Aerodynamic test with self-propelled scale model

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Abstract. This research presents a new experimental technique for the testing prototypes of aerodynamic devices of heavy freight vehicles. This technique allows the evaluation and recording of aerodynamic variables, being an alternative to the experimental limitations present in a wind tunnel, or the complexity and costs associated to the real-scale experimental test. For this new methodology a radio-controlled reduced-scale model is used, equipped with different instruments for recording aerodynamic variables. The experiment was performed at the runway in the Chilean Air Force Base in Santiago, at a speed of 90 [km/hr]. The results demonstrate that this technique allows recreating more realistic conditions of the aerodynamic phenomena, obtaining reliable values for the aerodynamic drag, at a low cost.

1. Introduction
Today, the effects of global warming have driven the development and introduction of energy efficiency policies aimed at reducing pollutant emissions in the industry, whether by ecological incentives or by multinational agreements that seek to stop global warming. This, coupled with the variability of fossil fuel prices, pushes freight transport to develop new ways to reduce fuel consumption. Of the technologies available to maximize the use of diesel in transportation, the use of aerodynamics stands out for its simplicity, quick installation and low impact in its operations. Research carried out in Chile [1] shows that the incorporation of aerodynamic technologies allows a reduction in fuel use of up to 15.34%, making it one of the most promising ways to reduce its energy consumption in this industrial sector. However, the use of aerodynamics devices requires a thorough knowledge and understanding of the fluid movement of air around a moving vehicle, so the design of these aerodynamic devices is closely linked to the applications of fluid equations and their turbulent phenomena, or the development of meticulous experimental trials.

For the design of an aerodynamic device there are three possible options: the use of numerical models, the scale model test or the real-scale evaluations. Each of them has strengths and weaknesses that can limit their effectiveness. In the case of scale trials the main problem is the size of the model with which it will be worked, which is closely linked to the size of the wind tunnel to be used. Considering the wind tunnel tests performed in different international laboratories [2], it is seen that in order to achieve a dynamic similarity in which the three main parameters: the Prandtl, Reynolds and Mach numbers, But for these parameters to be in optimal ranges, a larger laboratory is needed than those available in Chile.

On the other hand, the use of Computational Fluid Dynamics (CFD) allows the modeling of a large number of different geometries and configurations, but the resolution and accuracy of its results is conditioned by the ability of the computer to use (FLOPS), and same time to apply a reductionist criterion of variables in order to guarantee a convergent result, which eliminates certain turbulent
phenomena that are highly complex to simulate, such as the rotating movement of the wheels of the vehicle and the displacement of the floor. Finally, the last type of test is the real-scale tests, which because of their high costs allows the evaluation of a very small number of prototypes. Due to the limitations of each type of test, a new experimental aerodynamic evaluation technique is proposed, using a model of a transport vehicle, self-propelled and 1:6 scale of the original called GRSV (Ground Research Scale Vehicle), thus combining the different advantages of a full-scale test and the use of scaled-down models to obtain an appropriate phenomenological similarity to evaluate different aerodynamic devices.

2. Objectives
The objectives of the present research work are to evaluate the effectiveness of this methodology, considering the size and the speed of the GRSV. The specific objectives are:

• Implement and evaluate the technical feasibility for performing aerodynamic scale tests with self-propelled vehicles.

• To determine the effectiveness of the new experimental procedure, comparing the results with the real scale test, wind tunnel experiment and CFD analysis.

3. Methodology
The calculation methodology to be used to obtain the aerodynamic drag of the GRSV will be the Energy Conservation Method [3]. In addition, two control points will be used; comparing the static pressure measurements with the results obtained using CFD.

The first stage of the project was the realization of several computational simulations, in order to evaluate the sensitivity of the instruments to be built and installed on the GRSV and the magnitude of the aerodynamic forces involved in this experiment, considering the Reynolds number in each case.

| Type of analysis | Re. Number |
|-----------------|------------|
| CFD             | 805,000    |
| GRSV 25[m/s]    | 805,000    |
| GRSV 30[m/s]    | 1,006,000  |
| Real Truck Scale Model | 4,360,000 |

3.1. CFD Simulation
Several fluid dynamics simulations were performed with the digital model of the GRSV test vehicle, using ANSYS software with different air flow velocities.

In order to optimize computational capacities, we used the mean symmetry configuration of the three-dimensional model, with a total of 6,486,766 tetrahedral elements in the mesh, taking care of the size relation between elements, its geometric distortion and distribution around the study model and domain.

The simulation was performed in a steady formulation, with gravitational effects and first-class Dirichlet-type boundary conditions, without Poiseuille profile in the velocity function [5]. The upper and lateral limits of the domain were considered without friction, whereas for the lower limit it was considered as a real rough wall with displacement of the same speed and direction as the air flow. Furthermore, a standard isotropic turbulence of 0.1% was established for the entire domain [6].
The air was considered as ideal gas without temperature variation and with one atmosphere of absolute pressure, while for the exit of the domain was configured with barometric pressure equal to zero. The mathematical model used to calculate the turbulence was the two equations k-e model, with standard values for turbulence constants and kinetic energy [4].

For an interpolation that ensures numerical stability, second order models were implemented for all convergence criteria, while the algorithm to solve the iterative process was the SIMPLE method (Semi Implicit Method for Pressure Linked Equations). The results were verified by numerical convergence and the mass balance between the inflow and outflow zone of the domain.
At this stage, the two control points were chosen for the reading and comparison of the static pressure between the simulation and the scale test. These two points are located in two areas where robust pressures are measured: In the center of the front face (called P1) and the other in the back face (P2), in order to capture the influence of the formation of the boundary layer [7] between the floor and the bottom of the GRSV.

The results obtained at this stage indicate that the aerodynamic drag force is approximately 190 [N], a magnitude that can be detected by decelerating GRSV at a test speed of more than 15 [m/s].

4. Experimental Development
The scale model of the truck is used to design and build the GRSV is an average geometric design characteristic of a configuration of tract and semitrailer, with a short cabin and two tractor axles. For the trailer, an 18-foot format was chosen with two rear axles, while all components and parts of the trailer remained the same 1:6 scale. The cabin was built with composite materials, while for the trailer was used high strength aluminum and wood. The constructive design of the GRSV allows to install numerous instruments and sensors within it, up to a maximum of 20 kg of equipment in a safe way.
In order to achieve the objectives proposed in this research, the vehicle was equipped with a long-range radio-control system and a 10 Hp electric motor with high-performance LiPo batteries, and to guarantee the uniformity of its displacement, it was equipped with an inertial electronic system to maintain the vehicle's steering at high speeds. Additionally, a camera was installed in the upper part of the cabin that transmits in real time to the operator, facilitating its safe driving over long distances. Within the GRSV were installed three accelerometers, a GPS and 30 static pressure sensors with digital data logger, with sampling rates of 20 readings per second. These pressure sensors were built using three ATMega2560 microcontrollers and BMP180 digital sensors. A Pitot tube was also installed on the front of the GRSV and several temperature sensors, both for recording environmental conditions and for monitoring their systems interns. For the environmental variables, a portable weather station was used. Optionally the GRSV was equipped with two Pitot rake arrangements, constructed by 3D printing that allows recording the profile of the boundary layer in areas of interest. Finally, the GRSV with batteries and instruments on board has a total weight of 41 [kg], with 2.95 [m] long, 0.47 [m] wide and 0.67 [m] high. Its maximum speed is 110 [km/hr] using 8-cell LiPo.

**Figure 6.** Final aspect of GRSV in runway.

**Figure 7 and 8.** Interior view of GRSV: Truck (left) and trailer (right).
5. Experimental tests
The calibration tests were carried out at the Aeródromo de Vitacura in Santiago, while for the experimental trials the main runway in the Base Aérea El Bosque of the Chilean Air Force in Santiago was used.
Two-way displacements were performed on the 1.5 km long runway to eliminate environmental effects, at a maximum speed of 70 [km/h]. A group of displacements were made to record the static pressure in the control points at constant speed, while the other group of displacements were used exclusively to apply the Coast Down method, where the speed decay was recorded in between the 70 [km/hr] and 40 [km/hr], because in this interval the braking effects due to the aerodynamic drag is greater than the mechanical friction [2].

![Figure 9. GRSV in runway of the El Bosque Chilean Air Force Base.](image)

6. Results obtained
Approximately 80,000 data are obtained for each displacement, which helps to discriminate and compare different displacements to obtain significant values and valid tests, discarding those where the velocity was not stable or wind was detected in the test zone.
At the truck control points, mean static pressure values of 120 [Pa] for the front zone and -15 [Pa] on the rear face, which are compared with those obtained with the CFD simulations, presenting a difference greater than 10% in both cases, which could be explained by the type of turbulence model used in numerical modeling.
For the values of the aerodynamic drag, the GPS readings a continuous decay of the speed (Figure 10), and using the energy conservation equation of the Coast Down tests in the different speed sections, is obtained the values of the coefficient of drag according to each Reynolds number. These values are compared with those in the literature to similar Reynolds numbers [2] and those obtained with CFD at different speeds (Figure 11).

| Table 2. Static pressure in control points at 25 [m/s] with different techniques. |
|---------------------------------|
| GRSV | CFD | Error [%] |
|------|-----|----------|
| P1  | 120 | 140      | 15     |
| P2  | -15 | -12      | 20     |
**Figure 10.** Continuous decay of the speed of GRSV during coast down test.

**Figure 11.** Variation of drag to different Reynolds number and scale model
For the case of the maximum test speed, the drag coefficient values are closer to those expected, as seen in Figure 12, when compared to those expected for scale trials [2] and in the real-size tests [3].

![Figure 12. Drag coefficient according to experimental technique.](image1.png)

If we compare the aerodynamic drag values obtained by the Coast Down method using the GRSV, with those resulting from the CFD calculation for the different values of the Reynolds number and decomposing between the effects of mechanical friction and the air flow, we obtain a coherent quadratic relation between the values of the total drag force and the speed of GRSV (Figure 13).

![Figure 13. Forces acting in the GRSV for each test speed.](image2.png)
7. Conclusions
From the results obtained with the tests using the GRSV, it is possible to conclude that:

a) This test method is a viable, inexpensive and rapid experimental technique, compared with wind tunnel trials. It also incorporates the effect of ground movement and wheel rotation, making this method a more realistic technique because reproducing complex turbulent phenomena, while facilitating and betterment the testing of multiple aerodynamic devices, compared to CFD simulations, thanks on-board instrumentation and current 3D printing. Also, it is verified the stability in the taking of data in the displacements at high speed, which will allow carrying out specific studies of the behavior of the air flows under the GRSV and in the turbulent wake of the same.

b) It is a reliable procedure at speeds above 65 [km/h] due to the influence of the effect of mechanical friction and rolling drag, which increase the value of the total drag. This negative effect cannot be easily corrected, because due to the high test speeds, the vehicle needs a mass and inertia that allows it to maintain the control and stability in the displacements.

c) The Energy Conservation Method to determine the drag coefficient presents an important dispersion at low velocities, which is consistent with the recommendations related to the work scale [2 & 3], which forces the GRSV to perform tests at its maximum speed.

Reference

[1] Agencia Chilena de Eficiencia Energética 2015 *Catálogo Tecnologías Eficientes* para el Transporte de Carga Pesada (Santiago: Ministerio de Energía Gobierno de Chile)

[2] Rae & Pop 1984 *Low-Speed Wind Tunnel Testing* (New York: Wiley Publications)

[3] Corey D 2002 *A Ground-Based Research Vehicle for Base Drag Studies at Subsonic Speeds* (California: NASA Dryden Flight Research Center)

[4] Thwaites B 1960 *Incompressible Aerodynamic* (New York: Dover Publications)

[5] Shames I 1995 *Mecánica de Fluidos* (Santa Fé: McGraw-Hill Interamericana)

[6] Anderson J 1991 *Fundamentals of Aerodynamics* (New York: McGraw-Hill)

[7] Schlichting H 1972 *Teoría de la Capa Límite* (Bilbao: Ediciones Urmo)