Analysis of the action of aerodynamic forces in case a passenger train

S Arsene, I Sebeșan
Polytechnic University of Bucharest, Department of Railway Rolling Stock, District 6, Splaiul Independenței, No. 313, Bucharest, Romania
E-mail: sorinarsene@gmail.com

Abstract. The growing need for mobility, cumulative with the technological development of the last decades, represents the elements that led to achieving and increasing travel speeds for the rail transport system. Currently, for classical trains formed from locomotives and wagons, the maximum travel speeds admitted into circulation are between 200 km/h and 250 km/h. Regarding the trains consisting of the multiple high-speed electric frames, they have values of the maximum permissible speeds in the range 300 km/h and 450 km/h. For obtaining such sizes of the travel speeds, it would not have been possible without having previously studied the aerodynamic phenomena much more closely which occur during the movement of vehicles. The present paper is in the same order with the studies they are pursuing analyzing the influence of aerodynamic forces acting on a train. In this regard, we considered the case of a classic passenger train made up of a motor vehicle (locomotive) and many towed vehicles (wagons). To be able to observe, how aerodynamic forces acting and what are their values, will be used a simulation program on the flow of air. The importance of determining the values and distribution of aerodynamic forces stems from the fact that they directly affect the energy consumed while traveling and in some cases even the vehicle safety.

1. Introduction

At increase the train running speeds, aerodynamic problems become more and more prominent and significantly influence the operational safety of trains and the amenity of passengers. [1]

With the speed-up of train, many engineering problems which have been reasonably neglected at low speeds, are being raised regarding aerodynamic noise and vibrations, impulse forces occurring as two trains intersect each other, impulse wave at the exit of tunnel, ear discomfort of passengers inside train, etc. These are of major limiting factors to the speed-up of the train system. [2]

During the movement of a train, on the railway vehicles that make up it, there are a few forces that allow it to move. The arrangement of these forces is done as follows: in the sense of the movement of the train, the traction force \( F_t(v) \) developed by the power equipment on the motor vehicles, and in the opposite direction to the movement, the sum of the resistance forces \( \sum R_i(v) \) that opposes the displacement and the braking force \( F_b(v) \) used to reduce the speed or to stop the train. In any time of the moving train, the corresponding values of these forces must (corresponding to the speed of the vehicle) to be smaller or equal to the threshold limit of the force of adhesion \( F_a(v) \) of the wheel track. Under these conditions, the equilibrium equation (1) for the forces acting on the vehicle in the longitudinal direction (the direction of travel of the train) can also be written in mathematical form according to [3-8] as follows:

\[
F_t(v) - \sum R_i(v) - F_b(v) = 0
\]
The values of the amount of resisting forces opposing movement, in situation where the vehicle would be moving in flat and alignment conditions (straight line without level deviations in vertical and transverse direction), are dependent on a series of frictions [3-8], such as: those in the axle bearings, rolling and / or slip between the wheel and the tread, with the air, of the current collector (patina, pantograph) and the contact line, etc.

To establish a mathematical relationship that can be used to calculate the values of the sum of resistant forces, it must consider many parameters that come during the movement.

A solution to this problem is given using empirical computational formulas obtained experimentally.

In the literature [3-11] the first to establish an empirical mathematical relationship by which the value of the amount of forward resisting forces was determined in the case of a railway vehicle was W.J. Davis. At present, its formula is generalized as a second-degree polynomial function (2)

\[ \sum R_i(v) = A + B \cdot v + C \cdot v^2 \]

where: \( \sum R_i(v) \) - the sum of the total rolling resistance of a railway vehicle; A - mechanical rolling resistance [N]; B - coefficient of non-aerodynamic drag resistance [N/(km/h)]; C - drag coefficient determined by aerodynamic phenomena [N/(km/h)^2]; v - vehicle speed [km/h].

The aerodynamic drag force is proportional to the square of the train running speed. [1] As a result, most of the train drag is caused by aerodynamics with the speed-up of high speed train. [12] From some experimental results of real trains, aerodynamic drag of the traditional train at the speed of 120km/h occupies 40% of total drag, trains with blunt head at the speed of 160km/h, accounts for 75%, while train at the speed of 300km/h with a 10-meters long streamlined-head takes up for 75%. [11] Aerodynamic performance is closely related to shapes of head and tail and is necessary to optimize the head and tail shape of high speed train. [2, 11-13]

2. Case study

In present, in Romanian rail passenger transport, most trains are of the classic type, consisting of a motor vehicle (locomotive) and a certain number of towed vehicles (wagons).

In the fleet of vehicles in operation at the national railway transport company in Romania (SNTFC "C.F.R. Călători" -S.A.), an important share of trains formed is with the single-deck wagons.

From the point of view of the gauge (shape) characteristics of these wagons are of several types. What is significantly different in the construction of such vehicles is that in the newer generation they have in their construction some careen (skirts, hull) that are placed in the wagon part of the wagon between the chassis and the running track.

For the analysis in this article, we considered two distinct situations: a first situation is when the train consists of an electric locomotive of the type LE 060 EA of 5100 kW (as shown in figure 1) and a number of three single-deck wagons which have no careen, of older construction (as shown in figure 2).

The second situation analyzed is when the train formed has the same type of motor vehicle and number of three single-deck wagons, with such a hull. (as shown in figure 3).

About the determination of parameter C (regarding aerodynamic resistances) in the generalized relation of Davis, in the literature [7-17] this is explained considering the forces generated by the air flow in the Cartesian coordinate system (3), as follows:

\[ C_i = 2 \cdot F_i / (S \cdot \rho \cdot v^3) \]

where: \( i \) - represents the axes of the Cartesian coordinate system Ox, Oy, Oz; S - cross section of the vehicle (m^2); \( \rho \) - air density in which the vehicle is traveling (kg/m^3);

Aerodynamic forces can be determined both experimentally by using scale models in aerodynamic tunnels or using airflow simulation programs.
From the point of view of the flow simulation in work [12], three flow regions are distinguished: the nose region around the front of the train; the boundary layer region along the length of the train (for the train side, train roof and train underbody); the wake region behind the train.

**Figure 1.** The 3D model of the LE 060 EA of 5100kW locomotive (values expressed in mm).

**Figure 2.** The 3D model of the single-deck wagon without a hull (values expressed in mm).

**Figure 3.** The 3D model of the single-deck wagon with a hull (values expressed in mm).
3. Simulation of airflow

In the airflow simulation process, we started from geometric modeling in 3D format, at a scale of 1:1, of the constructive forms of the two types of vehicles involved in the composition of each analyzed train, as seen in the figures 1, 2 and 3.

After this step, we assembled each individual train (a motor vehicle and three towed vehicles) (see figures 4 and 5).

![Figure 4](image1)

**Figure 4.** The 3D geometrical model for the first type of train analyzed – T1(values expressed in mm).

![Figure 5](image2)

**Figure 5.** The 3D geometric model for the second type of train analyzed – T2(values expressed in mm).

The airflow simulation is performed for twelve-point values of the train speed in the range of 0km/h to 200 km/h.

Coincidentally with this range, we considered twelve-point values (which have been kept constant) regarding the air flow along the train, namely 1m/s, 5m/s, 15m/s, 20m/s, 25m/s, 30m/s, 35m/s, 40m/s, 45 m/s, 50 m/s and 55 m/s.

Other input parameters used in the flow simulation were considered appropriate for the trains moving situation under normal atmospheric pressure and temperature conditions as can be seen in table 1.

| Units       | Values |
|-------------|--------|
| Pressure    | PA     | 101325 |
| Temperature | K      | 293.2  |

Table 1. Air input data.
Then, we delineate an air flow volume (see figure 6) for the two types of train analyzed, as follows:
- In the vertical direction: a plane located at the level of the running surface of rail and a second plane situated at 15 m from the first.
- In the transverse direction two symmetrical planes at 10 m from the longitudinal plane of the train are considered.
- In the longitudinal direction: we started the transverse plane of the locomotive from which we considered a plane located 100 m from it (for the rear of the train) and a second plane at 20 m (for the front of the train).

Figure 6. Volume of air delimited for flow.

In figure 7 and 8 are shows the distribution of dynamic air pressure in the longitudinal section of which train considered, resulting from simulations performed for a flow rate of 55 m/s.

Figure 7. Distribution of the dynamic pressure air to speed of 55 m/s from the first type of train analyzed.
**Figure 8.** Distribution of the dynamic pressure air to speed of 55 m/s from the second type of train analyzed.

Still at the same air velocity value (55m/s) in figure 9 and 10 are shows the pressure distribution exerted on the train surface.

**Figure 9.** The pressure exerted on the train at a speed of 55 m/s from the first type of train analyzed.

**Figure 10.** The pressure exerted on the train at a speed of 55 m/s from the second type of train analyzed.
In figures 11 and 12 is show the evolutions of the aerodynamic forces during the simulations performed for the two types of trains analyzed and taking into account the twelve values of the air flow velocities considered.

**Figure 11.** Variation of aerodynamic forces during flow simulation of air, in case of train without careen.

**Figure 12.** Variation of aerodynamic forces during flow simulation of air, in case of train with careen.
Considering the type of train being analyzed, the stabilized values resulting from the aerodynamic force simulations are shown in tables 2 and 3 for trains without careen and in tables 4 and 5 for train with careen.

**Table 2.** Stabilized values of aerodynamic forces resulting from simulation, to low speed of the train without skirt.

| Units | Values |
|-------|--------|
| V [m/s] | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| $F_a$ [N] | 7.38 | 185.62 | 745.32 | 1678.35 | 2989.29 | 4678.31 | 6732.37 |
| $F_{a,x}$ [N] | 6.38 | 161.06 | 646.77 | 1458.67 | 2599.83 | 4063.48 | 5852.28 |
| $F_{a,y}$ [N] | -0.08 | -3.07 | -11.44 | -28.12 | -48.33 | -72.08 | -115.23 |
| $F_{a,z}$ [N] | 3.71 | 92.22 | 370.22 | 829.67 | 1474.57 | 2317.21 | 3326.01 |

**Table 3.** Stabilized values of aerodynamic forces resulting from simulation, to high speed of the train without skirt.

| Units | Values |
|-------|--------|
| V [m/s] | 35 | 40 | 45 | 50 | 55 |
| $F_a$ [N] | 9180.33 | 11987.82 | 15181.78 | 18780.24 | 22721.63 |
| $F_{a,x}$ [N] | 7975.60 | 10424.03 | 13202.68 | 16329.84 | 19752.69 |
| $F_{a,y}$ [N] | -154.94 | -220.10 | -252.03 | -314.11 | -401.12 |
| $F_{a,z}$ [N] | 4543.60 | 5915.99 | 7490.82 | 9270.12 | 11222.43 |

**Table 4.** Stabilized values of aerodynamic forces resulting from simulation, to low speed of the train with skirt.

| Units | Values |
|-------|--------|
| V [m/s] | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| $F_a$ [N] | 54.38 | 172.40 | 694.03 | 1562.36 | 2774.39 | 4315.70 | 6207.04 |
| $F_{a,x}$ [N] | 5.25 | 145.40 | 585.59 | 1317.07 | 2344.69 | 3651.30 | 5248.79 |
| $F_{a,y}$ [N] | -50.23 | -8.59 | -38.87 | -86.56 | -156.19 | -117.35 | -163.54 |
| $F_{a,z}$ [N] | 20.16 | 92.23 | 370.47 | 835.95 | 1474.88 | 2297.71 | 3309.21 |

**Table 5.** Stabilized values of aerodynamic forces resulting from simulation, to high speed of the train with skirt.

| Units | Values |
|-------|--------|
| V [m/s] | 35 | 40 | 45 | 50 | 55 |
| $F_a$ [N] | 8441.06 | 10961.75 | 13997.97 | 17278.93 | 20960.80 |
| $F_{a,x}$ [N] | 7256.99 | 9284.80 | 11855.69 | 14628.63 | 17719.18 |
| $F_{a,y}$ [N] | -52.37 | -273.71 | -396.73 | -525.47 | -615.94 |
| $F_{a,z}$ [N] | 4311.02 | 5820.44 | 7431.59 | 9180.87 | 11180.63 |

Analyzing the stabilized values of the aerodynamic forces resulting from the simulation, it is found that in the case of the train with hull, lower values of these forces are obtained. This is very well
observed for the longitudinal aerodynamic forces \((F_{a,x})\) shown in the percentage reporting rate between the two types of trains, made in figure 13.

![Figure 13](image_url)

**Figure 13.** The percentage of diminishing the longitudinal aerodynamic force values for the train with hull.

### 4. Conclusions

Starting from the construction of geometric shapes of 3D models (made on a scale), for the three types of vehicles (see figures 1, 2 and 3) that are part of the two types of trains analyzed (hull and without hull), it is carried out assembly with are shown in figures 4 and 5.

Then for the two cases of the trains analyzed, it is delineated a volume to simulate which the air flow, see figure 6.

In the figures 7 and 8, it is show the longitudinal median plane of the trains, on which are willing the isolines of the dynamic pressures of air.

As expected, the front part of the train (the locomotive) bears the highest air pressure in time of movement, as can be seen in figures 9 and 10. An increase in pressure on the train is also seen around crossings from one vehicle to another, but also on equipment under the vehicle (between railway track and chassis) or at the upper level of the electric motors vehicles (electric locomotive’s), in area of the power supply system (placed on the roof).

These pressure values of air are appropriately transposed into aerodynamic forces. The distribution of aerodynamic forces in the Cartesian coordinate system it can be seen from tables 2, 3, 4 and 5. From these tables you can see how to obtain the highest values in the longitudinal direction, which correspond to aerodynamic resistances.

Another high component of the aerodynamic forces is obtained in the vertical direction. The existence of this size can be explained by the occurrence and evolution of the soil effect in the flow area, but also by the fact that between the railway track and the chassis of the vehicles there is a space of approximately 0.86 m in which the air can easily penetrate during the movement.

In the case of train made up of wagons with a hull (skirt) at the bottom it can be seen that: by the presence of this element mounted on the vehicle it as a decrease in the values obtained for the longitudinal aerodynamic forces is determined (from simulation results) with a percentage of around 10% (see figure 13).
It is worth mentioning that: the program used for simulating the air flow performs the meshing in the volume and the boundary layer area with elements in the form of the rectangular parallelepiped, and with respect to the mathematical model used for anticipating the turbulences that occur during the flow is the equation Favre Navier-Stokes, the k-ε model.

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