TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special II, April, 2024

STUDY ON THE AERODYNAMICS OF FREIGHT TRAINS USED IN CONTAINER TRANSPORT

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Abstract: *The paper aims to study the aerodynamic phenomena generated in the case of freight trains. Their study is carried out by the numerical method of simulation with a Computational Fluid Dynamics - CFD type analysis. For this process, it starts from the basic elements that correspond to the 3D geometric modeling of the elements that make up a freight train that is used in Romania (vehicles and track). The type of freight wagons studied is the one generated by platform vehicles, which are used in the transport of containers. The final proposed goal is to identify how the variation in forward resistance (from an aerodynamic point of view) is influenced by the layout of the load on a freight train used in the transport of containers.*
Key words: *aerodynamics train, freight trains, transport of containers, aerodynamic drag.*

1. INTRODUCTION

To provide a functional integrated sustainable transport service (for both freight and passenger traffic), the use of optimized intermodal solutions is imperative. Through them, on the one hand, economic efficiency is pursued, but also an increase in terms of safety in operation.

In the case of passenger transport, this intermodality manifests itself mainly in metropolitan and urban areas by increasing the number of available means of transport. If we refer to freight transport, it will connect the logistic points that serve the community (ports, modal terminals, railway stations, airports) and will include the need to connect two or more means of transport (rail – road, air – road, naval – railway – road).

In other words, the use of the intermodal transport system must start from the current basic conditions regarding energy efficiency and compliance with environmental norms. In practice, two directions can be distinguished that are often interconnected, namely: the efficiency of energy or fuel consumption for the provision of the service, respectively the integration and compliance with increasingly severe climate norms. The approach started at the end of the 20th century, to use cargo containers in a standardized way, is part of this process of optimizing intermodal transport solutions.

By means of intermodal cargo containers, the safe transport of goods can be carried out, without the need to find specific means for each transported product once the mode of transport used is changed (from sea to rail or road and vice versa). The requirements imposed on such equipment vary widely. These start from those related to specific structural resistance in the handling of containers used in intermodal transport, and the creation of safety zones for goods, and can reach the one related to their specific identification within the transport system.

The use of trains in the intermodal transport chain of containers represents a solution that offers high transport capacity, modularity, and increased efficiency [1]. On the other hand, the characteristic of modularity determines the uniqueness of the composition of a convoy of wagons that are included in the composition of a train [2]. This in turn generates in chain optimization problems related to energy or fuel consumption. The layout of such a shuttle train for the intermodal transport of containers can be seen in Fig. 1.

According to specialized literature [3, 4], the efficiency of freight transport by train can be achieved either by increasing operating speeds or by increasing the length of the train, by adding wagons. For both proposed situations, problems of an aerodynamic nature are generated instead.

Fig.1. Intermodal container transport train, source CFR Marfă website

As the speed of a freight train increases, its forward resistance will also increase. The main cause being determined by the higher pressure exerted by atmospheric air in the frontal area of the vehicle at the head of the train. Regarding increasing the length of the train, it should be taken into account that this solution is applicable only within the limits of the traction possibilities of the motor vehicle (locomotive) and the constructive parameters of the track. Where applicable, there will be additional side friction between the atmospheric air and the towed vehicles (wagons) added to the original train length.

The space between vehicles used in rail passenger transport is relatively small and limited, regardless of whether these trains consist of wagons with close or similar construction characteristics [5, 6], or if electric multiple units (EMUs) are used [7 - 9], respectively the multiple units are diesel (DMU) [10]. Compared to the situation encountered in passenger traffic, in freight traffic the distance between wagons is greater.

In a series of reports published in 2008 [11] and 2015 [12] by the Rail Accident Investigation Branch (RAIB), it is shown how by combining the aerodynamic forces generated by the movement of the train, with that resulting from the cross-wind gusts can lead to overturning the empty containers from the platform wagons that transport them (see Fig. 2).

2. REGULATIONS

2.1 Types of containers and their arrangement on wagons

At the global level, the constructive characteristics of freight consumers are regulated by means of the ISO 668 standard, the last update of which is from the year 2020.

Fig.2. Overturned containers from Report 12/2009 [11] and Report 19/2015 [12]

A brief centralization of these characteristics can be found in Table 1. Regarding the constructive characteristics necessary for railway vehicles, to be used in container transport, are found in the International Union of Railways (UIC) files: UIC 571-2, UIC 571-4 and UIC 592.

Table 1

General characteristics regarding ISO 1496-1 cargo containers.

Container		Length L (m)		Width W (m)		Height H (m)	
Type	Noted	Ext.	Int.	Ext.	Int.	Ext.	Int.
45’	1EEE	13.716	13.542	2.438	2.330	2.896	2.655
	1EE					2.591	2.350
40’	1AAA	12.192	11.998	2.438	2.330	2.896	2.655
	1AA					2.591	2.350
	1A					2.438	2.197
	1AX					< 2.438	1.054
30’	1BBB	9.125	8.931	2.438	2.330	2.896	2.655
	1BB					2.591	2.350
	1B					2.438	2.197
	1BX					< 2.438	1.054
20’	1CCC	6.058	5.867	2.438	2.330	2.896	2.655
	1CC					2.591	2.350
20’	1C	6.058	5.867	2.438	2.330	2.438	2.197
	1CX					< 2.438	1.054
10’	1D	2.991	2.802	2.438	2.330	2.438	2.197
	1DX					< 2.438	1.054

Platform wagons used in the transport of containers are identified in accordance with UIC 438-2 by means of markings corresponding to the series letters L (platform wagons on independent axles), R and S (platform wagons on bogies). A more accurate specification of such a wagon is made by means of index letters, as follows:

- dune type of container transported (g – container ≤ 60' feet ≈ 18 m, gg – container > 60' feet ≈ 18 m),
- the number of axles that make up the wagon (n – 4 axles with a load limit > 60 tons, or 6 axles with a load limit of > 75 tons),
- the moving speed of the wagon (s – maximum speed 100km/h or ss – maximum speed 120km/h).

Taking into account the previously stated, we can identify platform wagons on bogies inscribed Rgs(s) (Rgs - they run only in domestic traffic as they no longer cover all types of cargo containers that appeared - 10', 20', 30', 40', 45'), respectively Sgns(s) (Sgns – used in international traffic).

In accordance with the provisions of the UIC 592 sheet, the arrangement of the containers on the surface of the wagon is carried out according to the attachment points located on the wagon (see Fig. 3, the points painted in yellow). On a wagon with the identification mark Sgnss, 14 transverse axes are arranged in the horizontal plane for the positioning of the container attachment points. Arrangement of these axes, in the longitudinal plane of the vehicle, is made according to the scheme shown in Fig. 4.

Fig.3. Platform wagon with highlighting of attachment points, source Đuro Đaković website

This arrangement takes into account the possibility of transporting as many types of containers of different lengths as possible, so as not to exceed the maximum loading capacity of the wagon (60' feet ≈ 18 m). The most used containers are: 20' feet ≈ 6 m, 30' feet ≈ 9 m and 40' feet ≈ 12 m.

The operational use of such a wagon generates three distinct situations, namely:

- the wagon runs without a load (empty wagon),

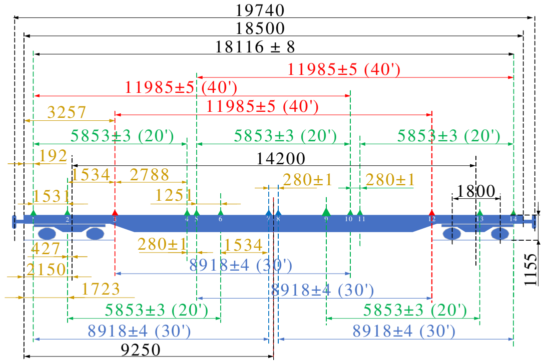


Fig.4. Arrangement of attachment points (in mm)

- the second variant is when the wagon is loaded to the maximum loading capacity,
- the third situation is when the wagon is used at a partial loading capacity.

The maximum capacity loading of a wagon is obtained when, by using two or three containers of the same type, or two containers of different length, they generate a length value of 18 m by summing them and whose cumulative mass does not exceed the value maximum allowed per wagon (see Fig. 5).

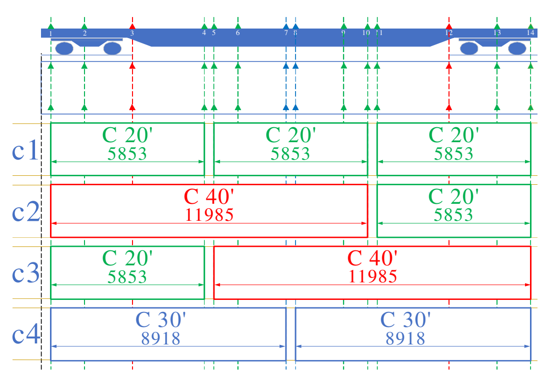


Fig.5. Wagon loaded to maximum capacity (in mm)

Due to the discontinuities created in the air flow, we can say that a partial use of such a wagon intended for the transport of containers is obtained when one or two containers are loaded whose total length determines a value less than 18m and which have a loaded mass which is at or below the maximum permissible limit of the wagon.

If we analyze the situations that can be generated by partial charging, we can identify the following situations:

1. Single container loading:

a. Whose length is 20' ≈ 6 m, presents 7 distinct cases (see Fig. 6),

b. Whose length is 30' ≈ 9 m, presents 4 distinct cases (see Fig. 7),

c. Whose length is 40' ≈ 12 m, presents 3 distinct cases (see Fig. 8),

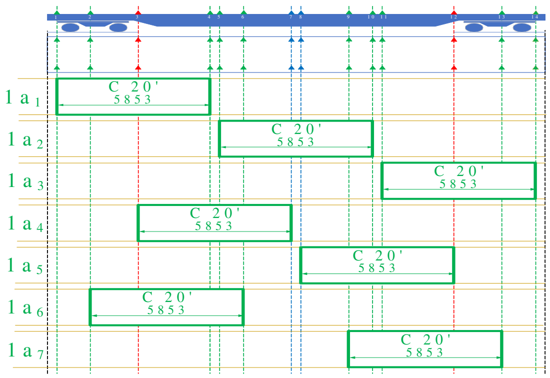


Fig.6. Wagon loaded at partial capacity with 20' type container (in mm)

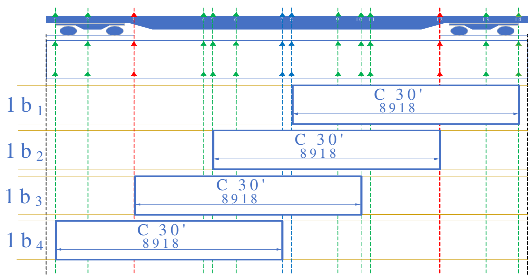


Fig.7. Wagon loaded at partial capacity with 30' type container (in mm)

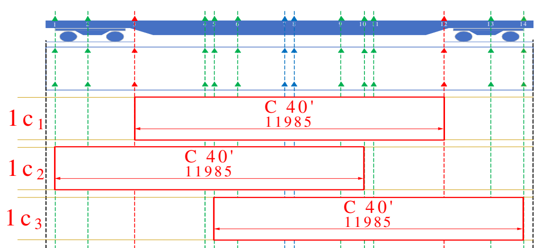


Fig.8. Wagon loaded at partial capacity with 40' type container (in mm)

2. Loading with two containers:

a. Identical, with a length of 20' ≈ 6 m, presents 5 distinct cases (see Fig. 9);

b. Different, with the length of 20' ≈ 6 m and 30' ≈ 9 m, presents 8 different cases (see Fig. 10).

Cumulating all these situations resulting from the partial loading of the wagon, we can find that we have 14 different ways of arranging the 3 types of containers used individually, and another 13 ways when we talk about the transport of two containers. When it is taken into

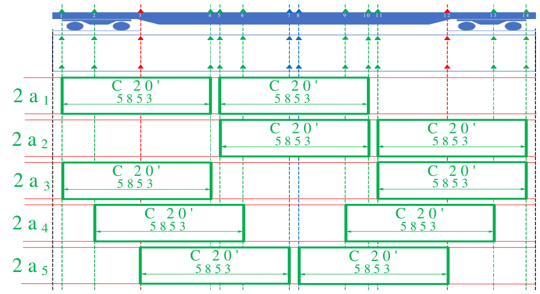


Fig.9. Wagon loaded at partial capacity with two 20' container type (in mm)

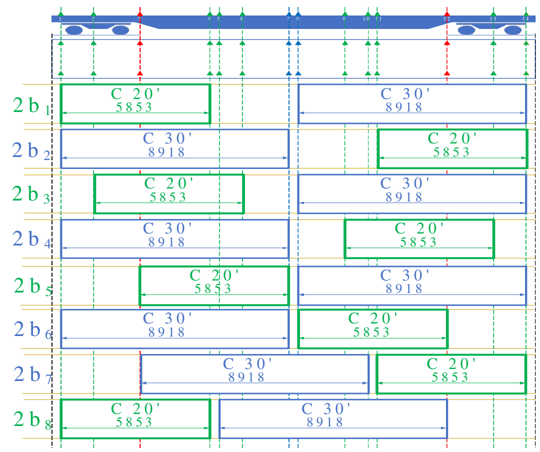


Fig.10. Wagon loaded at partial capacity with two container types 20' and 30' (in mm)

account that in addition to the 27 different situations of partial loading of the wagon, there are also the 4 cases of loading at maximum capacity, we obtain a variation in the arrangement of the containers of 31 different cases. To these is also added the situation when the train can only consist of unloaded wagons, which leads us to 32 possible cases to be analyzed from an aerodynamic point of view.

2.2 Aspects regarding train forward motion resistance

Knowing the forward resistance of a train is necessary both in terms of the efficient operation of such a convoy of vehicles, as well as in the construction of new such equipment. Mathematical relationships that are applicable to all types of trains, in order to determine the resistance to the advance, must be of a general nature and to the same extent be specific to each vehicle that is included in the composition of such a convoy.

The aerodynamic component of any vehicle's drag is a significant one that cannot be decoupled from the other drag components. In the series of standards EN 14067-1 to 6, which regulates the aerodynamic analysis process applicable to railway vehicles, it stipulates as a relation for the calculation of the forward resistance, applicable in certain driving conditions (running in alignment, without wind gusts and at speed constant of the train), the equation of degree 2 dependent on the speed with which the train moves. This relationship for determining the value of the sum of the forces opposing the movement, was established empirically (experimentally) at the beginning of the 20th century by JW Davis [5, 13] (1).

$$\sum R_t(v) = A + B \cdot v + C \cdot v^2. \qquad (1)$$

where: $\sum R_t$ (v) – the sum of the total forward resistance of a railway vehicle; A – mechanical rolling resistance [N]; B – coefficient of non-aerodynamic forward resistance (or quantitative air losses displaced by vehicle ventilation) [N/(km/h)]; C – coefficient of forward resistance determined by aerodynamic phenomena [N/(km/h)2]; v - vehicle speed [km/h].

According to the data found in the literature [5, 14], the values of these parameters can be found in table 2.

Table 2

Davis relation coefficient values for vehicles in the intermodal container train.

Vehicle type	A [N]	B [N/(km/h)]	C [N/(km/h)2]
LE 060	1700,1	11,8	0,4
Empty wagon	376,704	0	0,22159
Loaded wagon	1765,8	0	0,35316

The representation of the forward resistance characteristic, specific to each type of vehicle that makes up the container transport train, both in the situation in which it is loaded and when the movement is carried out without containers, is presented in Fig. 11.

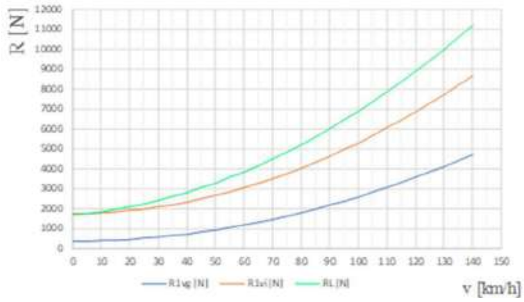


Fig.11. Wagon loaded at partial capacity with 40' type container (in mm)

The simulation of air flow around freight trains raises a series of problems related to, on the one hand: the variety of the way the spaces between the vehicles are arranged (a fact that predisposes to the appearance of turbulence while moving), and on the other hand, the great length that has such a train.

Among the calculation methods, noted in the evolution of the air flow simulation process around freight trains, we distinguish [15]: method of Navier-Stokes equations with Reynolds average (RANS); large turbulence simulation (LES) method; the detached eddy simulation (DES) method; the detached delay eddy simulation (DDES) method; improved detached eddy delay simulation (IDDES) method.

In all these methods, the air flow is treated as a three-dimensional incompressible flow process, to which are added the analytical concepts of modeling the turbulences unfolding around the vehicles. Turbulences are identified according to the number of differential equations considered that determine the turbulent viscosity [5, 16], as follows: one-equation model: Spalart–Allmaras (SA); two-equation model: k-ε type models where they are: standard k – ε model, Re-Normalization Group (RNG) k – ε model, realizable k – ε model; the k-ω models that include: the standard k-ω model, the shear Stress transport turbulence (SST) k-ω model.

3. SIMULATION

3.1 Simulation models

Mathematical modeling of the airflow field around rail vehicles has been increasingly developed over the last decade.

3.2 3D geometric models

In order to simulate the flow of air, around an intermodal container transport train, both the type and shape of the motor vehicle used (locomotive) and the possibilities of arranging the wagons towed from the train body are taken into account. Starting from this aspect, the present work analyzes the situation generated by the electric locomotive with the highest degree of use in Romania (LE 060 EA of 5100kW), to which a convoy of four wagons is attached for traction. This solution of using a number of four towed wagons was adopted, taking into account on the one hand the volume of calculation required to carry out the simulations (which increases significantly with the number of vehicles that make up the train, each wagon having a length of approximately 20 m), but at the same time it was sought to present as much variation as possible regarding the way the containers are arranged.

The arrangement of the way of composing the train is made in such a way as to take into account the 32 possible loading cases of a container transport wagon, which can enter into the composition of a train. The locomotive considered for towing, allows reaching maximum travel speeds between 120 km/h and 200 km/h. This variation of the maximum speed being determined by the value of the ratio of the mechanical gear used. The 3D geometric model of the locomotive [5, 6] was made in order to simulate the air flow (see Fig. 12).

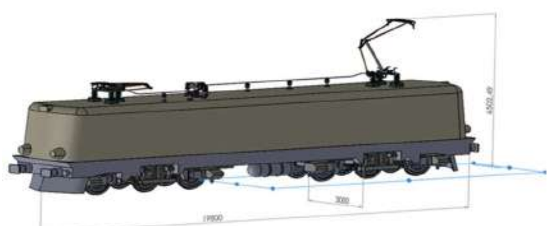


Fig.12. 3D model locomotive LE 060 EA (in mm)

With regard to towed vehicles, the situations resulting from the composition of a train consisting of independent Sgnss platform wagons on bogies, which can transport containers whose length is less than or equal to 60' feet, will be analyzed.

This type of wagon has 4 axles, 2 axles per bogie, a loading limit > 60 tons and a maximum travel speed of 120km/h. Taking into account the specified type of wagon and its constructive characteristics, the 3D geometric model of the vehicle was made according to Fig. 13.

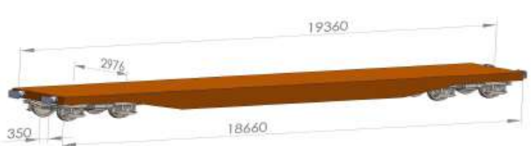
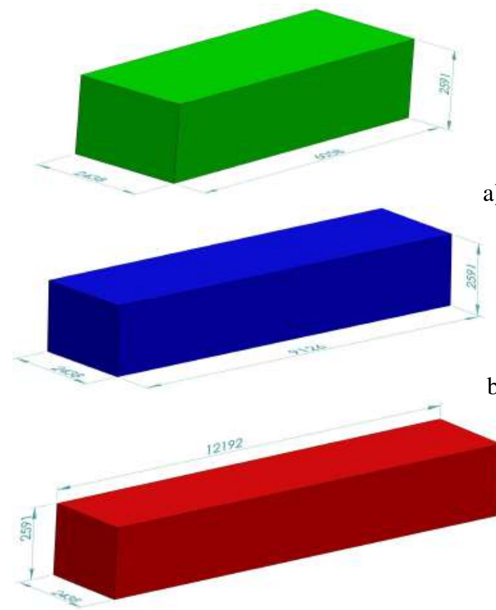


Fig.13. 3D model platform wagon Sgnss (in mm)

At the same time, 3D geometric models of the 3 types of containers (20', 30' and 40' respectively) that will be placed successively on the wagon, depending on the analyzed situation, were made (see Fig.14).



a) 20’

b) 30’

c) 40’

Fig.14. 3D container models (in mm)

The 3D geometric modeling of the infrastructure elements, on which the intermodal container transport train is located, is carried out taking into account EN 14064-6 regarding the height of the ballast bed, to which is added the height of the partially buried sleepers, and of the rails (see Fig. 15).

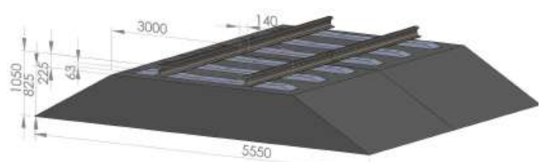


Fig.15. 3D container models (in mm)

3.3 Flow simulation

For this process, an air volume was delimited around the train, encompassing the adjacent spaces around it, so that the flow lines are not affected (see Fig. 16).

The simulation is carried out starting from the hypothesis of the train moving in normal atmospheric conditions (pressure of 101325 Pa and temperature 293.2 K) in which the train would

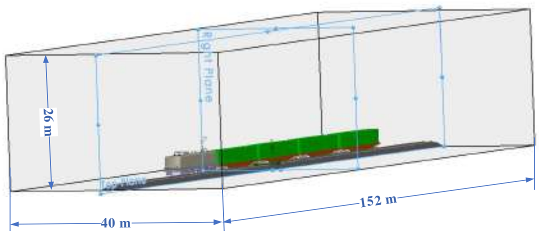


Fig.16. Volume of air delimited for flow

move with point values of the speeds kept constant within the range of 5m/s – 40m/s. The variable step for speed increase is 5m/s.

From the total of possible situations to be analyzed (see 2.1), in the present work the results obtained in the air flow simulation process will be presented, for the situation in which the intermodal train is used to transport containers that are 20 feet (6m) in size.

The magnitudes of the stabilized aerodynamic forces, resulting from this process, corresponding to the loaded train (Fig.5 case C1) and empty train situations are centralized in Table 3. Here also the values corresponding to the aerodynamic component given by Davis's relation are found. For partial loads (Fig. 6 and Fig. 9) at a travel speed between 30m/s – 40m/s the values resulting from the simulation are presented in Table 4.

Some images resulting from the simulation process regarding the distribution of the dynamic air pressure in the plane of the longitudinal section of the train, at an air flow speed of 40 m/s, are presented in Fig. 17. They correspond to situations 1a2 (Fig. 6) and 2a4 respectively (Fig. 9).

Table 3

Aerodynamic resistances for empty and loaded train.

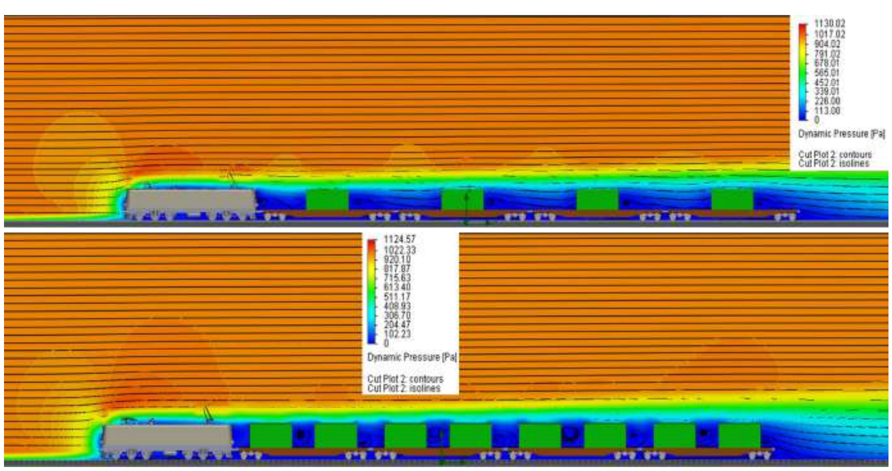
V [m/s]	$R_{A\ sim.}$ [N]		$R_{A\ Davis}$ [N]	
	Empty train	**Loaded train**	**Empty train**	**Loaded train**
5	187,72	347,18	201,39	244,02
10	643,49	734,05	805,58	976,10
15	1434,09	1685,62	1812,56	2196,21
20	2531,17	2879,52	3222,33	3904,38
25	3934,98	4624,25	5034,88	6100,60
30	5624,03	6414,81	7250,23	8784,89
35	7655,72	8580,68	9868,37	11957,17
40	9952,38	11333,20	12889,30	15617,52

Table 4

Aerodynamic resistances for partially loaded train.

Load type	$R_{A\ sim.}$ [N]		
	30 [m/s]	**35 [m/s]**	**40 [m/s]**
1a1	8047,57	10910,64	14230,69
1a2	8395,97	10972,97	14783,21
1a3	8119,62	11024,47	14688,67
1a4	7973,49	11541,29	14123,36
1a5	7967,34	10926,52	14250,44
1a6	8503,67	10845,83	14210,49
1a7	8215,75	11166,67	15421,62
2a1	7359,62	10253,55	13045,63
2a2	7426,50	10581,60	13774,89
2a3	7699,24	10451,48	14407,44
2a4	8202,19	11105,45	16395,15
2a5	7804,37	10570,96	13817,63

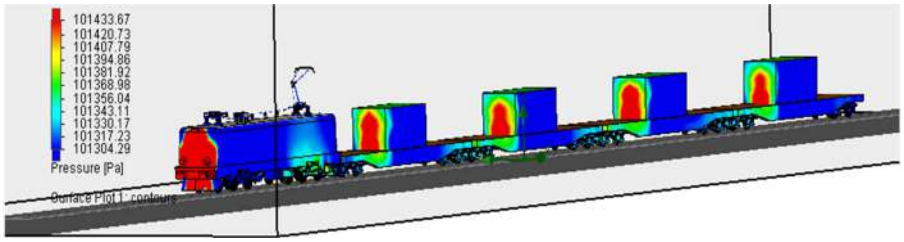
The air pressures exerted on the front fenders of the vehicles in the direction of travel are presented in Fig. 18.



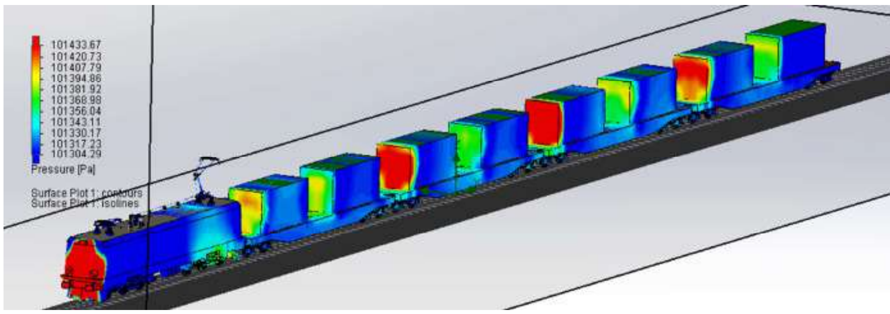
Load type 1a2

Load type 2a4

Fig.17. Dynamic air pressure distribution in the longitudinal plane of the train



Load type 1a2



Load type 2a4

Fig.18. Pressures exerted on the front fenders of the train

4. RESULTS ANALYSIS

Comparing in percentage terms, the results obtained from the simulation of the air flow with the one corresponding to the forward resistance, determined by the aerodynamic phenomena of Davis (see Fig. 19), we can find:

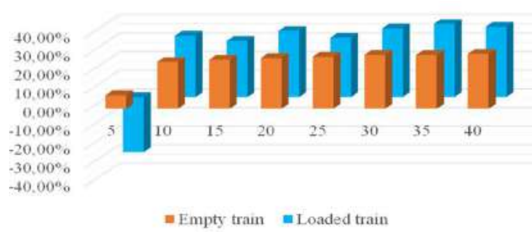
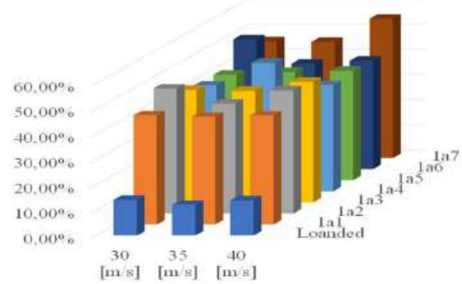


Fig.19. Dynamic air pressure distribution in the longitudinal plane of the train

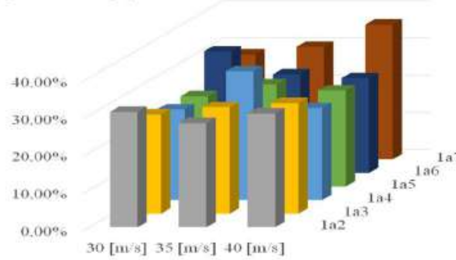
- for the situation of the train consisting of empty wagons, we can see how the values obtained from the simulation are lower by up to 30%,
- for the situation of the train consisting of loaded wagons, we observe that this percentage increases to 40% except for the speed of 5m/s when a value higher than 30% was obtained from the simulation.

If we carry out the same type of analysis for the arrangement of the containers on the wagon (see Fig. 20 and Fig. 21) in the case of the partially loads shown (Fig. 6 and Fig. 9) where the situation of the respective empty train of the loaded, we find:

- in both situations the values obtained for the partial load are higher compared to the two benchmarks considered,
- for the situation in Fig. 6 container layout, the increase compared to the empty train reaches about 52%, and to 33% for the loaded train benchmark,
- fine arrangement Fig. 9 shows an increase of 64% compared to the empty train and about 45% compared to the loaded train.

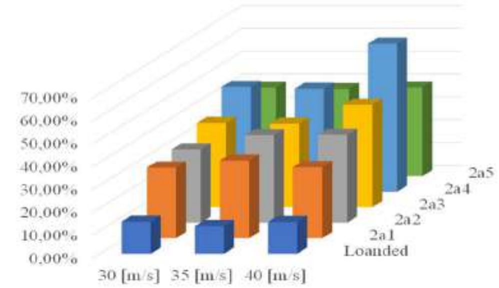


report to empty train.

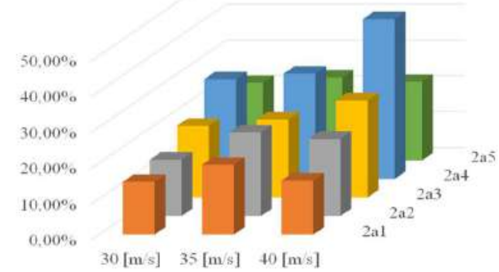


report to loaded train.

Fig.20. Dynamic air pressure distribution in the longitudinal plane of the train with one container of 20' on the wagon (case of Fig. 6)



report to empty train.



report to loaded train.

Fig.21. Dynamic air pressure distribution in the longitudinal plane of the train with two containers of 20' on the wagon (case of Fig. 9)

5. CONCLUSION

Although the speeds at which the freight trains are operated are not high (usually up to 120 km/h), the aerodynamic phenomena raised by these structures (successions of vehicles) are some complex ones, which manifest themselves visibly especially in the process numerical simulation. In order to highlight these aspects more clearly, we can list some elements encountered in carrying out this study, namely:

- freight trains can have a mixed composition, which implies a variety in the sequence of towed vehicles entering such a train (the study was carried out on a train with identical wagons);

- the constructive complexity specific to each type of freight wagon must be modeled geometrically (in the present case, the simplest version of a platform wagon was chosen);

- account must be taken of the way in which the goods are arranged in the wagon, the degree of its loading and the spacing between them, so that a safe transport can be carried out starting from the existing standards, norms and regulations (were carried out and analyzed a series of numerical simulations using CFD-type programs, for the aerodynamic study of different loading situations of platform wagons used in the transport of 20' containers);

- last but not least, the considerable length of such a train at the level of hundreds of meters that must be simulated (in the analyzed case, the solution of limiting the number of wagons in the train to a maximum of 4 was adopted, so that the necessary resources calculations that are used in the simulation process can be supported from a technical point of view).

From this analysis, it can be seen how in situations of partial loading of the containers on the wagon, the turbulence created in the air gaps between them, generate higher values of the aerodynamic resistance in the process of movement, compared to the situation of loading at full capacity, which affects significantly the energy consumption of such a train.

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Studiu privind aerodinamica trenurilor de marfă utilizate în transportul de containere

Lucrarea urmărește studierea fenomenelor aerodinamice generate în cazul trenurilor de marfă. Studierea acestora se realizează prin metoda numerică de simulare cu o analiză de tip Computational Fluid Daynamics - CFD. Pentru acest proces, se pornește de la elementele de bază ce corespund modelării geometrice 3D a elementelor ce intră în compunerea unui tren de marfă ce este utilizat în România (vehicule și cale de rulare). Tipologia vagoanelor de marfă studiată este cea generată de vehiculele platformă, ce sunt utilizate în transportul de containere. Scopul final propus este acela de a identifica modul cum este influențată variația rezistenței la înaintare (din punct de vedere aerodinamic), de către dispunerea încărcăturii pe un tren de marfă utilizat în transportul de containere.

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