

An Experimental Methodology for Measuring of Aerodynamic Resistances of Heavy Duty Vehicles in the Framework of European CO₂ Emissions Monitoring Scheme

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ABSTRACT

Due to the diversity of Heavy Duty Vehicles (HDV), the European CO₂ and fuel consumption monitoring methodology for HDVs will be based on a combination of component testing and vehicle simulation. In this context, one of the key input parameters that need to be accurately defined for achieving a representative and accurate fuel consumption simulation is the vehicle's aerodynamic drag. A highly repeatable, accurate and sensitive measurement methodology was needed, in order to capture small differences in the aerodynamic characteristics of different vehicle bodies. A measurement methodology is proposed which is based on constant speed measurements on a test track, the use of torque measurement systems and wind speed measurement. In order to support the development and evaluation of the proposed approach, a series of experiments were conducted on 2 different trucks, a Daimler 40 ton truck with a semi-trailer and a DAF 18 ton rigid truck. Two different torque measurement systems (wheel rim torque sensors and half shaft torque sensors) were used for the measurements and two different vehicle tracking approaches were investigated (high precision GPS and opto-electronic barriers). Results were pooled and compared against results from similar measurements performed by the OEMs at their own proving grounds. The method was proven to be accurate. The analysis showed good repeatability and reproducibility characteristics and a good sensitivity of the method. Based on the findings it was decided that this measurement methodology is suitable and can be included in the European legislation.

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INTRODUCTION

The European Commission (EC) in joint collaboration with Heavy Duty Vehicle manufactures (ACEA) and other research bodies has been preparing a new legislative framework for monitoring CO₂ emissions from Heavy Duty Vehicles (HDV) in Europe. The core of the upcoming CO₂ monitoring methodology is based on vehicle simulation. This approach offers the possibility to accurately capture the highly diverse characteristics of HDVs and their influence on fuel consumption and CO₂ emissions, without heavily increasing the complexity and the costs for vehicle certification. A series of studies have been performed to demonstrate the advantages

of a simulation-based approach and lay down the lines for a future certification scheme [1]. Similar simulation-based approaches have been so far adopted by other major HDV markets, e.g. GEM in the USA or the Fuel Economy Standard 2015 of Japan.

One of the key parameters affecting fuel consumption and CO₂ emissions of HDVs, particularly under highway and extra urban driving conditions, is their aerodynamic performance. Aerodynamic drag is identified as the most influential parameter when it comes to vehicle energy consumption for long haul delivery missions and other relevant high speed HDV

operations (e.g. intercity coaches). Long haul delivery and intercity passenger transport account together for ca. 60 % of CO₂ emissions generated by HDVs in Europe [2]. Thus it is of key importance for a CO₂ monitoring methodology to be able to accurately capture the aerodynamic performance of HDVs, both on an comparative level, e.g. the difference in aerodynamic performance between 2 vehicles, and on an absolute level, e.g. the exact resistance introduced by the vehicle's aerodynamics. A new methodology was necessary for measuring the vehicle aerodynamic drag and also the necessary input variables to be used in a vehicle simulation model.

A study [3] funded by the EC investigated possible options for measuring the aerodynamic resistances of an HDV, mainly focusing on two types of tests: coast-down and constant speed measurements. The study compared the benefits of a coast down based approach with respect to a steady state speed test one. The analysis considered elements of existing standards for vehicle road load calculation such the SAE standards J2881 [4], J2978 [5], the EPA standard EPA-HQ-OAR-2010-0162, the only public standard at the time for HDV road load calculation as well as the provisions of the ISO standard 10521-1, (chapter 5.5), which fully includes the procedures of the previously mentioned SAE standards. Result revealed that although these tests might be suitable for the road load determination of light duty vehicles, a series of issues would not allow for the adoption of one of these standards. Some of which were:

- Simplifications in the test procedures and assumptions which may result in inaccuracies
- The coast-down drivetrain losses (e. g. idle differential friction), different to the normal powered case, which are not taken into account
- The wind velocity is only limited and in certain cases not considered for the data analysis in any way.
- Only constant road gradients are considered, but even on most appropriate test tracks slopes exist
- A correction of tire inflation pressure to temperature differences between garage and test track environment, suitable only for LDV tires at 3 bar.

The conclusions of this analysis resulted in a proposal to adopt a constant speed based approach for the experimental determination of HDV aerodynamic resistances. A first draft proposal on a possible constant speed based test was provided by ACEA, based on internal testing at various OEM sites. This proposed methodology was then further supplemented, based on the findings of the (LOT2) campaign and evaluated both by OEMs and independently by the Joint Research Centre (JRC) of the European Commission. This paper presents the results of the evaluation campaign together with a brief overview of the testing methodology.

PROPOSED METHODOLOGY

General

The general model (eq 1) that describes the aerodynamic resistances applied on a vehicle is considered by the vehicle simulator to be used for CO₂ monitoring.

$$F_{air} = C_d(\beta) \cdot A_{cr} \cdot \frac{\rho_{air,ref}}{2} \cdot v_{air}^2 \quad (1)$$

where:

F_{air} = air drag [N]

C_d = air drag coefficient [-]

β = average air flow angle (yaw angle) [°]

A_{cr} = cross sectional area of the vehicle [m²]

$\rho_{air,ref}$ = air density at reference conditions, [kg/m³]

v_{air} = wind velocity [m/s]

Scope of the constant speed testing methodology is to determine the aerodynamic drag coefficient (C_d) as a function of the yaw angle (β) with direct torque measurement. To achieve this, the wheel torque of the driven wheels, the vehicle velocity, the actual air flow velocity (vehicle velocity plus wind) and the air flow direction are measured synchronously over straight motion on a test track. Measurements are performed at two different constant vehicle speeds (V_{low} and V_{high}) under defined conditions. The V_{low} of the testing is a constant velocity between 10 - 15 km/h while the target V_{high} should be between of 85 - 90 km/h. In case a vehicle cannot achieve the foreseen high speed, the maximum achievable vehicle speed is applied.

Given the abovementioned measured data and information regarding the slope profile of the test sections, it is possible to calculate the road load of the vehicle (see [Figure 1](#)) based on the following qualified assumptions:

- rolling resistance force (F_{rol}) independent of vehicle speed¹
- air drag force being quadratic to the velocity

The aerodynamic drag is calculated, for yaw angles (β) between 0 and 3°, based on the actual measured air flow velocity.

In addition to the key elements of the test demonstrated in [Figure 1](#), important parameters of the procedure include the use of high precision positioning instrumentation for accurate recording of vehicle position and ground speed (opto-electronic barriers or very high precision GPS system), weather information and data retrieved from vehicle sensors. Detailed specifications are foreseen for each instrument and for the sampled signals.

1. Rolling resistance is influenced by vehicle speed. However the analysis presented in the paper shows that this influence is limited under the defined test conditions and does not affect significantly the calculated air drag force. Studies are ongoing in order to find a way to include the effect of speed on rolling resistance value into the AD calculation method.

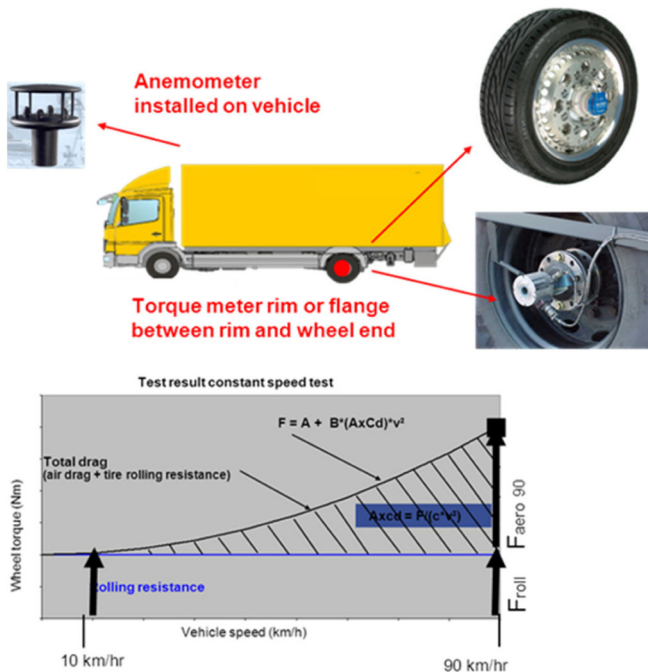


Figure 1. Key points of the proposed testing methodology

Test Track

In terms of the testing ground different types of test track geometries are foreseen (Figure 2). The important factor in this case is the execution of measurements in both directions in order to cancel out to the best possible extent the effects of ambient wind. The test track must have straight section(s) where the measurements are performed. An extra straight length before each measurement section is foreseen in order to allow for the stabilization of wind flow around the vehicle or the drivetrain torque after cornering.

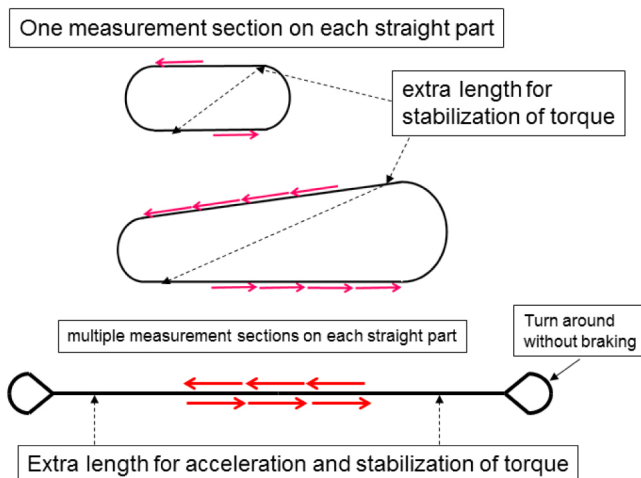


Figure 2. Testing grounds and segments

Test Sequence

The test is comprised of 5 phases, the preparation phase, the warm up phase, the high speed test phase, the low speed test phase and control phase as described below.

Preparation Phase

During this phase, the various measurement instruments are mounted on the vehicle and their good operation is checked (e.g. the drive-wheels should be checked for proper rotation with installed torque meters or half shafts). The vehicle's mass is measured or calculated and the tyres are checked for the maximum allowable inflation pressure. The proper vehicle and trailer (if present) heights are verified.

The positioning equipment is also set up during this phase, either only on the test track (final definition of test section via installation of the opto-electronic barriers) or on the vehicle and on the test track via high precision differential GPS.

Data registration of all relevant measurement signals is verified and the engine is left at idling for preconditioning without parking brake.

Warm-Up Phase

During this phase the vehicle is driven for 90 minutes at V_{high} to assure that the tyres reach a constant pressure and temperature level, and that the powertrain and drivetrain reach a constant coolant and lubricant temperature level. During this phase, the vehicle is driven in both track directions in order to achieve a balanced warm up of the tires and collect data for subsequent control checks, and for determining the misalignment and position error of the mobile anemometer.

At the end of the warm up phase, the vehicle is brought to a standstill on a selected area of the test track. The vehicle is slowed down carefully without braking and rolled out for the last meters, with free clutch / neutral gear and engine switched off. Once still and in zero torque conditions, the torque sensors mounted on the vehicle are checked for drift and are subsequently zeroed.

High Speed Test Phase

After the zeroing of the torque sensors the vehicle is driven for a minimum of 2 km at V_{high} in order to reach stabilization again. Subsequently the V_{high} test is performed. During testing it must be ensured that:

- the driving speed is constant at least for the defined measurement sections and the preceding stabilization sections
- the vehicle is driven through the measurement section along a straight line without steering
- the amount of recorded measurement sections leads to enough valid "evaluation sections" in the data processing
- a minimum of 20 measurement sections for each driving direction are performed with an equal amount of sections driven in both directions; e.g.: either enough rounds on an one-way circuit track with two measurement sections or an equal amount of measurements driven in each direction on a circuit or straight line track with one measurement section,