Experimental analysis for aerodynamic drag of the electric locomotives

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Abstract: *The purpose of this paper is to make a comparative analysis on the influence of the aerodynamic drag, in case of the electric rail vehicles for a series of situations encountered in exploitation. The article presents experimental results obtained following a geometric modelling at scale 1: 12, on a modular model for the electric locomotives LE 060EA 5100kW and LE-MA 060 TransMontana 6000kW. Tests were made at INCAS (National Institute for Aerospace Research "Elie Carafoli") in the subsonic wind tunnel.*

Key Words: *aerodynamic resistance, electric locomotives, experimental modelling.*

1. INTRODUCTION

The drag growth leads to an increase of the tensile force required for towing. If the tractive force developed by motors vehicles exceeds the limit of adhesion it can produce the skidding of wheel axle and the stick-slip phenomenon can occur, with harmful effects both on locomotive traction performances and on loads of the axles driving system. [1], [2], [3]

The general formula of drag for the railway vehicles, known as Davis' relation [3], [4], [5], [6], [7], [8], is given in (1)

$$R_t = a + b \cdot v + c \cdot v^2 \tag{1}$$

where R_t – total drag of the train;

a –mechanical resistances at rolling caused by axle loads;

$b \cdot v$ –non aerodynamic drag;

$c \cdot v^2$ – aerodynamic drag;

v – speed of the vehicle.

Aerodynamic phenomena of a vehicle increase its drag, with the square of velocity, fact which becomes more evident at high velocities.

In the literature of specialty [8], [9], [10], [11], [12], [13], [14], [15], the explanation of the "c", parameter corresponding to the determination of the drag, given by the aerodynamic phenomena, from Davis' equation for rail vehicles moving at speeds up to 250 km / h, in the longitudinal direction is expressed in the form given by relation (2):

$$c = \frac{C_x \cdot S \cdot \rho}{2} \tag{2}$$

where C_x –aerodynamic coefficient of air sliding (also known as the coefficient of air penetration) (dimensionless);

S – front surface of the vehicle in cross section (m^2);

ρ – density of the moving vehicle air (kg/m^3).

The aerodynamic frontal coefficient C_x of the vehicle is determined in turn by the relationship (3):

$$C_x = \frac{2 \cdot F_x}{S \cdot \rho \cdot \bar{v}^2} \tag{3}$$

where F_x – the frontal sliding force (N);

$\bar{v}$ – velocity of the fluid (air) (m/s)

In the article „Aerodynamics of high-speed railway train” [16] the authors state that in a series of tests made in a “test tunnel” on TGV trains at a speed of 260 km/h they found that “Of the total aerodynamic drag, about 80% is given only by the body train aerodynamics, 17% of aerodynamics is due to the pantograph system and other devices on the train and the remaining 3% is caused by the braking mechanisms, etc.”

In the same article, another study on ICE trains showed that “depending on the cross section shape of the motor vehicle, on its roof equipment, and on that located between the chassis and the running plane and also depending on the existence of hulls or skirts that conceal the external equipment (fig. 1 and 2) the friction can be reduced and consequently the air drag coefficient can be lowered.”

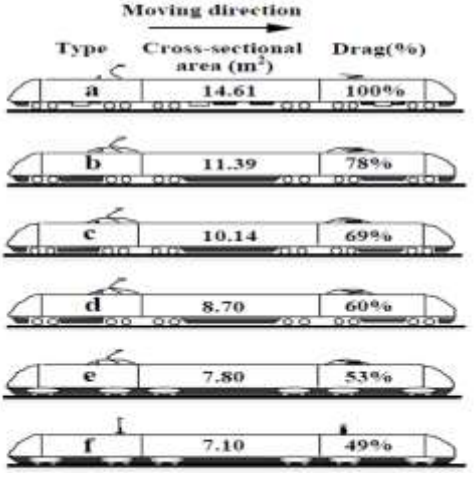

Fig. 1 – “Aerodynamic drag on ICE (the hatching area is the device to smooth the structures underneath train” [16]

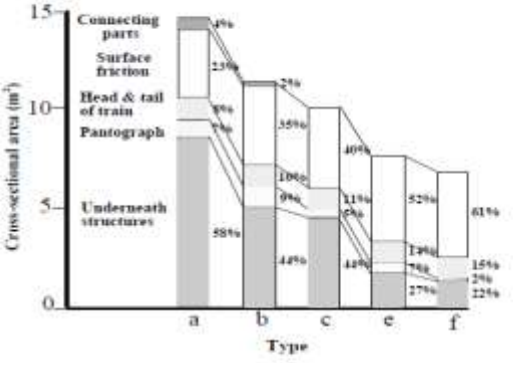

Fig. 2 – “Aerodynamic drag components of ICE” [16]

As shown, the analysis of drag, caused by aerodynamic phenomena, with electric rail vehicles, may be decomposed into:

- resistances caused by the design of the vehicle housing;
- resistances caused by the equipment located on the roof;
- resistances caused by equipment between the rolling plan and chassis plan.

In what follows only the first two categories will be considered, as they have the largest share/role in the aerodynamic drag of the vehicle.

In the case of the two vehicles (LE 060EA by 5100 kW and LE-MA 060 Trans Montana de 6000kW) Davis's equation, determined experimentally by the AFER (Romanian Railway Authority), in accordance with the sheets UIC (International Union of Railways) can be expressed as relations (4) [17] and (5) [18], respectively.

$$R_{LE} = 177 + 0,59 \cdot v + 0,0333 \cdot v^2 \ [daN] \tag{4}$$

$$R_{LE\text{-}MA} = 296,84 + 5,1347 \cdot v + 0,0649 \cdot v^2 \ [daN] \tag{5}$$

2. TESTS AND ANALYSIS OF RESULTS

In order to determine the aerodynamic resistance for different situations encountered in the operation of the electric locomotives type LE 060 EA by 5100 kW and LE-MA 060 TransMontana 6000kW, I made a scale geometric modelling 1:12, for the housing/box and for the equipment placed on the roof of the vehicle (pantographs, circuit breaker, high voltage insulators etc.), on a modular model that was introduced in the INCAS subsonic wind tunnel fig. 3 (National Institute for Aerospace Research - Development "Elie Carafoli").

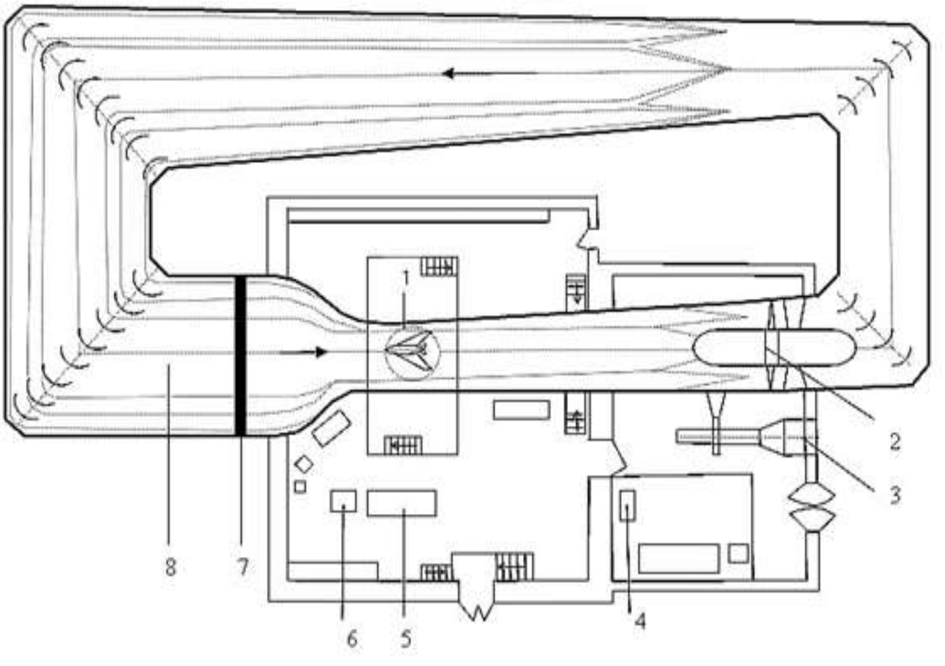

Fig. 3 – The scheme of INCAS subsonic wind tunnel
1 - control room, 2 - motor, 3 - engine cooling system, 4 - power supply panel, 5 - control panel, 6 - control panel for motor, 7 - section to minimize turbulence, 8 – quiet room

In the aerodynamic tunnel, global strains, aerodynamic forces and moments, due to the airflow in the experimental area are measured with an external six-components balance, of pyramidal type (fig. 4). Electrical signals are stored using a data acquisition system.

The measured values are in counts (the signal impulse). To determine the actual values of forces and moments it is necessary to multiply the values? with those 6 constants which have been determined when calibrating the balance. In this case only one measuring channel was used namely the channel appropriate to establish the drag.

Fig. 4. – The external balance of pyramidal type

The model modularity allows a total of 17 tests. These tests were performed at velocities ranging from 10 m/s to 55 m/s. Also, a series of punctual tests have been performed, at a speed of 40 m/s and 55 m/s respectively.

The first two tests, were carried out at a speed of 40m/s, with scale models of the two locomotives, without equipment located on the roof.

These values, having the role to determine the aerodynamic drag, corresponding to the LE 060 EA boxes of 5100 kW Fig. 5, and LE-MA 060 TransMontana 6000kW Fig. 6, respectively.

Fig. 5 – Test no. 1 – LE 5100kW without equipment

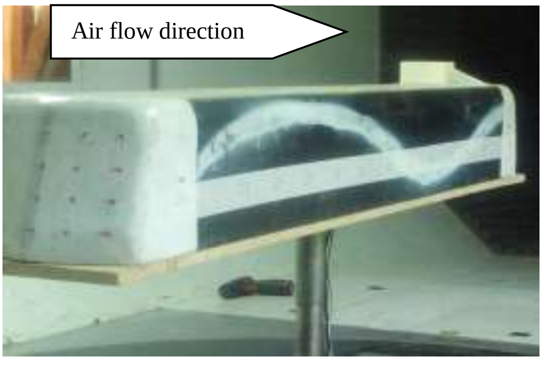

Fig. 6 – Test no. 1 – LE-MA 6000kW without equipment

The remaining tests were grouped into two categories according to the type of locomotive analysed. The tests ranging from 3 to 9 inclusively are performed for the LE 060 EA of 5100 kW locomotives (Fig. 7 – Fig. 13), and those ranging from 10 to 17 inclusively are performed for the LE-MA 060 TransMontana 6000kW locomotives (Fig. 14 – Fig.21).

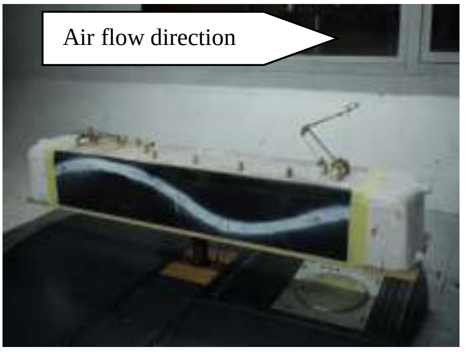

Fig. 7 – Test no. 3 – LE 5100kW with the back pantograph up, in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive

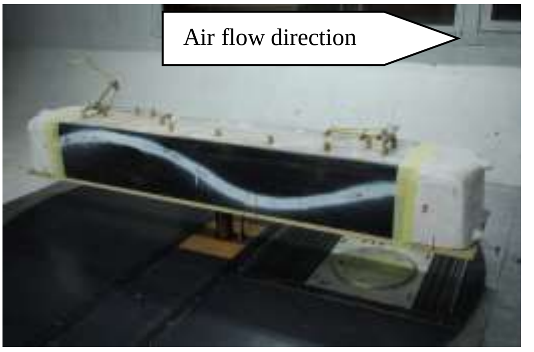

Fig. 8 –Test no. 4 – LE 5100kW with the front pantograph up, in the direction of the air flow at the maximum working height and with the arms articulation oriented towards the inside of the locomotive

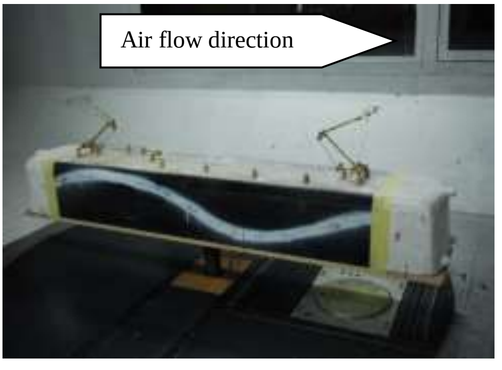

Fig. 9 – Test no. 5 – LE 5100kW with both pantographs raised at maximum working height and the articulations of the arms oriented towards the inside of locomotive

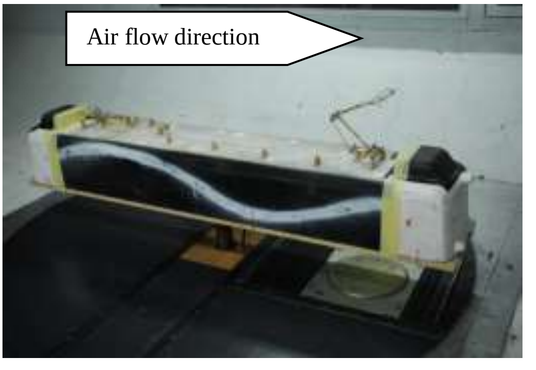

Fig. 10 – Test no. 6 – LE 5100kW with the back pantograph high, meaning of air flow at the maximum working height, articulation arms oriented towards the inside of locomotive and air conditioning located on the box

Fig. 11 – Test no. 7 – LE 5100kW with the front pantograph up in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive and air conditioning located on the box

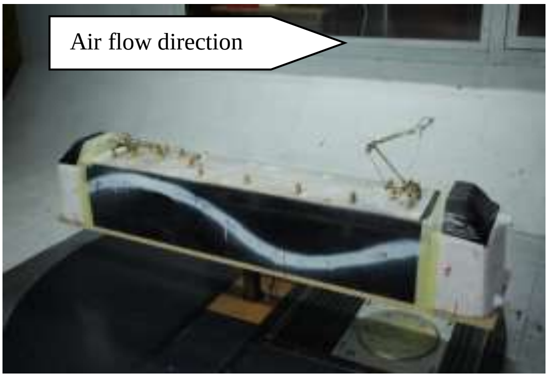

Fig. 12 – Test no. 8 – LE 5100kW with the back pantograph up in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive and embedded air conditioning

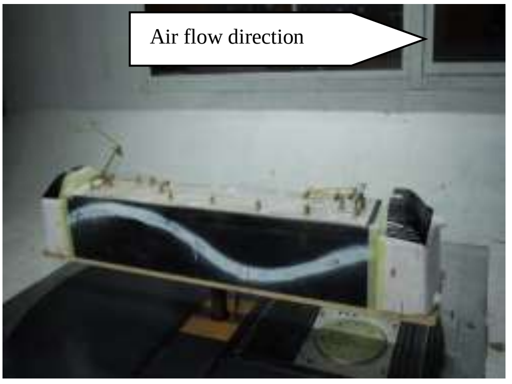

Fig. 13 – Test no. 9 – – LE 5100kW with the front pantograph up in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive and embedded air conditioning

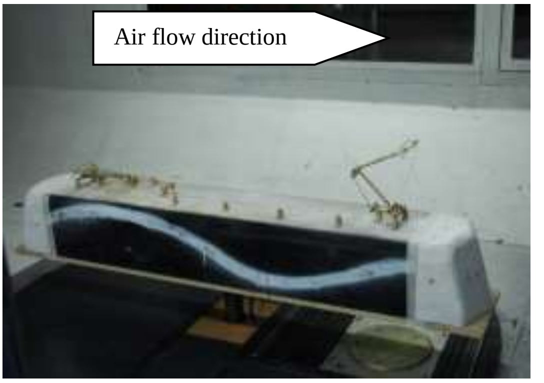

Fig. 14 – Test no. 10 – LE-MA 6000kW with the back pantograph up in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive

Fig. 15 – Test no. 11 – LE-MA 6000kW with both pantographs raised at maximum working height and articulations of the arms oriented towards the inside of the locomotive

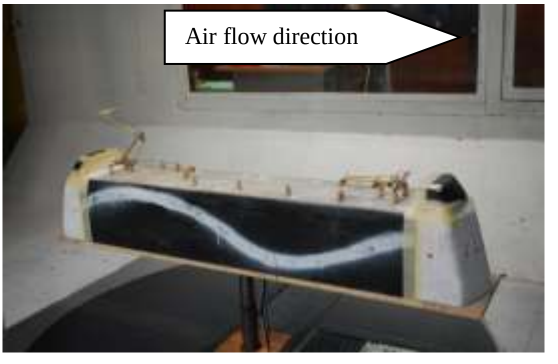

Fig. 16 – Test no. 12 – LE-MA 6000kW with the front pantograph up in the direction of the air flow at the maximum working height and the arms articulation oriented towards the inside of the locomotive and embedded air conditioning

Fig. 17 – Test no. 13 – LE-MA 6000kW with the front pantograph up, in the direction of the air flow at the maximum working height and the arms articulation oriented towards the outside of the locomotive and embedded air conditioning

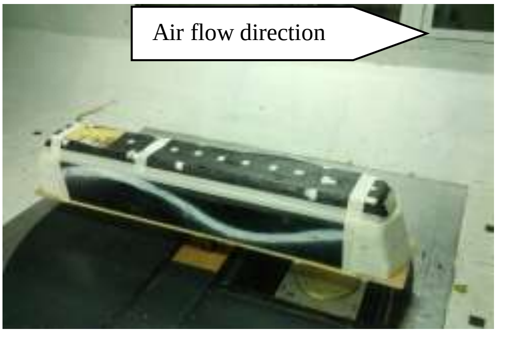

Fig. 18 – Test no. 14 – LE-MA 6000kW with the front pantograph up, in the direction of the air flow at the maximum working height, and the arms articulation oriented towards the outside of the locomotive and streamlined equipment's located on the roof

Fig. 19 –Test no. 15 – LE-MA with the back pantograph up, in the direction of the air flow at the maximum working height, and the arms articulation oriented towards the inside of the locomotive and streamlined equipment's located on the roof

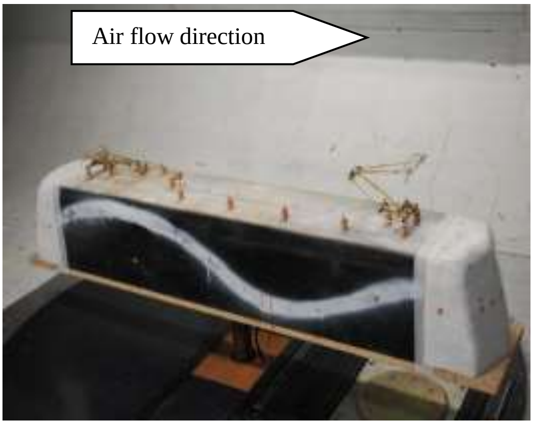

Fig. 20 – Test no. 16 – LE-MA 6000kW with the back pantograph up, in the direction of the air flow at the minimum working height, and the arms articulation oriented towards the inside of the locomotive

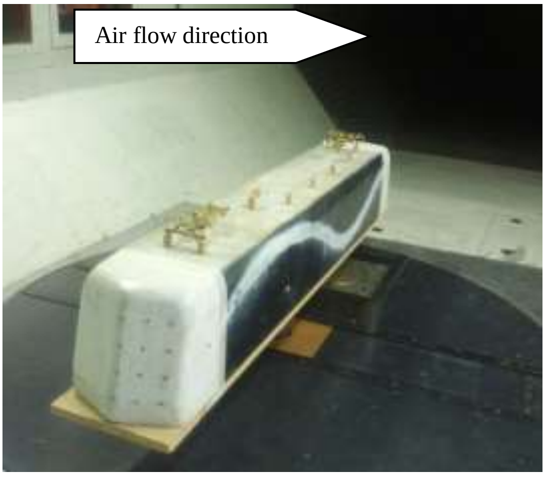

Fig. 21 – Test no. 17 – LE-MA 6000kW with both pantographs lowered and arms articulation oriented towards the inside of the locomotive

The results derived from the tests performed on the two types of locomotives geometric scale model for the aerodynamic drag caused by the box and by the equipment placed on the roof of the vehicle are presented in Table 1.

After processing the experimental data, both for the variations in velocity and the point values- in this case I have considered the speed of 40m/s –(144km/h – the value of 140km/h representing the maximum operational speed with which is able of the locomotive on base lines), a series of comparisons of between the aerodynamic drag values can be performed, namely:

1. The equipment located on the locomotive roof (pantographs, circuit breaker, high voltage insulators) increases the area of the transverse section of the vehicle and creates air flow turbulences, leading to an increase in the aerodynamic drag, as it can be seen in Fig. 22 and Fig. 23.;

Table 1 – The results of the experimental tests

Tests LE 060 EA by 5100 kW

Nr. exp.	R_{ia} [ct.]	R_{ia} [daN]	Test	v [m/s]
1	809	2,765162	Test 1	40
2	845	2,88821	Test 2	40
3	75	0,25635	Test 3	10
4	154	0,526372		15
5	269	0,919442		20
6	410	1,40138		25
7	585	1,99953		30
8	796	2,720728		35
9	995	3,40091		40
10	1257	4,296426		45
11	1554	5,311572		50
12	1869	6,388242		55
13	1023	3,496614	Test 4	40
14	1931	6,600158		55
15	1016	3,472688	Test 5	40
16	1930	6,59674		55
17	1011	3,455598	Test 6	40
18	1934	6,610412		55
19	1029	3,517122	Test 7	40
20	1959	6,695862		55
21	78	0,266604	Test 8	10
22	164	0,560552		15
23	285	0,97413		20
24	439	1,500502		25
25	636	2,173848		30
26	866	2,959988		35
27	1085	3,70853		40
28	1377	4,706586		45
29	1724	5,892632		50
30	2127	7,270086		55
31	1112	3,800816	Test 9	40
32	2150	7,3487		55

Tests LE-MA 060 TransMontana 6000kW

Nr. exp.	R_{ia} [ct.]	R_{ia} [daN]	Test	v [m/s]
33	82	0,28028	Test 10	10
34	175	0,59815		15
35	295	1,00831		20
36	442	1,51076		25
37	615	2,10207		30
38	833	2,84719		35
39	1088	3,71878		40
40	1354	4,62797		45
41	1679	5,73882		50
42	2046	6,99323		55
43	1099	3,75638	Test 11	40
44	1211	4,1392	Test 12	40
45	2239	7,6529		55
46	1141	3,89994	Test 13	40
47	2106	7,19831		55
48	1336	4,56645	Test 14	40
49	2491	8,51424		55
50	89	0,3042	Test 15	10
51	205	0,70069		15
52	347	1,18605		20
53	553	1,89015		25
54	783	2,67629		30
55	1049	3,58548		35
56	1360	4,64848		40
57	1688	5,76958		45
58	2088	7,13678		50
59	2553	8,72615		55
60	1046	3,57523	Test 16	40
61	1066	3,64359	Test 17	40

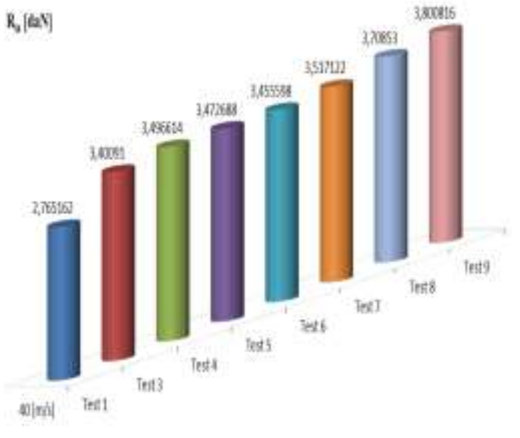

Fig. 22 – Aerodynamic drag values for LE 060 EA by 5100 kW

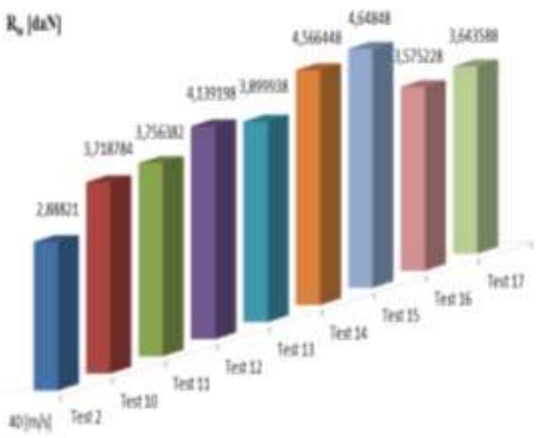

Fig. 23 – Aerodynamic drag values for LE-MA 060 TransMontana 6000kW

2. Depending on the situations analysed for the two types of locomotives this equipment leads to an increase in percentage of the aerodynamic drag, which varies in the present case between 22,99% and 37,45% for LE 060 EA of 5100 kW Fig. 24 and between 28,76% and 60,95% for LE-MA 060 TransMontana 6000kW Fig. 25, respectively;

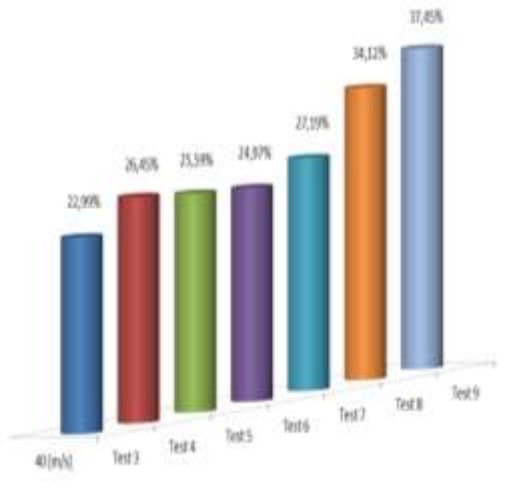

Fig. 24 – Percentage increase of aerodynamic drag caused by the equipment located on the locomotive LE 060 EA of 5100 kW compared to Test 1

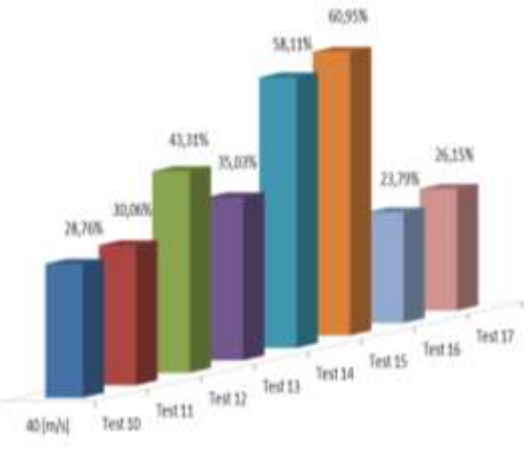

Fig. 25 – Percentage increase of aerodynamic drag caused by the equipment located on the locomotive LE-MA 060 TransMontana 6000kW compared to Test 2

3. Taking as a reference, the way of using of the pantograph utilized at Romanian Railway Company at/situated at the maximum working height to capture the current and voltage supply, it can be seen that the drag varies as a percentage, according to the situations encountered in service for the two locomotives as follows: for LE 060 EA by 5100 kW the variation is between 1,61% and 11,76% Fig. 26, and for LE-MA 060 TransMontana 6000kW is between -3,86% and 25% Fig. 27.;

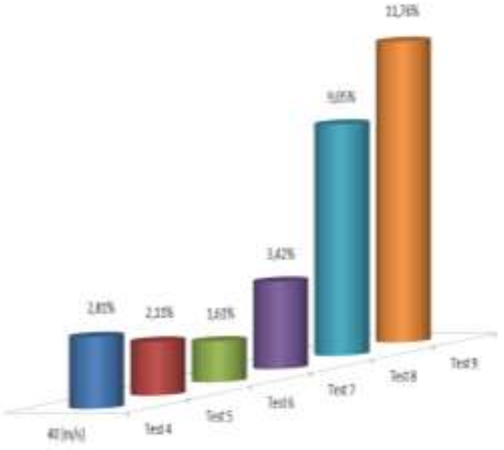

Fig. 26 – Percentage change in aerodynamic drag for LE 060 EA by 5100kW in relation to Test 3

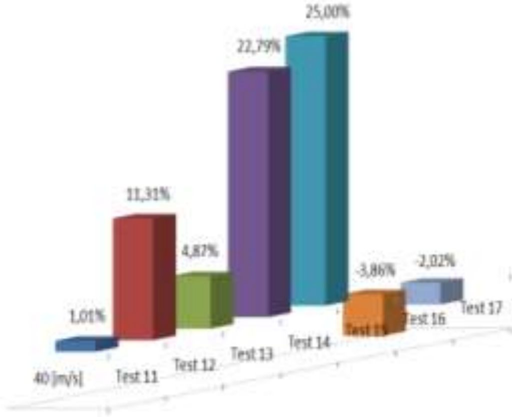

Fig. 27 – Percentage change in aerodynamic drag for LE-MA 060 TransMontana 6000kW in relation to Test 10

4. The change in the speed of movement of vehicles, ranging between 10 m/s and 55 m/s determines the increase of aerodynamic drag according to Fig. 28 for LE 060 EA by 5100kW and Fig. 29 for LE-MA 060 TransMontana 6000kW and changes in cross-section;

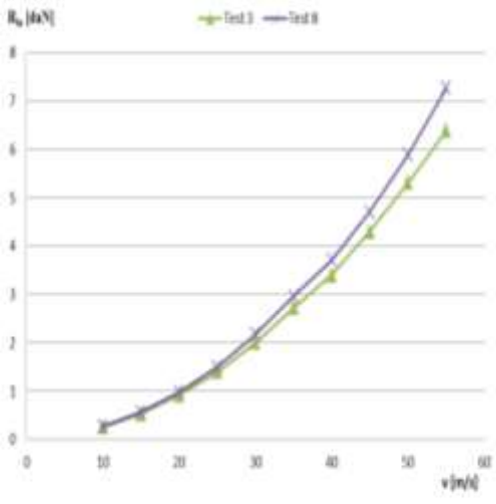

Fig. 28 – Variation of aerodynamic drag resistance for LE 060 EA by 5100kW depending on the speed of movement

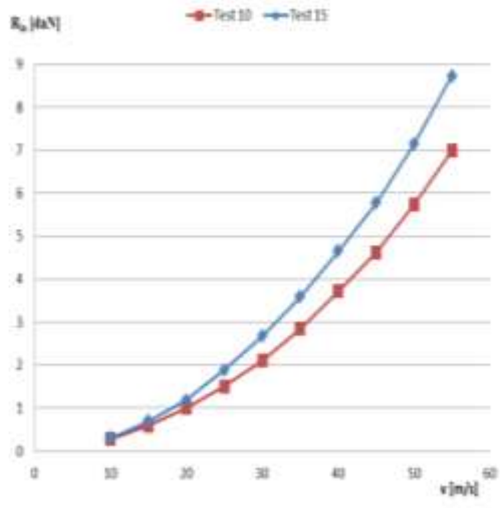

Fig. 29 – Variation of aerodynamic drag resistance LE-MA 060 TransMontana 6000kW depending on the speed of movement

5. With the variation of speed, if one also takes into account the increasing of the cross section area, determined by the streamlining of the air conditioning fitted on the vehicle, or of the equipment located on the roof, a percentage increase of the aerodynamic drag ranging between 4% and 13.8% (Fig. 30), and between 8,54% and 27,32% (Fig. 31), respectively can be found.

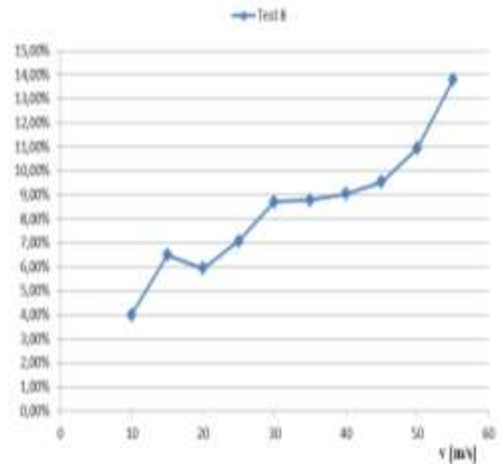

Fig. 30 – The variation of the percentage of the aerodynamic drag determined by the streamlining of the air conditioning fitted to the vehicle depending on the speed for LE 060 EA by 5100kW

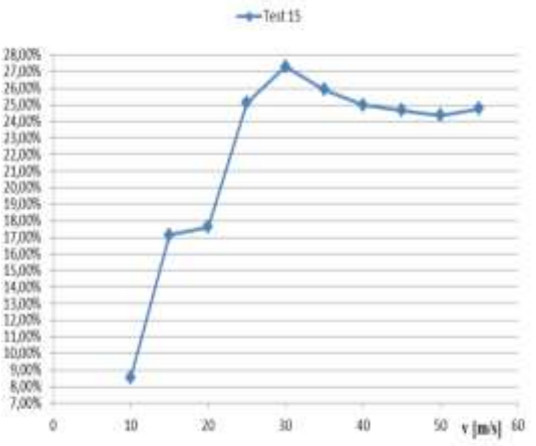

Fig. 31 – The variation of the percentage of aerodynamic drag determined by the streamlining of the equipment on the roof depending on the speed for LE-MA 060 TransMontana 6000kW

6. Between the two types of locomotives analysed an increase in percentage of the aerodynamic drag between 4,65% and 13,69% can be observed by comparing test 10 to test 3 Fig. 32, and between 14,10% and 25,97% respectively when comparing test 15 to test 8 Fig. 33, at changes of the travel speed;

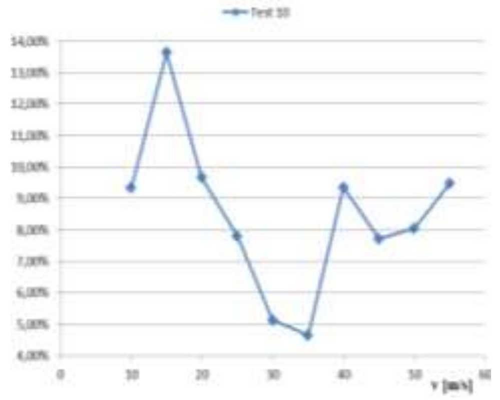

Fig. 32 – The variation of the percentage of the aerodynamic drag by comparing test 10 with test 3 at changes in travel speed

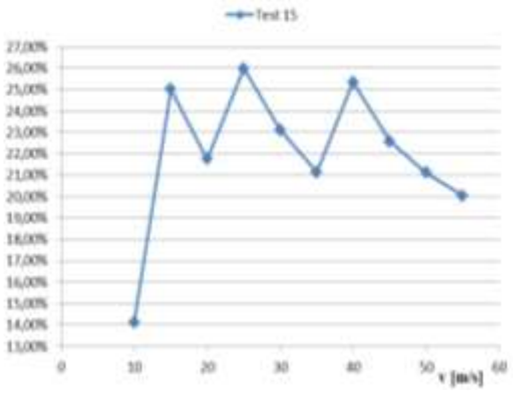

Fig. 33 – The variation of the percentage of aerodynamic drag by comparing test 15 with test 8 at changes in travel speed

7. By using the second pantograph, in the direction of the air flow, namely in the direction of movement of the vehicle, with the articulation arms oriented towards the inside of locomotive, in the case of LE-MA 060 TransMontana 6000kW and by considering as a reference, in a first stage, the situation when the locomotive operates with the pantograph raised at the minimum height for safe capture, the percentage variation of the aerodynamic drag resistance is the between 1,91% and 30,02%. When the locomotive is pushed, with pantographs lowered, the percentage variation of the aerodynamic drag resistance are between 2,06% and 27,58% Fig. 34;

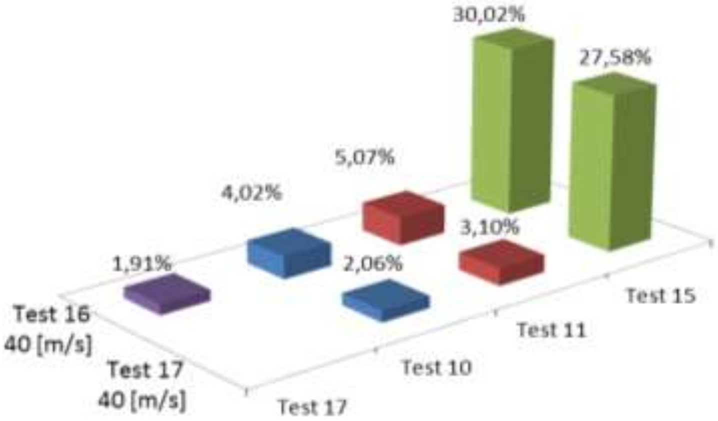

Fig. 34 – The percentage variation of the aerodynamic drag for the second pantograph raised, taking as reference the tests 16 and 17

8. The use as a reference of the case when both pantographs on the locomotive LE-MA 060 TransMontana 6000kW are lowered (in order to analyse the influence of the operating pantograph type: the front pantograph (p.f.), or the back pantograph (p.s.)) allows the observation of the percentage changes in the aerodynamic drag as follows: for p.f. these are between 3,10% and 25,33%, and for p.s. between -1,88% and 27,58% Fig. 35

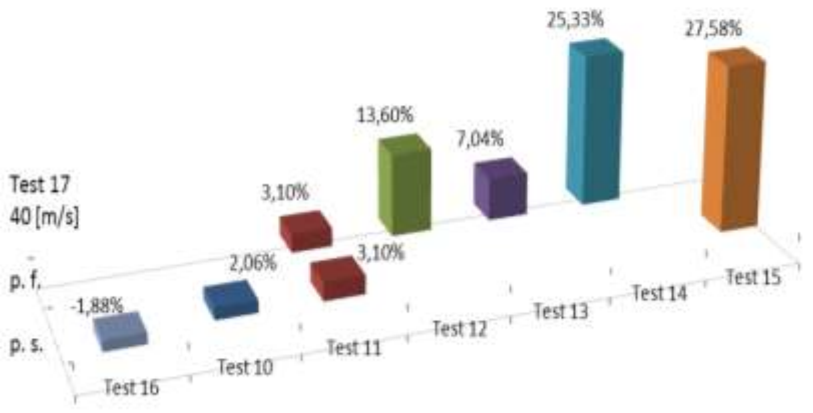

Fig. 35 – The percentage variations of the aerodynamic drag for a second pantograph raised, taking as a reference tests 16 and 17

4. CONCLUSION

After testing the electric locomotives LE 060 EA by 5100kW and LE-MA 060 TransMontana 6000kW in the subsonic tunnel at INCAS, following a geometric modelling at scale: 1:12, it was found that the aerodynamic drag, given by the equipment located on the roof causes an increase of 22,99%, and 28,76%, respectively, for the current usage at CFR Romanian Railway Company (with the back pantograph up, in the direction of the air flow and arms articulation oriented towards the inside of the locomotive) of the two motors vehicles, with pantograph open to capture at the maximum height and a travel speed of 40 [m/s]

Successive upgrades of the locomotive LE 060 EA of 5100kW which resulted in an increased cross-sectional area, by fitting the air conditioning equipment necessary for the conditioning of the driver's compartment at the bottom of the locomotive roof, which involves an increase in the aerodynamic drag by 1,61%, compared to the current usage at CFR Romanian Railway Company at a travel speed of 40 [m/s], and their streamlining over the whole driver's compartment caused an increase of 9,05%.

Using the first pantograph, with the arms articulation oriented towards the inside, from the direction of travel, for the locomotive LE 060 EA of 5100kW causes an increase in aerodynamic resistance by 2,81% as compared to the current usage at CFR with pantograph open at the same height of capture and a speed of 40 [m/s], respectively of 3,42% when the air conditioning is mounted and of 11,76% when it is streamlined.

In the case of LE-MA 060 TransMontana of 6000kW, an increase in aerodynamic resistance is found from the beginning, due to the constructive form of the locomotive box , as compared with the LE 060 EA of 5100kW, namely the 2,765162 [daN] (LE) to 2,88821[daN] (LE-MA), which means an increase in the percentage of 4,45%. This increase is given by the mounting of the front of the cabin of which base is vertical considerably increasing the drag. The lowest aerodynamic drag, for LE-MA, is obtained when for the power supply, from the catenary, the pantograph is raised at minimum height for safe capture namely 3,575228 [daN] (Test 16). Worth mentioning, that this value is less than to that achieved for the case when both pantographs are lowered, namely 3,643588 [daN] (Test 17). According to the references considered, for the determination of the percentage variation of the aerodynamic drag, it is found that compared to Test 16, Test 17 has an increase of 1,91%.

Comparing Test 13 to Test 12, one can found that the influence of positioning mode (arms articulation oriented towards inside or outside of the locomotive of the active pantograph, used for capturing the necessary energy, has an important role in increasing the aerodynamic drag. Rates transposition of the two aerodynamic drag values shows a difference between them of 6.13% at a speed of 40 [m / s], but if reporting is made to test 17 or test 16 a doubling of the percentage of aerodynamic drag is found from 7.04% to 13.60, and from 9.08% to 15.77%, respectively.

This demonstrates that the use of the pantograph in Test 12 is not an effective aerodynamic solution.

Another aspect, which influences the aerodynamic drag refers to the location of the pantograph on the vehicle (in the front of the locomotive in the direction of movement (p.f.) or in the back (p.s.)), as illustrated by comparing Test 14 to Test 15. The difference in percentage of the aerodynamic drag between the two tests, for the speed values of 40 [m/s] and 55 [m/s] is of 1,80%, and 2,49 %, respectively. This demonstrates that the most effective placement of the pantograph, from the point of view of aerodynamic resistance that it generates is its front location.

Partial or total streamlining of the equipment positioned on the roof of locomotives, does not represent a viable solution which enables the decreasing of the aerodynamic drag, because it increases the cross-sectional area of the vehicle. If this solution is used, these bottoms must be profiled, in order to reduce the turbulence created by the equipment on the roof. Preferably would be that much of the equipment located on the roof box to be introduced in the vehicles, reducing the cross-sectional area and air flow can no longer generate turbulence caused by these. The system of streamlined skirting and the introduction of the equipment inside of the vehicle box, are the criteria especially used with the electric high-speed trains.

As it can be observed, the modernizations made up-dating of the vehicles has, have increased the aerodynamic drag to advancement that lead implicitly leading to an increase in the power consumption required towing of a certain tonnage.

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