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INFLUENCE OF ROAD SLOPES IN THE TURBOCHARGER'S BEHAVIOR

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Abstract. *The pursue for more efficient and less polluting engines have led researchers to adopt strategies to improve internal combustion engines (ICE). One of these strategies is the use of turbochargers, that provide the supercharge needed to maintain power when emission and weight limit engine projects are applied. In that context, a proper characterization of the turbocharger's behavior is required in order to guide it's development. The purpose of this article is to obtain the operation of a turbocharger associated with a vehicle submitted to a real driving cycle, and evaluate the influence of the road's slopes. A real driving cycle is obtained in a Brazilian Highway to simulate the turbocharger's characteristics on a heavy-duty vehicle under usual conditions of a road scenario. The results are obtained first considering the vehicle in a plane surface and, in sequence, in the real road relief. The simulations are made in GT Suite Software, from Gamma Technologies, using the engine and turbocharger data obtained in dynamometer tests, and the vehicle and driving cycle characteristics. At the end of the simulation, the turbocharger's angular speed over time is obtained for both situations and it is possible to compare them and conclude that the relief accentuates the medium speed. In the tests conducted, the raise was of 12,7%. Therefore, to well represent reality in simulations, the road slope has to be considered.*

Keywords: *Turbocharger, Driving cycles, Heavy duty vehicle, Computer simulation.*

1. INTRODUCTION

Turbochargers have been applied to Internal combustion engines (ICE), both Diesel and Otto, as a way of increasing performance while reducing the engine greenhouse gases emission and fuel consumption. The turbocharged engines recover energy from the exhaust gases and use it to compress the inlet gases, boosting it's efficiency. (Baêta *et al.*, 2015, 2018; Baêta, 2006). This increased efficiency is desirable so that the engine can be optimized in terms of emissions, manufacturing cost and fuel consumption. Because of this, it is important to know the behavior of this component in order to best apply it. The proper combination of the engine and the turbocharger allows better operating conditions for both, thus making better use of the exhaust gas energy and avoiding undesired faults of the component. (Brunetti, 2012).

The strong relationship between the well functioning of the turbocharger and the ICE efficiency has led to the development of different techniques to study this turbomachinery characteristics. Turbochargers under constant angular speeds are evaluated in standard test benches, for example. (Galindo *et al.*, 2006, 2013, 2017). However, transient behavior is natural in a real condition turbocharger operation, as the vehicle work under variable speeds, causing variable air flow into the turbocharger and, therefore, transient angular speeds during its functioning. Serrano *et al.* (2017, 2009,?); Wu *et al.* (2017) and Wu *et al.* (2017) have highlighted the need to simulate real road conditions in order to achieve a more accurate analysis. That can be done using driving cycles.

Standard driving cycles are profiles of vehicle speed over time developed to simulate real driving conditions for different vehicles in various road contexts. These cycles are applied nowadays in emission validation, the vehicle is submitted to it and the emission parameters are measured and evaluated. According to ABNT (2008), the homologation of vehicles by emissions tests is required by law in Brazil for all light vehicles and for engines applied in heavy vehicles. In these tests, driving cycles are used, that is, the vehicle is subjected to a sequence of speeds over a period of time, which are intended to represent the actual driving conditions in a city, on a highway, or in rural environment. There are several standard cycles developed for the evaluation of emissions of each type of vehicle.

An example of a transient cycle is the European Transient Cycle, or ETC, a transient cycle that was implemented in Europe in the year 2000 and is used in the approval of road vehicles. The complete ETC cycle lasts for 1800 seconds with an average speed of 59 km / h.(ABNT, 2008)

Standard driving cycles, however, consider that the vehicle is traveling in a plane road. As is done by Roso *et al.* (2016), it is possible to obtain specific driving cycles, characteristic of a city or a rout developed by any driver. These cycles consider characteristics of the location and even the way of driving of an individual. A real driving cycle is obtained in this article, aiming to represent with greater fidelity the actual operating conditions of a ICE submitted to a real rout and topography. This paper aims to simulate a vehicle and it‘s turbocharger under a real driving cycle, allowing a comparison of it's operation considering no road slope, as it is usually done in standard driving cycles, and the real road relief. This way, it is possible to evaluate if cycles that do not consider the road slopes represent well the reality.

To achieve that, a computational one-dimensional model of the vehicle is created and submitted to the cycle. The input conditions required for the simulations are the experimental parameters of a turbocharged diesel ICE obtained in dynamometer test bench in steady state, the characteristics of a vehicle in which the turbocharger is applied, and the cycle‘s informations. The results for each cycle are compared.

2. METHODOLOGY

The methodology used to achieve the article's goal is divided in three main parts. The first is the real driving cycle measurement, the second, the acquisition of the steady state engine data to be inserted in the simulation, and the third, the simulation itself, including in the model the vehicle characteristics, and the engine and cycle data obtained in the previous steps.

2.1 Real driving cycle obtainment

A real driving cycle was obtained using *Global Positioning System* GPS on a heavy truck's rout. The speed of the vehicle over time, distance, and altitude were measured and recorded for 18 minutes, with a sampling rate of one acquisition every 2 seconds approximately, using the app GPS Speedometer for smartphone, from California Cyber Developers ®. The rout used is shown in Fig. 1, on the Expressway Presidente João Goulart in Rio de Janeiro.

The slopes of the road were then calculated based on the height and the distance traveled, and inserted into the computational model. The cycle obtained aims to represent the road profile of a Brazilian highway.

For the Simulations, these data obtained resulted in two driving cycles. Both cycles present the same speed profile over time, the only difference between them is the slope considered. In one, the road slope considered is zero, that is, as if the vehicle was transiting in a plane rout. In the other cycle, the road slope obtained in the GPS measurement is considered.

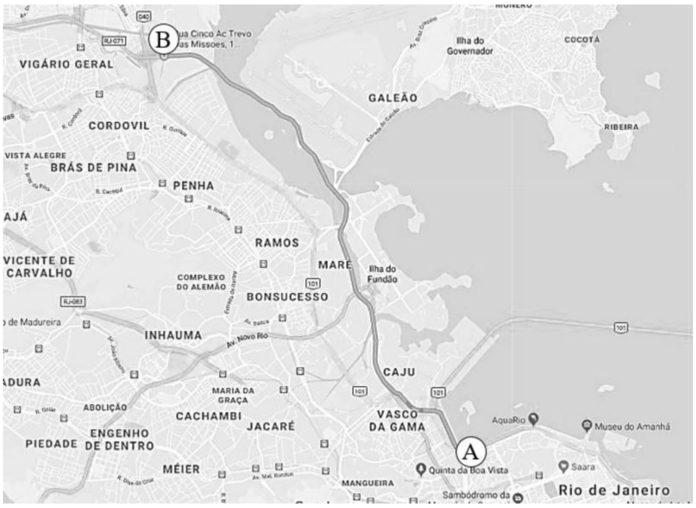

Figure 1. Rout used to obtain the driving cycle used in the simulations.
Developed by the authors using *Google maps*.

2.2 Engine steady state conditions

Experimental tests in a dynamometer bench are performed with *Cursor 13* from *FPT Industrial*, an 13 liters diesel engine. Table1 presents the engine characteristics. A waste gate turbocharger and an after cooler are adopted. It is an engine with volumetric compression ratio of 16.5, which represents a typical heavy-duty engine applied in Brazil's vehicles. The dynamometer test is done to obtain and plot the engine map, in which different engine torque values are measured in different engine speeds and accelerator pedal positions. For each of these conditions, the turbocharger's angular speed is also measured. The results are used as boundary conditions in the computational vehicle model.

Table 1. Main characteristics of the engine

N° of cylinders	6
Configuration	In line
Displacement volume	12880 cm^3
Volume compression ratio	16.5 $\pm$0.8
Bore $\times$ Stroke	135.0 $\times$ 150.0 mm
Injection type	Direct injection
Charging system	Turbocharger with waste gate valve, after cooler and oil refrigeration
Moment of inertia	1.44 kg m^2
Engine control system	Electronic central unit
Engine emissions regulations	EURO V
After treatment	Selective catalytic reduction with urea injection
Ignition order	1-4-2-6-3-5

The engine was tested on a dynamometer, outlined in Fig. 2. An alternating current dynamometer with maximum: 5000Nm / 8000kW) is used; The measuring torque flange (HBM T10F), which allows both the speed of rotation of the engine and its load, combined with a program for control and acquisition of data were adopted. The pressure inside the cylinder is measured using the AVL GH14DK piezoelectric transducer, with a fuel analysis using a timeless data battery (AVL IndiModul 622), combined with a high rotary shaft encoder (AVL 365). Heat Release Rate (RLT) and heat transfer rate were calculated using a combustion analyzer (AVL IndiCom); The ratio air/fuel was measured using a broadband oxygen sensor and a lambda meter (ETAS LA4).

The fuel injection is controlled by the FeV Fuelcon system and the fuel consumption is determined by means of a coriolis mass flow sensor (Emerson Micro Motion Elite CMF010). A thermal and mass flowmeter (ABB Sensyflow) is used to measure the admitted air flow and to record the turbo speed during the experiment. The turbocharger was instrumented with an electromagnetic speed sensor, the Jaquet DSE 0603 DSH.

The purpose of the dynamometer test is to obtain the turbocharger speed for each engine operating point. That is, for different values of torque, rotation, and positions of the accelerator pedal, the rotation of the turbo is obtained. The results are used as input conditions in the vehicle's computational model.

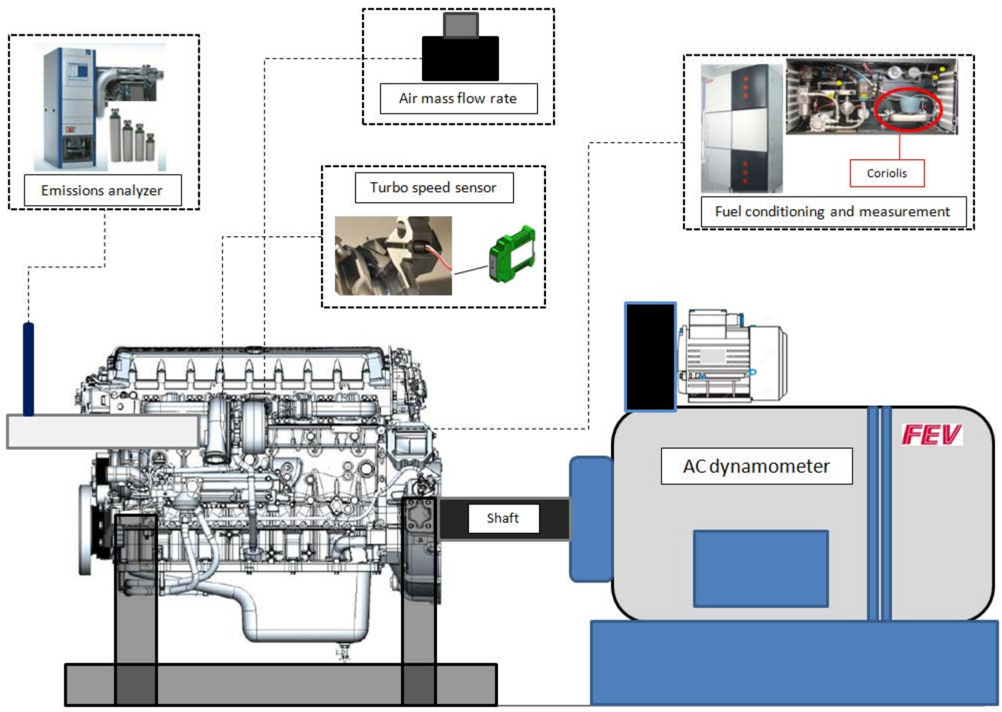

Figure 2. Dynamometer used in the engine tests in steady state conditions. Developed by the authors with material provided from the engine producer.

2.3 Vehicle simulation

The vehicle model is done in the GT-Suite software by Gamma Technologies. Having the speed target over time and the engine map defined, these data are inserted in the vehicle simulation together with the vehicle's characteristics. The heavy truck in which the engine described above is applied has it's main features presented in Tab.2. Figure 3 shows the software main interface.

Table 2. Main characteristics of the vehicle

Vehicle Frontal Area	8.14 m^2
Vehicle mass	23.000 kg
Vehicle Drag Coefficient	0.5
Gear Ratio 1^{st}	13.8
Gear Ratio 2^{nd}	11.54
Gear Ratio 3^{rd}	9.49
Gear Ratio 4^{th}	7.93
Gear Ratio 5^{th}	6.53
Gear Ratio 6^{th}	5.46
Gear Ratio 7^{th}	4.57
Gear Ratio 8^{th}	3.82
Gear Ratio 9^{th}	3.02
Gear Ratio 10^{th}	2.53
Gear Ratio 11^{th}	2.08
Gear Ratio 12^{th}	1.74
Gear Ratio 13^{th}	1.43
Gear Ratio 14^{th}	1.20
Gear Ratio 15^{th}	1.0
Gear Ratio 16^{th}	0.84
Differential Final Ratio	3.73

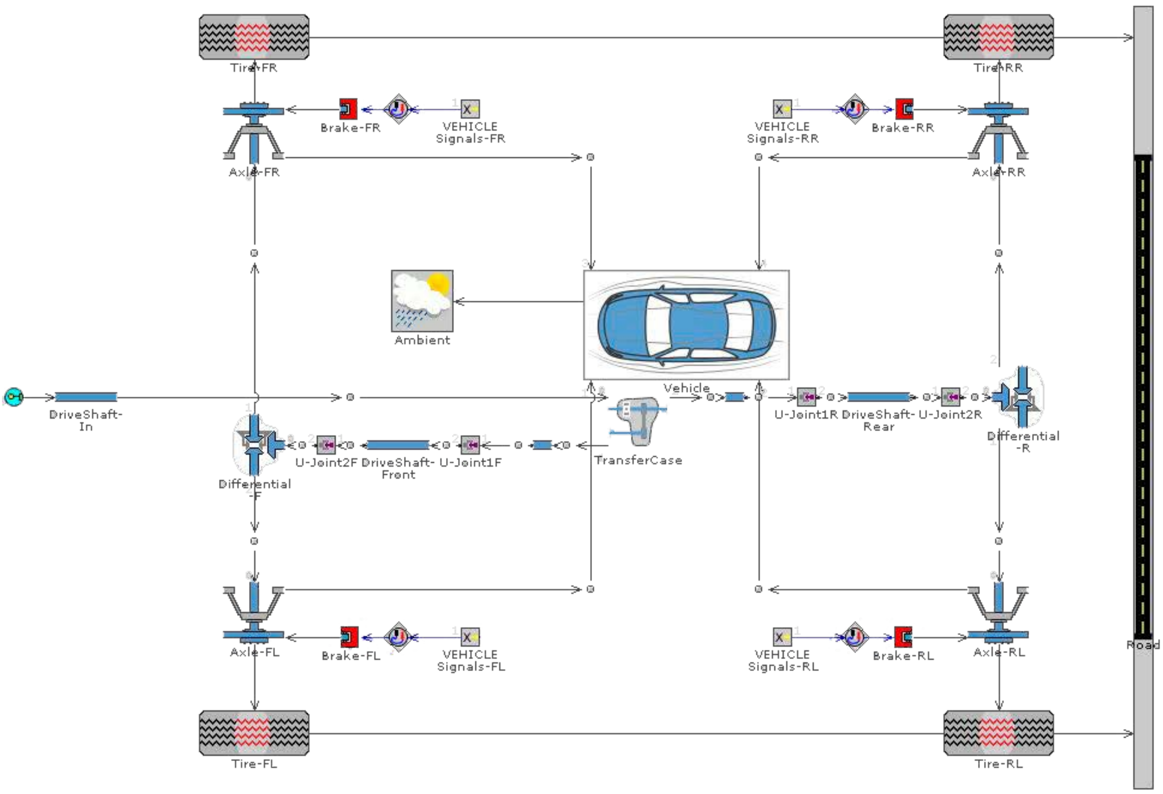

Figure 3. GT Suite main interface. Developed by the authors using GT-Suite Software.

On the computer model, transient engine speed, torque and accelerator pedal position necessary to achieve the chosen driving cycle's speeds are calculated. This is done through the differential equation of motion Eq.1 integrated in time.

The left side of Eq. 1 is the torque required to accelerate the effective inertia. I_{trans1} and I_{trans2} represent inertia in the input and output of transmission system respectively. Drive-shaft and axle moment of inertia are I_{dsh} and I_{axl}. R_d and R_t represent final drive and transmission ratio for each gear. Vehicle speed (ω_{drv}) over time (t) is related to wheel radius (r_{whl}) and vehicle mass (M_{veh}). Aerodynamic forces are indicated as (F_d), rolling resistance forces as (F_{rot}) and gravity forces as (F_{grd}) Technologies (2016).

The turbocharger's speed is then defined for each transient engine speed, torque and accelerator pedal position point. Obtaining it's speed over time profile. The simulation was conducted twice, one considering the road as plane and one inserting the road slope in the model.

$$\tau_{vehicle} = \left[I_{trans1} + \frac{I_{trans2}}{R_t^2} + \frac{I_{dsh}}{R_t^2} + \frac{I_{axl}}{R_d^2 R_t^2} + \frac{M_{veh} r_{whl}^2}{R_d^2 R_t^2}\right] \frac{d\omega_{drv}}{dt} \left[\frac{I_{trans2}}{R_t^3} + \frac{I_{dsh}}{R_t^3} + \frac{I_{axl}}{R_d^2 R_t^3} + \frac{M_{veh} r_{whl}^2}{R_d^2 R_t^3}\right] \omega_{drv} \frac{dR_t}{dt} + \left[\frac{F_{aer} + F_{rol} + F_{grd}}{R_d R_t}\right] r_{whl} \quad (1)$$

The simulations are done centered in the driving cycle obtained previously. The turbocharger's speed is calculated to each vehicle speed presented in the cycle. A gear shifting strategy is defined analysing the engine's power curves. Aiming optimized power, the engine is set to work between 1000 and 2000 rpm, when the engine speed achieves those values, the software acts changing the gear adopted for that time.

Two simulations are performed, one considering the vehicle traveling at the speeds of the cycle obtained, but with the inclination zero, that is, in the plane; and another considering the slopes calculated for the path over time.

3. RESULTS AND DISCUSSION

The driving cycle obtained through GPS is presented in Fig.4. The speed over time is plotted for the 18 minutes of cycle. The mean speed is 75,11 km/h whit a minimum speed at the start of the cycle, of 2,5 km/h, and a maximum speed of 89km/h achieved in the second half of the driving cycle. The driving cycle presents multiple periods of acceleration (positive and negative), which is a typical behavior of a vehicle on a real road condition.

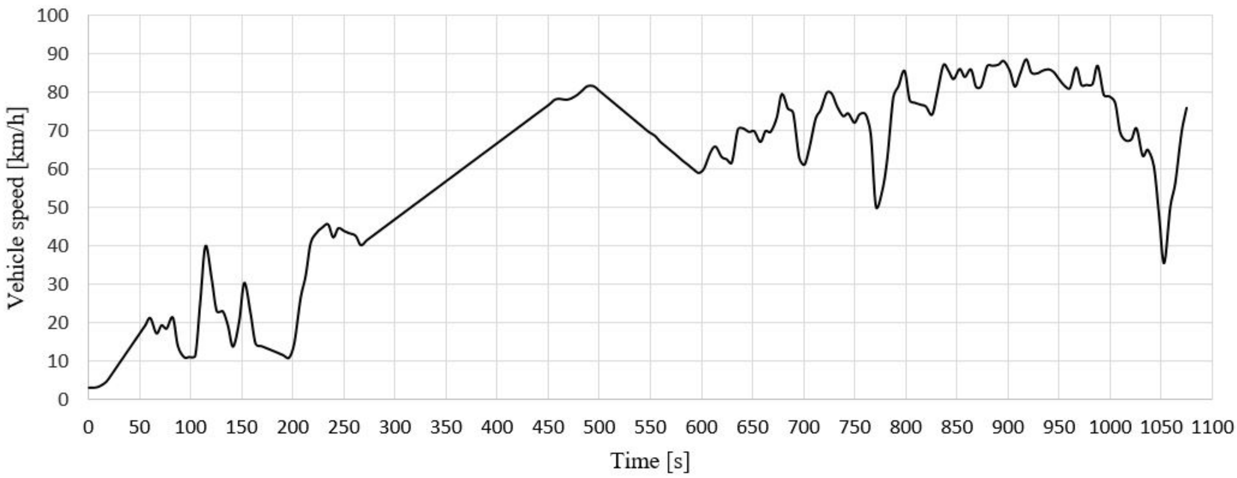

Figure 4. Driving cycle. Developed by the authors.

Figure 5 presents the altitude over distance for the road in which the cycle was measured. There are portions of the graphic that shows negative altitude, what is expected once the rout was obtained in a sea level road, with possible under zero altitudes. It is observed a high altitude increase between 60 and 150 seconds of cycle, in which the vehicle gets to 60m, the rest of the altitude profile presents lower variations.

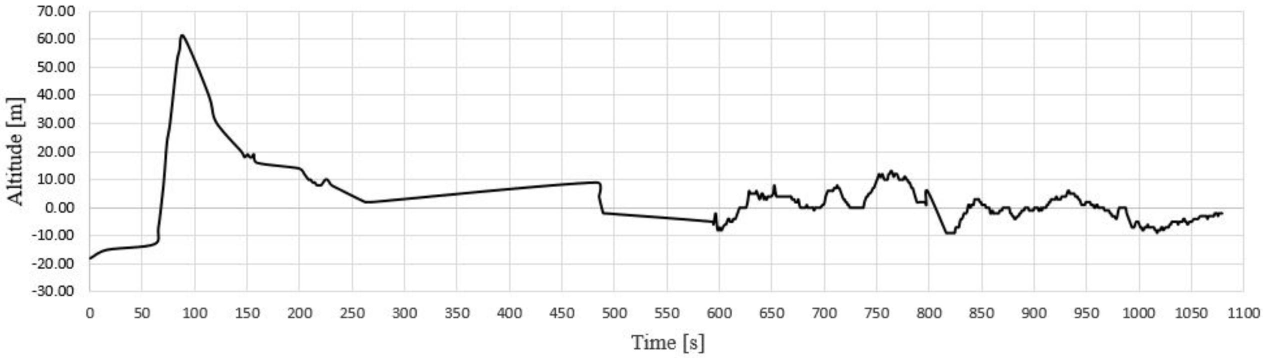

Figure 5. Road altitude through distance. Developed by the authors.

The dynamometer test results are presented in Fig.6 and 7. In Fig.6, the engine speed and torque points are plotted for different accelerator pedal positions (10, 20, 50, 70 and 100%). In Fig.7, the turbocharger's working conditions are also presented in means of speed. It's speed is given for each point of acceleration pedal position and engine speed or points of torque and engine speed in the second graphic.

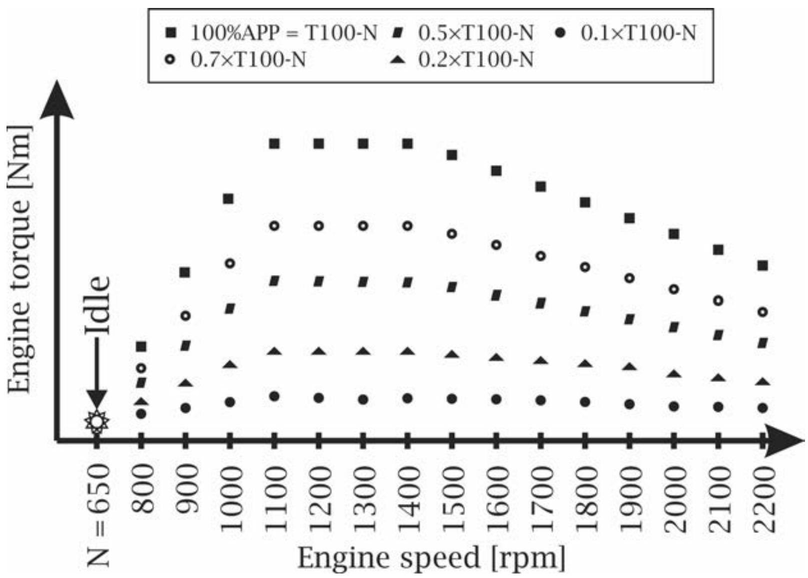

Figure 6. Engine map obtained in dynamometer test. Developed by the authors.

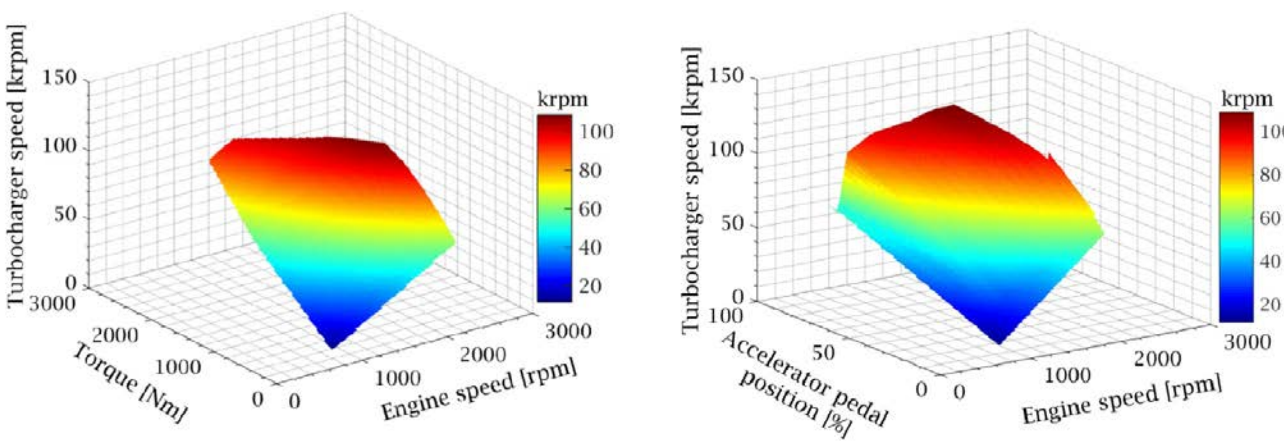

Figure 7. Turbocharger's maps obtained in dynamometer test. Developed by the authors.

These data and the driving cycle, together with the vehicle characteristics, are used to obtain the turbocharger's speed through time when the vehicle is traveling in the driving cycle.

The results for both of the simulations are presented in Fig. 8, as it can be seen, the angular speed is accentuated in the situation in which the road slope is considered, the raise is of 12,7%. It can also be observed that the peak in the turbocharger's speed profile coincides with the higher peak in the altitude profile, making the effect of road slope evident.

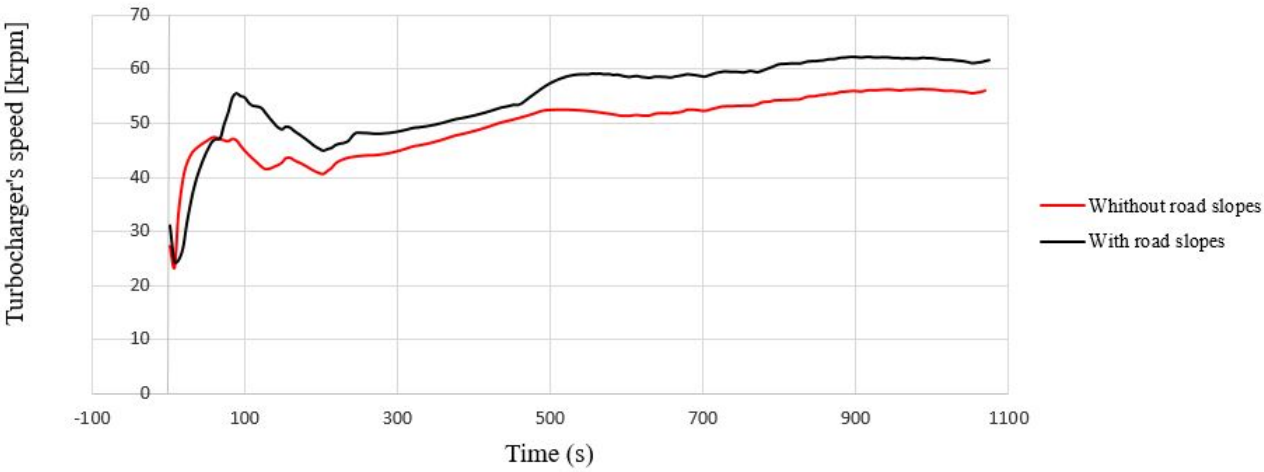

Figure 8. Turbocharger speed through time. Developed by the authors.

Therefore, the road slope is a factor that should be considered when analyzing turbochargers behavior. Simulations with standard driving cycles used in emission regulations, for example, do not represent the real road conditions. Different places with different topography characteristics will cause different effects in the engine functioning and, therefore, in the turbocharger as well. Those effects should be considered when evaluating project specifications for a turbocharger. An Engine applied in a road in a specific Brazil's state will not have the same working conditions as one applied in an other place, for example.

4. ACKNOWLEDGEMENTS

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