Uma Análise Abrangente do Teste de Coastdown: Um Estudo sobre Variáveis de Resistência à Desaceleração

Maria Augusta de M. Lourenço
Osmar Medeiros S. de Oliveira
Rafael Iuliano Sambiase
Roger Guilherme
Volkswagen do Brasil – Way to Zero Center

Eduardo Augusto P. Gonçalves
Rafael Rezende dos Santos
Volkswagen do Brasil – Complete Vehicle Development

Vinícius Carneiro da Costa
Volkswagen do Brasil – Emissions Laboratory

RESUMO

Buscando adequação as legislações vigentes, a indústria automobilística se empenha em busca de novas tecnologias capazes de reduzir as emissões de poluentes e CO2e. Do ponto de vista veicular, todos os elementos que resistem ao movimento são passíveis de melhoria: resistência a rolagem dos pneus, aerodinâmica, inércias girantes, atrito de freio entre outros. No Brasil, a resistência à desaceleração é avaliada pelo ensaio de ‘Desaceleração em Pista Livre’ ou ‘Coastdown’ (ABNT NBR 10312). Apesar da clara metodologia, os testes incluem desafios: construção de pistas; preparação de veículo; condições atmosféricas favoráveis; investimentos em equipamentos; tempo de preparação e execução; e variações experimentais. A abordagem é justificável perante atividades de homologação final dos produtos, porém, torna-se demasiadamente onerosa (em tempo e custo) ao ambiente de desenvolvimento de novos produtos e, em adição, não se aplica para avaliar contribuições cujo benefício pode ser mascarado pelas incertezas inerentes ao processo de medição. Ante a problemática exposta, este trabalho visa avaliar as variáveis físicas capazes de descrever o comportamento de resistência de desaceleração de um veículo, baseado na literatura, objetivando sua aplicação a atividades de desenvolvimento.

A Comprehensive Analysis of Coastdown test: A Study on Deceleration Resistance Variables

Maria Augusta de M. Lourenço
Osmar Medeiros S. de Oliveira
Rafael Iuliano Sambiase
Roger Guilherme
Volkswagen do Brasil – Way to Zero Center

Eduardo Augusto P. Gonçalves
Rafael Rezende dos Santos
Volkswagen do Brasil – Complete Vehicle Development

Vinícius Carneiro da Costa
Volkswagen do Brasil – Emissions Laboratory

ABSTRACT

Seeking to comply with current legislation, the automotive industry is looking for new technologies capable of reducing pollutant and CO2e emissions. From a vehicle perspective, all elements that resist movement are subject to improvement: tire rolling resistance, aerodynamics, rotational inertia, brake friction, among others. In Brazil, resistance to deceleration is assessed by the 'Coastdown' test (ABNT NBR 10312). Despite the clear methodology, the tests include challenges: track construction; vehicle preparation; favorable atmospheric conditions; investment in equipment; preparation and execution time; and experimental variations. The approach is justifiable for final product homologation activities, however, it becomes too onerous (in time and cost) for the new product development environment and, in addition, it is not applicable for evaluating contributions whose benefit may be covered by the uncertainties inherent in the measurement process. Given the presented problem, this work aims to evaluate the physical variables capable of describing the deceleration resistance behavior of a vehicle, based on literature, aiming its application to development activities.

INTRODUCTION

Considering the global warming scenarios, all over the world institutions and governments have indicated goals and are making efforts to quantify and control carbon emissions [1], looking for more efficient and sustainable energy solutions. One example is the Sustainable Development Goal 7 of the United Nations, which aims to promote clean energy research and technology with international cooperation by 2030 [2]. Another example is the Paris Agreement, signed by many countries in 2015, pursuing efforts to mitigate global temperature increase [3]. In order to achieve this goal, it is necessary to reduce the greenhouse gases (GHG), which are directly related to CO_2 emissions from the transportation sector and, hence, from vehicle fuel consumption [3].

This way, the automobile industry plays an important role in climate change and has been encouraged to develop products that save energy, reduce consumption and emissions [2], mitigating the environmental impact [1]. Understanding the global scenario, Volkswagen also positioned itself by presenting the Way to Zero strategy, aiming for decarbonizing the company and its products, intending to be net carbon neutral by 2050 [4].

On the other hand, whenever this topic is addressed, attention is focused mainly on the development of new engines and even new technologies based on electrification. Although applying new technologies and electrification are important, improving the current vehicle development and homologation processes also brings benefits. Improving vehicle processes impacts all vehicles (combustion, hybrid, and electric), impacting more countries. In the Brazilian context, where large-scale electrification is not a short-term alternative, given the lack of charging infrastructure and the high cost of electric vehicles compared to average combustion vehicles, alternatives for improving vehicle energy efficiency, including conventional ones, are needed.

It is known that there are parameters outside the powertrain that can significantly influence energy efficiency and vehicle emissions [1], such as those responsible for vehicle resistance to movement. The main forces for movement resistance are due to air and tire rolling resistance [5, 6], and most simplified analyses consider only these resistances [7]. Although the majority of works in literature focus on these forces, other parameters such as tire pressure, atmospheric temperature [8], transmission efficiency, brake friction, and so on have been overlooked, which should also be discussed once they present a huge impact [6].

From the vehicle development and homologation process, the resistance to movement evaluation is performed through the coastdown test, one of the most frequent tests where road load coefficients at certain speeds and road conditions are measured [8]. During the homologation, these coefficients are reproduced on chassis dynamometers to carry out emission and fuel economy measurements for conventional internal combustion engine vehicles [5] and for hybrid and electric vehicles, having the possibility to evaluate, for example, the pure battery range [8]. Despite the energy source, the road load coefficients have a strong impact on overall results [6].

Several methodologies can be used to determine the vehicle resistance to movement. In Brazil, the automotive coastdown tests are used to determine the parameters that describe vehicle behavior – this methodology is described in ABNT NBR 10312 [9]. The scope of ABNT NBR 10312 is the light-duty road vehicle, specifically the road load measurement and dynamometer simulation using coastdown techniques from vehicle free deceleration on the road. It specifies the equipment applied to perform the measurements and the test methodology, for example, the test road conditions, the acceptable atmosphere and environmental parameters, and how the vehicle should be prepared. Moreover, it also gives a guideline on the test procedures and how to make the calculation based on the road experimental data [9].

Despite its widespread use, the approach described in ABNT NBR 10312 poses some difficulties for the industry:

1) Dependence on a flat and suitable road surface for carrying out the tests.

2) Dependence on a physical and representative vehicle with at least 3000 km of travel and 10% to 50% wear on the tire tread.

3) Favorable atmospheric conditions (temperature, longitudinal/transverse wind, and atmospheric pressure).

4) Testing equipment and its range of uncertainty.

5) Time required for the entire test, including preparation, availability of the vehicle on the test track, execution of the tests, validation, and analysis of the results.

6) Result tied to the original track.

Given this context, this study seeks to assess the physical variables that can describe a vehicles deceleration resistance behavior, drawing on existing literature, with the goal of applying these findings to development activities.

METHODOLOGY

The methodology is based on the literature research about this topic, focusing on the main equations that describe the vehicle deceleration movement, discussions about studies regarding the main influence parameters, how they affect vehicle calculations and measurements and, hence, vehicle energy efficiency.

Figure 1 illustrates and summarizes the main influence parameters in vehicle resistance during the deceleration on the coastdown procedure. These parameters will be explored, starting with an overview of the coastdown standard test and the vehicle dynamics base concepts, followed by the specific influence variables and how they, as a result, impact vehicle resistance. Finally, a critical analysis and discussion about the most relevant parameters are performed.

Figure 1. Overview of coastdown influence factors.

Moreover, an experimental evaluation of a coastdown in a chassis dynamometer is also performed to show the possibility of predicting the coastdown result of a different vehicle version, once a reference vehicle and the movement equations are known. The experimental procedure will be detailed in the experimental evaluation section.

COASTDOWN STANDARD TEST

Among the vehicle deceleration regulations, it is worth mentioning the American standards. Firstly, the SAE J1263 defines the road load measurement and dynamometer simulation using coastdown techniques, covering measurement of vehicle road load on a dry, straight, flat road at speeds less than 113 km/h [10]. Similarly, the SAE J2263 standard regarding road load measurement using onboard anemometry and coastdown techniques, which establishes a procedure to obtain the vehicle road load force for speeds between 115 and 15 km/h, resulting in an equation of road load force as a function of speed [11]. As test conditions, for example, it defines the operation on a dry and flat road under 20 °C, 98.21 kPa, without wind and precipitation, with transmission in neutral [11].

In Brazil, the similar standard ABNT NBR 10312 details the experimental preparation, conditions, procedures, and calculations, controlling the parameters to obtain results as representative as possible. Regarding the test conditions, some of the main test specifications are presented. The road should be straight, flat, clean, dry, and varying at maximum ± 1,5% inclination from the end to its beginning. The reference temperature is 20°C (between 5°C and 35°C allowed), and the pressure is 101.325 kPa (between 91 and 104 kPa allowed). The temperature and pressure are measured during the test, so the results have their values corrected according to temperature and pressure, allowing a fair comparison among tests performed in different atmospheric conditions.

Moreover, the longitudinal wind limit is 3 m/s on average (5 m/s peaks allowed), while the lateral limit is 2 m/s. These limits establish boundaries to minimize the effect of the wind on the coastdown results. Also, the tire treadwear should be from 10% to 50% wear, and a 30-minute vehicle warm-up before the test is performed, so the vehicle systems that are temperature dependent, such as tires, fluids, and lubricants, present a more representative performance. Besides, it is recommended to perform a vehicle break-in for at least 3000 km [9]. Although the roughness of the road is not directly controlled, the indication of the road location is required. The standard also recommends checking wheel balancing, suspension adjustment, steering alignment, brake adjustment, and maintenance [9]. Further, before the test begins, the steering wheel must be turned at least once from lock to lock, and, if the brakes are applied during the test, it is recommended that this process be repeated [9], so brake resistances are minimized.

After the preparation and measurement of the test conditions, the test procedure is initiated. The vehicle is accelerated to an initial speed of 105 km/h (29.17 m/s) or higher, the transmission is set to the neutral position, and the vehicle is freely decelerated. The time measurements start at 100 km/h (2.78 m/s) and go until 30 km/h (8.33 m/s) or less, at every interval of 10 km/h (2.78 m/s) maximum. At least 5 tests should be performed in each direction of the track [9]. The standard also presents another possible procedure based on two deceleration intervals, but for the proposed evaluation of the current work, this will not be detailed. By the end of the test, it is obtained how the deceleration speed varies as a function of time, and it reflects the vehicle movement resistance. The higher the resistance, the faster the vehicle will decelerate.

In order to describe this overall resistive force to vehicle movement, the standard presents a generic equation of the force as a function of its speed, by a second-degree equation. It is presented in Equation (1), where F (N) is the modulus of the resistance force, f_0 (N) is the coefficient of the zeroth order term, f_2 (N/(m/s)^2) is the coefficient of the second order term, and V (m/s) is vehicle speed [9].

$$F = f_0 + f_2 V^2 \tag{1}$$

These coefficients are calculated based on Equation (2), once the vehicle effective mass m (kg) is known and the speed (ΔV (m/s)) and time (Δt (s)) variations are measured. It is important to highlight that m is calculated according to Equation (2) as a function of the test vehicle mass M (curb weight plus 136 (kg)) and the equivalent mass of the rotational inertia m_e (kg). If m_e value is not available, it can be estimated by 3% of M [9]. The coefficients f_0 and f_2 are corrected to the standard conditions of temperature and atmospheric pressure, defined in ABNT NBR 10312 (20°C and 101.325 kPa). All analysis performed in the current work considers the standard conditions as the basis.

$$F = m\,\Delta V/\Delta t = f_0 + f_2 V^2 \tag{2}$$

$$m = M + m_e \tag{3}$$

Figure 2 presents an example of a generic light-duty compact vehicle coastdown result considering f_0 = 110 N and f_2 = 0.04 N/(km/h)^2.

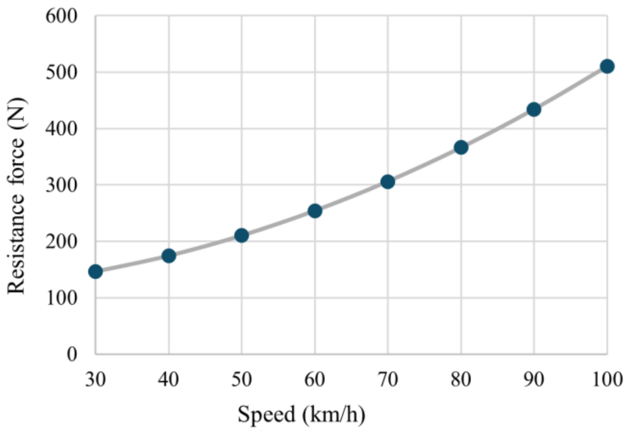

Figure 2. Example of coastdown result of a light vehicle.

VEHICLE DYNAMICS

The study of vehicle dynamics can be divided into three main categories: longitudinal dynamics, which has a greater influence on traction; lateral dynamics, which is essential for maneuvers and stability; and vertical dynamics, related to user comfort but also influencing maneuvers and traction due to weight transfer. From the deceleration perspective of the longitudinal dynamics, the focus of the current work, a comprehensive analysis needs detailed knowledge of the forces on the vehicle [12].

Longitudinal dynamics is based on Newton's Second Law [12], where it is possible to identify the resistance forces acting on the vehicle, which, in the proposed analysis, correspond to the coastdown resistances. Figure 3 shows the main forces acting on the vehicle, such as the aerodynamic drag D_A (N), the rolling resistance R_x (N), the vehicle traction force on the tire F_x (N), and the hill resistance force $Wsen\theta$ (N), where W is the vehicle weight and θ is the road inclination angle. In cases of uphill, this component resists the movement, while in cases of downhill, this component will reduce the traction load requested from the engine.

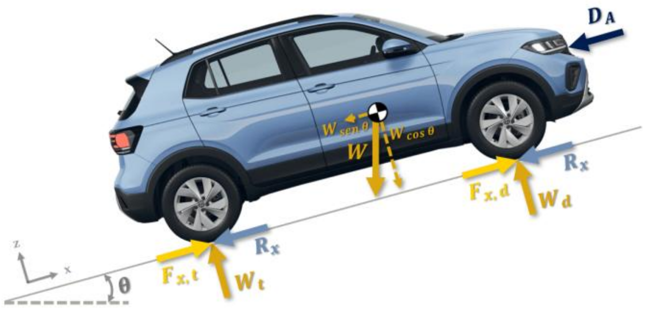

Figure 3. Longitudinal forces on the vehicle.

The equations from the resistance forces presented in Figure 3 are detailed in the following Equations (4) and (5) [12,13], where the ρ_{ar} (kg/m^2) is the air density, C_D is the aerodynamic drag coefficient, A_f (m^2) is the frontal area of the vehicle, V (m/s) is the vehicle speed, f_r is the rolling resistance coefficient, m (kg) is the vehicle mass, and g (m/s^2) is the acceleration of gravity.

$$D_A = ½\, \rho_{ar} C_D A_f V^2 \quad (4)$$

$$R_x = f_r\, mg \cos\theta \quad (5)$$

Moreover, it is noteworthy that the traction force value of F_x, as in Figure 3 and in Equation (6), is the net value on the tires, already limited by engine capacity, clutch, transmissions, and mechanical differential [12,14,15]. The traction force on the tires is a function of the input from the torque of the engine T_e (Nm), the ratio of the combined transmission and final drive N_{tf} and its efficiency η_{tf}, the tires effective rolling radius of the tire r (m), and also from the rotational inertia that consumes part of this force, where I_e is the inertia of the engine, I_t is the inertia of the transmission, I_d is the inertia of the driveshaft, I_w is the inertia of the wheel (tire, rim and axle shaft), N_f is the ratio of the final drive, and a_x (m/s^2) is the linear acceleration.

$$F_x = T_e N_{tf} \eta_{tf}/r - \{(I_e + I_t)\, N_{tf}{}^2 + I_d N_f{}^2 + I_w\}\; a_x/r^2 \quad (6)$$

It is important to highlight the efficiency of the combined transmission and final drive η_{tf} represents the impact of the mechanical and viscous losses in the driveline components (transmission, driveshaft, differential, and axles) [12]. η_{tf} efficiency varies widely according to the driveline torque and viscous losses occur even when the torque is zero. Efficiencies between 80% and 90% are typically used to characterize the driveline [12].

Once the forces acting on the vehicle are known, it is possible to apply Newton's 2nd Law to the vehicle, as shown in Equation (7), to obtain its linear acceleration a_x (m/s^2).

$$m\, a_x = F_x - D_A - R_x - Wsen\theta \quad (7)$$

When analyzing the longitudinal dynamics from the deceleration perspective of the coastdown test, the engine is disabled, and the transmissions are in a neutral position. This way, there is no more input torque from the engine. On the other hand, during the deceleration process, where a_x assumes negative values, there are still F_x values due to the inertia of the intermediate components that keep rotating.

INFLUENCE VARIABLES ON COASTDOWN

From a vehicle perspective, all elements that resist movement impact the vehicle dynamics and can be improved to enhance vehicle deceleration performance. As an example, energy is lost in the tires, road, bearing friction, tire rotation, aerodynamic resistance, tire drag, driveline friction, and suspension system [8]. Moreover, parameters such as air temperature, vehicle speed, and tire inflation pressure can also affect the road load [8].

Taking as bases the terms of Equation (7), the main influence elements are discussed and detailed in the following, divided by mass, traction force on the tire, aerodynamics, and rolling resistance. Moreover, the test conditions impact the overall vehicle results and are also discussed.

MASS – The vehicle mass directly affects its acceleration and overall performance. The higher the mass value, the harder it is to accelerate, as seen in Equation (7). Once it impacts acceleration, it also impacts the traction force, as seen in Equation (6), adding (deceleration) or subtracting (acceleration) values to the engine input. Besides, it also affects the other resistances that are weight-dependent, such as the rolling resistance (Equation (5)) and the weight component in inclined tracks.

Although the impact of mass variation is not the focus of recent research, since its influence is already well established in literature, a study of powertrain efficiencies showed vehicle mass has a significant impact upon vehicle passive system efficiency, greater than aerodynamics, indicating that lightweighting vehicles is a way to increase efficiency [16].

TRACTION FORCE ON THE TIRE – As seen in Equation (6), the intermediate components between the engine and the tires' contact with the ground play an important role in the effective traction force. Besides the input torque T_e and transmission ratios, the efficiency η_{tf} and the rotational inertias are the main influencing factors.

Rotational inertia – Like the mass, the rotational inertia affects vehicle acceleration. In Equation (3), the standard ABNT NBR 10312 presents simplified analyses considering its effect as an additional equivalent mass of the rotational inertia m_e (kg) and that it could also be estimated as 3% of the vehicle mass [9].

On the other hand, it is known that every vehicle from every automaker will have its own rotational inertia. A more precise approach will present the rotational inertia effect on the drivetrain as in Equation (6) [12], where each component inertia (I_e - engine, I_t - transmission, I_d - driveshaft, I_w - wheel including tire, rim and axle shaft) is individually analyzed and its influence is adjusted according to the intermediate transmission ratios (N_{tf} and N_f) for the analysis point (tire axle).

Analyzing Equation (6), during acceleration ($a_x > 0$), the right term of the equation is negative, representing the inertia consuming part of the force from the engine. During deceleration ($a_x < 0$), as in coastdown situations, although the engine is disconnected and there is no input torque (T_e), the right term of the equation is positive. This way, there will be a residual traction force (F_x) on the tire, once the rotating components are still moving the wheels forward. As this effect is proportional to acceleration, it is more significant at the beginning of the test and loses influence when deceleration is slower, and the vehicle approaches rest.

Efficiency – This parameter combines transmission and final drive elements and represents the losses (mechanical and viscous) in the driveline components (transmission, driveshaft, differential, and axles) [12]. This efficiency is mainly caused by the driveline's friction loss and oil splash loss [8].

Friction is a significant factor in mechanical components, such as the transmission internal friction, differential friction, wheel bearings friction, brake friction, and so on. On the other hand, quantifying these losses in single components is still a challenge. Frequently, they are combined with viscous losses in a loss value or percentage based on tests and development experiences. Depending on the approach, simplifications are performed as presented by Swift (1991) [17], indicating contributions from transmission losses and brake drag are small (< 12 N) and could be incorporated into the rolling resistance term. These are approximations, and their applications depend on the required accuracy of each analysis, including the methodology considered for determining the rolling resistance coefficient, which is discussed in a following subsection.

As a literature example, Zhao et al. (2019) [18] performed an analysis of these losses on individual components for electric vehicles and showed their impact on coast resistance and energy consumption. As the main results, they highlight that oil splash loss can be effectively reduced when lowering immersion depth and that a 30% reduction of gearbox oil reduced coasting resistance by 4%, and energy consumption by 1.5%. They also analyzed the influence of brake clamp drag by removing the front brake clamp during a coastdown test with a maximum speed of 70 km/h due to safety concerns, showing a coasting resistance approximately 12.5% lower, indicating that brake clamps with lower drag yield lower energy consumption. However, it is noteworthy that analysis of single components may have to be compromised when they are integrated with other components and influence the overall system [18].

AERODYNAMICS – Aerodynamic drag is the resistance of the air to the movement of the vehicle, since when flowing over the vehicle, the air generates normal pressure and shear stress on the body, generating pressure drag and friction forces, with pressure drag being the most significant [12,13].

Vehicle shape – The aerodynamic performance is strongly influenced by vehicle aerodynamic contour or shape [18] and by the air [8], as seen in Equation (4). The vehicle C_D coefficient and frontal area A_f are the parameters that represent the vehicle shape, and they directly impact the vehicle performance. While smoother vehicle shapes like sedans present better aerodynamics, rougher shapes such as those in pickup vehicles go in the other direction. These parameters are defined during the product development process, looking for lower values according to the goals of each project.

Speed – The net speed between vehicle and air is an important influence in aerodynamic drag [17]. Although the speed range for the coastdown test is already established, they are influenced by the wind, adding or subtracting to the net speeds. Besides, it is noticeable the influence of the aerodynamic components in the road load results, due to the quadratic speed term [17] seen in Equation (4), which matches the similar term in Equation (1) defined by the standard ABNT NBR 10312, in case speed dependency is disregarded in other resistance parameters, such as many rolling resistance approaches [17].

ROLLING RESISTANCE – The rolling resistance is a main influencing factor on the prediction of vehicle energy consumption [19] and environmental impact. Various investigations have shown that lowering 10% to 30% of this resistance can result in fuel economy of 2% to 6% [1]. This way, the usage of low-rolling resistance pavements (negative texture surfaces, small-size aggregates, structures with high stiffness, and repaired) and/or low-rolling resistance tires is recommended while keeping enough skid resistance to ensure vehicles stop safely [1].

It depends on the characteristics of pavements and the tire properties [1,8]. It is the energy loss in contact between the tires and the road surface and is the main resistance in low-speed situations [12]. As an example, the aerodynamic force becomes equal to rolling resistance only at speeds of 50-60 m/s [12]. This is mainly caused by hysteresis in the tire materials due to their deformation when in contact with the ground [13] and, consequently, providing energy dissipation [20] of the stored energy in the tire mainly into heat [1,8].

Besides the mass impact already discussed, the rolling resistance coefficient f_r is one of the main influence factors, and its realistic determination is a challenge and focus of ongoing research due to the complex interaction processes between tires and pavements [1]. This value can be measured through several methods (drum, trailer, coastdown, and so on). Although there are different devices to measure rolling resistance, empirical relationships from measurements significantly depend on testing methods and conditions [1]. Depending on the required accuracy, the rolling resistance coefficient can be estimated by the coastdown test results [17]. This value can also be modeled via simulation based on the Finite Element Method (FEM), considering all the energy loss in the vehicle-tire-pavement system, which is difficult and time-consuming [1].

In automotive applications, the f_r varies between approximately zero and 0.3 [20]. There are also approximations through values according to the type of track, such as, for example, from 0.01 to 0.015 for concrete, from 0.023 for asphalt in poor condition, and from 0.033 to 0.055 for stone pavement in good condition [20]. These values are approximations and can be estimated based on equations from the literature, but the variations in results are significant.

At low-road speeds, the rolling resistance is well approximated as a constant, but velocity dependence is needed at higher speeds [17], due to the increase of flexing work and vibration in the tire [12]. The influence of speed becomes more pronounced when it is combined with lower inflation pressure [12]. Equations (8) to (14) present some of the main approaches present in the literature to calculate f_r, considering V in m/s. It is possible to observe that the speed dependence varies significantly depending on the proposed approach. More details and comparisons among these rolling resistance equations can be found in Lourenço (2024) [14].

$$f_r = 0.013+6.5/3.6\cdot 10^{-6}\cdot V \qquad [21]\ (8)$$

$$f_r = 0.011+0.01944\cdot(0{,}0223694V)^{2{,}5} \qquad [22]\ (9)$$

$$f_r = 0.09\cdot 10^{-2}+2\cdot 10^{-5}V/3.6+4\cdot 10^{-12}(V/3.6)^4 \qquad [23]\ (10)$$

$$f_r = 0.01+2.24\cdot 10^{-4}V \qquad [12]\ (11)$$

$$f_r = 0.0136+1.44\cdot 10^{-7}V^2 \qquad [13]\ (12)$$

$$f_r = 0.015+7\cdot 10^{-6}V^2 \qquad [20]\ (13)$$

$$f_r = 0.01(1+V/576) \qquad [24]\ (14)$$

Tires – From the tire perspective influence on the rolling resistance, its materials, structures, and dimensions are significant. The materials and thickness of both the tire sidewalls and the tread determine its stiffness and energy loss during rolling [12]. For example, although hysteresis in the tread rubber is important for good wet traction, it decreases rolling resistance performance, while a worn-out, smooth tread shows rolling resistance coefficients up to 20% lower than new tires [12].

Tire manufacturers test their products and provide tire rolling resistance (also known as RR), according to ISO 28580 [25]. This standard presents a tire rolling resistance measurement method for passenger cars, trucks, and buses under controlled steady-state laboratory conditions using a drum test bench and includes a method for correlating measurement results to allow inter-laboratory comparisons [25]. The values measured according to the standard reflect the tire characteristics and not the overall rolling resistance coefficient, since it also depends on the road. As a literature example, Zhao et al. (2019) [18] analyzed these coefficients for an electric vehicle and found out that, when comparing a larger coefficient to a lower coefficient tire, it yields an average 8% reduction of coasting resistance, implying 3% energy reduction.

Regarding tire inflation pressure, it determines the tire elasticity and, in combination with the load, the deflection in the sidewalls and contact region of the tire. Besides, the effect on rolling resistance also depends on the ground elasticity [12]. For example, on soft surfaces like sand, high pressures elevate ground penetration and lead to higher coefficients, while lower pressures decrease ground penetration and increase tire flexure. The conclusion is that the optimum pressure depends on the surface deformation characteristics [12]. On medium plastic surfaces such as dirt, the effects on the tire and ground are approximately balanced, and the rolling coefficient is nearly independent of inflation pressure. Finally, on hard (paved) surfaces, the coefficient decreases with higher inflation pressure since tire flexure is significantly reduced [12]. As a literature example, in the case of hard surfaces, research by Gong et al. (2020) [8] for an electric vehicle showed that, when the pressure is 20% less, average coasting resistance increases by 1% to 3%.

Road – The impact of road conditions (roughness, inclination, dirt) on the resistance are known, and a lot of effort has been made to identify the correlation between rolling resistance and its influence factors, such as surface texture of pavements [1]. Jazar (2017) [20] already presented different values according to each type of pavement, where soft and rough surfaces result in higher rolling resistance than hard and smooth surfaces [1]. Besides, it was found that a 6% to 30% change in rolling resistance can be caused by the change of surface texture, for example, double-layer porous asphalt concrete (aggregate size of 2/6) provides 8% to 10% lower rolling resistance than the single-layer porous asphalt concrete (aggregate size of 6/16) [1].

TEST CONDITIONS – Although performed in standard boundary conditions, results of multiple tests vary due to variations in environmental parameters over and above standard conditions [6], influencing the parameters already presented.

Vehicle preparation – Many factors in vehicle preparation are known to influence the coastdown results, such as oils, vehicle running-in, tire running-in, vehicle alignment, brake adjustment and running-in, vehicle conditioning before and during the test, and so on, affecting mainly the drivetrain efficiency. When put together, they present a significant impact on results. However, quantifying their isolated contributions is still a challenge, as their values can be overlooked when compared to the big influences, such as rolling resistance and aerodynamics. This way, the standards, such as ABNT NBR 10312, indicate, for example, that tires should be from 10% to 50% wear and the vehicle has traveled at least 3000 km [9], so the automaker can prepare their vehicles according to the guidelines, looking for the better combination of parameters inside the allowed ranges.

Temperatures – Among the driving resistances, the drag and rolling resistances are temperature dependent [7]. The higher the temperature, the lower the air density considered in aerodynamic resistance. Moreover, at higher ambient temperature and pavement temperature, the overall temperature of tires increases, and the modulus of the rubber material decreases, reducing energy dissipation and rolling resistance [1,12]. Gong et al. (2020) [8] presented, for EVs, that with the atmospheric temperature in the 6 to 32°C range, the resistance is decreased by 0.48% for every 1°C increase.

The ambient temperature can impact the powertrain system efficiency as well, for example, in the gearbox, where lower temperature leads to higher oil viscosity and higher oil splash loss, lowering the gearbox efficiency [18]. Choi et al. (2024) [7] presented the road load variations according to temperature, showing that among aerodynamic drag and rolling resistance, rolling is the main one affected, then proposing temperature correction factors.

Wind speed – As seen in Equation (1), the aerodynamic resistance presents a greater impact for higher speeds. In an ideal scenario, there is no wind, and the vehicle speed is the only one considered. On the other hand, if there is headwind or tailwind, the net speed changes, and this resistance changes as well.

EXPERIMENTAL EVALUATION

In order to illustrate the potential and practical application of the knowledge presented in this paper, the calculation methodology (proposed here) was used on a vehicle whose coastdown values were previously determined through on-track coastdown measurements. The objective of this analysis was to prove the viability of using analytical methods for product development activities, avoiding the complexity, time-consuming, and cost of the physical on-track measurement process.

As a base, this work used a compact 1.0 vehicle with a manual transmission (MT) with a conventional 5th-gears gearbox and, as an objective of calculation and comparison, the same vehicle model with an automatic transmission (AT) with a torque converter. This work aims to estimate the road load of the AT vehicle based on the MT vehicle.

Also, some important characteristics of these vehicles and considerations should be addressed. The tires of both vehicles have approximately the same dynamic radius and rolling resistance coefficient. Therefore, in this case study, the main analyzed contributions are related to mass, aerodynamics, and transmission. Regarding mass, there is a difference of 57 kg between the two vehicles, where the AT vehicle is noticeably heavier due to the contribution of the transmission, but also due to other accessories that, in the marketing view, make it more "desirable" for consumers. Regarding aerodynamics, the AT vehicle has aerodynamic values approximately 1% higher than the reference MT vehicle, already considering both contributions of the aerodynamic drag coefficient and the vehicle frontal area ($C_D A_f$).

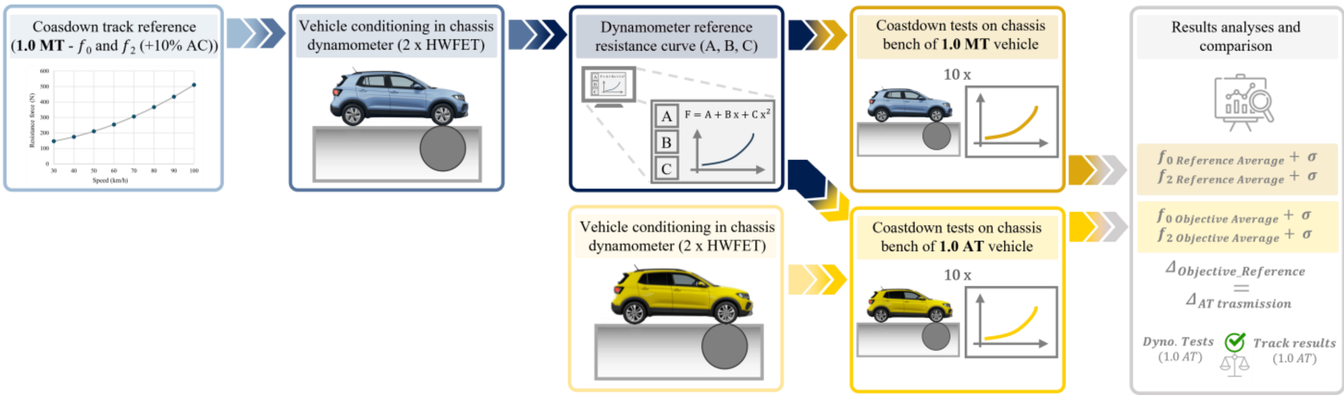

Figure 4. Overview of coastdown test methodology performed at the chassis dynamometer.

The experimental step-by-step methodology is presented in Figure 4. To calculate the transmission contribution, tests in a chassis dynamometer laboratory were performed. As seen in the image, the process starts with the reference value of the MT vehicle obtained at the on-track coastdown test. These values were applied to adjust the coastdown curve on the chassis dynamometer. Then, a vehicle warm-up was performed by running two HWFET (Highway Fuel Economy Cycle) in sequence, in order to warm vehicle components, such as tires, lubricants, and so on, once they are influenced by the temperature, impacting the results. The next step was to obtain the dynamometer adjustment curve (A, B, and C coefficients), expressed as a quadratic equation as a function of speed, as in Equation (15). These coefficients are the reference setup values for all the following experiments.

$$F = \mathrm{A} + \mathrm{B}\,V + \mathrm{C}\,V^2 \qquad (15)$$

Thus, 10 deceleration coastdown tests were performed at the chassis dynamometer for the reference vehicle MT. Once the reference vehicle was established, the AT was analyzed with a similar procedure. The dynamometer was again set with reference vehicle coefficients, two HWFETs were run for warm-up, and 10 coastdown tests were done in sequence.

After the tests, the measured data were analyzed. To obtain the automatic transmission contribution, the Monte Carlo analysis was applied for the mean values and their respective standard deviations. Monte Carlo is a sampling technique used for obtaining a probabilistic approximation to a model solution [26]. It repeats an experiment many times and generates a large amount of randomized data to better describe the system [27]. The idea is that by increasing the samples, the average value gets closer to its true value [28]. This way, it was possible to increase the quantity of data to calculate more representative average values and their standard deviations for each vehicle under evaluation.

The data from the dynamometer follows the A, B, and C forms as coefficients for the resistance force, as shown in Equation (8). On the other hand, the approach proposed by the standard NBR10312 disregards the linear dependency of the speed (second term B), resulting in only two coefficients. Aiming to perform a similar analysis, an adjustment was performed by keeping the quadratic coefficient (C) and absorbing the small linear speed influence of coefficient B into a new equivalent coefficient A. This way, the resulting A and C coefficients are representative of f_0 and f_2. Finally, the transmission contribution was obtained as the difference delta between the coefficients from the reference vehicle (1.0 MT) and the objective vehicle (1.0 AT), as illustrated in Figure 4.

It is noteworthy that chassis dynamometer tests present uncertainties due to bench setup configuration adjustments that can impact vehicle consumption [19]. On the other hand, during the coastdown experiments, the vehicle is not driven, so the driving style of the driver does not significantly affect the current analysis as it would be in a consumption evaluation. Moreover, the laboratory represents a controlled environment, where many of the influencing parameters on the results can be avoided or minimized. This way, although realizing the conditions of chassis dynamometer tests, they still represent a plausible and alternative solution to perform vehicle coastdown evaluations when compared with the on-track coastdown test and its conditions defined by the NBR10312.

RESULTS AND DISCUSSIONS

Regarding experimental results, after applying the procedures presented in the previous section, the evaluated vehicles test results were compared with the on-track coastdown results. By adding the delta of the transmission contribution to the coefficients from the reference vehicle (1.0 MT), the objective vehicle (1.0 AT) resistance was obtained. These values were compared with the on-track coastdown results of the 1.0 AT and are presented in Figure 5. By analyzing Figure 5, the calculated resistance force is slightly higher than the on-track measurement. It is observed that the higher the speed, the higher the gap between the curves.

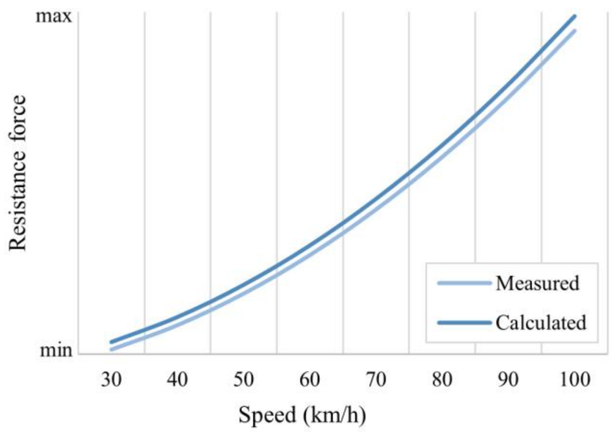

Figure 5. Comparison between the resistive force by the proposed method and the on-track result (1.0 AT vehicle).

When looking at the coefficients, the resistance curve calculated with the proposed methodology presents a 6.8% higher value of f_0, which represents less than a 10 N difference. Moreover, regarding f_2, this difference is 2% higher, representing less than 0.001 N/(km/h)^2. Although the force difference increases with speed, the percentage difference decreases once the force values, the bases for the percentage, are higher, making the percentage difference less outstanding, varying between 5.7% and 3.2% in the range of 30 km/h and 100 km/h.

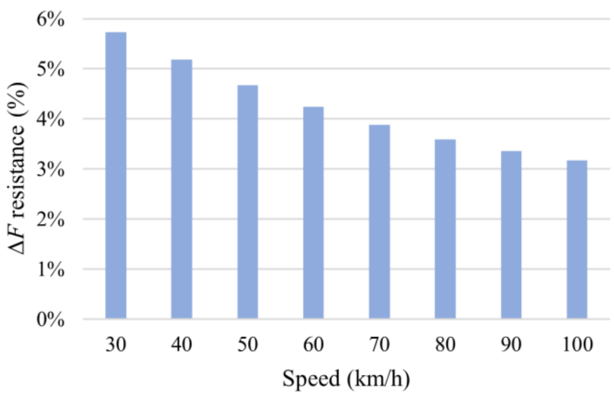

Figure 6. Percentual differences in resistance force between the proposed method and the on-track result (1.0 AT).

The presented values are considered coherent and accurate enough, since the experimental procedures of the NBR10312 allow variations in a larger range than the ones observed. This way, the results show that the proposed methodology succeeded in predicting the resistance values of the AT vehicle.

CONCLUSIONS

Aware of global warming and the environmental impacts caused by the automotive industry, this work was motivated by the search for alternatives that can improve vehicle efficiency with a focus on analyzing and improving the coastdown process. This way, this paper presented an analysis of the variables involved in the coastdown test, highlighting the main influence variables, including analyses based on literature and on laboratory experiments. An overview of the current standard applied to coastdown tests in Brazil was presented, showing its methodology, allowed variations, and also the challenges involved in carrying out these tests.

Moreover, the main longitudinal vehicle dynamics equation that details the deceleration movement was addressed and correlated with the approach proposed by the standard, showing it is a simplified approach that reflects the behavior described by the physical equations based on Newton's Second law. In the following, knowing the equations, discussions based on literature research were carried out regarding the main influence factors that affect the parameters that describe vehicle resistance to movement and, hence, vehicle energy consumption. Further, an experimental evaluation of a coastdown in a chassis dynamometer was carried out, showing it is possible to predict the coastdown result of a different vehicle version based on an established reference vehicle.

Finally, the objective of the proposed analysis was achieved, showing the viability of using analytical methods to obtain the coastdown results. Besides, the on-track test procedures allow many variations that significantly impact the results. The proposed approach avoids complexity and is less time- and cost-consuming when compared with the physical on-track measurement process. Thus, calculating coastdown values analytically, whether purely based on physics or using data from tests and chassis dynamometer laboratories, reduces these variations. This way, these values could be used as references for analysis and product development.

FUTURE PERSPECTIVES

Once the main physics equations were presented, the use of dynamometric chassis benches is known to the automakers, and the experimental procedures and acceptable variation parameters are established on the government standard, it is possible to calculate and predict the results of coastdown tests, as well as to validate the calculations with experimental results from laboratory and road tests. This will make it possible in the future to save time, resources, and work on carrying out tests.

Furthermore, the research on coastdown resistance will keep on going in the next decades, as it is vital to electric vehicles. They tend to be heavier due to battery weight, implying higher resistance to movement when compared to conventional combustion. This way, there is an effort to optimize these values, to have more efficient vehicles [8,18] and present a better driving range relying on the battery. Research on key factors for range and energy consumption of electric vehicles showed that an 18% reduction of coasting resistance contributed to a 5.5% reduction of energy consumption in the analyzed case study, being the most influential factor analyzed on the energy consumption improvement [18].

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