# Accuracy and precision of the drag and rolling resistance coefficients obtained by on road coast down tests

**José Ignacio Huertas***
Department of Mechanical Engineering
Tecnológico de Monterrey
Eugenio Garza Sada 2501, Monterrey, México
*jhuertas@itesm.mx

**Gustavo Andrés Álvarez Coello**
ERGON - Automotive Engineering Research and Development Center
Universidad del Azuay
Av. 24 de Mayo 7-77, Cuenca, Ecuador
galvarezc@uazuay.edu.ec

## Abstract

Studies on energy efficiency in vehicles require as input data values for the drag (*Cd*) and the rolling resistance (*Fr*) coefficients obtained under real operational conditions of the vehicles. Frequently, these values are unknown for the case of cargo and passenger transportation vehicles, which are the largest consumers of fuel among ground vehicles. The accepted measurement methods for the determination of *Cd* and *Fr* are expensive and are still being questioned for their low capacity to reflect the real operational conditions of the vehicles. This work evaluates the level of accuracy and precision of *Cd* and *Fr* obtained by on road coast down tests, which is an easy to implement and affordable alternative method to obtain those coefficients under real operational conditions. We added to this method the influence of the road grade and the use of the generalized reduced gradient technique to minimize the differences between the speed obtained by an analytical model, where *Cd* and *Fr* are an unknown, and the instantaneous speed measured during cost down tests conducted following the testing protocols recommended by the SAE J1263. This combined method was applied to a sample of 19 vehicles. The obtained values of *Cd* and *Fr* showed an average accuracy error < 5.2 % and an average precision error < 6.1%, that are acceptable for studies in energy efficiency in vehicles.

**Keywords**: Vehicle performance, generalized reduced gradient, energy efficiency in vehicles.

## Symbols

| | |
|---|---|
| $A$ | *Vehicle transversal area* |
| $C_d$ | *Drag coefficient* |
| $F_d$ | *Drag force* |
| $Fr$ | *Rolling resistance coefficient* |
| $g$ | *Gravity* |
| $m$ | *Vehicle mass* |
| $\rho$ | *Air density* |
| $P$ | *Atmospheric pressure* |
| $Rg$ | *Gravity force* |
| $Rx$ | *Rolling resistance force* |
| $T$ | *Ambient temperature* |
| $V$ | *Measured vehicle speed* |
| $V'$ | *Vehicle speed estimated by the analytical model* |
| $\theta$ | *Road slope* |

## 1. Introduction

Ground vehicles are one of the largest consuming sectors of the energy produced globally (~% 27.5 of the world energy consumption in 2014 (IEA, 2017) and the most important source of atmospheric pollutants (~ 17.4% of the $CO_2$ emissions, (IEA, 2016). Energy efficiency studies show that aerodynamic ($F_d = ½\ Cd\ A\ \rho\ V^2$ ) and rolling resistance ($Rx = Fr\ mg\ Sen\theta$ ) forces are the main sources of energy consumption in the vehicles operation, after the inertial forces and engine inefficiencies (Pascoa et al, 2011). These studies use values of the drag (*Cd*) and the rolling resistance (*Fr*) coefficients as input data. The USEPA lists *Cd* values reported by the manufacturers of the vehicles sold in the US. Nevertheless, these values are unknown for the cargo and passenger transportation vehicles, which are the largest fuel consumers among ground vehicles as they operate a large number of hours per day, pulling heavy loads (Zhang et al, 2015). This is because the cargo and passenger vehicles are usually built on a multipurpose ladder chassis, upon which local enterprises put together non-standardized bodyworks that satisfies client's particular requirements. As a result, this industry is not under the strict regulations of the car manufacturing industry and therefore these local enterprises are not obligated to evaluate the energy and environmental performance of their vehicles.

*Cd* characterizes the force of the air acting over the surface of the moving vehicle. *Cd* is determined inside a wind tunnel testing facility with real scale vehicle mounted on a conveyor belt, which allows including the rotation of the wheels effect (SAE, 2012). These tests are highly expensive and are still being questioned for their low capacity to reflect the real operational conditions of the vehicles (Pascoa et al, 2012; Sandberg, 2011). As an alternative, the on road coast down test has been used. It consists in taking the vehicle to speeds above 120 km/h, eliminate the tractive force to the wheels by setting the gearshift into neutral, and register the vehicle's speed until it comes to a complete stop. Originally the objective of this test is to evaluate the values of the resistant forces acting on the vehicle at certain speed and road conditions aiming to reproduce them on proving stands (dynamometers with or without rollers) for the measurement of fuel consumption and emission of air pollutants. To obtain *Cd* using coast down data, the measured values of speed are compared against the speed values estimated by an analytical model where *Cd* is unknown. The analytical model estimate vehicle speed as a result of a balance the forces acting on the vehicle . It was first described by Hoerner in 1935 (Hoerner, 1935). Diverse approaches have been used to implement the coast down test, most of them differing in the way measurements are made, the type of variables that are recorded and the technique used to compare the estimated speed with the measured speed. After decades of experience, experimentalists concluded that the best results could be obtained with a velocity vs time curve. After 2000 several organizations have attempted to standardized the coast down testing procedure (Bosch, 2000; SAE, 2010; United Nations, 2014). As GPS technology evolved, these tests became easy to implement at low-cost, and with the advance in computing technology, nowadays there are a number of ready-to-use methods to obtain the *Cd* using the speed-measured values.

*Fr* characterizes the rolling resistance generated in the interaction wheel-road. The rolling resistance depends on multiple factors such as material, drawing, manufacturing process, inflation pressure and the working temperature of the wheels. Four standard methods exist for measuring or estimating rolling resistance: Drum (laboratory) measurements, measurements by trailer, coast-down procedures and fuel consumption measurements (Sandberg, 2011). Initially, the process of determining the *Cd* by on road tests required a previous knowledge of *Fr*. Afterwards it was found that *Fr* could be obtained simultaneously with *Cd* (Dayman, 1976) assuming that the rolling resistance force changes with the speed of the vehicle while the aerodynamic force changes with the square of the speed. Currently, it is usual to add all the forces opposing to the movement of the vehicle (except for the aerodynamic and gravity forces) to the rolling resistance. These include bearing friction and energy dissipated in the suspension.

Previous discussion has shown that nowadays the process of obtaining *Cd* and *Fr* by on road coast down tests is a well-accepted engineering practice in the automotive industry for the case of passenger cars and light duty vehicles. However, there are still different alternatives for obtaining *Cd* and *Fr* values from the data obtained in coast down tests, with unknown accuracy and precision levels (Passmore et al, 1994). Furthermore, existing protocols for coast down tests require the use of straight, zero-grade roads to perform the tests. However, under real conditions, it is hard to find segments of roads that fulfill those requirements long enough to complete the tests.

This work incorporates the influence of road grade and the use of the generalized reduced gradient technique to complement the method for obtaining the *Cd* and *Fr* by on road coast down tests aiming to obtain reproducible results with acceptable levels of accuracy and precision for applications related to the reduction of fuel consumption on cargo and passenger vehicle fleets.

## 2. Materials and Methods

Aiming to evaluate the levels of precision and accuracy obtained in the determination of *Cd* and *Fr* applying the generalized reduced gradient (GRG) technique to the results of the on road coast down tests, we replicated this methodology (coast down test + GRG) to a group of vehicles. Then we obtained their *Cd* and *Fr*, and evaluated statistically, their levels of precision and accuracy. Next, we will describe the experimental work performed, the application of the GRG method for obtaining *Cd* and *Fr*, and the statistical analysis carried out to evaluate precision and accuracy.

### 2.1 Experimental work

The tests were performed following the SAE J1263 (SAE, 2010) testing protocols. These protocols specify conditions to conduct the coast down tests such as ambient temperature (5-35°C), frontal (<16 km/h) and transversal wind speed (< 8 km/h), track conditions (dry, slope < 0.5%) and the wheels (>75% of their original drawing, nominal inflation pressure).

We replicated the tests on 17 passenger cars and two transit buses (Table 1). In all the cases, the vehicles were taken to ~120km/h to start the test on an asphalt-paved road in good conditions. Subsequently, the vehicle coasted down with the transmission in neutral position while a GPS registered the vehicle speed and altitude at a frequency of 1 Hz, until it came to a complete stop. Tests were repeated at least 10 times in one and in the opposite way of the road. We used a GPS with a maximum sampling frequency of 10 Hz and speed resolution of 0.01 km/h. Table 2 shows the technical specifications of the instrumentation used.

The frontal area of the vehicles was measured taking a high-resolution picture to the front view of the vehicle at a distance of ˜10 m. Afterwards, the pixels enclosed inside the vehicle's silhouette were counted, and a scaling factor obtained with a known dimension inside the picture was applied. The weight of the vehicles was measured right before starting the test, employing a scale with a resolution of 1 kg. The ambient temperature was measured using a thermometer with a resolution of 1ºC and the atmospheric pressure was measured using a barometer with a resolution of 1 mmHg.

Table 1. Vehicles used in this work

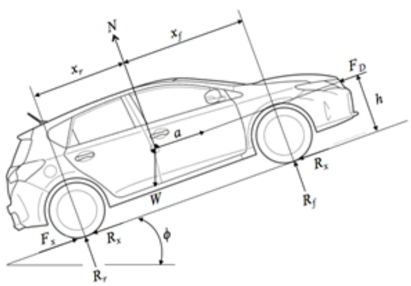
| *Automaker* | *Model* | *Manufacturing Year* | *Frontal Area* $m^2$ | *Weight* *kg* |
|---|---|---|---|---|
| *BMW* | *118* | 2012 | 2,14 | 1370 |
| *Chevrolet* | *Aveo* | 2004 | 2,13 | 1180 |
| *Chevrolet* | *Captiva* | 2009 | 2,63 | 1775 |
| *Chevrolet* | *Corsa* | 2005 | 2,01 | 1160 |
| *Chevrolet* | *Express Van* | 2001 | 3,17 | 2634 |
| *Chevrolet* | *Sonic* | 2011 | 2,12 | 1260 |
| *Chevrolet* | *Spark GT* | 2011 | 2,19 | 1190 |
| *Ford* | *Explorer* | 2010 | 3,06 | 1587 |
| *Ford* | *Focus* | 2013 | 2,24 | 1450 |
| *Irizar* | *Autobus NN* | 2010 | 8,47 | 14250 |
| *Irizar* | *Autobus NU* | - | 8,47 | 14460 |
| *Mini* | *Cooper S Bayswater* | 2013 | 1,98 | 1210 |
| *Mini* | *E* | 2009 | 1,98 | 1640 |
| *Nissan* | *Sentra* | 2006 | 2,02 | 1180 |
| *Nissan* | *X-Trail* | 2006 | 2,53 | 1517 |
| *Renault* | *Clio* | 2006 | 1,89 | 1110 |
| *Seat* | *Ibiza* | 2010 | 2,05 | 1230 |
| *Toyota* | *Corolla* | 2007 | 2,04 | 1177 |
| *Volkswagen* | *Bora* | 2007 | 2,11 | 1460 |

Table 2. Technical characteristics of instruments used this study

| Variable | Symbol | Instrument | Resolution |
|---|---|---|---|
| Time | *t* | GPS | Position: 3.0 m 2D-RMS<br>Accuracy: < 3m CEP (50%)<br>Frequency: 1 Hz |
| Position: latitude, longitude, altitude | - | | |
| Speed | *V* | | |
| Slope of the track | *θ* | | |
| Mass of the vehicle | *m* | | 1 kg |
| Atmospheric pressure | *P* | Barometer | 1 mmHg |
| Ambient temperature | *T* | Thermometer | 1$^{o}$C |
| Frontal area | *A* | Camera + CAD software | High resolution picture |

## 2.2 Speed model

The predicted vehicle speed ($\hat{V}$), at any time during a coast down test, was calculated by solving the differential equation number 4, subject to the initial conditions under which the test was performed. In this study, it was assumed that *Cd* and *Fr* are independent of vehicle speed. From fluid mechanics, it is known that the drag coefficient *Cd* changes with Reynolds Number, i.e. with the speed of the vehicle. However this variation is negligible (<1%) for the speed range in which the ground vehicles are used (*V* < 120 km/hr). Similarly, at high speeds (>120 km/h) the rolling resistance coefficient *Fr* grows exponentially with the speed (Gillespie, 1992 ). However, at low speeds (<120 km/h) changes in *Fr* are also negligible.




$$R_x = F_r\, mg \cos\theta \qquad (1)$$

$$F_d = \frac{1}{2} C_d \rho_a A V^2 \qquad (2)$$

$$R_g = mg \;\text{sen}\,\theta \qquad (3)$$

$$-m\,\frac{d\hat{V}_{(t)}}{dt} = R_x + F_d + R_g \qquad (4)$$

Figure 1. Forces acting on the vehicle during an on road coast down test

## 2.3 Application of the reduced gradient method to obtain *Cd* and *Fr* from coast down test data

*Cd* and *Fr* are obtained as those values of *Cd* and *Fr* that minimize the absolute differences between the measured speed *(V)* and the estimated speed $(\hat{V})$, for all times (*t*) at which the vehicle speed was sampled during the coast down test. This minimization becomes a non-linear programming problem where the objective function is:

$$\textbf{Minimize}\ \left(\sum (V_{(t)} - \hat{V}_{(t)})^2\right)_{(Cd,Fr)} \qquad \textbf{(5)}$$

subject to restrictions 1 to 4, and to the no negativity condition for the *Cd* and *Fr* variables. Multiple numeric methods exist to solve this nonlinear programming problem. The reduced gradient method (GRG) stands out among the many other methods due to its simplicity. The GRG is a method used for optimization in nonlinear problems that belongs to the family of the reduced gradient techniques. It converts the restricted problem into an unrestricted one by direct substitution. This method requires and initial estimated value.

### 2.4 Evaluation of the accuracy and precision of *Cd* and *Fr*

The coast down test plus the GRG methodology was replicated more than 10 times to a group of vehicles in order to obtain their *Cd* and *Fr.* For every vehicle the average *Cd* and *Fr* values were obtained and compared against the corresponding reference values. In the case of *Cd,* the reference values where the ones measured by the automakers. In the case of *Fr,* the reference values were the ones reported in the literature on tire performance studies. As a measurement of accuracy error, we reported the relative percent difference.

The levels of uncertainty of *Cd* and *Fr* were determined as the confidence interval values for these variables, considering they assume a T-student statistical distribution. The level of confidence used was 95%.We reported as the precision error, the proportion of this interval with respect to the average value obtained for the aforementioned variable.

## 3. Results

Tests were performed in different locations on asphalted roads where the average atmospheric pressure was 75kPa and the average ambient temperature was 20ºC. Figure 2 illustrates the obtained results.

Figure 2.a shows values of speed measured in a coast down test for the case of a transit bus of 90 passengers. Additionally this figure shows the effect of solving equation 4 with arbitrary initial values of *Cd* and *Fr,* and with the obtained values for these variables using the GRG technique. In the latter case, Figure 2.a shows that the estimated speeds reproduced the measured values and therefore these values correspond to representative values of *Cd* and *Fr* for the conditions under which the tests were performed.

*Accuracy:* Figure 2.b compares the obtained values for *Cd* against the in-laboratory measured values of *Cd* and reported by the car manufacturers. For the case of *Fr,* Figure 2.c compares the obtained values in this paper against the ones reported by Wong et al (2008) for tires rolling on asphalted surfaces. The accuracy of the obtained values was measured as the relative difference between the measured value and the reference values. The average relative difference was 5.2% and 14% for *Cd* and *Fr* respectively. Differences up to 18% were observed for *Cd*, however, on those extreme cases the authors are not certain that the values used as reference values correspond exactly to the vehicles used during the tests.

The coast down test plus the GRG technique attributes to *Cd* the contributions from all the forces opposing to the vehicle's motion that vary with the square of the speed, regardless of whether those forces correspond to the definition of an aerodynamic force or not. Likewise, this methodology attributes to the *Fr* the contributions of all the forces that vary linearly with the speed irrespective of whether those forces are rolling resistant or not. This means that there should be potential differences between the *Cd* and *Fr* values measured in laboratory and the ones measured through coast down tests. Our results show that those differences are small for the conditions of our experiments. The results of greatest interest, for energy efficiency studies, are the ones obtained by on-road tests, because they reflect the vehicle's real operating conditions. The obtained results in this study show that for the cases of ground vehicles transporting passenger and cargo at $V < 120$ km/h, these differences are minor (<5%), which agrees with Morelli et al (1981). It is important to stress that the values reported in this study are not valid for vehicles traveling at speeds grater that 120 km/h.

*Precision:* The vertical lines in figures 2.b and 2.c represent the precision obtained for *Cd* and *Fr*. It was found that this level of uncertainty represents an average of 6.1% and 8% of the *Cd* and *Fr* measurements, respectively. Figure 2.a also shows that the speed profile obtained experimentally exhibit irregularities that were caused by the non-perfect flatness of the road. This observation evidences the importance of including instantaneous measurements of the road grade simultaneously with speed measurements during the test. GPS have low precision in their measurements of altitude. Therefore, the measurement of road grade represent the major source of uncertainty when determining *Cd* and *Fr* by on road coast down tests under real conditions. These results on precision show that the determination of *Cd* and *Fr* through coast down tests under the same working conditions of the vehicles, plus the use of the GRG methodology generates results with acceptable levels of accuracy and precision for studies on energy efficiency in vehicles.

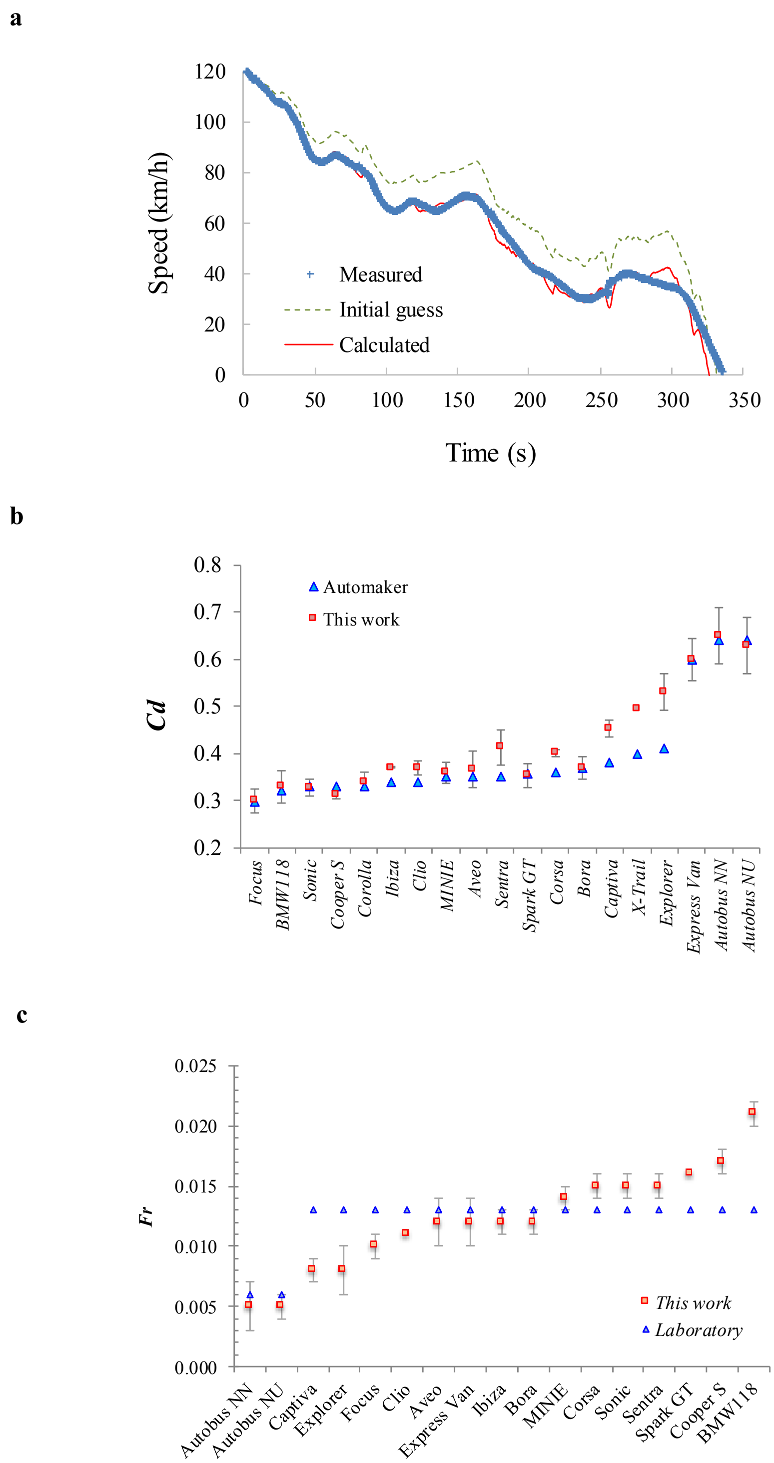



Figure 2. Results of applying the on-road coast down tests together with the GRG technique to the determination of the vehicles' *Cd* and *Fr* coefficients. (a) Measured and estimated speeds during a coast down test of a 90-transit bus. Comparison of the values obtained for (b) *Cd*, and (c) *Fr* against the measured values in laboratory. The vertical line describes the precision of *Cd* and *Fr*.

## 4. Conclusions

Currently there is need for an affordable and easy to implement methodology to determine *Cd* and *Fr* values, under real conditions, and with acceptable levels of accuracy and precision for studies on energy efficiency in cargo and passenger vehicles. To address this need we proposed the use of on road coast down tests with the use of modern speed measurement technologies (GPS) in combination with the generalized reduced gradient method, and the inclusion of instantaneous road grades effects.

Multiple coast down tests (>10) over a sample of 19 vehicles, and the use of the generalized reduced gradient technique, showed that this combination generates *Cd* and *Fr* results with accuracy levels and precision appropriate for studies on energy efficiency in vehicles. The average accuracy error was < 5.2% and the average precision error was < 6.1 %.

This methodology generates *Cd* values that encompass all the forces opposing to the motion of the vehicle and are proportional to the square speed, and *Fr* values that embody all the forces that are proportional to the vehicle speed, irrespective of whether those forces correspond to aerodynamic forces or to the rolling resistance forces, respectively. These values reflect the real average performance of ground vehicles at speeds below 120 km/h.

## Acknowledgements

This study was partially financed by the Mexican Council for Science and Technology (CONACYT). The authors thank the contributions of Dr. Daniel Cordero, from the Universidad del Azuay during the experimental tests.

## References

Bosch (2000). Empirical determination of coefficients for aerodynamics drag and rolling resistance. *Automotive Hand Book*. 5th edition. 339-340.
Dayman, B. (1976). Tire rolling resistance measurements from coast-down tests. *SAE Technical Paper Series* 760153. Doi:10.4271/760153.
IEA (2016). CO2 emissions from fuel combustion highlights*. International Energy Agency.*
IEA (2017). World Energy Statistics 2017. *International Energy Agency.*
Gillespie, T.D. (1992). *Fundamentals of Vehicle Dynamics*. SAE international.
Hoerner, S. (1935). Determination de la resistance aerodynamique des vehicules par la methode en roue libre, *Z. Versuch. Dtsch. Ing*., 79:1028—1033
Morelli, A. (1981). Automobile aerodynamic drag on the road compared with wind tunnel tests. *SAE Technical Paper Series.* Volume: 1. ISSN: 0148-7191
Páscoa, J.C., Brójo, F.P., Santos, F.C., Fael, P.O. (2012). An innovative experimental on-road testing method and its demonstration on a prototype vehicle. *Journal of Mechanical Science and Technology.* 26 (6):1663-1670
Passmore, M.A., Le Good, G.M. (1994). A Detailed Drag Study Using The Coastdown Method. *SAE Technical Paper Series.* 940420.
SAE (2010), SAE J1263 201003. Road load measurement and dynamometer simulation using coast down techniques. *SAE International.*
SAE (2012). SAE J1252 201207. Wind tunnel test procedure for trucks and buses. *SAE International.*
Sandberg U., Haider M., Conter M., Goubert L., Bergiers A., Schwalbe Gernot G.K., Zöller M., Boujard O., Hammarström U., Karlsson R., Ejsmont J. A., Wang T., Harvey J.T. (2011). Rolling resistance basic information and state-of-the art on measurement methods. Models for rolling resistance. In *Road Infrastructure Asset Management systems* (MIRIAM), 2011.
United Nations (2011). E/ECE/324 Regulation No. 83 (Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements), page 101, Annex 4, Appendix 3
White, F.M. (2008). *Fluid mechanics*. McGraw-Hill. 7th edition
Wong, J.Y. (2008). *Theory of Ground Vehicles*. 4th ed. 2001: Wiley
Zhang, D., Ivanco, A., and Filipi, Z. (2015). Model-based estimation of vehicle aerodynamic drag and rolling resistance. *SAE Int. J. Commer. Veh.*8(2):433-439. doi:10.4271/2015-01-2776.

**Biography**

**Dr. Jose Ignacio Huertas:** Mechanical engineer from Los Andes University, Colombia (1988). Doctor of Science from Washington University, St. Louis, USA (1997). Associate professor at Los Andes University until 2002. Currently, full time professor at Tecnológico de Monterrey, Mexico. Has formed and leaded the Energy Research Group in Colombia and the Automotive Engineering Research Center-CIMA in Mexico. Has published more than 45 papers mainly related to energy and air pollution. Has graduated 6 PhD and 61 MSc. students. Has completed 90 research projects financed by private companies and governmental institutions. Currently works as researcher of the Energy and Climate Change Research Group of the School of Science and Engineering at Tecnológico de Monterrey. Is member of the national system of researcher in both Mexico and Colombia.

**MSc. Gustavo Alvarez**: Automotive engineer from Universidad del Azuay, Ecuador (2012). Master in automotive engineering at Tecnológico de Monterrey, Mexico (2014). Currently, associate professor at Universidad del Azuay and works as researcher of the ERGON - Automotive Engineering Research and Development Center. Has worked in projects related to energy evaluation, air pollution and sustainable transport and mobility with private companies and governmental institutions. Has graduated 2 MSc. and 7 undergraduate students.