SOME ASPECTS REGARDING THE IMPACT OF AERODYNAMICS ON FUEL CONSUMPTION IN RAILWAY APPLICATIONS

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Principala consecinţă a unui flux de aer în jurul unui tren aflat în mişcare constă în apariţia unei rezistenţe aerodinamice şi a unei distribuţii de presiuni pe suprafeţele frontal şi lateral ale vehiculului. Valoarea în sine a rezistenţei la înaintare (în cazul în care aceasta poate fi estimată iniţial prin simulări) poate favoriza în final o mai bună proiectare a întregii transmisii de putere a locomotive. Rezistenţa la înaintare poate fi estimată prin intermediul a două metode experimentale: metoda tracţiunii şi metoda mersului lansat. În timp ce prima necesită echipamente complexe, cea de-a doua este mult mai simplă din punct de vedere al numărului de elemente necesare experimentului. Scopul principal al acestei lucrări constă în analiza şi evidenţierea importanţei formei aerodinamice a vehiculelor feroviare, având în vedere că performanţele acestora sunt influenţate de rezistenţa aerodinamică la înaintare. În vederea ilustrării influenţei formei aerodinamice a cutiei locomotivei s-a ales cel mai nou model disponibil pe piaţa locală a transporturilor feroviare, respectiv locomotive diesel clasa 621 EGM a SNTFC "CFR Călători" S.A.

The main consequence of on air flow surrounding a moving train resides in the aerodynamic drag and a certain pressure distribution on the frontal and lateral surfaces of the vehicle. The actual value of the aerodynamic drag (if pre-determined) may lead to a more accurate design of the whole locomotive power transmission. The aerodynamic drag may be estimated by using two specific experiments: the traction method and the free launch method. While the first one uses highly sophisticated equipment, the second is easier to use due to the relative low number of devices required. The present work's main goal is to illustrate the importance of aerodynamic design of the railway vehicles, as their performances are influenced by the aerodynamic drag. In order to illustrate the influence of the aerodynamic shape of o locomotive body, we have chosen the latest diesel model available on the local market, the Class 621 EGM locomotives, currently in service at the national passenger railway operator, CFR Călători SA.

Keywords: aerodynamics, locomotives, diesel fuel consumption.

1. Introduction

It is a general common fact that in the case of any railroad administration, the increment of the speed rates including the one of the diesel traction has led to the development of issues regarding the aerodynamic drag and energy consumption [1].

The classical formula of the aerodynamic drag of a railway vehicle is known as being a second degree polynomial with the shape $A+BV+CV^2$[2].

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The formula is known as “the Davis formula” and can be applied to the alignment and plateau traffic. The term A stands for all the mechanical resistances during the motion, generally dependent to the weight per axle. Term *BV* stands for all the other types of non-aerodynamic drags.

Usually, term *B* is splitted in other two terms, B_1 and B_2; the first stands for the loss of quantity during the motion while the second term stands for the resistances caused by loss of gearing and the ones that depend on the train weight[3].

Regarding the CV^2 term, the Davis formula is a provisional one, because it takes into account only the first three terms of a serial progression representing the total resistance.

The aerodynamic drag is expressed through the third term. It becomes obvious the fact that at high speed rates, this term becomes predominant due to the square of the velocity. Due to this reason, one of the possible improvements in aerodynamic drag is to reduce this term as much as it can be reduced. In practice, this fact could be translated by adopting a body shape with a form and a front surface that would maintain the *C* constant (which takes into account quite all of these aspects) at a minimum value.

In the area of speed rates under 300 km/h [1], the term CV^2 expresses with adequate accuracy the external aerodynamic drag [4]. The *C* term can be splitted as follows:

$$C = C_x \cdot S \cdot \rho \cdot \frac{1}{2} \quad (1)$$

where C_x – the coefficient of air penetration (dimensionless); S – the frontal surface of the vehicle: ρ – the density of the air.

Also, there have to be taken into account the following aspects:

- The vehicle (the train) is moving through a non-stationary air-mass and the wind may have major influence, including on the alignment and plateau traffic;
- The density probability of the speed of wind follows an approximate Gaussian distribution;

The C_x coefficient can be measured with maximum accuracy in wind tunnels [8], but correct enough approximations can be also achieved by launching the vehicle on a known slope, only when knowing the other mechanical resistances.

The influence of the wind can be expressed through two correction coefficients, k_w and k_y (both being functions of the speed of train and of the speed and wind direction).

The k_w coefficient expresses the relative velocity of the train compared to the one of the air (resulting from the speed of movement and from the speed of the wind). This applies, in the same way, to the B_1 term.

The k_y coefficient expresses the change of the penetration coefficient C_x in case of aerodynamic drag. Another effect on the aerodynamic drag to motion resistance is determined by tunnels. The tunnel effect has been recently carefully studied, especially in the case of high-speed trains. This effect can be expressed through a coefficient, noted still as k_t [6].

The influences of the gradients and curves are also to be taken into account in order to express the accurate value of the total drag.

Thus, by noting the specific aerodynamic drag with r and the specific resistance given by the gradient with i respectively r_c for the specific resistance given by the curve (all expressed in N/kN), the total mechanical and aerodynamic drag of a locomotive may be written as follows:

$$R = r \cdot m \cdot g = \left[A + \left(k_w B_1 + B_2 \right) V + k_t k_w k_y C_x S \rho \cdot \frac{1}{2} \cdot V^2 \pm i + r_c \right] mg \quad [\text{N}] \qquad (2)$$

The locomotive has to generate the necessary traction power to mainly overcome its own total mechanical and aerodynamic drag and the rest of the train and after, to allow it to be hauled within the required speed limits.

The C factor from the Davis equation has a determining role within this fact, especially during the movement, where it is predominant.

The present study proposes the analysis of one of the most important means of reducing the fuel consumption by reducing the C coefficient.

The most important consequence of the existence of a still part of the aerodynamic drag coefficient is the fact that when a train is integrated in rigid consists, or even in double or triple sets it runs faster and spends less energy than when it is integrated in a single configuration.

This reality is reluctant to the theoretical calculus of the motion and consumption, based on the use of the conventional formulas of the aerodynamic drag. Thereafter, the strictly use of the empirical formulas of the aerodynamic drag can generate erroneous results.

2. The practical case study

In the specific case of long cylindrical shapes (as the ones used in locomotive casings) there are two coefficients that matter the most:

- The frontal aerodynamic coefficient, C_x
- The lateral aerodynamic coefficient, C_y

When dealing with the calculus of the specific aerodynamic drag, the most important coefficient to be taken into account is the frontal one [9]. Its influence is best illustrated by the following equation:

$$C_x = \int_S C_p \frac{dS_x}{S_r} = \int_S \frac{p - \bar{p}}{\frac{1}{2} \bar{\rho} \cdot \bar{u}^2} \cdot \frac{dS_x}{S_r} = \frac{F_x}{\frac{1}{2} \rho \cdot \bar{u}^2 S_r} \qquad (3)$$

C_x may be determined theoretically by integrating the pressure coefficient, C_p. In the equation above F_x – the total effective force to which the body is subjected to; $\bar{u}$ - the average fluid speed [m/s]; S_r – the reference surface [m^2]; ρ – the fluid density [kg/m^3].

$$C_y = \int_S C_p \frac{dS_y}{S_r} = \frac{F_y}{\frac{1}{2}\rho \cdot \bar{u}^2 S_r} \qquad (4)$$

For the lateral parts of the vehicle the appropriate coefficient, C_y, will be calculated in a similar manner. Thus,

The mechanical labour of the traction forces for a locomotive hauling a train with the total mass $\overline{m}$ on the $\Delta S = S - S_0$ distance may be written as:

$$L_0 = \int_{S_0}^{S} F_0 dS \qquad (5)$$

where $F_0 = \overline{m} \cdot f_0 = \overline{m} \cdot \left(\frac{1}{\beta} \cdot \frac{dv}{dt} + r_t \pm i + r_c + f_f \right)$ stands for the traction force produced by the locomotive. The specific mechanical drag of the locomotive is $r_t = A + (k_w B_1 + B_2)V + k_t k_w k_y C_x S\rho \cdot \frac{1}{2} \cdot V^2 \pm i + r_c$. In this case, the total necessary traction force will be:

$$F_0 = \overline{m} \cdot \left(\frac{1}{\beta} \cdot \frac{dv}{dt} + A + (k_w B_1 + B_2)V + k_t k_w k_y C_x S\rho \cdot \frac{1}{2} \cdot V^2 + r_v \pm i + r_c + f_f \right) \qquad (6)$$

The indicated mechanical labour produced when burning 1 kg of diesel fuel is:

$$l_i = \tilde{C} H_i \qquad (7)$$

where $\tilde{C}$ - const.; H_i – the lowest caloric value of the diesel fuel.

The elementary fuel consumption of the locomotive is:

$$dC_D = \frac{1}{\tilde{C} H_i} \cdot \frac{F_0}{\eta_l} dS \qquad (8)$$

where η_l - the output/turnover of the locomotive

By integrating formula (6), we will achieve:

$$C_D = \frac{1}{\tilde{C} H_i} \int_{S_0}^{S} \frac{F_0}{\eta_l} dS = \frac{\overline{m}}{\tilde{C} H_i} \left[\frac{1}{\beta} \int_{S_0}^{S} \frac{1}{\eta_l} \cdot \frac{dv}{dt} dS + \int_{S_0}^{S} \frac{1}{\eta_l} \cdot \left(A + K_1 V + K_2 C_x S_r \rho \frac{1}{2} V^2 \right) dS + \int_{S_0}^{S} \frac{r_v}{\eta_l} dS \pm \int_{S_0}^{S} \frac{i}{\eta_l} dS + \int_{S_0}^{S} \frac{r_c}{\eta_l} dS + \int_{S_0}^{S} \frac{f_f}{\eta_l} dS \right] \qquad (9)$$

where $K_1 = k_w B_1 + B_2$; $K_2 = k_t k_w k_y$.

3. The influence of C_x on fuel consumption.

The 621 class locomotive's actual body shape has very poor aerodynamics due to the large frontal surface and sharp edges on every corner (see the figure on the right). The main goal of this study is to demonstrate that a non-aerodynamic vehicle body may influence the fuel consumption, especially at high speeds.

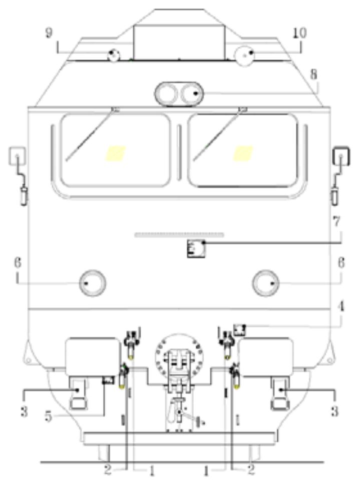


Fig. 1. The frontal surface of the class 621 EGM locomotive
1 – main air couplings; 2 – auxiliary air couplings; 3 – main electrical plug; 4 – electro-pneumatic brake cable; 5 – electro-pneumatic brake plug ; 6 – headlights; 7 – multiple unit plug; 8 – central headlight; 9,10 - horns

The simulation or determination of the influence of C_x on fuel consumption can be done by imposing more conditions, such as:

- The alignment and plateau traffic at a constant speed (100 km/h);
- Traffic within the curve etc.

In formula (9) the term that includes C_x and draws attention is:

$$\int_{S_0}^{S} \frac{1}{\eta_l}\cdot\left(A + K_1V + K_2C_xS_r\rho\frac{1}{2}V^2\right)dS \quad .$$

The variation of the coefficient is influenced by the following factors:

- Shape and size of the frontal surface of the locomotive;
- The pressure variations on the frontal surface;
- The additional aerodynamic strains.

After the experimental analysis, for the new streamlined form of the car body there have been achieved lower values of strains at the level of the frontal surface. When dealing with the calculus of the specific aerodynamic drag, the most important coefficient is the frontal one. The size of the frontal surface of the locomotive 621 EGM is approximately 11,5 m^2.

Under these conditions, the value of the C_x coefficient is approximately 0,6. In order to reduce the aerodynamic drag some practical measures have been taken (e.g. reduce the frontal surface or increase the angle of the frontal body in order to reduce the full frontal impact force and pressure [13].

Fig. 2 presents a new and improved aerodynamic shape, with rounded edges and perfectly smooth at the upper side of the body, so that all possible discontinuities have been removed.

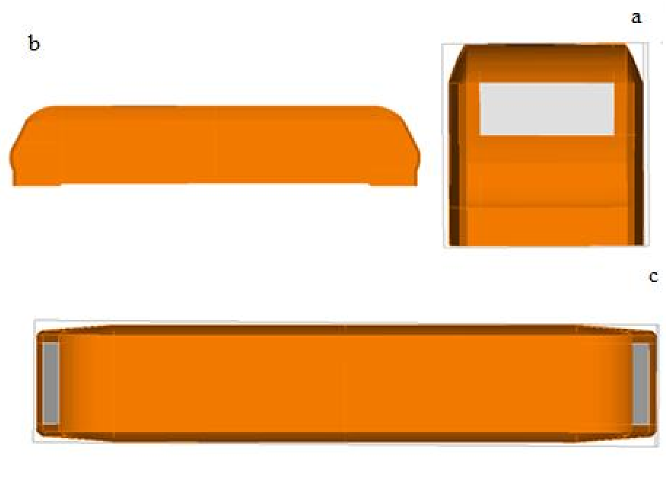


Fig. 2. The new aerodynamic shape
a) frontal surface; b) lateral view; c) 3D view

In Figs. 3 (a, b, c and d) and 4 (a-c) one can observe the main pressure fields surrounding the locomotive body at the speed of 100 km/h (its top speed). All simulations are done using special FEA software, NISA 3D Fluid. As the simulations proved, the main aerodynamic stresses occur at the upper side of the body, due to the sharp edges and the aerodynamic shock induced by the air conditioning unit which is placed right above the driver's cab. The situation is obvious for both, the frontal air flow and lateral wind as well.

The aerodynamically improved body is, in fact, the main body which may be redesigned as close as a perfectly smooth hull [13, 14], by adjusting the upper-frontal surfaces of the body and placing a specific casing above the entire roof (fig 2.).

Figs. 5 show that in this hypothetical case (when the entire body has a design which is much more close to a hull than the original one) the efforts are reduced, assuming the same conditions (constant speed of 100 km/h) and lateral wind.

Due to this, the new C_x resulted as 0.54, which is 10% lower than the initial one and much closer to the lower limit of 0.5, which is considered to be the best in case of the rail vehicles. Consequently, the entire aerodynamic drag was reduced by 10% (other factors are negligible) and thus, fuel consumption under these specific conditions may be reduced. It is important to highlight that fuel consumption in railway applications is a very complex issue and aerodynamic drag has its influence but only at high speeds. For the moment, in Romania the top speed that may be achieved by diesel traction is 120 km/h, but only on very few stretches of lines (e.g. - Vințu de Jos - Simeria). The rest of the lines are operated at speeds around 70 km/h, for which the aerodynamic drag is not a current problem.

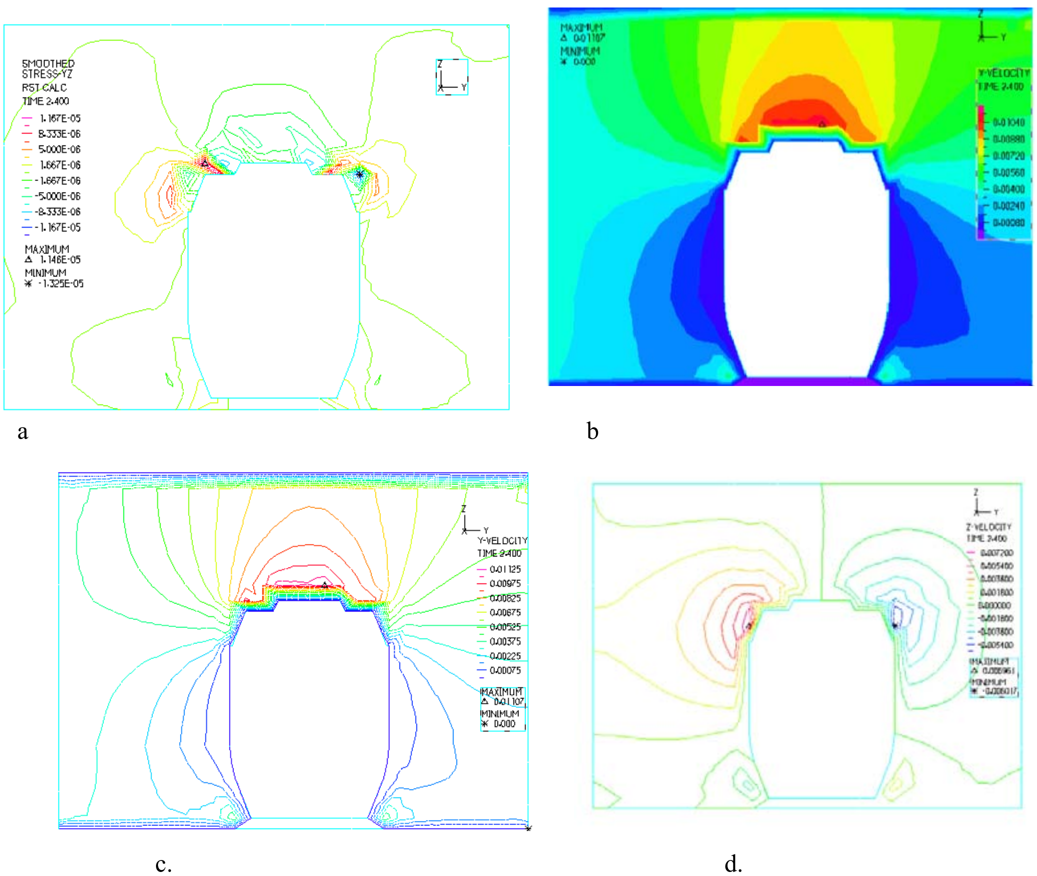
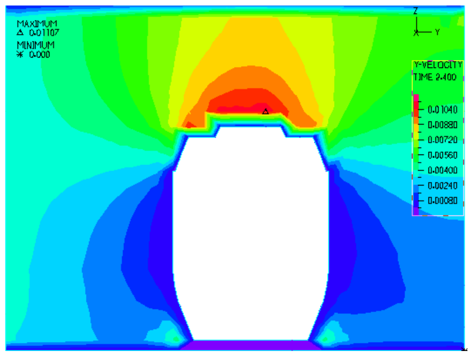
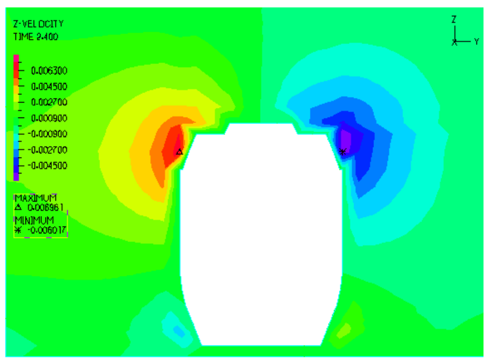


Fig. 3. Simulations of fluid flow around 621 EGM class locomotive

a) transversal section for lateral wind load; b) transversal section for frontal wind load c) fluid flow at the superior part; d) lateral wind a.



b.



c.

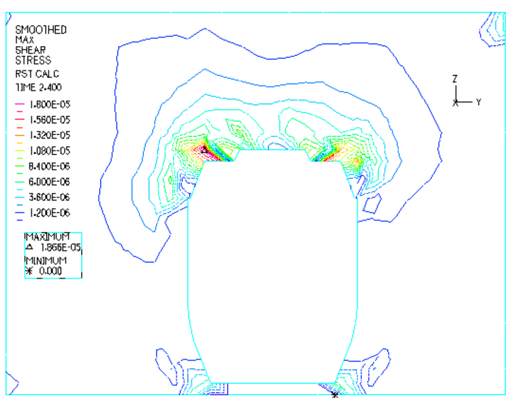


Fig. 4. Simulations of fluid flow around 621 EGM class locomotive
a) upper side flow and loads; b) lateral load c) pressure distribution

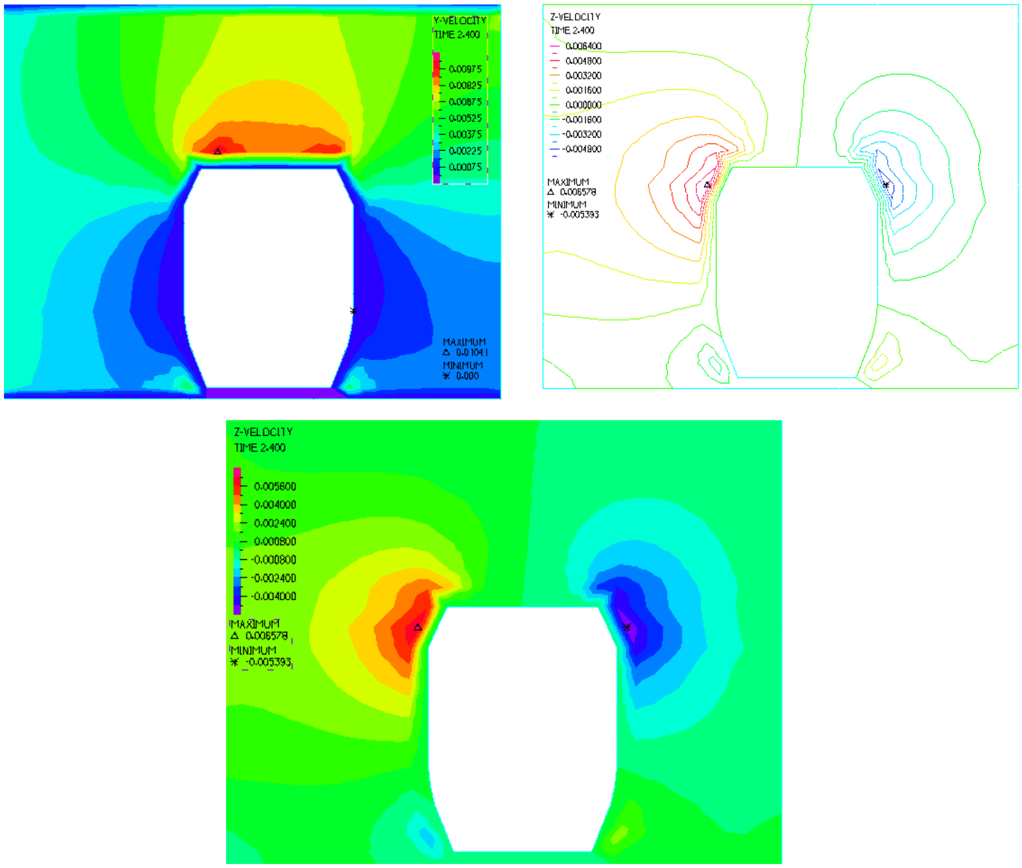


Fig. 5. Simulations of the air flow around the improved body shape
a) transversal section for frontal wind load ; b) transversal section for the lateral flow; c) upper side flow

4. Conclusions

The present work has illustrated the importance of aerodynamic design of the railway vehicles, as their performances are influenced by the aerodynamic drag.

Fuel consumption in railway applications is a very complex issue and aerodynamic drag has its influence but only at high speeds. Therefore, all the simulations were made considering the 100 km/h top speed.

Taking as a starting point the real body shape of the 621 EGM class locomotives and proposing a new and improved one we have demonstrated that the body shape and the size and quality of the frontal and lateral surfaces are, indeed, influencing the aerodynamic drag and thus, the fuel consumption. The analysis and solution proposed showed that even at 100 km/h and using the appropriate hull shape for the locomotive body, the C_x coefficient may be reduced and, thus, improve the fuel consumption, although at higher speeds more sophisticated shapes are used.

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