and h3) with increasing train speed, the lift coefficient gradually rises, and this rise continues up to 250 km / h. Next, as the flow velocity under the train increases at distances h2 and h3, and the pressure below the train decreases as a result vertical forces in the opposite direction of the vertical axis (towards the ground) increases.
Consequently, the lift force gets more negative, assisting in stabilizing the train as it moves. Thus, increasing the train speed up to 350 km / h at these two distances will not raise the instability of the train. Nevertheless, according to the lift coefficient diagrams in two cases, h1 and h0, it is observed that the lift force rises if the train speeds up. However, in case h1, the lift coefficient appears to remain around -0.04, while in the case of h0, with increasing speed, it can be seen a significant increase in vertical forces upwards, so that at a speed of 350 km / h \( C_L \) reaches -0.003. Therefore, given the shape of the curve and the value of \( C_L \) (Figure 8b), it seems not to be in the stable range. This issue can be quite hazardous when the wind blows or passes through different tunnels. Besides the points mentioned above, through comparing the lift coefficients at different distances (Figure 8b), it is inferred that as the ground clearance rises, the total lift coefficient decreases gradually. For example, at a speed of 50 km / h for the distance h3 (as the minimum ground clearance) \( C_L \) is equal to -0.08, and for the case h0 is equal to -0.0154. Also, at 350 km / h, the \( C_L \) coefficient for h3 and h0 bags is -0.058 and -0.003, respectively.

In general, from the previously mentioned issues, it can be concluded that at a distance of h0, the drag coefficient does not differ much from other cases (maximum 8.6%). Despite this, through examining the lift coefficient, it appears that the train gradually loses its stability with increasing its speed, so the use of this distance is completely ruled out. The reason can be attributed to the high flow rate of air (compared to h2 and h3) under the train, which generates a powerful upward lift force. For the h1 case, the total lift coefficient is quite desirable at low speeds and the vertical forces are completely downward. However, with increasing speed to 250 km / h, the vertical upward forces increase significantly, and the lift coefficient decreases to -0.04. Therefore, applying this distance for high speeds, especially in the presence of cross-winds and tunnels, and considering other parts in the lower part and over the train necessitates further investigation. The h2 and h3 cases possess a reliable lift coefficient for all speeds and will not get unstable as the speed rises in the given range.
Figure 8: Friction and pressure components of a) (left column) drag coefficients and b) lift (right column) for ground clearance and different train velocities.

Figure 9(a) demonstrates the ratio of the friction component to the pressure component of the drag coefficient, and Figure 9(b) illustrates the ratio of the pressure component to the friction of the lift coefficient at different velocities and ground clearances. As illustrated in Figure 9a, the pressure and frictional forces ratio increase slightly with decreasing the ground clearance (at most speeds). Nevertheless, not all ratios in different distances and speeds change drastically and almost remain in the range of 4.5 to 5.7 times. Perhaps, since the drag coefficient is highly affected by the frictional forces on the train body, the speed and ground clearance will not significantly affect the drag coefficient. Undoubtedly, the length of the body and the area of the body will have a greater effect on the frictional forces and, consequently, the drag coefficient. Figure 9b exhibits the ratio of the pressure component to the friction of the lift coefficient at different speeds and ground clearance. As presented in Figure 9, frictional forces slightly affect the lift coefficient as opposed to pressure forces. As the ground clearance rises, the flow velocity profile under the train flattens, and its diffuser effect decreases (Figure 10), so the pressure under the train decreases less. Hence, the effect of the difference in pressure forces at the top and bottom of the train is reduced, and therefore the effect of the pressure component of the lift coefficient decreases. As the ground clearance decreases (in cases h1 and h2), the ratio of pressure to friction forces fluctuates in the range of 19 to 32, depending on the flow velocity. This is the overcoming of high and low pressure differences of the train over the viscous forces at different speeds. In the h3 case, for different speeds, this ratio is nearly constant and in the range of 34 to 41, implying the complete dominance of the pressure forces applied to the train over the frictional forces.

Figure 9: (a) the ratio of the friction component to the pressure component of the drag coefficient (b) the ratio of the pressure component to the friction coefficient of the lift
3.3 Velocity profiles under the train

Figure 10 illustrates the dimensionless horizontal velocity profile by the train speed in terms of the ground clearance, which is non-dimensional utilizing the height h0 for all ground clearances, and also for three train speeds 50, 250, and 350 in 3 specified cross-sections (1 (left column), 4 (middle column) and 6 (right column)). In this figure, in order to maintain the brevity and also due to the high similarity of the dimensionless velocity profiles at various speeds, only three velocities have been shown. Section 1 is located just below the front panel of the train. The collision of the air flow with this panel causes the flow to return in this area due to the negative flow velocity. In section 1, the negative dimensionless velocity for different ground clearances is nearly 0.2 (left column, Figure 10).

Another point to be considered in section 1 is that as the ground clearance decreases, the maximum speed under the train increases. Increasing the speed under the train in this area has reduced the pressure under the train. As a result, the resultant of pressure forces increases in the vertical direction downwards, which its effect on increasing the lift coefficient downwards by decreasing the distance was observed in Figure 10. Passing through the front panel of the train, the velocity profile becomes irreversible, and as can be seen in the two sections 4 and 6, with increasing the ground clearance, the dimensionless horizontal velocity profile is irreversible and gradually becomes more expansive.

**Figure 10:** Non-dimensional horizontal flow velocity profile under the train in three sections 1 (left column), 4 (middle column) and 6 (right column) and for speeds (a) 50 km/h, (b) 200 km/h And (c) 350 km/h

Figure 11 illustrates the dimensionless velocity profile of the flow under the train for cases h0 to h4 at different velocities and in 6 different sections. The difference between this figure and Figure 10 is in their non-dimensionalization ways. In Figure 10, all ground clearance heights are made dimensionless using h0, while in Fig 11, non-dimensionalization is made by their own clearance height.
As shown in Figure 11, the three sections 1, 2 and 3 are related to the head of the train as section 1 is located under the front panel of the train. In the first three sections, the dimensionless speed profiles are very similar for different speeds. The most significant difference in these profiles is related to the speed of 350 km / h, which in all cases, the maximum speed is reported to be slightly higher than other speeds. Another striking point that can be observed in the velocity profiles is that as the ground clearance decreases, at all speeds, the maximum speed rises and the location of this maximum speed tends toward the ground. For example, the maximum values of dimensionless velocity in section 2 increase from 1.2 in case h0 to more than 1.4 in case h3. Another notable point is that in sections 1 and 2, which are related to the front panel of the train, a negative velocity occurs that indicates the flow reversal, which is due to the effect of the panel. As shown in Section 2, as the ground clearance decreases, the value of the negative dimensionless velocity decreases from -0.23 in the case h0 to -0.11 in case h3.

In the middle of the train (section 4), the variation in dimensionless velocities increases with increasing velocity and especially in the ground clearance. In the case h0, the average dimensionless speed passing under the train is 50 km / h compared to the train speed, and for speeds of 150, 200, 250, and 350 km / h, it is 4%, 4.4%, 5.5%, and 12% higher, respectively. While for the h3 case, the maximum difference of the average dimensionless speeds between the two speeds of 50 and 350 km / h is 4.3%.

Toward the end of the train (sections 5 and 6), the difference in speed profiles at different train speeds gradually increases. This is especially evident in the h0 and h1 cases. At the end of the train (section 6) at a speed of 350 km / h, the average dimensionless speed passing under the train in cases h0, h1, h2, and h3 is 29%, 25%, 24%, and 13% higher than the train speed of 50 km / h, respectively. Increasing the induced speed under the train can upset the balance of pedestrians and railway workers around the tracks. Plus, Ma et al. [36] showed that increasing the flow speed under the train expands the percentage of passengers who get on or
off the train. Based on Figure 10 by increasing the train speed to 350 km / h, the maximum speed increases from 8 to 29% in all sections.

**Figure 11** Non-dimensional horizontal flow velocity ($u/u_i$) profile under the train in all cases versus Non-dimensional ground clearance height ($h/h_i$)

Figure 12 reveals the air mass flow rate ratio at the beginning of the train (section 3) to the transient mass flow rate at the end of the train (section 5) $\frac{m_5}{m_3}$. Reducing the ground clearance affects the flow velocity profile under the train and the air flow around the train. This lower ratio indicates that a higher percentage of air under the train is inclined to both sides of the train and exits on both sides, as shown in Figure 12. Comparing these ratios at different ground clearances decreases as the ground clearance is reduced. Two significant reasons for this are the reduction of the cross-section of the passing air and the reduction of the speed at shorter distances. The only exceptions for this section are for speeds of 50 km / h and case h3, where the flow rate has increased by 3%. In [3] Obtained similar results. Figure 12 shows that as the train speed increases, firstly, this speed ratio increases. For example, at h0 for 50 km / h, this ratio is 0.68. At 250 km / h, this ratio is 0.91, implying that a small percentage of the air under the train inclines to both sides. So less side flow is generated. This can be attributed to the air being drawn around the train to the mainline of the flow below the train at higher speeds.

**Figure 12:** a) Determination of sections 3 and 5 to measure the volumetric flow rate b) Schematic image of the side flow of the flow under the train Different c) Mass flow rate ratio in two sections 3 and 5 $\frac{m_5}{m_3}$.

The results reveal that although the most negative lift force is at H3, the maximum air flow velocity under the train increases substantially compared to other distances. Former relevant studies have demonstrated that this increase in speed can upset the balance of passengers as well as pedestrians and workers around the train. Therefore, it seems that the distance h3 is also problematic in this regard.
Hence, the best distance seems to be h2 considering all conditions. (For further research, it is necessary to consider the cross-wind effects, more precise geometry).

Figure 13 displays the shear stress contour generated on the train floor and time-averaged trace lines in the train head area for different cases. In front of the train, there is a separation zone caused by the panel installed in the front of the train. As the ground clearance decreases, the length of this bubble-like region relative to case h0 decreases by 32 and 58 percent, respectively, which are named l2 and l3 in Figure 13, respectively. Due to this separation bubble, the maximum dimensionless velocity increases below this area (Figure 11).

Figure 13 indicates that as the train speed increases, the length of the separation zone does not undergo changes that much, and this zone is affected most by the ground clearance. Despite this, as the train speed rises, the shear stress created on the train floor increases.

One of the substantial ratios that are considered in the study of air flow around the train is the amount of air that deviates from under the train to both sides of the train. By examining the mass flow of air in the two initial and final sections of the train and obtaining their ratio, it is determined how much air has come out from under the train to both sides. As can be seen in the figures, in this regard, longer distances (h0) have the highest value, i.e., the flow rates of sections 5 and 3 are closer to each other. In other words, it has the least amount of exhaust air from around the train. However, as shown in Figure 13, at speeds above 250 km/h, the air outlet at h2 is approximately 15% higher than at h0.

**Figure 13**: Shear stress and time-averaged trace lines in the front area of the train floor

Examining the shear stress and the separation bubble zone under the train, it is concluded that reducing the ground clearance reduces the size of this bubble zone. Moreover, it is observed that with increasing speed, the size of this separation zone is not affected much, although the amount of shear stress increases significantly,
which should be taken into account to determine the alloy utilized (in terms of strength) in the nose area of the train.

4. Conclusion

In this research, the effect of high-speed train speed and train ground clearance for five train speeds of 50 km / h, 150, 200, 250, and 350 km / h, and also ground clearances of 0.048, 0.092, 0.136, and 0.22 times the train’s height is numerically simulated utilizing the Unsteady $k-\omega$ SST turbulence model. Comparing the results acquired by the URANS method with laboratory results and high order methods demonstrates that the $k-\omega$ SST model holds a high capacity for predicting lift and drag forces. The train under consideration in this paper is the ICE3 train. In this paper, to assess the stability and balance of trains and passengers, the aerodynamic coefficients of lift and drag as well as air flow velocity profiles under the train are investigated.

By examining and making comparisons at different speeds, it was inferred that at all distances, regarding drag forces, the speed of 250 km / h can be considered as the critical speed to maintain the drag coefficient constant, considering the curvature of the graph and also since the difference between the total drag coefficient in the last two speeds is less than 5%. It appears that in terms of lift forces, the distance $h1$ is a limit distance. This implies that no matter how much the train speed increases up to this distance, the negative lift coefficient does not undergo tangible changes. Having said that, as this distance expands further, by increasing the speed (or possibly the effect of cross-winds or crossing the tunnel), the lift coefficients will rise and can cause the train to lift off the rails. This information can determine the train speed range for various ground clearances.

It was discovered that with increasing velocity at different distances, the contribution of pressure and friction components in the drag coefficient did not change that much. In contrast, by reducing the ground clearance at different speeds, the ratio of frictional forces to pressure forces increases up to 4.5 times. The profile
of air flow velocities under the train demonstrates an increase in dimensionless speed as the ground clearance rises, except at the front area of the train, at different speeds. This increase is specifically evident at speeds of 350 km / h and leads to a 29% increase in some sections under the train. This increase in speed can upset the balance of passengers and pedestrians, and workers around the train.

References


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Figure 1: Trimetric views, front and side of the ICE3 express train
Figure 2: Solution domain and boundary conditions.

Figure 3: Surface meshing system.

Figure 4: Total drag coefficient on the train from the beginning of the solution up to 7 seconds.
a) Horizontal velocity below train at x=0.08 m  b) Vertical velocity behind the train at x=10 m

Figure 5: Effect of mesh grid cell number on velocity profile in various sections.

Figure 6: Comparison of friction and pressure components of lift coefficient determined by different networks.
Figure 7: Comparison of pressure coefficient of present work with laboratory data [33] and numerical simulation by IDDES method [3]
Figure 8: Friction and pressure components of a) (left column) drag coefficients and b) lift (right column) for ground clearance and different train velocities.

Figure 9: (a) the ratio of the friction component to the pressure component of the drag coefficient (b) the ratio of the pressure component to the friction coefficient of the lift
Figure 10: Non-dimensional horizontal flow velocity profile under the train in three sections 1 (left column), 4 (middle column) and 6 (right column) and for speeds (a) 50 km/h, (b) 200 km/h and (c) 350 km/h.
Figure 11: Non-dimensional horizontal flow velocity \((u/u_{in})\) profile under the train in all cases versus Non-dimensional ground clearance height \((h/h_i)\).

Figure 12: Schematic image of the side flow of the flow under the train Different in \(\frac{m_5}{m_3}\).
Figure 13: Shear stress and time-averaged trace lines in the front area of the train floor